

BAYESIAN UPDATING OF VULNERABILITY ASSESSMENT FOR A SHIELD TUNNEL UNDER ADJACENT EXCAVATION DISTURBANCES

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Vulnerability is a fundamental component of risk and its understanding is essential for evaluating infrastructure reliability and mitigating risks associated with their damages. The work focuses on refining the disturbance vulnerability framework established for specific geological formations, and enhancing its adaptability to transfer to other geological environments. This endeavor contributes to avoiding substantial computational costs. A novel methodology is developed that utilizes field measurements to update vulnerability model of shield tunnels. It incorporates the numerical simulation-based vulnerability analysis and a surrogate modeling technique into the Bayesian updating framework, where statistical characteristics of relevant design parameters are accordingly considered. An illustrative scenario is herein employed to illustrate and verify the proposed framework. Several indicators for excavation disturbances are herein provided, specifically emphasizing the horizontal displacement of tunnels as a measure of their performance when confronted with nearby foundation excavations. Understanding such vulnerability is essential for evaluating infrastructure reliability and mitigating risks associated with their damages. To characterize the uncertainty of disturbance intensities, the lateral deflection of diaphragm walls is employed as an intermediate variable to indirectly condition tunnel displacement. The present work achieves a significant update of the excavation-induced vulnerability model based on a local damage database, facilitating probabilistic assessment of damage states in existing tunnels caused by deep foundation excavations across diverse geological environments.

Keywords: Bayesian updating, excavation disturbances, vulnerability assessment, surrogate model.

1. Introduction

With the rapid development of urban subway, the demand for underground parking and supermarkets near tunnels has grown. Geotechnical activities, such as deep foundation excavations, inevitably affect the initial stress state of surrounding strata, causing soil movement and subsequent tunnel deformation, and leading to deformation of nearby structures, accelerate the degradation of structural performance, and result in tunnel segment cracks, water leakage, joint openings, misalignments, and other damages (Zhang 2022). This can further cause significant risks to structural integrity and directly threaten the safe operation of subway systems.

Current research on the impact of adjacent disturbances on existing tunnels, mainly involve four approaches (Liang et al. 2018): field monitoring model testing, semi-analytical method, and numerical simulation. Each method has its advantages, limitations, and scope of applicability. Field monitoring and model testing provide realistic representations of engineering conditions but require substantial time and resources. Semi-analytical methods based on elastic theory can preliminarily provide disturbed displacement and stress fields, yet their input parameters often differ considerably from actual geological conditions. Numerical methods, leveraging complex constitutive models, can effectively describe the mechanical behavior of soil and structures under adjacent disturbances, particularly in complex geological conditions, and nevertheless, they are limited by hardware resources, require high modeling proficiency, and exhibit weak generalization capabilities.

Furthermore, the above methods often remain confined to deterministic analyses, with limited discussions on the uncertainty of disturbance intensity and the vulnerability assessment of adjacent tunnels. The performance levels of an infrastructure are defined by damage thresholds known as limit states, which describe the boundaries between different damage conditions or states (Wu et al. 2009; Argyroudis et al. 2019). However, the vulnerability framework based on specific strata often suffers from discrepancies between geotechnical parameter values and actual engineering conditions, particularly regarding the influence of variability in soil compressibility, making it difficult to accurately evaluate tunnel damage under different strata conditions.

The Bayesian algorithm enables the probabilistic updating of soil parameters and has been applied in risk assessments of deep foundation excavations (Lo and Leung 2019, Xie et al., 2019). However, research on updating algorithms for tunnel damage evaluation under adjacent excavation disturbance conditions remains

scarce. Moreover, due to the complexity of disturbance scenarios, a systematic framework for tunnel vulnerability evaluation under disturbances has yet to be established. To address these challenges, this study employs numerical orthogonal experiments to construct surrogate models linking tunnel damage indicators to physical and mechanical parameters under adjacent excavation disturbances. According to Bayesian updating, a probabilistic mapping between tunnel damage indicators and engineering design parameters is established. Combined with a vulnerability evaluation process for tunnels under adjacent excavation disturbances, vulnerability curves for tunnels under specific strata and engineering parameters are derived. The proposed method can provide valuable guidance for quantifying tunnel damage and implementing recoverability measures.

