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A research on subway physical vulnerability based on network theory and FMECA

Yongliang Deng [1], Qiming Li *, Ying Lu [2]

Department of Construction and Real Estate, School of Civil Engineering, Southeast University, Nanjing 210096, PR China

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ABSTRACT

Subway system is a critical and fundamental urban infrastructure and provides essential transport services for promoting economic development and social stability. Due to the serious result of operation interruption and accident, it is increasingly important for risk management to be proactive, targeted, and effective. In this paper, a new framework based on network theory and FMECA method is proposed to study the vulnerability of subway system, in the form of analyzing network efficiency by network theory and risk matrix in FMECA method. Then, a case study is used to demonstrate the effectiveness and feasibility of the framework in identifying the vulnerable and critical functional module in subway system and assessing severity of its failure modes. In the end, an organizational structure is put forward from three aspects of operation, research, and manufacturer for improving the subway safety level. This research would be conducive to provide recommendations and suggestions regarding safety provisions for subway operation to reduce the occurrence of accidental failures.

1. Introduction

Critical infrastructures, such as the national electrical grid, telecommunication and information networks, and transportation systems, provide essential products or services for promoting social and economic stability and healthy development. The economy of a nation and the well-being of its citizens depend on continuous and reliable functioning of infrastructure system (Ouyang, 2014). In China, with the constant quickening of urbanization, more and more people have made their homes in cities in pursuit of a better life. Currently, serious traffic congestion has become a bottle neck of urban development, which can directly influence city long-term and sustainable development (Tirachini et al., 2014). The European Unification of Accounts and Marginal Costs for Transport Efficiency (UNITE) project estimates the cost of traffic congestion in the UK, for instance, to be £15 billion/year ($23.7 billion/year) or 1.5% of GDP (Nash, 2003).

From perspective of historical experience, subway is invested when city is big enough at a certain stage of its development process. Up to the end of 20th century, there are 115 cities with subway, and the total length is over 7000 km. In contrast with other transportation systems, the subway has many obvious advantages, such as the capacity for a large volume of traffic, energy saving, zero-exhaust fumes and low noise (Martínez and Viegas, 2012). In view of this, the subway is becoming an increasingly appropriate means of relieving traffic congestion. China is a country with large population, contemporary Chinese cities are at a high-speed development period, and all aspects of the city are faced with rapid and drastic changes, especially in infrastructure construction (Li et al., 2014). With the rapid construction in these years, subway has been becoming one of the most important urban infrastructures in China today. By the end of December 2014, subways have already been put into operation in 22 Chinese cities with total mileage of 2700 km, and 15 other cities have been approved to construct their urban subways. The increasing pace of urbanization accelerated to subway project has ushered in a new period of great development in China.

Subway is a typical complex system with many special characteristics, such as large-scale, complicated spatially distributed, interconnected, and interdependent. The complexities stem mainly from a variety of complex functions and exogenous and endogenous functional dependencies and interdependencies (Wang et al., 2012). Subway is becoming gradually more complicated

* Corresponding author at: Room 1302, Yi Fu Museum of Architecture, No. 2 Sipailou of Xuanwu District, Nanjing, PR China.

E-mail addresses: dengyongliang@seu.edu.cn (Y. Deng), njlqming@163.com (Q. Li), luying_happy@126.com (Y. Lu).

[1] Present address: Room 1308, Yi Fu Museum of Architecture, No. 2 Sipailou of Xuanwu District, Nanjing, PR China.

[2] Present address: Room 1407, Yi Fu Museum of Architecture, No. 2 Sipailou of Xuanwu District, Nanjing, PR China.

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and mutually dependent along with the development of scientific technologies. Due to interdependences inside the subway system, the failure of one component may affect the normal function of other components or even diffuse directly or indirectly to the whole system (Colombi et al., 2013). Hence, component failure may lead to operation interruptions or accidents and cause tremendous economic, social, and physical disruption, amplifying negative consequences and affecting unforeseeable and haphazard sets of users. An example is the subway collision occurred on 27 September 2011 in Shanghai, which left 284 people injured and 95 hospitalized, was caused by a single small failure in a subway station power supply. As it stands, the source of this accident is a component failure in power system, then spreads to signal system, and diffuses to train system in the end, which directly leads to this accident. The whole process looks like a domino phenomenon. As this example indicates, the occurrence of component failures may not only cause damage to a single subsystem, but also spread to the other function related subsystems. It is apparent that increasing complexities and interconnectivities are making subway system more in need of systematic vulnerability analysis.

