

Jie Li
Wei Liu

Lifeline Engineering Systems

Network Reliability Analysis and
Aseismic Design



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Preface

One of the important signs showing the growth and prosperity of civil engineering in the twentieth century is the development and popularization of large-scale engineering networks. Regional engineering network systems such as electric power networks, urban water supply networks, gas supply networks, large-scale transportation networks, ..., all of them have a profound impact on human life and social progress. Because of their paramount importance, these engineering network systems are collectively called lifeline engineering systems or infrastructure systems.

However, in the early period of their development, the design of engineering network systems was mostly based on the planning design according to functional demand. To the network structural design of engineering systems, especially which is governed by disaster resistance performance, little attention has been paid. In the mid-1970s, the emergence of concept of lifeline earthquake engineering opened the first gap to break through this dilemma. In the following 40 years, starting from the seismic performance of buried pipelines and the earthquake disaster prediction of network systems, the researchers initiated a series of new research fields such as the vulnerability analysis of engineering structures, reliability analysis of engineering networks, optimization design of network topology and resilience analysis of engineering networks. These advances have formed the rudiment of a new branch of disciplines: engineering network reliability analysis and design.

The first author of this book has been involved in the research of lifeline engineering systems since the early 1990s. In the process of research, the author gradually formed such a basic concept: the disaster resistance design of engineering network system is an important part of engineering system design, and this kind of design should be based on the network reliability analysis. The author believes that the engineering network reliability analysis and design constitute an important hallmark of the development of civil engineering design theory in the new era. In fact, after a hundred years of developments, engineering reliability analysis and design has formed a complete theoretical framework: structural component reliability design—global structural reliability design—engineering network reliability design.

According to such a belief, this book is organized as the following four parts. After a brief introduction in Chap. 1, the first part of the book includes Chaps. 2 and

3, which introduce the seismic hazard analysis and advances in modeling of seismic ground motion, respectively. The second part, including Chaps. 4 and 5, describes the reliability analysis methods for structures in engineering network. Apart from the general reliability analysis methods, a global reliability analysis method of structure based on the probability density evolution theory is addressed briefly in this part. The seismic reliability analysis of a network system is the first key point of the book, which is the focus of the third parts and described in Chaps. 6 and 7. In this part, two reliability analysis methods of lifeline engineering networks, i.e. the connectivity reliability analysis and the functional reliability analysis, are introduced in detail, respectively. On the basis, the aseismic design and comprehensive control of composite lifeline system are addressed in the fourth parts of the book, including the topology optimization design methods for lifeline engineering networks, presented in Chap. 8, and the system control of composite lifeline engineering systems shown in Chap. 9, respectively. These contents constitute the fourth part of the book.

The book may be used as a textbook or research reference for graduate students and professionals in civil engineering. The level of the preparation assumed of the reader corresponds to that of the bachelor's degree in science or engineering.

The authors' sincere appreciations go firstly to Prof. Alfredo H-S Ang at the University of California, Irvine, and Prof. Pol. D. Spanos at Rice University, for their important advice in preparing the book and long-time friendship. Special thanks are also due to Prof. Bruce Ellingwood at Colorado State University, Prof. Dan Frangopol at Lehigh University, Prof. George Deodatis at Columbia University, Prof. Michael H. Faber at Aalborg University, Prof. Michael Beer at the Leibniz University of Hanover, Prof. Kok Kwang Phoon at the National University of Singapore and Prof. Yangang Zhao at Kanagawa University, for their valuable help and friendly encouragements. Taking this opportunity, the first author of the book would like to express his deep appreciation to his former students: Professor Jun He at Shanghai Jiaotong University, Prof. Lingli Chen at Shanghai University, Prof. Jianbing Chen and Prof. Wei Liu at Tongji University and Prof. Yuanfeng Bao at Xian Jiaotong University. Cooperation with them is always full of joy and inspiration. The authors are also indebted to their colleagues at Tongji University, Prof. Xilin Lu, Prof. Guoqiang Li, Prof. Yiyi Chen, Prof. Xianglin Gu and Prof. Qifeng Luo for their continuous cooperation and supports.

