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RESILIENCE-BASED POST-DISASTER RESPONSE AND RECOVERY STRATEGIES FOR A TRANSPORTATION-COMMUNITY SYSTEM

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Resilience-based Post-disaster Response and Recovery Strategies for a Transportation-community System

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ABSTRACT

Highway networks are critical lifelines for supporting emergency response and recovery activities in post-earthquake circumstances. Highway bridges are seismically vulnerable components of a highway network, and damaged bridges can disrupt road connections between cities, leading to severe delays in rescue operations in the emergency response phase and reconstructions of communities in the recovery phase. Therefore, efficient restoration of damaged bridges is of paramount importance to quick recovery of highway networks from earthquakes, thereby enhancing highway network resilience.

Post-earthquake restoration of highway bridges consists of two phases: the emergency restoration and the long-term restoration. Emergency restoration is performed in the emergency response phase and is just sufficient to support disaster relief activities. Prior studies on scheduling emergency bridge restoration activities assumed that all information on bridge damages and the corresponding restoration methods were known before conducting emergency restoration activities. However, in practice, emergency restoration is conducted with gradually revealed bridge damage information that is collected by emergency inspection activities. Given that emergency inspection and restoration activities can be performed simultaneously on a highway network, complex interactions among these activities can occur and may significantly affect the inspection routes and restoration schedules. Specifically, emergency inspection routes may change due to the blockage of highways for the emergency restoration of bridges on them; meanwhile, emergency inspection routes could also affect emergency restoration schedules because only the bridges that have been inspected will be scheduled for

emergency restoration. Meanwhile, given that bridge damage information is revealed gradually via inspection efforts, such real-time damage information may affect the following inspection routes and restoration schedules. How to account for such interactions and the real-time bridge damage information in emergency inspection routing and restoration scheduling remains a challenge. On the other hand, long-term bridge restoration is performed in the recovery phase and aims to fully restore all damaged bridges to their pre-earthquake conditions. Existing methods on long-term bridge restoration-scheduling problems used monotonically increasing functions to model the recovery processes of highway networks' functionality while neglecting the decrease of network functionality resulting from the restoration-downtime impact. The failure to take into account the impact of restoration downtime on networks' functionality may lead to the overestimation of highway network resilience, thereby resulting in inefficient bridge restoration schedules with significant restoration downtime of highways.

To address these challenges, this thesis aims to facilitate the post-earthquake recovery of highway networks by developing efficient bridge restoration strategies for a post-earthquake highway network. The specific objectives in this thesis are: (1) to understand the impact of interactions among emergency bridge inspection and restoration activities on the optimal emergency inspection routes and restoration schedules; (2) to develop a real-time decision-making tool for continuously updating emergency bridge inspection routes and restoration schedules based on the real-time bridge damage information collected by bridge inspection activities; and (3) to investigate the impact of restoration downtime on highway network resilience.

To achieve these objectives, mathematical optimization tools, including integer programming and decomposing techniques, are developed. Moreover, hybrid genetic algorithms are developed to efficiently solve these mathematical programs. These optimization models were tested on real highway networks in Sichuan, China, using data from the 2008 Wenchuan Earthquake.

This thesis concludes three key findings. First, the inspection-restoration interactions can considerably increase the complexity of the emergency inspection routes and restoration schedules, and simultaneously performing emergency inspection and restoration activities can aid in the significant improvement in highway network resilience. Second, updating the emergency inspection routes and restoration schedules in real-time by employing the proposed real-time inspection-routing and restoration-scheduling model can ensure the effectiveness and efficiency of emergency inspection and restoration operations. Third, taking into account the restoration-downtime impact on decreasing the highway network functionality can help to establish efficient long-term bridge restoration schedules, while neglecting such an impact can lead to the overestimation of highway network resilience.

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CHAPTER 1 INTRODUCTION

1.1 Research Background and Motivation

Destructive earthquakes frequently occurred worldwide in the last two decades, and the impacts of these earthquakes on communities have intensified due to the increased population intensity and urbanization in earthquake-prone areas (Guha-Sapir et al. 2017). For example, the 2015 Nepalese earthquake killed 8964 people and led to economic losses of around US$6.97 billion, or 35% of Nepalese's gross domestic product in 2012 (CEDIM 2015). Moreover, in 2011, the Christchurch Earthquake in New Zealand and the Tohoku Earthquake in Japan killed nearly 20,000 people and resulted in dramatic economic losses of more than US$400 billion (Kaiser et al. 2012; Kazama and Noda 2012). Furthermore, four major earthquakes from 2001 to 2010, i.e., the 2010 Haiti Earthquake (Bilham 2010; Kolbe et al. 2010), the 2008 Wenchuan Earthquake in China (Enz et al. 2009), the 2005 Kashmir Earthquake in Pakistan (Durrani et al. 2005), and the 2003 Bam Earthquake in Iran (Ghafory-Ashtiany and Hosseini 2008), killed more than 350,000 people.

In post-earthquake circumstances, highway networks play vital roles in relief operations and reconstruction processes, such as search and rescue, distribution of emergency supplies, evacuation of victims, and transportation of reconstruction materials and equipment. Consequently, seismic damages of highway networks can lead to not only the direct losses of physical infrastructure but also the substantial social and economic losses due to the disruption of relief and reconstruction operations.

Highway bridges are seismically vulnerable components of a highway network, and the damage of bridges can disrupt road connections between cities, leading to severe crises of rescue operations in the emergency response phase and a significant delay of the reconstruction of communities in the emergency recovery phase. For example, the Wenchuan Earthquake affected 2154 highway bridges, among which 52 bridges were completely destroyed and 70 were seriously damaged (Zhuang and Chen 2012). These damaged bridges resulted in the blockage of highways, which further impeded response and recovery actions. An example is the collapse of Caopo Bridge over the Caopo River, which disrupted the highway to Caopo Town for 60 days until a temporary bridge across Caopo River was built, resulting in a serious crisis of rescuing victims in Caopo Town (OSLR 2018). Moreover, the full recovery of these damaged highway bridges in the Wenchuan Earthquake took more than ten years (OSLR 2018), greatly affecting the recovery process of communities in the highway network. Therefore, efficient post-earthquake highway bridge restoration strategies are of paramount importance to both immediate disaster response and long-term recovery of communities.

Post-earthquake restoration of highway bridges can be divided into two phases: the emergency restoration in the emergency response phase and the long-term restoration in the emergency recovery phase (O'Connor 2010; ODOT 2017). In the emergency response phase, bridges in a highway network should be quickly inspected to provide damage information for emergency bridge restoration activities, which is just sufficient for supporting post-disaster relief operations. Prior studies that focused on scheduling emergency bridge restoration activities assumed that all information on bridge damages as well as restoration methods for these damaged bridges were known. However, in practice, emergency bridge restoration is performed as soon as the damage data of some bridges that are critical for supporting relief activities have been collected through emergency bridge inspection. Then both emergency inspection and restoration activities are performed simultaneously on the highway network, and the inspection routes and restoration schedules will be updated whenever further information on bridge damages is obtained. Accordingly, complex interactions among emergency inspection and restoration activities can occur and may significantly affect the following inspection routes and restoration schedules. Specifically, inspection routes may change due to the blockage of highways for the restoration of bridges on them; meanwhile, the restoration schedules could also be affected by inspection routes because only the bridges that have been inspected will be scheduled for emergency restoration. How to account for such interactions in routing and scheduling emergency bridge inspection and restoration activities remains a challenge, and the over-simplistic assumption that all bridge damage information is known before carrying out emergency bridge restoration activities makes existing scheduling methods inefficient and inapplicable for emergency bridge restoration.

Moreover, given that the initial emergency inspection and restoration plans are optimized based on the estimated damage states of bridges, and the real-time bridge damage information is only gradually revealed by inspection teams, decisions on emergency inspection routes and restoration schedules should be updated whenever the actual damage state of a bridge is found to be misestimated. For instance, if a bridge that is estimated to be slightly damaged is found to be actually seriously damaged, the inspection routes and restoration schedules should be updated immediately to avoid work teams passing through such an impassable bridge. However, a real-time decision-making tool for dynamically optimizing emergency bridge inspection and restoration plans is still a lack of study.

In addition to emergency restoration, one important key to efficiently recover highway networks from disasters is optimally scheduling long-term bridge restoration activities, which aim to fully restore damaged bridges to their pre-disaster conditions and may take months or years. Plenty of methods on long-term bridge restoration-scheduling problems have been developed with the aim of maximizing transportation network resilience (Ye and Ukkusuri 2015; Twumasi-Boakye and Sobanjo 2018; Zhang et al. 2018; Li et al. 2019). Generally, transportation network resilience in the recovery phase is defined as the network' post-disaster cumulative functionality in a time horizon (Bruneau et al. 2003; Frangopol and Bocchini 2011). These studies assumed that a highway network's functionality, which is the ability of a highway network to provide service to communities, would increase monotonically along with the recovery of physical damages directly caused by disasters. However, highway network functionality may temporarily drop during the restoration downtime of highways if passable highways are blocked for the restoration of bridges on them. Given that the precise appraisal of highway network resilience relies heavily on accurately modeling highway networks' functionality, the failure to take into account the restoration-downtime impact on networks' functionality may lead to the overestimation of highway network resilience, thereby resulting in inefficient bridge restoration schedules with long restoration downtime of highways.

1.2 Research Aim and Objectives

With the aim of facilitating post-earthquake recovery of highway networks, the present study develops novel methodologies for providing efficient bridge restoration strategies for a post-earthquake highway network. To achieve this aim, three objectives are set.

(1) To understand the impact of interactions among emergency bridge inspection and restoration activities on the optimal emergency bridge inspection routes and restoration schedules by developing a novel mathematical model as well as solution methodologies.

(2) To develop a real-time decision-making tool for dynamically updating emergency bridge inspection routes and restoration schedules based on the real-time bridge damage information collected via bridge inspection activities.

(3) To investigate the impact of restoration downtime on highway network resilience and the optimal long-term bridge restoration schedules by developing a novel functionality recovery model for highway networks.

1.3 Research Significance

The outcomes of this thesis are expected to help decision-makers develop efficient post-earthquake bridge restoration strategies and can provide both theoretical knowledge and practical implications for post-earthquake bridge inspection and restoration. The contributions of the proposed study are as follows.

First, this thesis can help to understand the interactions among emergency bridge inspection and restoration activities and thereby improve the efficiency of decision-making on optimally conducting these activities. The proposed mathematical models and solution methodologies can capture the complex inspection-restoration interactions and provide an approach for optimally routing and scheduling emergency bridge inspection and restoration activities to maximize highway network resilience.

Second, the proposed mathematical tools for real-time emergency bridge inspection routing and restoration scheduling can capture the effects of real-time bridge damage information on routing and scheduling problems. With such tools, decision makers are able to develop effective and efficient bridge restoration strategies in a dynamic environment.

Third, the proposed functionality recovery model that takes into consideration the impact of restoration downtime on networks' functionality can better appraise highway network resilience, and the proposed mathematical tool can improve the efficiency of long-term bridge restoration schedules by reducing the restoration downtime of highways.

1.4 Structure of the Thesis

This thesis consists of five chapters.

Chapter 1 introduces the main content of this thesis, including research background and motivation, research aim and objectives, research significance and contributions, and structure of this thesis.

Chapter 2 proposes a mathematical model to address the proposed post-earthquake emergency bridge inspection-routing and restoration-scheduling problem, which involves complex interactions among emergency inspection and restoration activities. This problem is formulated as an integer program with recursive functions that can account for the impacts of inspection-restoration interactions on the optimal inspection routes and restoration schedules. Additionally, a hybrid genetic algorithm that integrates a heuristic approach into a genetic algorithm to improve the computational efficiency of the algorithm in solving the proposed integer program is developed. Finally, the methodology is validated in a case study using data from the 2008 Wenchuan Earthquake in China.

Chapter 3 develops mathematical tools for the dynamic inspection-routing and restoration-scheduling problem using the decomposition technique and the integer programming technique, accounting for the real-time bridge damage information collected via inspection, with the aim of maximizing highway network resilience in terms of travel time. Additionally, a hybrid genetic algorithm that is specifically designed for adapting the dynamism in the proposed mathematical model is developed to effectively solve the dynamic model. The proposed mathematical model and the solution methodology are applied to a highway network in Sichuan, China, using data from the 2008 Wenchuan Earthquake.

Chapter 4 proposes a novel functionality recovery model for the optimization of post-earthquake bridge restoration schedules, with the aim of maximizing highway network resilience. Specifically, this model takes into consideration the impact of restoration downtime on the highway network's functionality to explicitly appraise highway network resilience, thereby generating efficient bridge restoration schedules. An integer program with recursive functions is developed to formulate the long-term bridge restoration-scheduling problem as well as the restoration-downtime impact on the network functionality. Next, a genetic algorithm is developed to solve the proposed model. Finally, the proposed methodology is validated using a highway network in Sichuan, China.

Chapter 5 presents the conclusions of this thesis, which have been identified by satisfying the present aim and objectives in Chapter 1. The main findings in this thesis are also presented. Finally, the limitations and potential extensions of this thesis are discussed.

