Structural Safety 70 (2018) 21–34

Contents lists available at ScienceDirect

Structural Safety

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

Seismic reliability evaluation of gas supply networks based on the probability density evolution method

Wei Liu [a,b,*], Zongcai Li [c], Zhaoyang Song [b], Jie Li [a,b]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[b] Department of Structural Engineering, Tongji University, Shanghai 200092, China
[c] State Power Economic Research Institute, Beijing 102209, China

A R T I C L E I N F O

Article history:
Received 18 March 2017
Received in revised form 30 September 2017
Accepted 1 October 2017

Keywords:
Seismic analysis
Network reliability
Connectivity index
Probability density evolution method

A B S T R A C T

An accurate and efficient reliability evaluation is necessary for network systems with uncertain conditions, especially for the lifeline networks subjected to earthquakes. This study takes gas supply networks as examples and establishes an approach to evaluate the seismic reliability of networks on the basis of the probability density evolution method. First, a nonlinear finite element model is established to simulate buried pipe networks that are subjected to earthquakes. Then, the seismic stresses of the pipes are derived, and the von Mises stresses of the pipes are calculated and used to judge pipe failure. Second, a connectivity index is defined to describe the connectivity between the source and the terminal. Third, on the basis of the probability density evolution method, network reliability is obtained after introducing a physically-based model to simulate ground motion field. Finally, two networks are used as examples to demonstrate the proposed approach, and the results are validated by the Monte Carlo simulation method and compared with a selective recursive decomposition algorithm.

1. Introduction

For network systems with uncertain conditions, reliability evaluation is a usual way to evaluate their performance. Lifeline systems, such as power, gas supply, and water distribution systems, play irreplaceable roles in sustaining modern society, particularly during earthquakes [1]. As these systems are usually distributed in a large area as networks, and the earthquake excitations are stochastic, reliability evaluation is commonly used to describe the performance of them during earthquakes. Therefore, an accurate and efficient reliability evaluation is essential for the performance evaluation of lifeline networks during earthquakes, and moreover, for the seismic design and planning of lifeline networks.

Network reliability evaluation is highly complex in nature because of a large number of network components, complex network topology, and dependence among component failures as a result of the same group of random sources, such as earthquake excitation. A simulation approach, which randomly generates samples of random variables, is often used to evaluate network reliability via the repeated simulation of network connections or flows. However, such an approach can only yield approximate results. Moreover, it requires a large number of simulations, even more than a million simulations, to achieve a result within an acceptable error, particularly for low-probability events [2]. This requirement may be unacceptable in practice because numerous simulations may be time consuming and costly for large-size networks.

As a consequence of the defects of the simulation approach, various non-simulation methods have been developed to calculate the connection reliability between two different network locations, i.e., the connection probability between the source and the terminal. In 1979, Dotson [3] firstly proposed a real time disjoint of minimal paths in network. Later in 1988, by replacing the edge-incidence matrix with an adjacency matrix and introducing the breadth-first search technology, a modified Dotson algorithm was developed by Yoo and Deo [4]. By introducing the concept of system structure function and combining Dotson algorithm with computer storage skills, Li and He [5] developed a recursive decomposition algorithm (RDA) for evaluating network reliability. The algorithm identifies disjoint path sets and disjoint cut sets and then calculates the connection and disconnection probabilities by summing up the probabilities of the identified disjoint path sets and disjoint cut sets, respectively. Moreover, because the sum of the connection and disconnection probabilities always equals 1, the algorithm employs a probabilistic inequality to control computation time and to ensure that the error is smaller than a given threshold. In

* Corresponding author at: Department of Structural Engineering, Tongji University, Shanghai 200092, China.

E-mail addresses: liuw@tongji.edu.cn (W. Liu), lzc_i07@163.com (Z. Li), 1007687239@qq.com (Z. Song), lijie@tongji.edu.cn (J. Li).

https://doi.org/10.1016/j.strusafe.2017.10.001
0167-4730/

2009, Liu and Li [6] improved the efficiency of the RDA by merging nodes and introducing network reduction technologies. However, the RDA in the aforementioned works assumes statistical independence among component failures. Apparently, this assumption is not reasonable because network components are all affected by the same earthquake and their failures are essentially statistically dependent. Considering the dependence among component failures, a correlation coefficient is generally adopted to describe the dependence. By assuming that the performance functions of components and two different components follow normal and joint normal distributions, Song and Ok [7] incorporated the RDA into a matrix-based system reliability method to calculate the disconnection probabilities between the source and the terminal under spatially correlated ground motions. Moreover, to improve the efficiency of the RDA, in 2012, Lim and Song [8] proposed a selective RDA (SRDA) by replacing the shortest path with the most reliable path and by using a graph decomposition scheme based on the probabilities associated with the subgraphs. The SRDA seems to be the most efficient algorithm for the reliability evaluation of networks. Non-simulation methods can immediately give accurate results for small-size networks and for some medium-size networks. Although non-simulation methods may provide results with an error boundary within an acceptable period for large-size networks, they may fail for many large-size networks and even for a lot of medium-size networks when the reliability of network components is moderate or low [9] because the disjoint path sets and disjoint cut sets which are needed to be identified to satisfy the error boundary increase exponentially. In fact, network reliability is triggered by basic random variables, such as those of ground motion. However, in order to evaluate the network reliability, these non-simulation methods must obtain the components reliabilities and correlation coefficients between different components. Apparently, these methods complicate the problem. Moreover, errors are introduced when some assumptions have to be introduced to compute network reliability on the basis of components reliabilities and the correlation coefficients between different components. If network reliability can be described directly with basic random variables, then the problem must be simplified, and the results must be more accurate.