Finally, we would like to thank our families for their long-lasting support and love.

Shanghai, China
June 2020

Jie Li
Wei Liu

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Chapter 1

Introduction

1.1 Lifeline Engineering Systems

Lifeline engineering systems, such as power systems, transportation systems, communication systems, water distribution systems, gas supply systems and so on, are essential to people's daily life. For modern society, such systems are the infrastructure systems supporting the function of modern city and regional economy.

As infrastructure systems, lifeline engineering systems are generally featured by owning three important characteristics. Firstly, they distribute in a large area, such as high-voltage electrical networks, regional transportation networks and urban water distribution networks, distribute in a large area. As a result, their performance is determined not only by the basic elements but also by the topology structures of the networks. Therefore, system analysis is important for the lifeline engineering systems to understand their performance comprehensively. Secondly, lifeline engineering systems are composed of different structural elements, i.e., engineering structures. For example, for the electrical power systems, there are generally buildings in power stations, high-voltage electrical equipment in transformer substations and high-voltage transmission towers in the transmission network. Similarly, roads and bridges in transportation systems and key buildings and equipment in communication systems are engineering structures as well. All these structures can be called as lifeline engineering structures. Their performance and operation states subjected to disasters determine whether the systems could maintain their functions or not. Thirdly, the performance of a lifeline engineering system directly or indirectly exerts influence on the other lifeline engineering systems. For example, whether electrical power systems work well has great impact on the operation of urban water distribution networks in the same area. Similarly, whether the transportation and oil transmission systems work well influences the operation of electrical power systems greatly. The interactions between different lifeline engineering systems become more apparent and extensive when serious disasters, such as strong earthquakes or hurricanes, happen. Considering the interactions between different lifeline engineering systems, a set of different lifeline systems can be regarded as a composite lifeline engineering system.

Certainly, other characteristics for different lifeline engineering systems can be found from different viewpoints. However, in this book only the structural characteristics of lifeline engineering systems are dealt with and therefore the other characteristics are not discussed.

The research on the disaster performance of lifeline engineering systems originated from the mid-1970s. In 1971, during the San Fernando earthquake, the infrastructure systems in San Francisco suffered serious damages. In the affected area, 11 power transmission lines and 47 highway bridges were destroyed, while more than 600 pipeline breaks appeared on water and gas systems. Meanwhile, the malfunctions of electrical power, water distribution and transportation systems after the earthquake attracted much attention (Duke & Moran, 1972). Based on the comprehensive investigation on this earthquake, the concept of lifeline earthquake engineering was presented and was accepted rapidly by the scientists and engineers (Duke & Moran, 1975). In 1974, a council, the Technical Council on Lifeline Earthquake Engineering (TCLEE), was founded in the American Society of Civil Engineers (ASCE). The first lifeline earthquake conference was organized by TCLEE in 1978 and the conference proceedings was published (Technical Council on lifeline Earthquake Engineering of ASCE, 1977). In 1983, a World Lifeline Earthquake Engineering Conference was organized by the American Society of Mechanical Engineers (ASME) in Portland (Arima, 1983). In 1984, during the 8th World Conference on Earthquake Engineering in Japan, lifeline earthquake engineering was first listed as a session to exchange ideas between researchers and engineers. Since then, lifeline earthquake engineering has always been listed as a session in the later World Conference on Earthquake Engineering. Since 1990, Chinese, Japanese and American researchers on lifeline earthquake engineering met every 4 years to hold the series China-Japan-U.S. Trilateral Symposia on Lifeline Earthquake Engineering.

After nearly 50 years, the knowledge on lifeline engineering has been formulated based on a broader background. With the advancements of research and application, some new topics, including lifeline wind engineering, damage detection and health monitoring of lifeline systems, the resilience of lifeline system and so on, have appeared. Now, the research on lifeline engineering is becoming an important driving force for modern civil engineering.

