Soil Dynamics and Earthquake Engineering 102 (2017) 160–171

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

# Modelling seismic fragility of a rock mountain tunnel based on support vector machine

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ARTICLE INFO

*Keywords:*
Fragility analysis
Rock mountain tunnel
Support vector machine
Uniform design method
Damage possibility

ABSTRACT

In the paper, an analytical method is proposed to develop seismic fragility analysis for rock mountain tunnels. We consider four types of uncertainties in the fragility analysis including different ground motions, tunnel depths, rock mass and lining thickness. By using the uniform design method (UDM), numerical experiment samples are generated. The verified dynamic numerical simulation (DNS) model is carried out to develop probabilistic seismic demand models. To optimize conventional methodology, a prediction technique support vector machine (SVM) is employed. The SVM model could help to reduce calculation resource. It is concluded that (1) the proposed uniform design-dynamic numerical simulation-support vector machine (UDM-DNS-SVM) method could provide accurate estimated fragility curves considering multiple uncertainties; (2) comparisons among the proposed fragility curves, case studies and empirical curves verified feasibility of proposed fragility curves.

## 1. Introduction

Tunnels are a significant part of transportation infrastructure, such as roads, pipelines and railways. In the last decade, three intensive earthquakes occurred in China: the 2008 Wenchuan Earthquake (Ms 8.0), 2010 Yushu Earthquake (Ms 7.1) and 2013 Lushan Earthquake (Ms 7.0). Although underground structure is not as vulnerable as ground structure, some deep buried tunnels were damaged by earthquakes in last two decades, such as the 1995 Kobe, Japan earthquake [6,52], 1999 Chi-Chi, Taiwan earthquake [57], 1999 Kocaeli, Turkey earthquake, 2004 Mid Niigata Prefecture, Japan earthquake [60] and 2008 Wenchuan, China earthquake [58]. Wang et al. investigated the earthquake induced damage of tunnels in the 1999 Chi-Chi earthquake [57]. Asakura et al. and Yashiro et al. studied the seismic response of mountain tunnels and the earthquake-induced damage to the tunnels [5,60]. Based on investigations of tunnel damages in the Wenchuan earthquake, Wang assessed the seismic-induced risk using the fuzzy mathematical method [58]. In a mountainous zone of a frequent earthquake area, tunnel is commonly a lifeline. Hence, it is important to analyse the possibility of seismic induced tunnel damage. Seismic fragility functions were developed to describe the possibility of a structure reaching a certain damage condition for a given intensity measure (IM) [53].

Data samples for fragility analysis could be obtained from three sources: (1) damage data, (2) expert opinions and (3) analytical analyses. Until now, most seismic vulnerability analyses for tunnels have been based on expert opinions [7,41] or investigations from past events [1]. The American Lifeline Alliance (ALA) developed fragility functions for tunnels in multiple conditions [1]. One difficulty of using empirical method is lack of damage data. Given the well-known limitations of the empirical method, an analytical approach is appealable to develop fragility curves for underground structures. Fragility analysis using numerical method has been widely used in various types of structures and geological conditions. Kappos et al. [25], Ramamoorthy et al. [49] and Lagaros and Fragiadakis [29] built up seismic fragility curves for buildings based on dynamic analysis. Karim and Yamazaki developed fragility curves for bridge piers using numerical simulation method [26]. Several fragility functions for bridges were formulated based on numerical simulations [35,43,48,53,61]. Salmon et al. established fragility functions for BART systems [50]. In recent studies, several studies developed fragility curves for geostructures based on numerical calculations [28,31,33,34,45]. Tunnels wise, Argyroudis and Pitilakis analysed seismic fragility curves for shallow tunnels in alluvial deposits [4]; Andreotti et al. established a quasi-static method in deriving seismic fragility functions for deep tunnels [3]; Le et al. proposed a similar quasi-static method based seismic fragility curves for shallow tunnels [33]; Osmi et al. used 3D nonlinear time history analysis to obtain the fragility curves for shallow rock tunnel [42]. The feasibility and validity of seismic fragility curves for tunnels were proven. However, methodology of seismic fragility analysis for rock mountain

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http://dx.doi.org/10.1016/j.soildyn.2017.09.002
Received 17 March 2017; Received in revised form 2 September 2017; Accepted 2 September 2017

tunnels was limited.

In the paper, uncertainties from ground motion, lining; tunnel depth and rock mass are considered. The uniform design method (UDM) is employed to design the numerical experiments. The UDM is an efficient experiment design method. Several studies used the UDM to generate experiment points to study limit state of the structure [15–17,24,28,34].

There are two types of seismic-induced deformation. One is axis and curvature deformation, which is along the longitudinal direction of tunnel. The other one is 'ovaling' deformation, which is perpendicular to the tunnel transversal section [21,56]. According to Newmark, the seismic design is determined based on a simplified analysis assuming that plane waves propagate in a homogeneous ground [40]. Therefore, to develop the seismic fragility for design, this study studies the seismic response of tunnels in the transversal direction.

The traditional dynamic numerical analyses were computationally demanding. Conventional numerical analysis were based on rigorous procedures. Within the last few years, in terms of fragility analysis, the back propagation neural network (BPNN) was usually used to reduce computing resources [29–32,36]. In fragility analysis for geo-structures, BPNN model has been used as a common prediction tool [11,12,31,34,39].

Although BPNN model is easy to develop, its calculation speed is slow when facing a large amount of data. Considering an optimization of the conventional prediction method, the support vector machine is used. The support vector machine (SVM) is one of the soft computing techniques like the artificial neural network. Recently it has been used in geotechnical engineering [18,20,62] and proven to be an efficient tool.