CHAPTER 2 MODELING INTERACTIONS OF EMERGENCY INSPECTION AND RESTORATION FOR THE POST-DISASTER RESILIENCE OF HIGHWAY NETWORKS

2.1 Introduction

Highway networks play major roles in post-earthquake rescue operations because the movement of rescuers and relief supplies to damaged cities relies heavily on highways, especially in rural and mountainous areas where cities are connected by a few highways. Highway bridges are seismically vulnerable components in a highway network, and the destruction of highway bridges due to earthquakes can disrupt highways connecting to cities in disaster areas. Thus, the rapid recovery of highway bridges is of permanent importance for the recovery of highway networks' functionality for supporting emergency relief operations.

Post-disaster emergency restoration-scheduling models for transportation networks have been widely studied, with the aim of maximizing transportation network resilience (Zhang and Miller-Hooks 2015; Zhang et al. 2017; Li et al. 2019). Though differing in many aspects, these models optimized restoration schedules based on the assumption that the actual damages of transportation systems, as well as the corresponding restoration methods for the damaged systems, were known immediately after a disaster. Such an assumption can lead to unfavorable consequences because the emergency restoration of transportation systems can be delayed for days or weeks for the inspection of all affected bridges within a regional post-disaster highway network, especially if there is no effective routing strategy for conducting bridge inspection activities. Ideally, emergency bridge restoration and inspection activities can be performed simultaneously on a highway network, with restoration works commencing once the damage information of some bridges as well as the materials and equipment required for restoring these bridges have been obtained via inspection. Therefore, inspection routing can affect restoration scheduling because only bridges that have been inspected will be scheduled for restoration, while restoration activities can also affect inspection teams' routes, since bridges under restoration are impassable to inspection teams. Nonetheless, existing studies on post-disaster emergency restoration scheduling neglected the discussion of the inspection-restoration interactions in their scheduling models, and approaches to address the post-disaster emergency bridge inspection-routing problem is a lack study as well.

To bridge the aforementioned research gaps in existing emergency restoration scheduling models for post-disaster highway networks, this chapter develops an integer program with recursive functions for modeling the proposed post-earthquake emergency inspection-routing and restoration-scheduling problem, with the aim of maximizing highway network resilience in terms of travel time. Differing from traditional emergency restoration-scheduling models, which mainly focus on the optimization of only restoration schedules, the proposed model is designed to reveal the complex impacts of inspection-restoration interactions on the optimal inspection routes and restoration schedules, by assuming that a number of inspection teams and restoration teams can work simultaneously on a highway network. Additionally, this chapter proposes a hybrid genetic algorithm (GA) that integrates a heuristic approach with a traditional GA to efficiently solve the proposed integer program, thereby meeting the need for quick decision-making in the emergency response phase. The proposed mathematical model and solution methodology will then be tested using data from the 2008 Wenchuan Earthquake in China. The proposed study in this chapter can provide decision-makers with efficient inspection-routing and restoration-scheduling tools to draft post-earthquake emergency response strategies for highway systems.

This chapter is organized as follows. Section 2.2 thoroughly reviews the existing scheduling methods for post-disaster restoration of transportation networks and reveals shortages of these methods. Section 2.3 defines the emergency inspection-routing and restoration-scheduling problem in detail and develops the mathematical model for the proposed problem. Section 2.4 develops a specific solution methodology for efficiently solving the proposed mathematical model. Section 2.5 uses an actual highway network to validate the proposed model and the solution methodology. Section 2.6 concludes with research findings and scientific and practical significance.

2.2 Literature Review

2.2.1 Transportation System Resilience

Holling (1973) originally defined resilience as an ecosystem's ability to absorb disturbance from the surrounding environment and still maintain its equilibrium state. Recently, the concept of resilience has been extended to the field of transportation systems, where it is defined as the ability of a transportation system to resist and recover from disasters (Murray-Tuite 2006; Bocchini and Frangopol 2012; Levenberg et al. 2017; Calvert and Snelder 2018). Then, Bruneau et al. (2003) extended the concept of resilience to infrastructure systems as a measure of the system's ability to absorb a shock and to recover rapidly after a shock, and thereafter extensive definitions of infrastructure system resilience have been proposed (Murray-Tuite 2006; Bocchini and Frangopol 2012; Levenberg et al. 2017; Calvert and Snelder 2018). A widely accepted quantitative definition of transportation network resilience was proposed by Miller-Hooks, et al. (2012), as a measure of how much function a transportation network is able to handle post-disaster compared with the function handled pre-disaster. In the context of a highway network, its functionality can be measured by various indicators, including travel time (Orabi et al. 2009; Bocchini and Frangopol 2012; Faturechi and Miller-Hooks 2014; Alipour and Shafei 2016; Twumasi-Boakye and Sobanjo 2018), travel distance (Frangopol and Bocchini 2011), traffic capacity (Chang et al. 2012; Zhang and Miller-Hooks 2015), accessibility (Ip and Wang 2011; Taylor 2012; Zhang and Wang 2016), connectivity (Peeta et al. 2010), and betweenness (Berche et al. 2009). Among these indictors, travel time is the most commonly used indicator for network functionality because travel time is considered the most critical factor affecting the movement of travelers on a damaged highway network, especially when they have to take long detours due to impassable highways (Orabi et al. 2009; Faturechi and Miller-Hooks 2015). A post-earthquake highway network with a short travel time may transport people and goods in a timely manner for conducting rescue and evacuation operations, as well as delivery of materials and equipment for restorations. Therefore, this study utilizes travel time as the measure of highway networks' functionality and quantifies highway network resilience in the emergency response phase as the temporal change in such functionality (Faturechi and Miller-Hooks 2014).

2.2.2 Post-disaster Restoration Scheduling and Inspection Routing for Transportation Systems

Post-disaster restoration-scheduling problems for transportation systems aim to quickly and efficiently recover the damaged systems' functionality. Post-earthquake restoration can be divided into two general phases: emergency or short-term restoration, and long-term restoration. Emergency restoration aims to quickly and partially recover damaged transportation systems for supporting emergency response operations, such as the movement of rescuers, the evacuation of victims, and the transportation of relief supplies, and can be finished in a few days, while long-term restoration intends to fully restore damaged transportation systems to their pre-disaster conditions and may take months or years (O'Connor 2010; ODOT 2017). Though differing in terms of functionality measures (e.g., travel time, travel distance, or accessibility), a majority of long-term restoration studies have shared the general objective of achieving the maximum system resilience (Orabi et al. 2009; Vugrin et al. 2010; Bocchini and Frangopol 2012; Chang et al. 2012; Ye and Ukkusuri 2015; Zhang et al. 2017; Vahdani et al. 2018).

On the other hand, existing studies on emergency restoration scheduling methods, focused on optimally satisfying victims' urgent needs in the emergency response phase by maintaining emergency response activities (Tzeng et al. 2007). These response activities can only be conducted after the damaged transportation system has been restored if such a system is seriously damaged after a disaster. For instance, Yan and Shih (2009) developed an integer program to optimally schedule post-earthquake emergency restoration activities for seriously damaged roadways, as well as schedule the subsequent relief distribution activities, considering that efficient restoration of roadways could improve the efficiency of relief distributions. With the aim of maximizing the post-disaster traffic capacity of a coupled railway-roadway network in the emergency response phase, Miller-Hooks et al. (2012) developed an mathematical model to optimize the selection of recovery activities for such a network, including restoring damaged infrastructure, constructing temporary roadways, and employing advanced traffic management strategies. This model also took into consideration resource constraints on conducting these recovery activities, including the amount of labor and budget. Similarly, aiming at maximizing the traffic capacity of a rail-based freight-transportation system in emergency response, Zhang and Miller-Hooks (2015) investigated the optimal schedules of short-term recovery activities for this system, accounting for resource limitations. Moreover, Faturechi et al. (2014) developed a model to maximize the post-disaster takeoff and landing capacities of a runway and taxiway network of an airport by optimally allocating the limited resources for performing emergency response activities. Given that impassable roads may become passable to restoration teams after restoration, Li and Teo (2019) optimized both emergency restoration schedules and routes of restoration teams for supporting delivery of relief supplies. Though differing in various aspects, the emergency restoration scheduling methods mentioned above have shared the same assumption that the damages of transportation systems and the corresponding restoration methods are immediately and completely known after a disaster, and therefore emergency restoration can commence immediately after a disaster. In reality, however, detailed damage information of a transportation network's components, such as bridges, and specific restoration methods for these components could only be revealed by inspection efforts. For instance, the China Ministry of Transport's guidelines for post-earthquake highway bridge inspection allow seven days for the preliminary inspection of those bridges that have a high probability of being seriously damaged (MTC 2013). Thus, emergency relief activities could be seriously delayed if emergency restoration commenced only after the actual damage states and damage types of transportation systems and their corresponding restoration methods were both fully understood – especially if no effective emergency inspection-routing strategy was available.

In real world scenarios, given that emergency bridge inspection only gradually reveals the damages of bridges in a highway network, it is reasonable to assume that emergency restoration of bridges can commence as soon as the bridge damage information that is crucial to emergency response is obtained via emergency inspection activities, and therefore, all emergency bridge inspection and restoration activities can be conducted simultaneously on the highway network. In such a situation, interactions between emergency inspection and restoration activities may affect both emergency inspection and restoration activities. For example, inspection routes can affect restoration schedules because only bridges that have been inspected will be scheduled for emergency restoration; on the other hand, restoration scheduling can affect inspection routing by changing the passability of highways – highways that contain bridges undergoing restoration are impassable by inspection teams, thereby leading to the changes in their routes.

Moreover, it should be noticed that the use of inspection vehicles is generally considered a practical and reliable approach for collecting post-disaster bridge damages, while other damage detection methods that rely on unmanned aerial vehicles or high-resolution satellite imagery may become impracticable in bad weather conditions (Vigo 2015). Although some studies have investigated the optimization of vehicle-based inspection routing to improve the efficiency of routine bridge inspection tasks on a completely passable highway network (Faber and Sorensen 2002; Yan et al. 2016), their models are inapplicable to the post-disaster emergency inspection-routing problem, which should take into consideration the impassability of highways due to damaged bridges and the aforementioned restoration activities. Lam and Adey (2016) have accounted for the impact of inspection activities on the restoration time in their proposed recovery model for a damaged roadway network by assuming that inspection to a bridge should be done prior to restoring the bridge, and their model has been applied to the assessment of functional capacity losses of road networks exposed to different disasters (Lam et al. 2018; Lam et al. 2020). Although the one-way impact of inspection activities on restoration scheduling have been considered in these studies, restoration schedules can also affect the routes of inspection teams on a highway network, and therefore, two-way interactions among inspection and restoration activities should be considered in planning emergency bridge inspection and restoration activities.

2.3 Problem Formulation and Assumption

In this section, the proposed emergency inspection-routing and restoration-scheduling problem and common terms used in this chapter are first defined. Then, the functionality used for the measurement of highway network resilience is introduced. Finally, model assumptions are presented and the mathematical model is formulated.

2.3.1 Emergency Inspection-Routing and Restoration-Scheduling Problem

After an earthquake, some cities in a highway network are set as relief command centers, each of which includes a number of work teams, i.e., inspection teams and restoration teams. First, seismic damages of bridges can be estimated using seismic damage assessment methods, and bridges' damage states can be divided into five levels based on (FEMA 2012): no damage, slight damage, moderate damage, extensive damage, and complete damage. This chapter assumes that the actual damage states of bridges are the same as their estimated damage states. Moreover, the purpose of emergency inspection in this chapter is to virtually and preliminarily inspect details of bridges' damages, such as locations and sizes of cracks, and to provide such damage information for relief command centers to determine the corresponding emergency restoration methods for each damaged bridge. Also, unlike long-term restoration that aims to restore all damaged bridges to their pre-earthquake conditions, emergency restoration intends to quickly and partially restore damaged bridges to support emergency relief operations; therefore, this chapter assumes that only the bridges in moderate, extensive, or complete damage will be inspected and restored in the emergency response phase, and their damage states decrease to slight damage after emergency restoration, as suggested by Bocchini and Frangopol (2012) that slightly damaged bridges are unlikely to effect the traffic function of highway segments. Moreover, bridges in no damage or slight damage are not considered for emergency inspection and restoration. After an earthquake, inspection works can commence immediately, while restoration works can commence once damage information of some bridges has been collected by inspection teams. Then, emergency inspection and restoration activities are performed simultaneously on the highway network until reaching the given working time limitation.

2.3.2 Definitions of a Highway Network

A highway system is abstracted as a graph $G = (N, H)$, consisting of a number of links and nodes, where $N = \{N_1^c, \ldots, N_{n_c}^c, N_1^b, \ldots, N_{n_b}^b\}$ is the set of nodes, including n_c city nodes N_i^c and n_b bridge nodes N_i^b, and $H = \{H_1, H_2, \dots, H_{n_h}\}$ is the set of n_h highway segments H_i connecting adjacent city nodes. $l = \{l_1, l_2, \dots, l_{n_h}\}$ is the length of highway segments; $v_0 = \{v_{0,1}, v_{0,2}, \dots, v_{0,n_h}\}$ is the set of design speed of highway segments; $c_0 = \{c_{0,1}, c_{0,2}, \dots, c_{0,n_h}\}$ is the set of traffic capacity of highway segments. Time t is discretized into small increments of equal duration, $t = \{0,1,2, \dots, T\}$, with T being the investigated time horizon. The notation used within the mathematical formulation is listed in Table 2.1 and Table 2.2.