Generally, lifeline engineering systems can be defined as the infrastructure systems which sustain proper operation and economic function of modern cities and communities (Li, 1999). This definition not only covers the previous research on urban lifeline engineering systems but also extends to regional lifeline engineering systems.

Considering the characteristic of research objective, a comprehensive investigation on lifeline engineering should include three levels, lifeline engineering structures, lifeline engineering networks and composite lifeline engineering systems. The research of lifeline engineering systems would provide scientific science methods and technical tools for modern lifeline engineering design considering performance in disaster scenarios and operational function in normal condition.

1.2 Damages of Lifeline Systems in Past Earthquakes

Among all kinds of natural disasters, strong earthquake is the biggest threat to lifeline engineering systems. During one strong earthquake, almost all kinds of lifeline engineering structures would suffer serious damages. Worse than that, part of or even all the functions of lifeline engineering systems will lose, including power cut, water supply stoppage and cell phone out of service. In some extreme cases, the whole system function will lose even if only some key structures suffer lightly or medium damages because of the fragility of lifeline engineering systems.

During many previous strong earthquakes, a lot of lifeline engineering systems suffered serious damages and lost their functions due to the strong earthquakes (Duke, 1971; Liu, 1986). Herein, the damages of some lifeline engineering systems are introduced under strong earthquakes in recent 30 years.

1. American Loma Prieta Earthquake in 1989 ($M_L = 7.2$) (EERI, 1990)

During the American Loma Prieta Earthquake, taking place on October 17, 1989, the damage of the power system was a prominent phenomenon. The serious damages of 230 and 500 KV high-voltage substations resulted in that over 1.4 million customers encountered power cut (Fig. 1.1). In San Francisco, many robberies happened because of power cut. Meanwhile, over 350 pipeline breaks appeared in the water distribution network and more than 1000 gas leakages appeared in the gas supply network. Many oil tanks on soft soil ground were destroyed also.

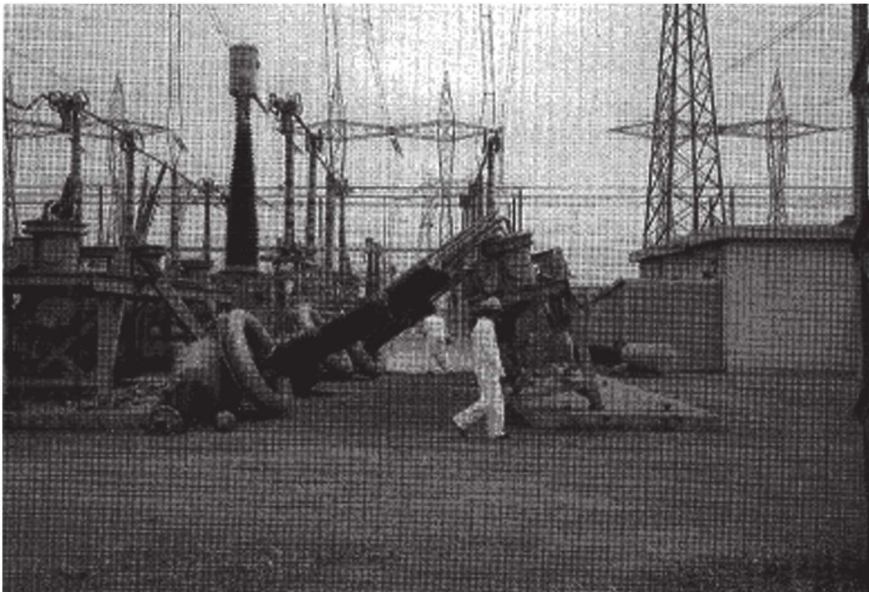


Fig. 1.1 Damage of high-voltage substations



Fig. 1.2 Damage of bridges

2. American Northridge Earthquake in 1994 ($M_L = 6.8$) (EERI, 1995)

During the American Northridge Earthquake, which happened on January 17, 1994, the transportation system was partially paralyzed due to the serious damages of some bridges (Fig. 1.2). Also, similar to the performance of the power system in American Loma Prieta Earthquake, many 230 and 500 KV high-voltage substations suffered serious damages. Moreover, a lot of high-voltage transmission towers collapsed due to soil liquefaction under the earthquake. As a result, more than 1.1 million customers encountered power cut. During the earthquake, 1400 pipeline breaks appeared in the water distribution network of Los Angeles. Meanwhile, over 150,000 gas leakages appeared in the gas supply network of Los Angeles, resulting in many fire accidents.