2. Bayesian updating framework for vulnerability assessment

2.1. Overview

The present methodology aims at establishing a Bayesian updating framework for vulnerability assessment of a shield tunnel subjected to adjacent excavation disturbances, addressing the limitation of tunnel damage and resilience databases in specific geological conditions. Fig. 1 outlines a schematic procedure involved in determining the vulnerability assessment as follows:

- (i) **Framework Initialization:** Preparation for the updating framework: the first step is to define soil and structural properties, relative position relationship, and definition of damage stages and expected performance targets.
- (ii) **Numerical modelling:** a finite difference model (FDM) of shield tunnels under adjacent foundation excavations is constructed. Extensive numerical simulations are performed to create a comprehensive database between the tunnel damage index (DI) and excavation disturbance indicator (EDI).
- (iii) **Surrogate Modeling:** Construct a quadratic response surface model with interaction terms using orthogonal experimental design and numerical simulations to capture key relationships between input parameters and tunnel damage indices.
- (iv) **Bayesian Updating:** Based on the design and field monitoring data for a specific project, the likelihood function under specific conditions is obtained by combining the surrogate model. Bayesian estimation is then used to determine the posterior probability distribution of tunnel damage indexes under adjacent excavation disturbance.
- (v) **Vulnerability Assessment:** Utilize the updated disturbance demand model and lognormal probability distribution to refine the tunnel vulnerability surface under adjacent excavation disturbances.

2.2. Definition of damage states

Horizontal displacement is a more suitable for assessing shield tunnel damage from adjacent deep excavations than convergence deformation. The Chinese metro code (CJJ/T202–2013) limits maximum horizontal displacement to 10–20 mm. To account for non-uniform tunnel movement, average horizontal displacement is used to characterize damage. Thresholds for tunnel horizontal displacement at different performance levels, based on the code and prior studies are listed in Table 1.

2.3. Construction of a surrogate model

Based on the FDM of a shield tunnel, an L25 orthogonal experiment design is performed. The variables include three indicators representing excavation disturbance intensity (tunnel depth H_r , horizontal distance between the tunnel and wall L_r , thickness of the diaphragm wall T_{wall}), one representing the stiffness of diaphragm walls (E_{wall}), and one representing soil compression modulus (E_{soil}). For each excavation scenario, four different excavation depths (H_{exc}) are considered, resulting in 25 test scenarios and 100 test points.

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

where Y represents the horizontal displacement of the tunnel, X_i represents the i th influencing factor, and ε is the error term. β_0 , β_i , β_{ii} , and β_{ij} denote the coefficients for the constant term, linear terms, quadratic terms, and interaction terms, respectively.