Table 2.1 Notation

Notations	
Sets	
N	set of network nodes, representing cities and bridges
H	set of highway segments
N^b	set of bridge nodes
N^c	set of city nodes
Parameters	
l	length of highway segments
v_0	design speed of highway segments
c_0	traffic capacity of highway segments
BDI_j	bridge damage index of bridge N_j^b, $\forall N_j^b \in N^b$
n_b	number of bridges in the highway network system
n_c	number of cities in the highway network system
n_h	number of highway segments in the highway network system
n_I	number of inspection teams in the highway network system

n_R	number of restoration teams in the highway network system
T	working time limitation
T_j^I	time required for inspecting bridge N_j^b, $\forall N_j^b \in N^b$
T_j^R	time required for restoring bridge N_j^b, $\forall N_j^b \in N^b$

Table 2.2 Decision variables and parameters to be calculated

Notations	
Decision variables	
x_{jkt}	a binary variable to indicate whether inspection crew k starts to inspect bridge N_j^b at time t
y_{jkt}	a binary variable to indicate whether restoration crew k starts to restore bridge N_j^b at time t
α_{ijk}	a binary variable to indicate whether inspection crew k inspects bridge N_j^b in sequence i
β_{ijk}	a binary variable to indicate whether restoration crew k restores bridge N_j^b in sequence i
Parameters to be calculated	
BDI_j^t	bridge damage index of bridge N_j^b at time t, $\forall N_j^b \in N^b$, $\forall t \in \{0,1,\ldots,T\}$
HDI_i^t	highway damage index of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\ldots,T\}$
R_T	highway system resilience
p_i^t	passability of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\ldots,T\}$
T_{ij}	pre-earthquake shortest travel time between city N_i^c and city N_j^c, $\forall N_i^c, N_j^c \in N^c$
T_{ij}^T	post-earthquake shortest travel time between city N_i^c and city N_j^c at time T, $\forall N_i^c, N_j^c \in N^c$
TR_i^t	travel time on highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\ldots,T\}$

c_i^t	residual traffic capacity of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
v_i^t	residual driving speed on highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
f_i^t	traffic flow on highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
t'	identified time
τ_{ij}^t	the shortest travel time between bridge N_i^b and bridge N_j^b at time t, $\forall N_i^b, N_j^b \in N^b$, $\forall t \in \{0,1,\dots,T\}$

2.3.3 Seismic Damage Assessment for Highway Networks

According to (FEMA 2012), the conditional probability of a bridge being in, or exceeding a particular bridge damage state d_s given a certain intensity of ground motion can be estimated using seismic fragility curves, as shown in Eq. (2.1),

$$P(d_s \geq DS_k | IM) = \Phi\left[\frac{1}{\beta_k}\ln\left(\frac{IM}{m_k}\right)\right], k = 1,2,3,4 \tag{2.1}$$

where DS_k is bridge damage state k and ranges from 1 to 4, representing slight damage, moderate damage, extensive damage, and complete damage, respectively; IM is the ground motion intensity; $\Phi(\cdot)$ is the cumulative density function of the standard normal distribution; m_k is the median value of the ground-motion intensity for the bridge damage state DS_k; and β_k is the standard deviation of the logarithm of the ground-motion intensity for the bridge damage state DS_k.

After an earthquake characterized by a given ground motion intensity IM, the probability of a bridge being in each of the five damage states can be calculated using Eq. (2.2),

$$
\begin{cases}
P(DS_0|IM) = 1 - P(d_s \geq DS_1|IM) \\
P(DS_1|IM) = P(d_s \geq DS_1|IM) - P(d_s \geq DS_2|IM) \\
P(DS_2|IM) = P(d_s \geq DS_2|IM) - P(d_s \geq DS_3|IM) \\
P(DS_3|IM) = P(d_s \geq DS_3|IM) - P(d_s \geq DS_4|IM) \\
P(DS_4|IM) = P(d_s \geq DS_4|IM)
\end{cases} \tag{2.2}
$$

where $P(DS_0|IM)$, $P(DS_1|IM)$, $P(DS_2|IM)$, $P(DS_3|IM)$, and $P(DS_4|IM)$ are conditional probabilities of a bridge in no damage, slight damage, moderate damage, extensive damage, and complete damage, respectively.

This chapter uses the bridge damage index (BDI) proposed by Dong et al. (2014) to convert the probabilistic damage states of a bridge to a deterministic value. The BDI of a bridge after an earthquake is calculated by summing the product of the probability of a bridge being in each damage state $P(DS_k|IM)$ and the corresponding BDI_k of each damage state, as shown in Eq. (2.3),

$$BDI = \sum_{k=0}^{4} BDI_k \cdot P(DS_k|IM) \tag{2.3}$$

where BDI_0, BDI_1, BDI_2, BDI_3, and BDI_4 are the mean value of bridge damage index corresponding to no damage, slight damage, moderate damage, extensive damage, and complete damage, and their values are 0, 0.1, 0.3, 0.75, and 1.0, respectively.

Based on the BDI value calculated by Eq. (2.3), the damage state of a bridge can be determined according to the five damage states' corresponding ranges of BDI (Gordon et al. 2004): no damage, $0 \leq BDI \leq 0.05$; slight damage, $0.05 < BDI \leq 0.2$; moderate damage, $0.2 < BDI \leq 0.525$; extensive damage, $0.525 < BDI \leq 0.85$; and complete damage, $0.85 < BDI \leq 1$.

This chapter uses the highway damage index (HDI) to classify damage states of highway segments into one of five levels: no damage, slight damage, moderate damage, extensive damage, and complete damage (Guo et al. 2017). The HDI of a highway segment is determined by the BDI of all bridges along the segment, as calculated by Eq. (2.4),

$$HDI = \begin{cases} \sqrt{\sum_{j=1}^{n_b} BDI_j^2} & \forall BDI_j \leq 0.525 \\ \infty & \exists BDI_j > 0.525 \end{cases} \tag{2.4}$$

where n_b is the number of bridges on the highway segment, and BDI_j is the BDI of bridge N_j^b on that segment. The damage state of highway segments can then be determined according to the five damage states' corresponding ranges of HDI: no damage ($HDI < 0.5$), slight damage ($0.5 \leq HDI < 1$), moderate damage ($1 \leq HDI < 1.5$), extensive damage ($1.5 \leq HDI < \infty$), and complete damage ($HDI = \infty$). It is noted that Eq. (2.4) suggests that a highway segment is considered to be impassable if it contains at least one bridge in extensive or complete damage state, i.e., any bridge with its BDI greater than 0.525.

Given that the driving speed and traffic capacities of highway segments may reduce if bridges on them are damaged, this chapter adopts Guo et al.'s study (2017) to estimate the residual driving speed v and traffic capacity c of highway segments: v and c are v_0 and c_0, $0.75v_0$ and c_0, $0.5v_0$ and $0.75c_0$, $0.5v_0$ and $0.5c_0$, 0 and 0, for highway segments in no damage, slight damage, moderate damage, extensive damage, and complete damage, respectively.

2.3.4 Residual Travel Time of Highway-bridge Networks

The travel time on a highway segment H_i at time t, TR_i^t, can be calculated using the Bureau of Public Roads function (Martin and McGuckin 1998), as shown in Eq. (2.5),

$$TR_i^t = \frac{l_i}{v_i^t} \times \left[1 + \alpha \left(\frac{f_i^t}{c_i^t}\right)^{\beta}\right], i, j = 1,2, \dots, n_C \tag{2.5}$$

where l_i is the length of highway segment H_i; v_i^t, f_i^t, and c_i^t are driving speed, traffic flow, and traffic capacity of H_i at time t; the values of function parameters α and β are 0.15 and 4, respectively. This study assumes that the traffic flow distribution on a highway network is user equilibrium, where users choose their routes with the shortest travel time, and the traffic flow f_i^t on each highway segment can be solved using the Frank-Wolfe algorithm (Florian and Hearn 1995).

Furthermore, based on the travel time of each highway segment TR_i^t, the pre-earthquake shortest travel time between cities, T_{ij}, and the post-earthquake shortest travel time between cities at time T ($t = T$ is a given working time after an earthquake), T_{ij}^T, can be calculated using the Dijkstra's algorithm (Hougardy 2010), which is designed to search efficiently for the shortest travel time paths between nodes in a given graph.

2.3.5 Quantification of Highway Network Resilience

Adapting the resilience qualification model for transportation networks developed by Faturechi and Miller-Hooks (2014) for a practical post-earthquake situation where some cities in a highway-bridge network are disconnected from the network due to complete damage of highway segments, this chapter calculates highway network resilience R_T as the change in highway network functionality, i.e., travel time, within a given time horizon T, as expressed in Eq. (2.6). The value of $F(t)$ indicates the damage condition of a highway network and ranges from 0 to 1, where the value 1 indicates that the functionality of the network has been fully recovered to its pre-earthquake level, and 0 indicates that no highway segment is passable.

$$R_T = \frac{1}{2n_P}\sum_{\forall i,j\in N^c, i\neq j}\frac{T_{ij}}{T_{ij}^T} \tag{2.6}$$

where T_{ij} is the pre-earthquake shortest travel time between city N_i^c and city N_j^c ; T_{ij}^T is the post-earthquake shortest travel time between N_i^c and N_j^c at time T; n_P is the total number of the shortest paths between n_c cities in the network, and its value is $\frac{n_c\cdot(n_c-1)}{2}$. R_T ranges from 0 to 1, and a larger value of R_T indicates a higher level of network resilience (i.e., the value of 1 indicates that the functionality of a network has fully recovered to its pre-earthquake level).

2.3.6 Model Assumptions and Problem Formulation

2.3.4.1 Model Assumptions

Based on prior studies of post-earthquake emergency response in general (Reed and Wang 1993; Yan and Shih 2007; Yan et al. 2014; ODOT 2017) and the specific cases of China and Japan (WCTPMC 2010; Zhuang and Chen 2012; TRB 2014; OSLR 2018), the present study has made several reasonable assumptions for the sake of easing the modeling of the proposed problem.

(1) Damages of a highway network only occur to bridges on them, while highway segments are not subject to damage.

(2) Work teams of both types can work continuously in time T and not run out of electricity, fuel, or restoration materials. Thus, they will not need to return to relief command centers for replenishment after they start their works.

(3) Only those bridges in moderate, extensive, or complete damage will be inspected or

restored. This is because those with slight damage or no damage are not likely to impede traffic in the emergency response phase.

(4) A bridge will not be scheduled for restoration until it has been inspected.

(5) Bridges under repair are blocked, and thus these bridges cannot be crossed by work teams. On the other hand, inspection works do not lead to the blockage of bridges, and thus bridges under inspection are passable if they are not in extensive or complete damage.

2.3.4.2 Model Formulation

The proposed inspection-routing and restoration-scheduling model can be formulated as (P):

$$\text{(P)}\ \max\ R_T \tag{2.7}$$

subject to

$$\sum_{\forall k\in\{1,2,\dots,n_I\}}\sum_{\forall t\in\{0,1,\dots,T\}} x_{jkt} \le 1, \forall\, j \in N^b \tag{2.8}$$

$$\sum_{\forall k\in\{1,2,\dots,n_R\}}\sum_{\forall t\in\{0,1,\dots,T\}} y_{jkt} \le 1, \forall\, j \in N^b \tag{2.9}$$

$$\sum_{\forall j\in N^b} x_{jkt} \le 1, \forall\, k \in \{1,2,\dots,n_I\}, \forall\, t \in \{0,1,\dots,T\} \tag{2.10}$$

$$\sum_{\forall j\in N^b} y_{jkt} \le 1, \forall\, k \in \{1,2,\dots,n_R\}, \forall\, t \in \{0,1,\dots,T\} \tag{2.11}$$

$$\sum_{\forall j\in N^b} \alpha_{ijk} \ge \sum_{\forall j\in N^b} \alpha_{i+1,jk}, \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_I\} \tag{2.12}$$

$$\sum_{\forall j\in N^b} \beta_{ijk} \ge \sum_{\forall j\in N^b} \beta_{i+1,jk}, \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{2.13}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} x_{jkt} = \sum_{\forall i\in\{1,2,\dots,n_b\}} \alpha_{ijk}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\} \tag{2.14}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} y_{jkt} = \sum_{\forall i\in\{1,2,\dots,n_b\}} \beta_{ijk}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\} \tag{2.15}$$

$$\sum_{\forall j\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}}\alpha_{ijk}x_{jkt}t+\sum_{\forall j\in N^b}\alpha_{ijk}T_j^I+$$
$$\sum_{\forall j\in N^b}\sum_{\forall p\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}}\alpha_{ijk}\alpha_{i+1,pk}x_{pkt}\tau_{jp}^t\le$$
$$\sum_{\forall p\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}}\alpha_{i+1,pk}x_{pkt}t\,,\forall\, i\in\{1,2,\dots,n_b-1\},\forall\, k\in\{1,2,\dots,n_I\} \qquad (2.16)$$