3. Japanese Kobe Earthquake in 1995 ($M_L = 7.2$) (Investigation Group of Kobe Earthquake, 1997).

The epicenter of the Japanese Kobe Earthquake, which happened on January 17, 1995, located in a populous modern city. The investigation on the damages of life-line engineering systems caused by this earthquake was the most comprehensive one in the history. During the earthquake, 5,438 people died and the direct economic loss was over 100 billion U.S. dollars. For the transportation system, six railroads crossing the earthquake areas suffered serious damages and many viaducts collapsed. Among 1,192 piers located in the highway from Osaka to Kobe, 611 piers were damaged and the damage rate was around 52%. Among those damaged piers, about 150 piers were destroyed and could not be repaired, which meant 13% piers should be rebuilt. Also, many damages appeared on the subway. For example, the tunnel roof of the Dakai subway station collapsed because the columns were damaged by shear force. After the earthquake, a 120 m long ground surface sank and the deepest location was over 3 m in the station area (Fig. 1.3). Also, Kobe Harbor was almost destroyed. About 80% embankment was destroyed and some cracks on embankment were 3 m deep. After the earthquake, one million customers encountered power cut and the repair process lasted 6 days. The damaged components of the power system included 48 275 and 77 KV substations and 446 power distribution circuits. The economic loss caused due to the damages of the substations and the distribution circuits was

Fig. 1.3 Surface subsidence due to the damages of subway station



over 55 billion Japanese Yen and 96 billion Japanese Yen, respectively. Among 1.36 million water customers in nine cities affected by the earthquake, including Kobe and Ashiya, 1.1 million customers encountered water stoppage due to 1,610 pipeline breaks in the water distribution network. A week later, only one third of the breaks were repaired. When the water distribution system recovered completely, two and a half months had passed. As a result, firefighting became very difficult due to lack of water. A newspaper report described the sad scene at that time, “firemen could do nothing but just see the fire burning with tears.” Meanwhile, gas supply system suffered serious damages and 5,190 gas breaks appeared. Among these breaks, 109 breaks appeared on medium-pressure pipelines. After the earthquake, 857 thousand customers encountered no gas supply and the repair work lasted three months. For the communication systems, 3,170 communication lines were damaged. 19.7% communication lines located in the south of Hyogo and centered in Kobe were cut off due to the failures of telephone switchboards or the damages of communication lines. Many communication equipments were destroyed and some communication buildings were out of service (Fig. 1.4).

4. Chinese Taiwan Chi-Chi Earthquake in 1999 ($M_L = 7.3$) (Architectural Institute in Taiwan, China, 1999)

During the Chinese Taiwan Chi-Chi Earthquake happened on September 21, 1999, 2,444 people died and 11,305 people were wounded. The economic loss reached 444 billion NT dollars. The transportation was disrupted in Central Taiwan, and many bridges, including Mingzu Bridge, collapsed. The railway stations of Central Taiwan and Chi-Chi suffered serious damages, including inflexion of rails and fall of train electrical lines. Meanwhile, due to the damages of the power system, 5.2 million customers covering a large area in the north and middle of Taiwan encountered power cut, resulting in a direct economic loss of 5.94 billion NT dollars. Also, the economic losses of water conservancy facilities and water pipelines were 4.72 billion and 950 million NT dollars, respectively.

