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Sensitivity analysis of structural health risk in operational tunnels

Wenli Liu[a], Xianguo Wu[a], Limao Zhang[b,*], Yanyu Wang[a], Jiaying Teng[c]

[a] School of Civil Engineering & Mechanics, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China
[b] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[c] School of Economics and Management, Jilin Jianzhu University, Changchun 130118, China

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ABSTRACT

During the operation of metro tunnels, structural performance could inevitably degrade due to the combined effects of the stochastic and disadvantageous environment. In order to reduce the randomness and uncertainty underlying the structural safety risk analysis in operational tunnels, this paper develops a novel hybrid approach to perform global sensitivity analysis. The deterministic and stochastic finite element (FE) model is used to develop the approximate relationship between input and output parameters with a high level of accuracy. Based on the simulated data from an FE model, a meta-model is constructed by a built Particle Swarm Optimization-Least Square Support Vector Machine (PSO-LSSVM) model. In this research, 10,000 groups of data are generated by the built PSO-LSSVM model, which provides data support for the global sensitivity analysis through Extended Fourier Amplitude Sensitivity Test (EFAST). The input variables with a high global sensitivity are identified as crucial variables which should be well controlled and managed during tunnel operation. A Hankou-Fanhu (H-F) tunnel section in the Wuhan metro system is utilized as a case study to verify the applicability of the proposed approach. Global sensitivity analysis enables the reduction of the epistemic uncertainty in tunnel structural safety management, providing insight into a better understanding of (1) the input-output causal relationships of the structural safety risk in operational tunnels, (2) the reduction of the epistemic uncertainty in project safety management of operational tunnels.

1. Introduction

The shield tunnel is one of the most common types of metro tunnels in soft soils [1, 2]. Hundreds of metro shield tunnels, which are usually designed to have a service life of 100 years, have been put into operation during the last decade [3]. However, during the operation of metro tunnels, structural performance may inevitably degrade due to the combined effects of the complex environment and multi-source uncertain factors [4]. Many types of research have focused on the performance of shield structures [5], the mechanism of shield deformation [6], the risk assessment of the shield [7], and numerical simulation [8]. The structural performance degradation of shield tunnels is mainly caused by external aggressive environmental effects and internal deteriorated material effects [4]. Herein, the external environment factors refer to unexpected earth pressure from geological conditions and nearby geotechnical activities [9], while the internal material factors include the deterioration of lining materials, corrosion of reinforcing rods, segment assembly error, etc.

Degradation of the structural performance can be reasonably represented by the evolution of structural responses, including displacement, defects, leakage and lining cracking. The performance can be measured by a single indicator at a member-level or by an integrated indicator at a system-level [10]. However, taken into account of the complex tunnel-soil interactions, it is very difficult to rigorously and precisely analyze structural responses of tunnels [11]. Indeed, various parameters, which affect and induce shield responses, such as water pressure, upper additional load, etc., need to be accurately calculated and effectively managed during tunnel operation. Hence, how to quantitatively and systematically evaluate relationships between environmental effects and tunnel safety and reduce the randomness and uncertainty of the tunnel system are of significant importance to the safety management of operational tunnels.

Current knowledge about randomness and uncertainty existing in the surrounding circumstance on tunnel-soil model is rather limited [12, 13], and thus, a sensitivity analysis method is proposed in this paper to help the administrator to identify the importance of the surrounding factors and their influences on tunnel responses. In this paper, the authors utilized a Global Sensitivity Analysis (GSA) method to detect the key input parameters in the tunnel operation. The GSA process was organized as follow: 1) the Finite Element (FE) and stochastic FE

* Corresponding author.
E-mail address: limao.zhang@ntu.edu.sg (L. Zhang).

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methods were adopted to accurately describe the interaction of the environmental effects and tunnel safety; 2) the Particle Swarm Optimization-Least Square Support Vector Machine (PSO-LSSVM) [14], based on the simulation data from FE and stochastic FE methods, was used as a meta-model to generate sufficient datasets for GSA; 3) the Extended Fourier Amplitude Sensitivity Test (EFAST) algorithm [15] was adopted as GSA method to distinguish key environmental effects in the tunnel operation.

In this paper, the sensitivity analysis of tunnel safety induced by surrounding factors is organized as follow. First, the literature review and methodology of sensitivity analysis used in this paper are introduced; second, the background of the case project, Hankou-Fanhu (H-F) tunnel section in the Wuhan metro system, is described and illustrated; third, the construction processes of FE, stochastic FE, PSO-LSSVM are introduced; fourth, the sensitivity analysis is adopted for identifying the importance of the input parameters and the influence on shield responses; next, the decision making from the results of sensitivity analysis is discussed; at last, the summary and conclusions are presented.