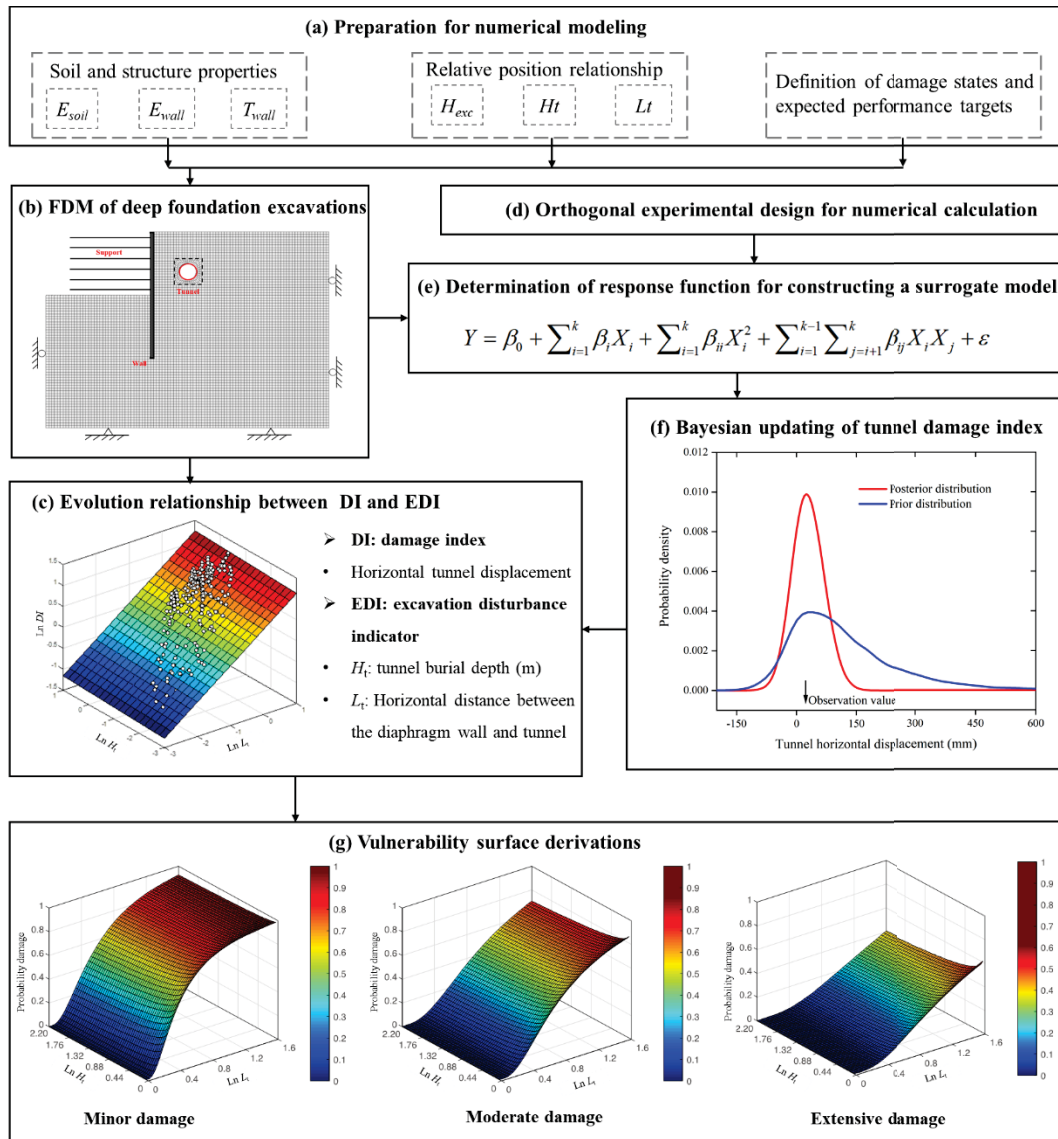


Fig. 1. Schematic procedure for updating vulnerability surfaces based numerical modelling and Bayesian algorithm.

Table 1. Definition of damage states for a tunnel subjective to adjacent disturbances.

Damage states DS	Damage index DI Horizontal displacement	Performance level
None	DI ≤ 5mm	No damage
Minor	5mm < DI ≤ 10mm	Normal availability
Moderate	10mm < DI ≤ 20mm	Available after repair
Extensive	DI > 20mm	Endangering life safety

2.4. Updating the damage index of tunnel linings

As elaborated earlier, the horizontal displacement of tunnels is defined as the damage index in the present study. Before applying the Bayesian model, the prior probability distribution of the tunnel damage index must be established. Monte Carlo sampling is then performed to generate 10,000 samples for abovementioned variables in Section 2.3, and the surrogate model is accordingly used to calculate the prior probability distribution $f(\cdot)$ of tunnel damage index.

For a hypothetical scenario, the likelihood function can be determined by combining the surrogate model and relevant design parameters from such hypothetical case. Based on the principles of Bayesian updating, the posterior probability distribution of tunnel damage index under adjacent excavation disturbances is expressed as:

$$f(\theta|y) = \frac{L(\theta|y)f(\theta)}{\int_{-\infty}^{+\infty} L(\theta|y)f(\theta)d\theta} \quad (2)$$

where $L(\cdot|y)$ represents the likelihood function. It can be anticipated that the predicted values of the tunnel damage index will consistently fall within the 95% confidence intervals of the two distributions and align more closely with the mean of the posterior probability distribution of the tunnel damage index. Additionally, the variability of the updated target values is also reduced.