The objective of the paper is to derive the fragility curves for rock mountain tunnels in an efficient way. The dynamic numerical simulation (DNS) method is used for fragility analysis. Moreover, the time-consuming procedure is optimized by using a properly trained SVM model. The UDM is adopted to generate uniformly distributed design points. Finally, accuracy and efficiency of the proposed fragility curves are validated with empirical curves and site investigations.

## 2. Methodology

### 2.1. Support vector machine

The SVM was proposed by Vapnik in 1995 [55]. The SVM could do data classification and data regression. There were four common types of kernel functions and they are listed in Table 1. Considering a good performance in non-linear regression, we chose the radial basis function as the kernel function. The advantages of the SVM are: (1) It could be used in fitting all kinds of functions; (2) It has a good robustness; (3) Based on a framework of Vapnik-Chervonenkis theory, the SVM has a solid theoretical basis. A SVM is consisted of three layers: an input layer, a hidden layer and an output layer. The architecture of the SVM is presented in Fig. 1. Further details of SVM could refer to Chang and Lin [13].

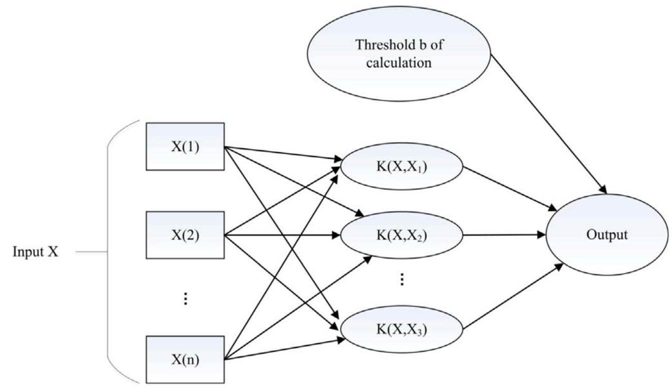


**Fig. 1.** Architecture of the SVM.

### 2.2. Uniform design method

The UDM is an experiment design method. It was developed to improve experimental efficiency [19]. In a conventional experimental design, q-factor and s-level experiments require a q to s-th power times of experiments. When there are 10 factors and 6 factor levels, $6^{10}$ = 60,466,176 experiments are required, which is an unbearable amount of experiments. The UDM only requires 6 experiments to complete the task. Although the number of design points decreases, the accuracy of the experiment is compensated by using multiple levels (usually more than 4 levels). The UDM has three characteristics [38]: (1) it fills design space with experiment points uniformly; (2) the amount of experiment points equals to the amount of factor levels. A uniform design table is expressed as $U_n(q^t)$, where n is the number of experiment design points, q represents the amount of factor levels, and t is the column amount. For example, when a $U_9(9^5)$ table is used, the largest factor levels can be any number below 9; (3) the amount of experiments is minimal with an acceptable accuracy. A significant process of UDM is to develop a suitable uniform design table. The specific procedures are as follows:

(1) The range of the factors, number of experiments and factor levels should be determined first. The parameters were defined based on their values of mean and coefficient of variance. The elastic modulus of the concrete material is listed in Table 2 according to Barbato et al. [9]. Using a random number generator in Microsoft Excel, the upper and lower boundaries were determined. The elastic modulus of rock is provided in Table 2 according to Hoek and Diederichs [23]. For convenience, the number of experiments was set as 40 because 40 different ground motions were implemented. The factor levels was also defined as 40.
(2) A uniform design table was defined by the number of factors and levels. In this paper, Data Processing System (DPS) software was used to generate uniform design tables [54]. A $U_8(8^4)$ table is given in Table 3 as an example. The centre discrepancy (CD) was used here to test the quality of the uniform design table. The centre discrepancy of the $U_8(8^4)$ table was 0.1534. A lower CD corresponds to better uniformity of the uniform design table. In the paper, a $U_{40}(40^3)$ table was used, and its CD was 0.025.
(3) After a uniform design table was developed, each row was used as a group to generate parameters samplings in numerical simulation. Using the elastic modulus $E_{(R)}$ of the rock mass as an example, when the value in the uniform design table was 3, the parameter using in the numerical model would be 970 + (4500-970)*3/40 =

**Table 1**
Kernel functions of the SVM.

| Name | Equation |
|---|---|
| Linear kernel function | $K(\boldsymbol{x}, \boldsymbol{x}_i) = \boldsymbol{x}^T\boldsymbol{x}_i$ |
| Polynomial kernel function | $K(\boldsymbol{x}, \boldsymbol{x}_i) = (\gamma\boldsymbol{x}^T\boldsymbol{x}_i+\gamma)^p$, $\gamma > 0$ |
| Radial basis kernel function | $K(\boldsymbol{x}, \boldsymbol{x}_i) = \exp(-\gamma\|x - x_i\|^2)$, $\gamma > 0$ |
| Two perceptron kernel function | $K(\boldsymbol{x}, \boldsymbol{x}_i) = \tanh(\gamma\boldsymbol{x}^T\boldsymbol{x}_i + \gamma)$ |

**Table 2**
Range of material and geometric parameters.

| RV | Distribution | Mean | COV (%) | Upper level | Lower level |
|---|---|---|---|---|---|
| Thickness of lining (m) | Normal | 0.3 | 5 | 0.315 | 0.285 |
| $E_{(RC)}$(MPa) | Normal | 295,00 | 5 | 309,75 | 280,25 |
| $E_{(R)}$ (MPa) | / | / | / | 970 | 4500 |