Considering the crucial role of subway in the development of the entire society, it is increasingly important for risk management to be proactive, as failures or breakdowns often result in great losses in many aspects (Mu et al., 2014). According to a statistics of Beijing subway operation accidents from 2008 to 2011, it indicates that about 70% operation accidents are caused by the occurring of various component failures. Thus it can be seen that the physical fault is the main cause of subway operation interruption and accident. Vulnerability and risk analysis are essential tools for proactive risk and crisis management (Johansson and Hassel, 2010). Hence, it is necessary to discern potential risks and vulnerabilities and formulate corresponding coping strategies, which is very important to improve the safety level of subway operation.

The paper is organized as follows: a literature review is summarized on the theme of vulnerability research and hazard analysis in Section 2. Then, Section 3 describes the methodology in this research, including an analytical framework, modeling approach, network theory, and FMECA method. Next, in Section 4, a case study is presented in which the subway network's vulnerable functional modules are identified in terms of network efficiency, and the failure modes are assessed based on risk matrix analysis. In the end, conclusions and suggestions concerning possible implementation issues and future study are provided in the final Section 5.

2. Literature review

Vulnerability is a term with different meanings in different research areas. Its definition is often ambiguous and sometimes misleading (Jönsson et al., 2008). In the present context, the research literature contains two related interpretations. The first is that vulnerability is a global system characteristic that expresses the magnitude of serious consequences following the occurrence of a specific hazardous event (Eusgeld et al., 2011). The other interpretation is that vulnerability applies to a system component or an aspect of a system (Aven, 2007). The term vulnerability is used here to describe a system property according to the first interpretation. There are also three important perspectives of vulnerability analysis: global vulnerability analysis (Johansson et al., 2007), critical component analysis and critical geographical locations analysis (Wang et al., 2013). Considering infrastructures are always distributed in a wide spatial range, Johansson et al. (2011) propose geographical vulnerability analysis to study the spatially oriented vulnerability involved.

Many models and methods have been implemented to study the vulnerability of systems, such as agent-based modeling (ABM) (Acosta-Michlik and Espaldon, 2008), System Dynamics (SD) (Mirchi et al., 2012), object-oriented modeling (OOM) (Eusgeld et al., 2009; Zhang and Yang, 2014), and network theory (Hearnshaw and Wilson, 2013). Among these existing vulnerability methods, network theory has the obvious advantage of describing the properties of complex infrastructure systems due to its adjacency matrix being able to completely characterize relationships between network nodes. It has been applied in many infrastructure systems, such as power grid system (Koç et al., 2013) and pipeline system (Ouyang et al., 2008). However, in current studies, almost all network models assume a fixed topological structure or independent relationships. Most of the infrastructures involved have an obvious network topology structure, and with relatively clear basic elements (i.e. nodes and edges) in the network. Only a few studies take into account interface topologies (physical connections) across infrastructure systems to minimize the consequences of component failure (Ouyang and Dueñas-Osorio, 2011). The physical properties of infrastructure components are inevitably ignored in the modeling process. In addition, the functional relationships between infrastructure elements may not be well captured in the network models.

The network analysis is a powerful tool to identify and assess the vulnerable components in infrastructure system from systematic view. However, it is argued that component failure is the root cause of system vulnerability. In reality, various events can lead to failures during the subway operation, such as random incidents, natural hazards and sabotage. Many studies have been carried out to understand these failure mechanisms and develop models and methods for effectively analyzing systems in order to provide protective measures (Kutlu and Ekmekçioğlu, 2012; Sause et al., 2012). To summarize, there are two main approaches, i.e., predictive approach and empirical approach (Johansson and Hassel, 2010).

The predictive approach mainly involves modeling or simulating the characteristics of a particular infrastructure system. The model is a reasonable simplification of the real infrastructure system and is analyzed by a corresponding software platform. An example is the inoperability input–output method (IIM) based on 1973 Nobel laureate Wassily Leontief's input–output economic model. This uses a linear matrix equation to express the inability of a system to achieve its designed function. Oliva et al. have developed an extension of IIM that expresses expert knowledge concerning infrastructure dependencies, involving a dynamic inoperability input–output model to provide valuable insights into the risk assessment and management of interdependent infrastructure systems (Oliva et al., 2011). Used in this way, the IIM approach is a great help in understanding how perturbations propagate among interconnected infrastructure systems and how to mitigate their effects (Crowther and Haimes, 2010). The empirical approach, on the other hand, its main purpose is to discern patterns relating to the propagation of failures and their consequences for society. It mainly aims to gain experience or knowledge through the analysis of past accidents or near misses, as learning from previous failure experiences is a valued and relatively pain-less process. McDaniels et al. (2007), for example, take an empirical approach by using major electrical power outages to understand how extreme events result in failures of infrastructure systems.

The Failure Mode, Effects and Criticality Analysis (FMECA) method is a typical empirical approach, which is very useful method to propose improvement measures through the analysis of potential failures and their effects on equipment, which appeared during the sixties in aviation industry and achieved good effect. The systematic application of this method has an important significance for failure mode diagnosis and location and system vulnerability improvement. It is a powerful tool for early