Fig. 1.4 Damages of communication tower



5. Chinese Wenchuan Earthquake in 2008 ($M_L = 8.0$) (State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 2008)

On May 12, 2008, a strong earthquake attacked Wenchuan in China. During the earthquake, the lifeline engineering systems suffered serious damages. In the affected area, 40 substations with 110 KV or higher voltage were damaged, resulting in that 180 transmission lines were out of service (Fig. 1.5). For gas supply systems, pipelines, equipments and other structures were damaged and the total number is as high as 51,000. For water distribution networks, 677 water factories and 138,000 km long pipelines were damaged in the affected area (Fig. 1.6). Taking the water distribution network of Mianzhu as an example breaks appeared on about 70% pipelines among 47 km-long mains pipelines, especially the gray cast iron pipelines and prestressed

Fig. 1.5 Damages of the power substation



Fig. 1.6 Crack of the pipe

cement pipelines. Because of the serious damages of the pipelines, a great deal of water leaked. When the water supply recovered on May 15, the leakage rate of the whole network was as high as 85%. Although the water supply increased from 35,000 tons per day before the earthquake to 50,000 tons per day after the earthquake, the water heads of many nodes were still very low, even zeros, resulting in the fact that water could not arrived at the third floor of many buildings.

6. Great East Japan Earthquake in 2011 ($M_L = 8.0$) (Mimura et al., 2011)

On March 11, 2011, the Great East Japan earthquake happened. During the earthquake, the lifeline engineering systems suffered serious damages. In the affected area, reported damaged included 3,546 damages along roads. For gas supply systems, 20 breaks appeared on middle-pressure gas pipes, and 773 breaks appeared on low-pressure gas pipes. Meanwhile, low-pressure pipes inside 7,132 houses were damaged. For water distribution networks, a suspension of water supply occurred in about 2,300,000 houses in east Japan just after the earthquake. In Sendai City, the damage rate of pipes, defined as the number of damage divided by piping length, was 0.02 (/km).

1.3 Main Content of the Book

The main purpose of the book is to supply a basic theoretical framework and a technical tool for those who are interested in lifeline engineering systems.

There are totally nine chapters and three appendices in this book. In Chap. 2, the seismic hazard analysis is introduced. For regional lifeline engineering systems, such knowledge is important to evaluate and to calculate the seismic reliability of lifeline engineering networks. In Chap. 3, the research advancements on seismic ground motion are introduced. After introducing the general power spectrum model

of ground motion briefly, the book focuses on the random ground motion field analysis based on physical background. In Chap. 4, the seismic analysis of buried pipeline is illustrated. Firstly, general seismic damage characteristics of buried pipelines are introduced briefly. Then, seismic response and seismic reliability analysis methods are introduced in detail. As buried pipelines are different in water distribution, gas supply and sewage systems, the suitability of these methods should be noted especially. In chapter 5, seismic analysis methods of engineering structures are presented. Besides the general seismic deterministic response analysis, a probability density evolution method for stochastic seismic response of structures is introduced and a global reliability analysis method for structures is described briefly. In Chaps. 6 and 7, two seismic reliability analysis methods of lifeline engineering networks, the connectivity reliability analysis and the functional reliability analysis, are introduced respectively. In Chap. 6, the seismic connectivity reliability analysis for general lifeline engineering networks is introduced. Particularly, a path-based and a cut-based recursive decomposition algorithm, which are suitable for large-scale networks, are presented. In Chap. 7, taking water distribution networks as an example, functional reliability analysis of lifeline engineering networks is introduced. In Chap. 8, the aseismic topology optimization design methods of lifeline engineering networks are presented. The basic idea of modern combinatorial optimization theory is introduced and its application to pipeline network is described in detail. In chapter 9, the seismic response simulation of composite lifeline systems and the system control based on simulation are introduced, respectively. These theories are related to the resilience of lifeline systems closely.

Three appendices are included in the book. In Appendix A, the basic knowledge of Boolean algebra is introduced. In Appendix B, the special analysis model for electrical power system is presented which is used in Chap. 6. In Appendix C, a useful seismic fire analysis model, which is used in Chap. 9, is introduced.

The authors believe that the contents described above have established the basic theoretical framework for seismic analysis and design of lifeline engineering systems.

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