For the reliability analysis of dynamical systems, the first-excursion probability is usually an important problem. The methods for this problem include out-crossing theory [10–12], numerical solution method [13], and simulation method [14]. However, because the complexity of the problem, these methods can only apply to some simple cases. Recently, a new approach for stochastic dynamical systems, the probability density evolution method (PDEM), was developed by Li and Chen [15]. The approach considers basic random variables and the physical equation of systems, and is capable of deriving the probability density function (PDF) of the target system responses. The PDEM can be employed to directly give network reliability on the basis of basic random variables, excluding components reliabilities and the correlation coefficients between different components. In this paper, taking the gas supply networks as examples, an approach based on the PDEM is proposed to evaluate the seismic reliability of networks. Following the introduction, a model for buried pipe systems is introduced briefly to give the seismic responses in Section 2. Also, in Section 2, besides seismic stresses, other effects, such as dead load, temperature change, and Poisson's effect are considered to give the von Mises stresses of buried pipes and a performance function is given. In Section 3, a connectivity index (CI) is introduced to describe the connectivity between the source and the terminal in a network. In Section 4, the PDEM is introduced to give the PDF of the CI and the connection reliability of the network can be readily given by integrating the PDF of CI from 0 to 1. In Section 5, a physically-based model is introduced to simulate the ground motion field which is used to give the seismic stresses of the buried pipes. In Section 6, the proposed approach is demonstrated by taking a hypothetical network and an actual gas supply network as examples. Also, the results are validated by the Monte Carlo simulation method and compared with the SRDA, and the computation time of the proposed approach is analyzed. At last, in Section 7, the conclusions are summarized.

2. Seismic stress analysis of pipes

2.1. Modeling for buried pipe systems

A finite element model for buried pipe systems [16], which can calculate the seismic responses of a whole pipe system, is adopted to calculate the seismic stresses of the pipes.

A buried pipe can be idealized as a beam on elastic foundation (BEF), as shown in Fig. 1, and its seismic responses can be obtained with a quasi-static approach. For the pipe in Fig. 1, the axial and lateral motion equations can be respectively described as [16]

$$EA\frac{\partial^2 u(x,t)}{\partial x^2} - k_A u(x,t) = -k_A u_g(x,t) \tag{1}$$

$$EI\frac{\partial^4 v(x,t)}{\partial x^4} + k_L v(x,t) = k_L v_g(x,t) \tag{2}$$

where EA and EI are the axial and bending stiffness of the pipe, respectively, k_A and k_L are the spring stiffness per unit length of the soil surrounding the pipe along the axial and lateral directions, respectively, $u(x,t)$ and $v(x,t)$ are the axial and lateral displacements of the pipe, respectively, $u_g(x,t)$ and $v_g(x,t)$ are the axial and lateral displacements of ground motion, respectively, and x is the coordinate along the pipe axis and t is the time.

When the BEF model is adopted, the pipe itself is simulated as a beam, and the pipe-soil interaction is simulated as axial and lateral springs. The axial spring can be described by the relationship between the slippage and the shear stress at the pipe-soil contact surface. According to the literature [17], a constitutive relationship curve for soil-structure interaction can be empirically described by the following hyperbola function:

$$\tau = \frac{\Delta u}{a + b\cdot\Delta u} \tag{3}$$

where τ and Δu represent shear stress and slippage at the pipe–soil contact surface, respectively, and a and b are constants whose physical interpretations are respectively given as follows:

$$a = 1/\left(\frac{\tau}{\Delta u}\right)_{\Delta u\to 0} = 1/k_I \tag{4}$$

$$b = \left(\frac{1}{\tau}\right)_{\Delta u\to\infty} = \frac{1}{\tau_{ult}} \tag{5}$$

where k_I is the initial stiffness and τ_{ult} is the shear strength at the pipe-soil contact surface.

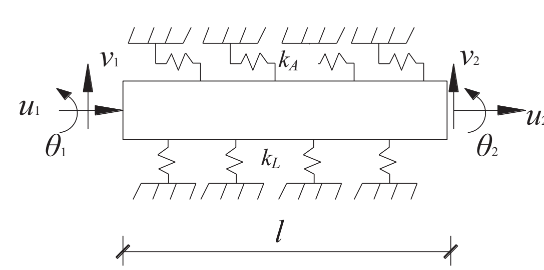

Fig. 1. Modeling pipe as beam on elastic foundation.