$$\sum_{\forall j\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}}\beta_{ijk}y_{jkt}t+\sum_{\forall j\in N^b}\beta_{ijk}T_j^R+$$
$$\sum_{\forall j\in N^b}\sum_{\forall p\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}}\beta_{ijk}\beta_{i+1,pk}y_{pkt}\tau_{jp}^t\le$$
$$\sum_{\forall p\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}}\beta_{i+1,pk}y_{pkt}t\,,\forall\, i\in\{1,2,\dots,n_b-1\},\forall\, k\in\{1,2,\dots,n_R\} \qquad (2.17)$$

$$\sum_{\forall t\in\{0,1,\dots,T\}}x_{jkt}\left(t+T_j^I\right)\le T,\forall\, j\in N^b,\forall\, k\in\{1,2,\dots,n_I\} \qquad (2.18)$$

$$\sum_{\forall t\in\{0,1,\dots,T\}}y_{jkt}\left(t+T_j^R\right)\le T,\forall\, j\in N^b,\forall\, k\in\{1,2,\dots,n_R\} \qquad (2.19)$$

$$x_{jkt},\alpha_{ijk}\in\{0,1\},\forall\, j\in N^b,\forall\, k\in\{1,2,\dots,n_I\},\forall\, t\in\{0,1,\dots,T\},\forall\, i\in\{1,2,\dots,n_b\} \qquad (2.20)$$

$$y_{jkt},\beta_{ijk}\in\{0,1\},\forall\, j\in N^b,\forall\, k\in\{1,2,\dots,n_R\},\forall\, t\in\{0,1,\dots,T\},\forall\, i\in\{1,2,\dots,n_b\} \qquad (2.21)$$

$$\sum_{\forall i\in\{1,2,\dots,n_b\}}\sum_{\forall k\in\{1,2,\dots,n_I\}}\alpha_{ijk}\ge\sum_{\forall i\in\{1,2,\dots,n_b\}}\sum_{\forall k\in\{1,2,\dots,n_R\}}\beta_{ijk}\,,\forall\, j\in N^b \qquad (2.22)$$

$$\sum_{\forall i\in\{1,2,\dots,n_b\}}\sum_{\forall l\in\{1,2,\dots,n_R\}}\sum_{\forall k\in\{1,2,\dots,n_I\}}\sum_{\forall t\in\{0,1,\dots,T\}}\beta_{ijl}x_{jkt}t+$$
$$\sum_{\forall i\in\{1,2,\dots,n_b\}}\sum_{\forall l\in\{1,2,\dots,n_R\}}\beta_{ijl}T_j^I\le\sum_{\forall k\in\{1,2,\dots,n_R\}}\sum_{\forall t\in\{0,1,\dots,T\}}y_{jkt}t-$$
$$\sum_{\forall i\in\{1,2,\dots,n_b-1\}}\sum_{\forall p\in N^b}\sum_{\forall k\in\{1,2,\dots,n_R\}}\sum_{\forall t\in\{0,1,\dots,T\}}\beta_{ipk}\beta_{i+1,jk}\tau_{pj}^t\,,\forall j\in N^b \qquad (2.23)$$

The objective function (2.7) seeks the maximum resilience R_T under a given working time T. Constraints (2.8) and (2.9) ensure that no bridge is inspected or restored more than once. Constraints (2.10) and (2.11) ensure that a work team can commence inspecting or restoring only one bridge at a time. Constraints (2.12) and (2.13) indicate the number of bridges that are inspected or restored by a work team; for example, if

$\sum_{\forall j \in N^b} \alpha_{ijk} = 1$and $\sum_{\forall j \in N^b} \alpha_{i+1,jk} = 0$, the number of bridges to be inspected by inspection team k is i. Constraint (2.14) establishes the relationship between non-independent decision variables x_{jkt} and α_{ijk}: specifically, if bridge N_j^b is inspected by inspection team k , $\sum_{\forall t \in \{0,1,\ldots,T\}} x_{jkt} = \sum_{\forall i \in \{1,2,\ldots,n_b\}} \alpha_{ijk} = 1$; otherwise, $\sum_{\forall t \in \{0,1,\ldots,T\}} x_{jkt} = \sum_{\forall i \in \{1,2,\ldots,n_b\}} \alpha_{ijk} = 0$. Similarly, constraint (2.15) establishes the relationship between non-independent decision variables y_{jkt} and β_{ijk}. Constraints (2.16) and (2.17) are recursive inequalities and establish the relationship between the start times of two adjacent work tasks performed by the same work team. For example, for inspection team k, the time interval between the start time of its task i, e.g., the inspection of bridge N_p^b, and its task $(i+1)$, e.g., the inspection of bridge N_q^b, should be no less than the sum of the inspection time for bridge N_p^b and the travel time from N_p^b to N_q^b. Constraints (2.18) and (2.19) ensure that all emergency inspection and restoration works are completed within T, and constraints (2.20) and (2.21) enforce binary-value requirements on the decision variables.

As an important part of the formulation of the inspection-restoration interactions, constraints (2.22) and (2.23) ensure that bridges will be scheduled for restoration only after they have been inspected. Moreover, given that the impacts of emergency restoration activities on the subsequent inspection routes and restoration schedules, i.e., the blockage or unblocking of damaged bridge, can lead to the changes of the between-bridge travel time, such impacts are included in the model by recursively calculating the between-bridge travel time, τ_{ij}^t. Specifically, when the inspection or restoration of a bridge is finished at time t', the network-state-related parameters, which include the set of bridges that have been inspected, the bridge damage index $BDI_j^{t'}$, the highway damage index $HDI_i^{t'}$, and the passability of highway segments p_i^t, will change. Such changes can further affect both $\tau_{ij}^{t'}$ and $TR_i^{t'}$ (Eqs. (2.4) to (2.5)). On the other hand, these network-state-related parameters remain unchanged at time t $(t \neq t')$ when work teams are inspecting or restoring bridges or on their ways to the bridges to be inspected or restored. Accordingly, these parameters should be recalculated recursively at each time t', defined as the "identified time" in this chapter, to update $\tau_{ij}^{t'}$. The process of updating $\tau_{ij}^{t'}$ is shown in Figure 2.1. First, at each identified time t', the $HDI_i^{t'}$ of highway segments can be calculated based on the $BDI_j^{t'}$ of highway bridges to estimate the residual driving speed $v_i^{t'}$, traffic capacity $c_i^{t'}$, and traffic flow $f_i^{t'}$ of highway segments (Eq. (2.4)). Next, based on $v_i^{t'}$, $c_i^{t'}$, $f_i^{t'}$, and the length of highway segments, the travel time between adjacent nodes can be calculated using Eq. (2.5). Meanwhile, extensively damaged bridges, completely damaged bridges, and bridges under restoration are labeled as impassable. Finally, the shortest travel time between bridges ($\tau_{ij}^{t'}$) and the shortest travel time between cities ($T_{ij}^{t'}$) can be calculated using Dijkstra's algorithm (Hougardy 2010) while avoiding to pass through these labeled nodes.

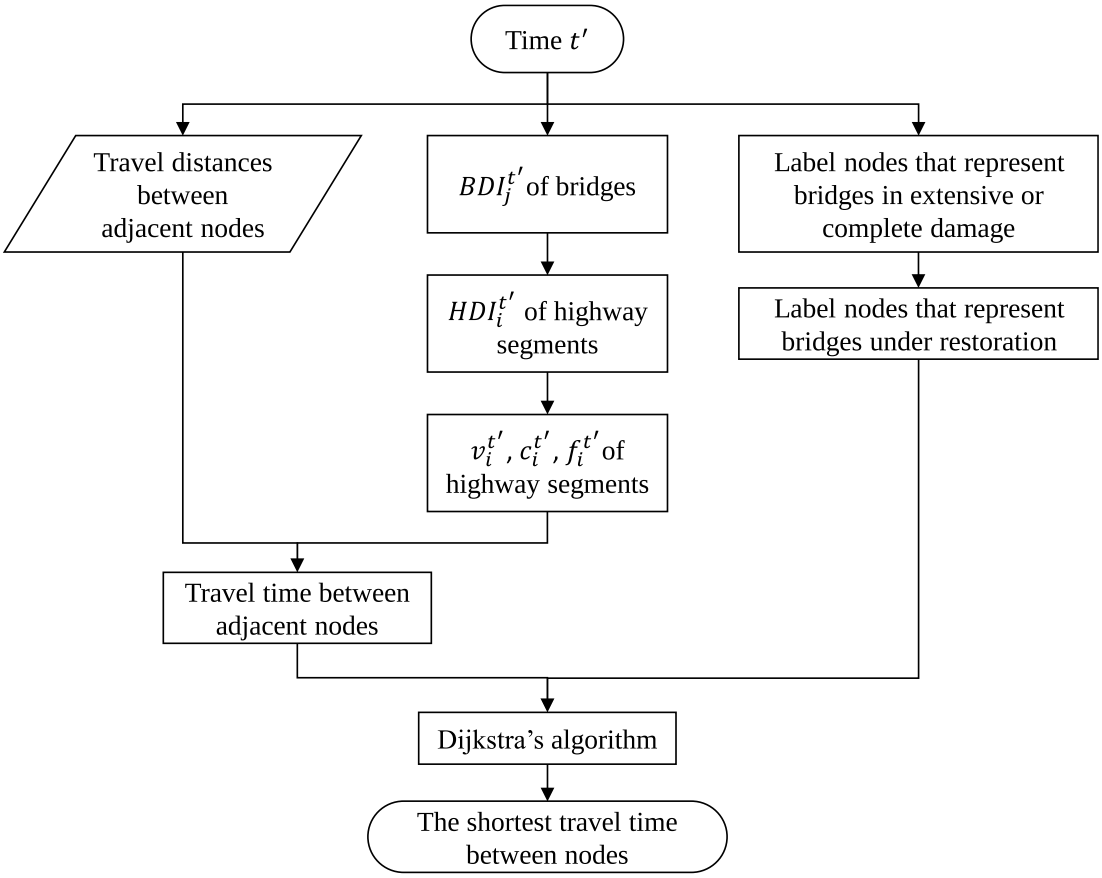


Figure 2.1 Calculation of the shortest travel time between nodes

2.4 Solution Methodology

2.4.1 Hybrid Genetic Algorithm

Both vehicle-routing and restoration-scheduling problems in transportation systems are usually considered as NP-hard problems (Yan et al. 2014; Balcik 2017), which means that it is impracticable to find the optimal solutions of these problems in a transportation network composed of a great number of nodes and links within the limited time. The specific problems to be solved in this chapter, which involve accounting for the complex inspection-restoration interactions, are more computationally complex than similar routing and scheduling problems. Accordingly, this chapter proposes a hybrid

GA (Figure 2.2) to efficiently solve the proposed integer program. First, a number of chromosomes are randomly generated to form the initial population, and each chromosome that consists of a set of decision variables represents a solution for the proposed integer program. Since α_{ijk} and $x_{jkt'}$, β_{ijk} and $y_{jkt'}$ are non-independent decision variables, if α_{ijk} and β_{ijk} are known, $x_{jkt'}$ and $y_{jkt'}$ can be calculated using constraints (2.14) through (2.17). Therefore, a chromosome needs only to represent α_{ijk} and β_{ijk} to form candidate routing and scheduling solutions. Additionally, the level of highway system resilience that can be reached at T through the implementation of such candidate routing and scheduling solutions can be calculated.

Then, elite chromosomes are selected from the initial population for crossover and mutation, using the roulette-wheel selection method, which are effective in selecting useful chromosomes in GAs (Goldberg 1989). In this method, chromosomes with large fitness values, i.e., large resilience values, are associated with proportionally large probabilities of being selected. After applying crossover and mutation operations to these elite chromosomes, new offspring will be generated. Next, the early-termination test, which is a heuristic approach and is specially designed for the proposed integer program, is conducted to accelerate the evolution of chromosomes by identifying and modifying the abnormal genes that hinder the improvement of chromosomes' fitness values. Details of the early-termination test are provided in the next subsection. After conducting the early-termination test, the fitness values of the offspring are calculated, and those with high fitness values are selected to update the population. Finally, if the stopping criterion, i.e., the maximum number of generations, is met, the hybrid GA will output the best fitness value (i.e., maximum highway network resilience) and the optimal inspection routes and restoration schedules.