2.5. Updating vulnerability evaluation

A logarithmic linear equation is used to describe the relationship between the DI and EDI, as presented in Eq. (3). The median threshold values for the selected excavation disturbance intensity, along with the corresponding damage states, are determined based on a regression model derived from the results of nonlinear numerical analysis and predefined criteria:

$$\ln(DI) = a_0 + a_1 \ln(EDI_1) + a_2 \ln(EDI_2) \quad (3)$$

where a_0 , a_1 and a_2 serve as fitting parameters of the regression equation; two excavation disturbance intensities are $EDI_1(L_i)$ and $EDI_2(H_i)$, respectively. The damage state definitions and threshold divisions for the tunnel, using horizontal displacement as the damage index, are determined by the standards. The relevant thresholds can be found in the "CJJ/T202-2013 Technical code for protection structures of urban rail transit." A log-normal distribution function is used to describe the tunnel vulnerability surface:

$$P(ds \geq ds_i) = \Phi \left[\frac{1}{\beta} \cdot \ln \left(\frac{EDI}{EDI_{ds_i}} \right) \right] \quad (4)$$

where $P(\cdot)$ represents the probability of exceeding a certain damage state; ds_i represents i th damage state; Φ is the cumulative probability function of the standard normal distribution; EDI_{ds_i} is the disturbance intensity threshold corresponding to the i th damage state, and β is the log standard deviation, which reflects the variability of the vulnerability surface. The posterior distribution of the tunnel damage index, obtained through Bayesian updating, is stored in the DI-EDI database. When disturbance conditions are similar but the geotechnical parameters, such as soil compressibility modulus, differ, the tunnel vulnerability evaluation index can be updated. This is done by combining the tunnel damage state and threshold definitions with the logarithmic distribution function used for vulnerability assessments.

3. An illustrative example

3.1. Numerical method-based vulnerability analysis

Fig.2 illustrates a finite difference model of a shield tunnel influenced by deep foundation excavations. To mitigate boundary effects, the soil domain is set to $12.9D$ in width and $10.32D$ in depth, where D represents the tunnel's outer diameter ($D=6.2\text{m}$). As depicted in Fig.2(a), the tunnel lining is modelled using elastic lining elements, with a thickness of $t=0.35\text{m}$ and a width of $b=1.0\text{m}$. The linings are characterized by an elastic modulus of 34.5GPa , a Poisson's ratio of 0.2 , and a unit weight of 25kN/m^3 . A foundation pit excavation was carried out near an interval tunnel in a certain city. The tunnel is buried at a depth of 15m , with the excavation depth of the pit reaching 16m and a width of 20m . The support system consists of a combination of multiple transverse struts and diaphragm walls. The specific parameter values are shown in the table 2. This numerical model has been validated as effective through the comparison with Zhang (2022).

Table 2. Soil parameters for an illustrative example.

γ /kN/m ³	c' /kPa	ϕ' /(°)	K_0	ψ /(°)	m	p^{ref} /kPa	ν	E_{50}^{ref} /MPa	$E_{\text{ur}}^{\text{ref}}$ /MPa	$E_{\text{oad}}^{\text{ref}}$ /MPa	R^f	G_0^{ref} /MPa	$\gamma_{0.7}$ /10 ⁻⁴
18	8	27	0.625	0	0.8	100	0.2	3.6	21	3	0.9	84	2

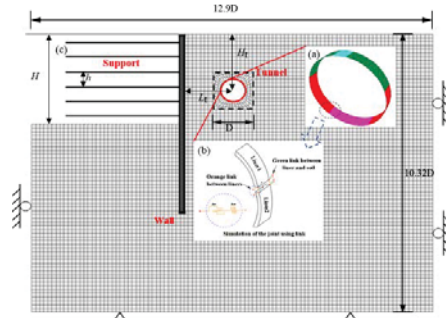


Fig. 2.FDM of a shield tunnel subjective to deep foundation excavations: (a) Tunnel lining; (b) the simulation; (c) foundation excavations with braced supports.

3.2. Bayesian updating-base vulnerability assessments

After obtaining numerous sample points from numerical simulations, a quadratic response surface with cross terms as mentioned in Section 2.3 is used to fit the data and calculate the coefficients. Table 3 presents specific coefficient values where the explanations of symbols 2_0 , 2_i , $^2_{ii}$, and $^2_{ij}$ can be found in Section 2.3. To evaluate the accuracy of the surrogate model, its predictions were compared with the results obtained from finite difference method (FDM) simulations. The comparison showed a strong correlation between the two sets of results. Specifically, the R-squared value from the correlation analysis was 0.971, indicating that the surrogate model predicts tunnel damage indices with a high degree of accuracy.