2. Literature review

2.1. Stochastic FE models

FE method is a general numerical approach which is used to solve approximately partial differential equations [16]. FE analysis is used to predict the structural response using numerical techniques to simulate the linear and/or nonlinear behavior of structural elements. However, the randomness and uncertainty always exist in constructing an FE model, such as unavoidable uncertainties in material, surrounding condition, load parameters, modeling, etc. Therefore, then FE analysis should be combined with probabilistic analysis, often named as finite element reliability analysis (FERA) or stochastic finite element analysis (SFEA) [17].

In SFEA, the input parameters are characterized as random parameters, and some techniques can be used to compute the statistical moments and probability density function (PDF) of structural response, such as the Monte Carlo Simulation (MCS). In order to apply SFEA, it is required to link a general-purpose FE analysis program, e.g., ABAQUS [18], with an existing reliability platform, e.g., NESSUS [19] or ISIGHT [20]. For instance, Python development environment (PDE) is supported by ABAQUS Graphical User Interface (GUI). Thus, in this paper, Python code is developed in order to automate the required FE analysis trails.

2.2. PSO-LSSVM model

There are several general methods can be used for pattern recognition and function fitting in recent years, such as an artificial neural network (ANN) [21] and support vector machine (SVM) [22]. Limitations such as overfitting, slow convergence speed, and poor generalization ability seriously hamper the practical application of ANN [22]. Overcoming the shortcomings of ANN, SVM improves computational efficiency and precision [23]. To reduce the complexity of the optimization process, a modified version, i.e., the least squares support vector machine (LSSVM), is proposed by taking constraints with equality rather than inequality to obtain a linear set of equations rather than a quadratic programming (QP) problem in the dual space [22]. LSSVM presents similar advantages as SVM, but an additional advantage of LSSVM is that it requires solving a set of only linear equations (linear programming), which is much easier and computationally more simple than quadratic programming [24]. Hence, LSSVM has excellent potential application in constructing the meta-model for sensitivity analysis.

Particle swarm optimization (PSO) is an algorithm for locating the optimum value of continuous nonlinear function introduced by Eberhart and Kennedy [25]. Actually, PSO is a simulation of nature inspired by swarming theory and it has relations with both evolutionary programming and genetic algorithm (GA) [25]. LSSVM can be used for constructing the meta-model for sensitivity analysis without considering how important parameters of LSSVM are determined. However, several parameters must be obtained for the LSSVM to achieve a high level of performance. Both GA and PSO have been used extensively for various optimization problems [26, 27]. PSO outperforms GA in multivariable function optimization because complex operations such as selection, crossing, and mutation are not required in PSO [14]. Thus, the PSO algorithm is employed to optimize the parameters of LSSVM, and a hybrid PSO-LSSVM algorithm that combines PSO and LSSVM is proposed for constructing the meta-model for sensitivity analysis.

2.3. EFAST algorithm

The sensitivity analysis is of great importance for model calibration and for determination of the key input parameters governing the system responses [28], which can reduce the Epistemic Uncertainty (EU) of project safety during tunnel operation. Sensitivity analysis techniques can be classified into two categories: namely, Local Sensitivity Analysis (LSA) and Global Sensitivity Analysis (GSA). LSA is implemented using a process in which one observes the changes in the model outputs caused by changing one parameter while the other parameters remain fixed to specific values [29]. LSA cannot be used to quantify the effects of interactions among parameters. However, the interaction among parameters cannot be neglected, particularly when the number of model parameters is large [30]. GSA can estimate both the global and the main sensitivity index of each parameter [31]. The Global Sensitivity Index (GSI) is the total contribution of each input parameter to the variance of the model output, including the parameter's main effect, i.e., main sensitivity index or first-order index, and all the interaction terms [16, 32].

The EFAST algorithm is a variance decomposition method, which uses a periodic sampling method and a Fourier transformation to partition the whole variance of the model output and quantify the degree to which variation in each input factor accounts for the output variance. In this study, the interactions of input/output parameters are investigated and quantified by the EFAST algorithm, which allows multiple input parameters to change simultaneously in different ranges.

In 1990, Sobol proposed a variance-based GSA method and the basic idea of this method is to investigate the influence of the variances of input parameters on the variances of output results [15]. Afterwards, the Sobol method was improved by Saltelli [33, 34] and [35]. Saltelli [36] unified the merits of the Sobol's method and the Fourier amplitude sensitivity test (FAST) method and proposed the EFAST [37].

3. Methodology

This section introduces the global sensitivity analysis process and methodology in operating tunnel-soil model, as shown in Fig. 1. The primary process of sensitivity analysis in this research is divided into three parts: 1) the construction of tunnel-soil model and generation of simulation data, including deterministic FE model analysis by ABAQUS and stochastic FE model analysis by ABAQUS; 2) the establishment of meta-model, including the implicit function fitting of risk factors by POS-LSSVM technique; and 3) the global sensitivity analysis, including Monte Carlo method simulation and global sensitivity analysis by EFAST method.

3.1. Stochastic FE model by ABAQUS

Based on the deterministic FE model, the random parameters of interest are updated for each FE analysis trial by ABAQUS. Based on the idea of parameter updating, a Python program [18] is developed for input random parameters updating. As in Fig. 2, the technological