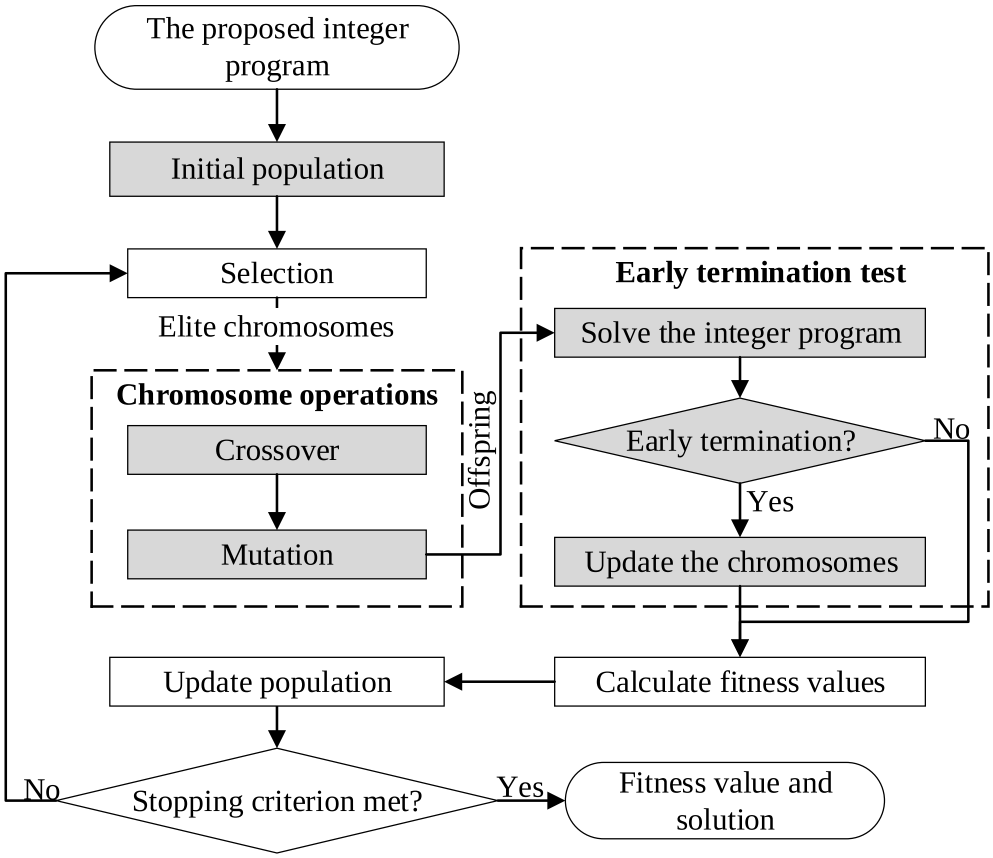


Figure 2.2 Process of the proposed hybrid genetic algorithm

2.4.2 Solution Encoding

A chromosome in a GA is considered as a feasible solution for the proposed integer program (P) if it satisfies all constraints in P. An encoding scheme that allows feasible chromosomes to be created, and chromosomes to be updated while maintaining their feasibility, is critical to the computational efficiency of a GA. The proposed encoding scheme for the proposed integer program (P) is shown in Figure 2.3. Each chromosome comprises two elements, with element_1 being the sequence of bridge inspection (i.e., α_{ijk}), and element_2 being the sequence of bridge restoration (i.e., β_{ijk}). Each element includes n_B genes, and these genes are encoded by n_B non-repeating integer numbers one to n_B, representing bridge IDs. Each element is further divided into n_I and n_R sub-elements, which respectively indicate work teams' inspection and restoration sequences. For example, as shown in Figure 2.3, the genes on sub-element$_{1,1}$ indicate the sequence of bridges to be inspected by inspection team_1, and the genes on sub-element$_{2,2}$ indicate the sequence of bridges to be restored by restoration team_2.

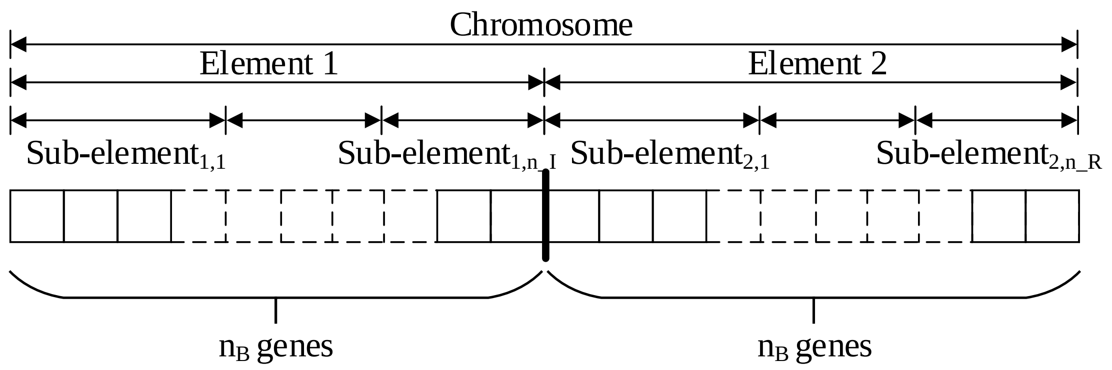


Figure 2.3 Encoding scheme for a chromosome

2.4.3 Early-termination Test

From pilot studies conducted in preparation for the current study, it was observed that the best fitness value of the population evolved very slowly over generations. After running numerous simulations based on these chromosomes, the early termination – a situation in which all work teams terminate their inspection and restoration works before reaching working time limitation T – was found to lead to the slow evolution of these chromosomes' fitness. The early-termination problem results from the inspection-restoration interactions and the inaccessibility of bridges within the highway network. Specifically, inspection teams would stop working if bridges they needed to inspect were inaccessible due to blockages of highway segments, and restoration teams terminated their work if the bridges they needed to restore were either inaccessible to them, or uninspected by any inspection teams.

To solve the early-termination problem, the early-termination test was designed to prompt the improvement of chromosomes' fitness values in each generation. As illustrated in Figure 2.4, this test begins with inputting a chromosome, and the first identified time t' is 0 when a disaster occurs. At that point, all work teams stay at relief command centers and are ready for work. The following identified time t', i.e., the earliest end time of ongoing inspection work $(t_{Ins,1}, t_{Ins,2}, \dots, t_{Ins,n_i})$ and ongoing restoration work $(t_{Rep,1}, t_{Rep,2}, \dots, t_{Rep,n_r})$, is calculated recursively. If t' is the time when inspection team i finishes the inspection of a bridge (i.e., $t' = t_{Ins,i}$), and the next bridge to be inspected by inspection team i, e.g., bridge N_k^b, is accessible, the program will update the information on bridges that have been inspected, as well as the time when inspection team i finishes the inspection of bridge k, and then move to the next identified time. On the other hand, if bridge k is inaccessible, the duration of ongoing work for inspection team i is set as infinite, meaning that inspection team i stays at where it is after finishing its current inspection work, after which, the identified time t' is re-calculated. Similarly, if t' is the time when restoration team j finishes the restoration of a bridge (i.e., $t' = t_{Rep,j}$), and the next bridge to be restored by restoration team j, e.g., bridge k, is not only accessible but also has been inspected, the program will update these network-state-related parameters, as well as the time when restoration team i finishes the restoration of bridge k, and then move to the next identified time. However, if bridge k is either inaccessible or uninspected, the duration of ongoing work for restoration team j is set as infinite, and then the identified time is re-calculated. Moreover, at each t', the program will test whether those work teams with end times being set as infinity can go to the bridge they had planned to visit next. The early-termination test will continue until $t' \geq T$. If t' is finite, the chromosome is deemed normal; otherwise, early termination will be enacted because work teams cannot move to their next bridges and terminate inspection and restoration work before reaching T.

With the implementation of early-termination test, the gene on a sub-element that leads to the early termination is extracted and moved to the end of that sub-element, deprioritizing the inspection and restoration of the particular bridge associated with that gene (Figure 2.5). Our preliminary study revealed that the evolution of the population was significantly improved after several generations when the proposed early-termination test was applied, as compared to when it was not.

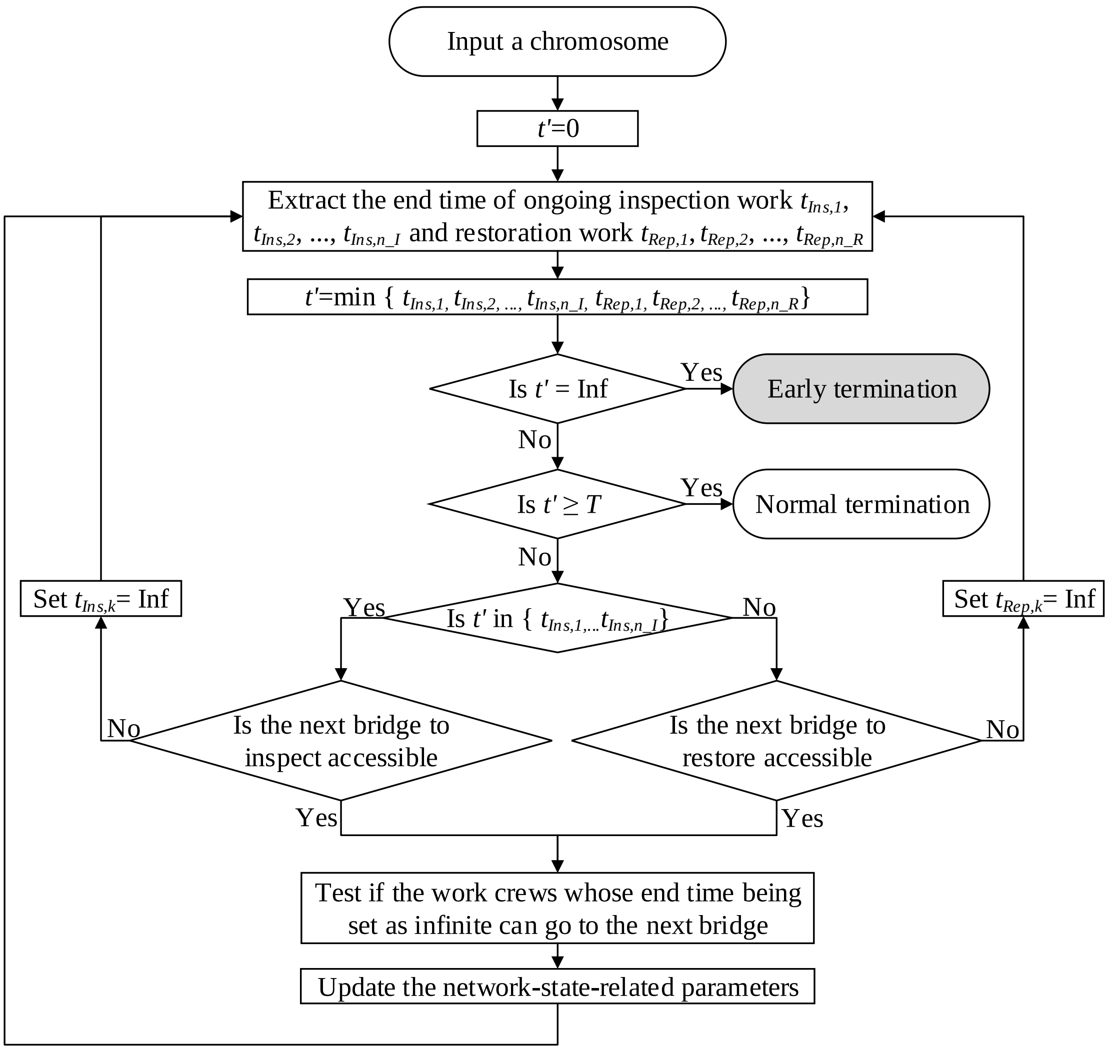


Figure 2.4 Process of the early-termination test

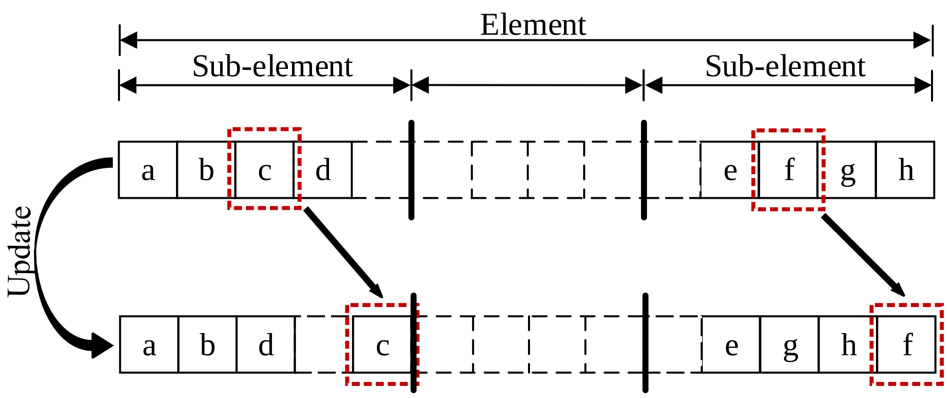


Figure 2.5 Update of a chromosome terminated early

2.5 Case Study

2.5.1 Experimental Design and Parameter Settings

The case study used a highway system in Sichuan, China (Figure 2.6), which included 25 cities, 37 highway segments, and 425 bridges, to illustrate the proposed methodology. Attributes of the highway network, including lengths, design speeds, and traffic capacity of highway segments, are recorded in Zhuang and Chen (2012) and are tabulated in Table 2.3. Moreover, due to the lack of data on the number and locations of relief command centers, as well as the number of work teams, this chapter assumed that three relief command centers were located in C1, C19, and C21 (Figure 2.6), and the number of inspection teams and restoration teams in these relief command centers were three, two, and one, respectively. The average emergency inspection time for one bridge by one inspection team was 30 minutes (Zhuang and Chen 2012).