Table 3. Soil parameters for an illustrative example

signs	Specific values of different influencing factors															
2_0	690.4															
2_i	0.0	20.7	-1583.5	-61.9	-52.0	73.2										
$^2_{ii}$	32.7	0.8	741.0	1.3	0.9	5.7										
$^2_{ij}$	-0.1	-14.9	-0.5	-0.7	-1.4	-0.3	67.5	46.7	-61.0	-31.9	2.3	-5.4	-0.7	-3.1	-0.7	2.6

As shown in Fig. 4, the predicted tunnel damage index values fall within the 95% confidence interval and are closer to the posterior mean, with reduced variability in the updated target values. The revised disturbance probability demand model, combined with damage thresholds and a log-normal distribution, updates tunnel vulnerability surfaces under adjacent excavations.

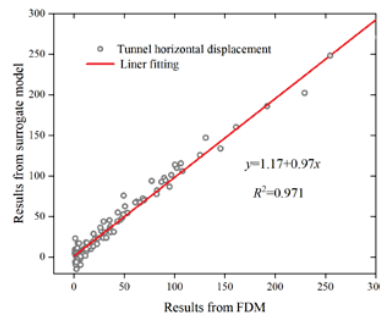


Fig. 3. Comparison of the results of surrogate model prediction and finite difference method.

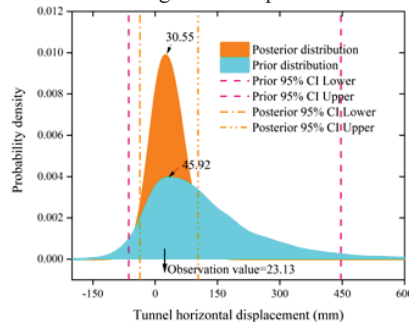


Fig. 4. The prior and posterior distributions of the tunnel damage index.

By employing the revised disturbance demand model, coupled with the threshold classification of tunnel damage states and the lognormal probability distribution function, the vulnerability surface of tunnels under adjacent excavation disturbances is updated, as described in Fig. 5. After Bayesian updating, the damage probabilities of the tunnel segmental lining for minor, moderate, and extensive damages show a slight decrease. Specifically, for a case with $L_i=20\text{m}$ and $H_i=21\text{m}$, the damage probabilities of these three damage states decrease by 3.8%, 10.4% and 16.8%, respectively.

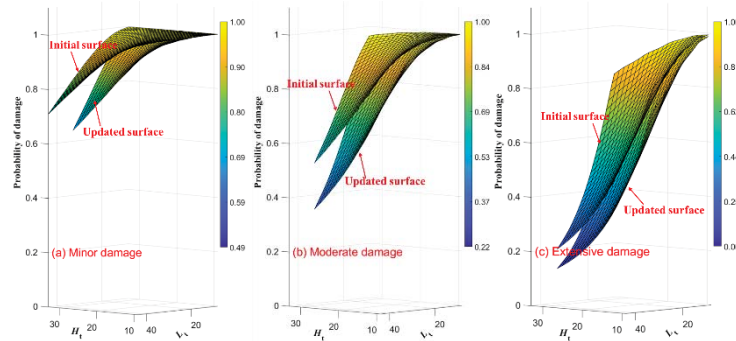


Fig. 5. Vulnerability surfaces for the initial and updated stratigraphic environments: (a) Minor damage; (b) Moderate damage; (c) Extensive damage.

4. Conclusion

This study successfully refines the numerical method-based vulnerability model of shield tunnels under adjacent excavation disturbances by using Bayesian updating. By constructing a surrogate model and incorporating actual engineering design parameters, the applicability of the tunnel disturbance damage database is enhanced, which is initially limited to specific strata.

Such improvement allows the model to be applied to a wider range of engineering activities, thereby increasing the robustness and versatility of the tunnel vulnerability assessment algorithm. The findings contribute to more accurate and adaptable risk assessments for tunnels affected by adjacent excavation disturbances.

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