The 2008 Wenchuan Earthquake was used as the earthquake scenario, and its peak ground acceleration distribution was adopted from (MTPRC 2009). Moreover, this chapter adopted bridges' seismic fragility curves in Chen et al. (2012), which were developed based on the real bridge damage data in the 2008 Wenchuan Earthquake (Table 2.4), to assess bridges' seismic damage states. The presumed pre-earthquake travel demand between cities is listed in Table 2.5, and the post-earthquake travel demand was set as 12 times of the pre-earthquake travel demand according to Li et al.'s study (2008), which found that the traffic flow after the Wenchuan Earthquake in the emergency response phase was approximately 12 times the pre-earthquake daily traffic flow.

This case study calculated the highway system resilience and the corresponding optimal inspection routes and restoration schedules for the first 72 hours after the earthquake, given that this period is considered as the "golden hours" for saving human lives (i.e., $T = 4320\ minutes$, and $t = \{0,1,2, \ldots ,4320\}$ with equal increments of one minute) (Verma and Chauhan 2015). Three sets of tests were conducted based on the same highway system and earthquake scenario. First, the system resilience that resulted from the proposed inspection-routing and restoration-scheduling model was compared with the resilience from a general inspection-routing and restoration-scheduling model without considering inspection-restoration interactions. Second, sensitivity analysis was conducted to investigate the impacts of the working time and the number of work teams, considered as resource limitations, on the system resilience. Finally, the computational efficiency and accuracy of the proposed hybrid GA were compared with that of a traditional GA without the proposed heuristic approach.

It is worth noting that the population size of a GA, i.e., the number of chromosomes in it, is typically defined as an exponential function of the number of genes on a chromosome, n_{gene} (Goldberg 1989). However, adopting such a definition in this case can lead to an overlarge population size and can significantly decrease the GA's computational efficiency. Therefore, the present study followed Xie and Xing's (1998) recommendation that the population size was set to be between n_{gene} and $2n_{gene}$. In the above-mentioned pilot studies, the algorithm parameters that were found to result in high computational efficiency were: population size of 200, 20 elite chromosomes, 200 generations, a crossover probability of 0.9, and a mutation probability of 0.3. The MATLAB computer language was used to program the mathematical model and the hybrid GA. All tests were performed on an Intel® Core™ i7-7700 CPU@ 3.6GHz with 32 GB RAM in a Microsoft Windows 10 environment.

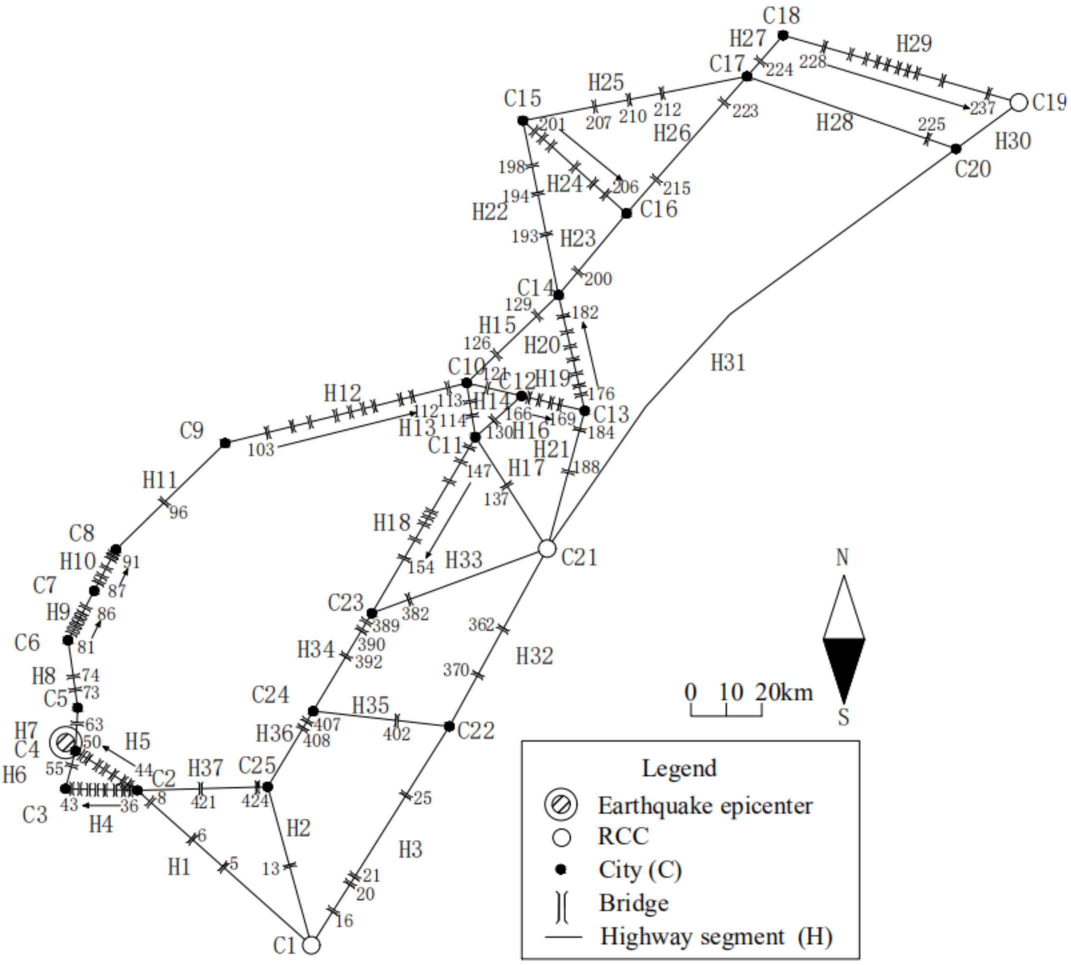


Figure 2.6 A highway network in Sichuan, China

Table 2.3 Attributes of highway segments

Highway segment H_i	City N_i^c	City N_j^c	Length (km)	Design speed (km/h)	Traffic capacity (pcu/day)	Bridges on H_i
H1	C1	C2	60	80	115200	1-8
H2	C1	C25	48	80	115200	9-14
H3	C1	C22	73	80	115200	15-35

H4	C2	C3	31	30	16800	36-43
H5	C2	C4	25	80	115200	44-50
H6	C3	C4	13	40	26400	51-57
H7	C4	C5	12	40	26400	58-69
H8	C5	C6	25	30	16800	70-80
H9	C6	C7	19	30	16800	81-86
H10	C7	C8	18	40	24000	87-91
H11	C8	C9	62	40	24000	92-101
H12	C9	C10	90	40	24000	102-112
H13	C10	C11	22	40	24000	113-118
H14	C10	C12	30	40	26400	119-123
H15	C10	C14	23	40	26400	124-129
H16	C11	C12	25	40	24000	130-134
H17	C11	C21	43	30	16800	135-146
H18	C11	C23	54	40	24000	147-165
H19	C12	C13	22	30	16800	166-173
H20	C13	C14	45	40	24000	174-183
H21	C13	C21	42	30	16800	184-190
H22	C14	C15	70	40	24000	191-198

H23	C14	C16	50	60	28800	199-200
H24	C15	C16	50	60	28800	201-206
H25	C15	C17	116	40	26400	207-214
H26	C16	C17	100	60	28800	215-223
H27	C17	C18	35	60	28800	224
H28	C17	C20	95	30	16800	225-226
H29	C18	C19	82	60	31200	227-237
H30	C19	C20	42	20	9600	238-252
H31	C20	C21	138	40	28800	253-361
H32	C21	C22	56	30	16800	362-374
H33	C21	C23	53	20	9600	375-388
H34	C23	C24	32	40	24000	389-401
H35	C22	C24	25	40	24000	402-406
H36	C24	C25	32	80	115200	407-419
H37	C2	C25	38	40	26400	420-425

Table 2.4 Parameters of bridges' fragility curves

Bridge types	Indicators	Bridge damage state			
		SD	MD	ED	CD
Simple supported beam bridge	ME	0.3911	0.4966	0.8901	1.0309
	LSD	0.4907	0.9012	0.3933	0.3498
Continuous beam bridge	ME	0.3548	0.5332	0.9611	1.7165
	LSD	0.0358	0.1020	1.0000	1.0000
Reinforced concrete arch-bridge	ME	0.2024	0.3682	0.9067	1.4682
	LSD	1.0000	1.0000	1.0000	0.4624
Masonry arch-bridge	ME	0.368	0.6121	0.8721	1.3038
	LSD	0.7987	0.6643	0.5463	0.3239

Note: ME = Median, LSD = Logarithmic standard deviation, S = slight damage, M = moderate damage, E = extensive damage, C = complete damage

Table 2.5 Pre-earthquake traffic demands between cities

City N_i^c	City N_j^c	Traffic demand (pcu/day)	City N_i^c	City N_j^c	Traffic demand (pcu/day)	City N_i^c	City N_j^c	Traffic demand (pcu/day)
C1	C2	2000	C2	C25	1000	C12	C21	500
C1	C3	200	C4	C5	200	C13	C14	400
C1	C4	300	C5	C8	200	C13	C21	400

C1	C5	300	C6	C8	200	C15	C19	500
C1	C8	500	C7	C9	300	C16	C17	600
C1	C9	300	C8	C9	500	C16	C19	600
C1	C10	500	C10	C13	600	C16	C22	1400
C1	C21	1500	C10	C21	200	C17	C18	800
C1	C22	1200	C11	C13	500	C17	C19	500
C2	C4	500	C11	C21	500	C18	C19	800
C2	C6	200	C11	C23	400	C19	C20	1000
C2	C7	200	C12	C13	400	C20	C21	2000

2.5.2 Results and Discussions

2.5.2.1 Results of Bridge Damage Assessment

The results of seismic damage assessment show that 167 bridges were in no damage, and 143, 70, 34, and 11 bridges were in slight, moderate, extensive, and complete damage state, respectively (Table 2.6). These bridges in moderate, extensive, or complete damage are shown in Figure 2.6. As aforementioned, only bridges in moderate, extensive, or complete damage were considered for emergency inspection and restoration, and the restoration time for these bridges referred to Instruction for Post-earthquake Bridge Emergency Repair Methods and Technology (WCTPMC 2010), which determined the emergency restoration time of a bridge based on its structural type, damage state, size, and the emergency restoration method, are shown in Table 2.6.

Table 2.6 Bridge damage states and emergency restoration time

Bridge ID	DS	RT	Bridge ID	DS	RT	Bridge ID	DS	RT
1	ND	-	143	ND	-	285	ND	-
2	ND	-	144	ND	-	286	SD	-
3	SD	-	145	ND	-	287	ND	-
4	SD	-	146	ND	-	288	ND	-
5	MD	2	147	MD	3.3	289	SD	-
6	MD	3.7	148	ED	4.5	290	SD	-
7	SD	-	149	ED	4.5	291	SD	-
8	ED	7	150	ED	9.7	292	SD	-
9	ND	-	151	ED	4.2	293	SD	-
10	ND	-	152	ED	2.5	294	SD	-
11	ND	-	153	ED	5.2	295	ND	-
12	ND	-	154	MD	1.2	296	ND	-
13	MD	2.7	155	SD	-	297	ND	-
14	SD	-	156	ND	-	298	ND	-
15	ND	-	157	SD	-	299	ND	-
16	MD	3.1	158	ND	-	300	ND	-

17	ND	-	159	ND	-	301	ND	-
18	SD	-	160	ND	-	302	ND	-
19	SD	-	161	ND	-	303	ND	-
20	MD	4.9	162	SD	-	304	ND	-
21	MD	3.4	163	ND	-	305	ND	-
22	ND	-	164	ND	-	306	ND	-
23	ND	-	165	ND	-	307	ND	-
24	ND	-	166	MD	2.9	308	ND	-
25	MD	3.2	167	MD	2.8	309	ND	-
26	ND	-	168	MD	1.4	310	ND	-
27	ND	-	169	MD	1.3	311	ND	-
28	ND	-	170	SD	-	312	ND	-
29	ND	-	171	SD	-	313	ND	-
30	ND	-	172	ND	-	314	ND	-
31	ND	-	173	ND	-	315	ND	-
32	ND	-	174	ND	-	316	ND	-
33	ND	-	175	ND	-	317	ND	-
34	ND	-	176	MD	3	318	ND	-
35	ND	-	177	MD	1.6	319	ND	-

36	MD	5	178	MD	2.1	320	ND	-
37	MD	2	179	MD	3.7	321	ND	-
38	MD	3.8	180	ED	8.4	322	ND	-
39	MD	4.1	181	ED	2.3	323	ND	-
40	ED	7.6	182	MD	2.7	324	ND	-
41	ED	5.6	183	ND	-	325	ND	-
42	ED	7.2	184	MD	3.2	326	ND	-
43	ED	7	185	SD	-	327	ND	-
44	MD	1	186	SD	-	328	ND	-
45	MD	1.8	187	SD	-	329	ND	-
46	MD	3.1	188	ED	8.2	330	ND	-
47	MD	1.8	189	ND	-	331	ND	-
48	MD	4.4	190	ND	-	332	ND	-
49	ED	2.1	191	ND	-	333	ND	-
50	ED	5.4	192	ND	-	334	ND	-
51	SD	-	193	MD	3.2	335	ND	-
52	SD	-	194	MD	3.6	336	ND	-
53	SD	-	195	ND	-	337	ND	-
54	SD	-	196	ND	-	338	ND	-

55	CD	840	197	ND	-	339	SD	-
56	SD	-	198	ED	9.7	340	SD	-
57	SD	-	199	SD	-	341	SD	-
58	SD	-	200	CD	768	342	SD	-
59	SD	-	201	ED	2.9	343	SD	-
60	SD	-	202	ED	5.3	344	SD	-
61	SD	-	203	ED	3.4	345	SD	-
62	SD	-	204	ED	2	346	ND	-
63	CD	480	205	MD	3.8	347	ND	-
64	SD	-	206	MD	1.2	348	ND	-
65	SD	-	207	ED	8.9	349	ND	-
66	SD	-	208	SD	-	350	ND	-
67	SD	-	209	SD	-	351	ND	-
68	SD	-	210	MD	3.3	352	ND	-
69	SD	-	211	SD	-	353	ND	-
70	SD	-	212	MD	3.2	354	ND	-
71	SD	-	213	SD	-	355	ND	-
72	SD	-	214	ND	-	356	SD	-
73	CD	312	215	CD	504	357	SD	-

74	CD	576	216	SD	-	358	ND	-
75	SD	-	217	SD	-	359	ND	-
76	SD	-	218	SD	-	360	SD	-
77	SD	-	219	SD	-	361	SD	-
78	SD	-	220	SD	-	362	MD	1.3
79	SD	-	221	SD	-	363	SD	-
80	SD	-	222	SD	-	364	SD	-
81	ED	8.7	223	CD	600	365	SD	-
82	ED	3.1	224	CD	576	366	SD	-
83	MD	4.6	225	MD	2.6	367	SD	-
84	MD	3.8	226	SD	-	368	SD	-
85	MD	1.2	227	ND	-	369	SD	-
86	ED	5.6	228	MD	4.9	370	MD	5
87	ED	6.5	229	ED	3.5	371	SD	-
88	ED	5.3	230	ED	6.9	372	SD	-
89	ED	7.5	231	MD	4	373	SD	-
90	MD	2.5	232	MD	2.5	374	SD	-
91	MD	4.3	233	MD	2.3	375	SD	-
92	ND	-	234	MD	3.7	376	SD	-

93	ND	-	235	MD	2.8	377	SD	-
94	SD	-	236	MD	1.9	378	SD	-
95	ND	-	237	MD	3.8	379	SD	-
96	MD	4.3	238	SD	-	380	SD	-
97	ND	-	239	NDD	-	381	SD	-
98	SD	-	240	ND	-	382	MD	1.6
99	SD	-	241	ND	-	383	SD	-
100	SD	-	242	SD	-	384	SD	-
101	ND	-	243	ND	-	385	SD	-
102	ND	-	244	ND	-	386	ND	-
103	MD	4	245	ND	-	387	ND	-
104	MD	1.7	246	ND	-	388	SD	-
105	ED	9.6	247	ND	-	389	ED	5.5
106	MD	4.9	248	ND	-	390	MD	3.7
107	MD	2.4	249	ND	-	391	SD	-
108	MD	3.7	250	ND	-	392	MD	2.2
109	MD	4.2	251	ND	-	393	SD	-
110	MD	5	252	ND	-	394	SD	-
111	MD	1.3	253	SD	-	395	SD	-

112	ED	7.6	254	SD	-	396	SD	-
113	ED	9.6	255	ND	-	397	SD	-
114	MD	1.3	256	ND	-	398	SD	-
115	SD	-	257	ND	-	399	SD	-
116	SD	-	258	ND	-	400	SD	-
117	SD	-	259	ND	-	401	SD	-
118	SD	-	260	ND	-	402	MD	1.2
119	SD	-	261	ND	-	403	SD	-
120	SD	-	262	ND	-	404	SD	-
121	CD	288	263	ND	-	405	SD	-
122	ND	-	264	ND	-	406	SD	-
123	ND	-	265	ND	-	407	MD	4.9
124	ND	-	266	ND	-	408	MD	1
125	ND	-	267	ND	-	409	SD	
126	CD	672	268	ND	-	410	SD	
127	SD	-	269	ND	-	411	SD	-
128	SD	-	270	ND	-	412	SD	-
129	CD	552	271	ND	-	413	SD	-
130	MD	4.6	272	ND	-	414	SD	-

131	SD	-	273	ND	-	415	SD	-
132	ND	-	274	ND	-	416	SD	-
133	ND	-	275	ND	-	417	SD	-
134	ND	-	276	ND	-	418	SD	-
135	ND	-	277	SD	-	419	SD	-
136	ND	-	278	ND	-	420	SD	-
137	MD	3.1	279	ND	-	421	MD	3.6
138	SD	-	280	SD	-	422	SD	-
139	SD	-	281	ND	-	423	SD	-
140	ND	-	282	ND	-	424	MD	2
141	ND	-	283	SD	-	425	ND	-
142	ND	-	284	ND	-			

Note: DS = bridge damage state; ND = no damage; SD = slight damage; MD = moderate damage; ED = extensive damage; CD = complete damage; RT = emergency restoration time (hours).

2.5.2.2 Optimal Highway System Resilience

The highway system resilience calculated by Eq. (2.5) dropped to 0.119 in the immediate aftermath of the earthquake, indicating that the travel time on the damaged highway network was 8.4 times the travel time on the pre-earthquake highway network. Moreover, the highway system resilience returned to 0.537 with the implementation of emergency inspection and restoration activities in the first 72 hours.

System resilience was also calculated from a general inspection-routing and restoration-scheduling model, in which the restoration of all accessible damaged bridges commenced after they had been inspected. In this model, the inspection routes were first optimized to minimize the total inspection time for inspecting all assessable bridges, and then restoration schedules were optimized using the proposed hybrid GA, with the objective of maximizing the highway system resilience. System resilience at the 72-hour mark calculated using this general model was 0.324, indicating that system resilience could be 65.7% higher in the first 72 hours by using the proposed model rather than the general inspection-routing and restoration-scheduling model. Thus, simultaneously performing emergency inspection and restoration activities can significantly improve system resilience, comparing to the general method that emergency restoration commences after all accessible bridges have been inspected.

Additionally, a test that aims to investigate the upper bound of highway system resilience in the proposed model was performed based on the assumption that damage information of bridges and their corresponding restoration methods were known in the immediate aftermath of the earthquake, and only emergency restoration activities were performed. Under such a condition, system resilience was 0.641 in the first 72 hours, and thus, the highway system resilience calculated by the proposed model was 83.8% of the upper bound. Therefore, the proposed model can be seen as an effective approach to solve inspection-routing and restoration-scheduling problems.

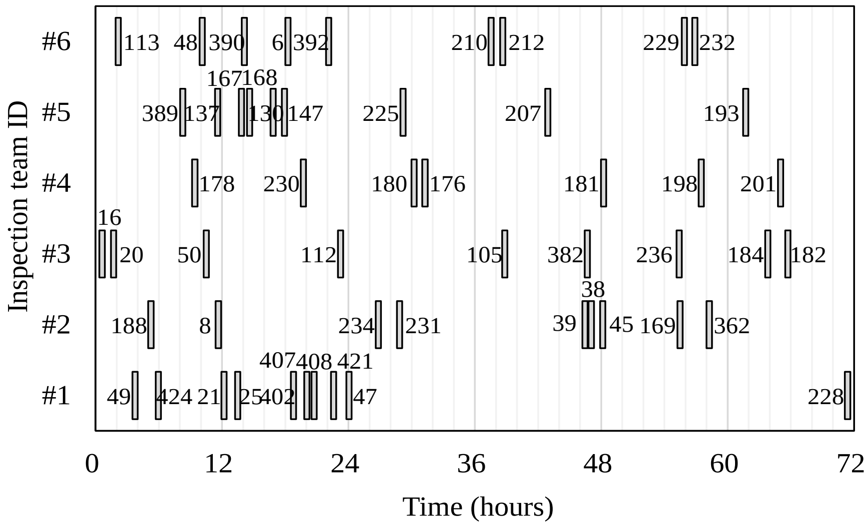
2.5.2.3 Optimal Inspection Routes and Restoration Schedules

During the first 72 hours after the earthquake, 53 bridges were inspected, and 45 of them were restored. The optimal inspection routes for each of six inspection teams and the optimal restoration schedules for each of six restoration teams are shown in Figure 2.7. The results show that bridges that are critical to highway system resilience could obtain emergency inspection and restoration in the first 72 hours, and all these critical bridges were in moderate or extensive damage states while restoring completely damaged bridges is beyond the working time limitation. The results are consistent with the suggestions in (WCTPMC 2010), where emergency inspection and restoration are only performed to bridges in moderate or extensive damage in the emergency response phase.

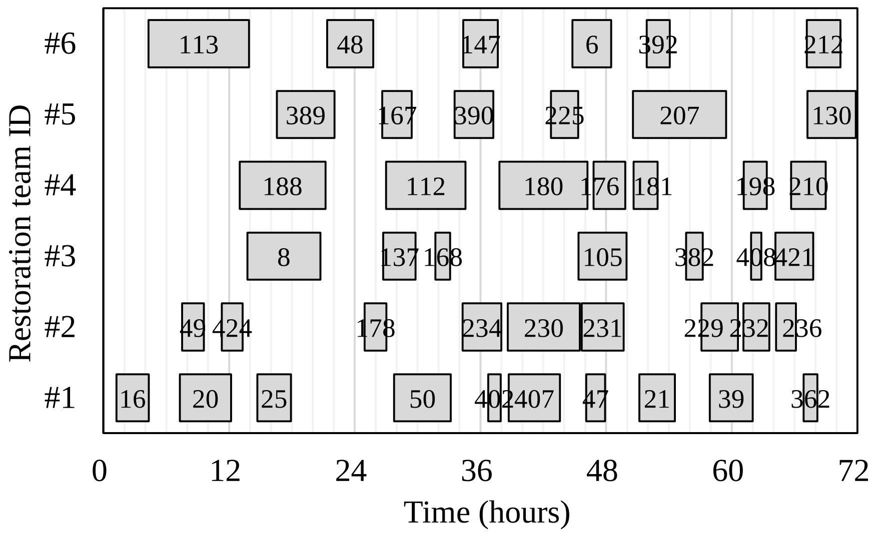
The optimal results also show that inspection-restoration interactions can significantly increase the complexity of inspection routes and restoration schedules and lead to the long waiting time of work teams. Take the inspection and restoration of bridge B176, B180, B181 on H20, and B198 on H22 as an example to explain such an impact. B180, B181, and B198 were in extensive damage, and B176 was in moderate damage. First, inspection team_4 traveled for about 11.5 hours from B230 to B180 for inspection. After inspection team_4 finished the inspection of B180, it departed from B180 to inspect B176, and meanwhile, restoration team_4 moved to B180 to restore this bridge. After inspection team_4 finished the inspection of B176, it stayed at this bridge for 14.4 hours, waiting for the restoration of B180. Once B180 had been restored and became passable, the inspection team_4 departed from B176 to inspect B181, and restoration team_4 departed from B180 to restore B176. After inspecting B181, inspection team_4 stayed at this bridge for 4.2 hours, waiting for the restoration of B176 and B181 since B181 blocked the way of inspection team_4 to B198 on H22. Once B181 had been restored, inspection team_4 traveled for about 3.7 hours from B181 to inspect B198, and restoration team_4 waited at B181 for around 4.2 hours before it departed from

B181 to restore B198. Accordingly, the working time of a work team consists of not only the travel time on the highway network and the inspection or restoration time of bridges but also the waiting time of work teams due to the inspection-restoration interactions, and the waiting time of an inspection team could be significant if its inspection route contained extensively damaged bridges.

Moreover, parts of the network were disconnected from the main network and could never be reached in the emergency response phase because completely damaged bridges cannot be restored in this phase. For example, C5 was disconnected and could not be reached in the emergency response phase due to the disruption of H7 and H8. This case is consistent with the actual situation. For example, Caopo City was disconnected from the highway network and became isolated for more than 60 days after the Wenchuan Earthquake due to the disruption of highways that contained completely damaged bridges (OSLR 2018).



(a) Optimal inspection routes



(b) Optimal restoration schedules

Note: The numbers on the bars are bridge IDs, and the length of a bar represents the inspection/restoration time

Figure 2.7 Optimal inspection routes and restoration schedules

2.5.2.4 Effect of Working Time Limitation

To investigate the impact of the working time on the highway system resilience, this study increased the working time limitation from 24 hours (one day) to 120 hours (five days) with an equal increment of 24 hours. As shown in Figure 2.8, the highway system resilience increased from the post-earthquake value of 0.119 to 0.327, 0.456, 0.537, 0.589, and 0.625, respectively. In other words, the system resilience increase by 188%, 282%, 371%, 424%, and 455% at the end of Day one to Day five, respectively. The results indicate that the highway system resilience can increase significantly in the first 24 hours after an earthquake by setting the working time limitation as 24 hours to prioritize the inspection and restoration of bridges critical to system resilience in this period.

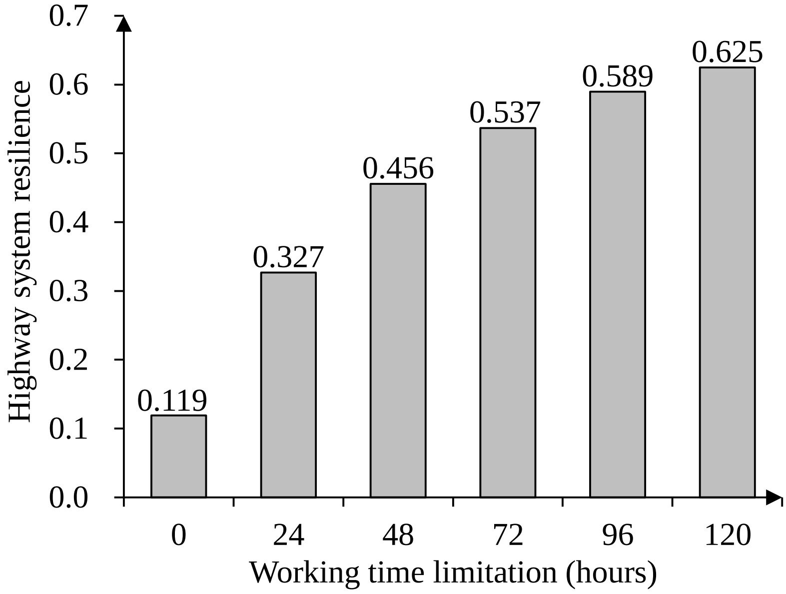


Figure 2.8 Impact of working time on highway system resilience

2.5.2.5 Effect of the Number of Work Teams

The impacts the number of work teams on the level of highway system resilience were investigated by two tests, as shown in Table 2.7. The first test that examined the impact of the number of inspection teams on highway system resilience included three experiments: E1 was the aforementioned experiment with six inspection teams; E2 and E3 contained three and nine inspection teams, respectively. In these three experiments, the number of restoration teams was the same, i.e., six. Comparison of system resilience at the 72-hour mark under all three experiments show that decreasing three inspection teams (i.e., E2 vs. E1) only slightly decreased the system resilience by 0.007, from 0.537 to 0.530, and the system resilience only increased by 0.005, from 0.537 to 0.542, if the number of inspection teams increased by three (i.e., E3 vs. E1) (Figure 2.9). The results indicate that changing the number of inspection teams can only slightly affect the levels of highway system resilience, and such a result can help decision-makers to optimally allocate inspection resources to achieve specific system resilience levels.

The second test also comprised three experiments: E1, E4, and E5 contained six, three, and nine restoration teams, respectively, while the number of inspection teams in these experiments was six. As compared to E1, system resilience dropped by 26.9%, from 0.537 to 0.393, if the number of restoration teams reduced by three (i.e., E4), while system resilience improved by 12.0%, from 0.537 to 0.602, if the number of restoration teams increased by three (i.e., E4 vs. E1). The results further prove that the key to considerable increases in highway system resilience is the restoration capacity rather than the inspection capacity.

Table 2.7 Numbers and locations of work teams

Experiment	Number of inspection teams	Number of restoration teams
E1	6	6
E2	3	6
E3	9	6
E4	6	3
E5	6	9

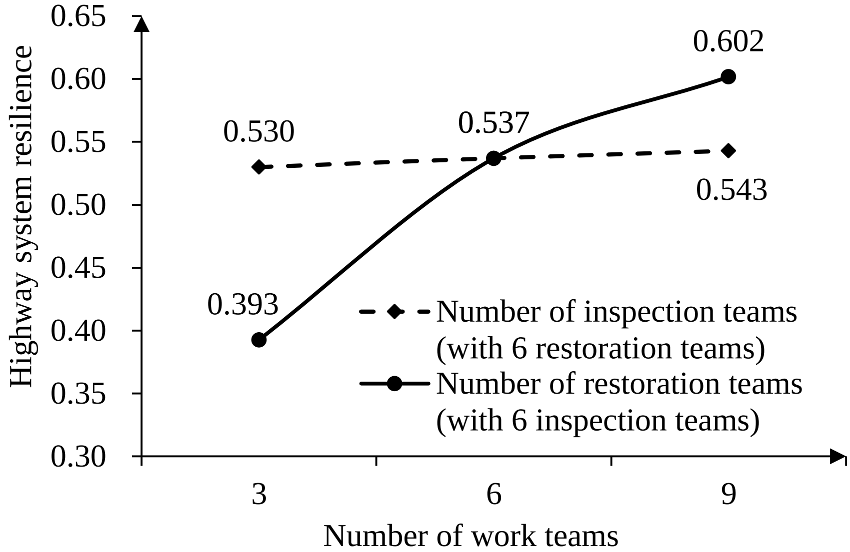


Figure 2.9 Impact of the number of work teams on highway system resilience

2.5.2.6 Performance of the Hybrid GA

Figure 2.10 shows system resilience at T along with the number of generations, generated by the proposed hybrid GA and a standard GA without incorporating the proposed heuristic approach, i.e., the early-termination test. As this figure indicates, the proposed hybrid GA converged at 110 generations with the maximum system resilience being 0.537, while the standard GA converged at 160 generations with a lower system resilience value of 0.459. Therefore, compared with a standard GA, the proposed hybrid GA has higher computational efficiency, i.e., 1.45 times faster, and can provide a better solution to the proposed problem.

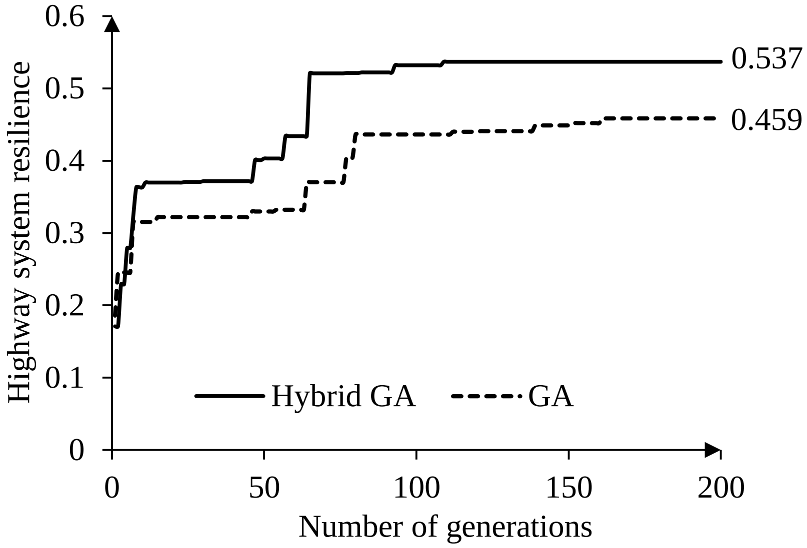


Figure 2.10 Evolution of resilience values across generations

2.6 Conclusion

2.6.1 Research Findings

Existing methods for post-earthquake restoration scheduling for highway systems has not incorporated parallel routing of inspections, but the results of the proposed study clearly prove the benefits of combing inspection and restoration activities. To investigate the impacts of inspection-restoration interactions on the proposed post-earthquake emergency bridge inspection-routing and restoration-scheduling problem, this chapter has developed an integer program with recursive functions for such a problem, with the aim of maximizing highway system resilience. Additionally, a hybrid GA that integrated a specially designed heuristic approach to a traditional GA to improve its computational efficiency was developed.

The proposed methodology was tested in a real highway network system in Sichuan, China, using data from the 2008 Wenchuan Earthquake. The results from the comparison of the system resilience calculated by the proposed inspection-routing and restoration-scheduling model with the resilience calculated by a general inspection-routing and restoration-scheduling model that all inspections are carried out prior to any restorations show that simultaneously performing inspection and restoration activities can lead to significant improvement in system resilience. The optimal results also show that the impacts of inspection-restoration interactions on the optimal inspection routes and restoration schedules were significant and complex, and such interactions should be taken into consideration in routing and scheduling emergency bridge inspection and restoration activities. Specifically, the waiting time of work teams resulting from inspection-restoration interactions may become significant if the inspection routes contain impassable bridges. Moreover, the investigation on the length of working time limitation indicates that the proposed model can prioritize the emergency inspection and restoration works to those bridges critical to system resilience within the working time limitation. The results of the sensitivity analysis regarding the impacts of the number of work teams on highway system resilience show that the restoration capacity, rather than the inspection capacity, can significantly affect the level of highway system resilience. Finally, the proposed hybrid GA was efficient in solving the proposed problem.

2.6.2 Scientific and Practical Significance

This chapter contributes to both knowledge and practice. Theoretically, the proposed mathematical model is expected to serve as a basis for further research on establishing efficient response and recovery strategies for a wide range of infrastructure systems (such as power supply systems, water supply systems, and telecommunication systems) as real-time interactions widely exist among response and recovery activities of these systems. For instance, the proposed model could be tailored for the emergency restoration scheduling of roadways and electric power facilities, by considering the interactions among these restoration activities: the restored roadways can provide accesses to damaged power facilities; meanwhile, the restored power facilities can provide power for conducting road repair works. Practically, the proposed modeling and solution methodologies, in the short term, can serve as practical tools for decision-making on routing and scheduling emergency inspection and restoration activities; and in the long term, the same tools will help decision-makers to craft optimal post-disaster response and recovery plans for highway networks, thereby mitigating social and economic losses resulted from earthquakes.

CHAPTER 3 MODELING DYNAMIC EMERGENCY INSPECTION ROUTING AND RESTORATION SCHEDULING TO MAXIMIZE POST-EARTHQUAKE HIGHWAY NETWORK RESILIENCE

3.1 Introduction

Highway networks are critical to post-earthquake rescue operations because they provide accesses for the movement of rescuers, evacuation of victims, and transportation of relief materials. A number of studies have investigated the post-earthquake emergency restoration scheduling methods for highway networks with the aim of maximizing highway network resilience (Zhang and Miller-Hooks 2015; Zhang et al. 2017; Li et al. 2019; Zhang and Wei 2020). Though differing in various aspects, these studies optimized the restoration schedules based on highway networks' post-earthquake damage states that were assumed to be known immediately after an earthquake or to be quickly and accurately estimated using seismic damage assessment methods, such as fragility analysis and nonlinear finite element analysis (Huria et al. 1993; Mander 1999; Dong et al. 2014; Lam and Adey 2016). However, such assumptions can lead to unfavorable consequences: given that the actual damage states of bridges can only be revealed via inspection and may be significantly different from the estimated ones due to uncertainties in the parameters of these seismic damage assessment methods, such as ground motion intensities, soil conditions, and construction materials of bridges, the optimal inspection routes and restoration schedules may turn inefficient and ineffective if bridges' actual damage states were different from estimated ones. Ideally, post-earthquake emergency bridge inspection and restoration activities are performed simultaneously on the highway network, with inspection activities collecting the actual bridge damage information for determining restoration methods and facilities, and restoration activities, thereafter, being performed on these inspected bridges. Although the inspection routes and restoration schedules are initially determined based on the estimated damage states of bridges, they should be updated whenever the damage state of a bridge is found to be misestimated via inspection. Nonetheless, the discussion of the real-time bridge damage information revealed via inspection is generally neglected in current methods for post-earthquake emergency inspection routing and restoration scheduling.

To bridge the aforementioned gaps in existing emergency bridge inspection routing and restoration scheduling methods, this chapter develops a mathematical model using the integer programming technique for modeling the proposed dynamic inspection-routing and restoration-scheduling problem, with the aim of maximizing the highway network resilience measured in terms of travel time. Specifically, the proposed dynamic problem is decomposed into a sequence of static inspection-routing and restoration-scheduling problems to reduce the computational complexity of the dynamic problem, and each static problem is formulated as an integer program. Unlike existing DVRPs and DSPs, which mainly emphasize on properly addressing only real-time information, the proposed model addresses not only real-time bridge damage information but also real-time interactions among inspection and restoration activities to ensure the effectiveness and efficiency of inspection routes and restoration schedules during the execution of emergency inspection and restoration. Additionally, this chapter integrates a heuristic approach into a GA that is specifically designed for addressing the dynamism in the proposed mathematical model to effectively solve the model, thereby satisfying the need for real-time decision-making in the emergency response phase. The proposed methodology is tested using a highway network in Sichuan, China, and the data from the 2008 Wenchuan Earthquake. It is hoped that the proposed study will serve as a basis for further studies of dynamic inspection-routing and restoration-scheduling problems, with a wider aim of providing decision-makers with real-time decision support for drafting efficient emergency management strategies for highway systems.

This chapter is organized as follows. Section 3.2 introduces research gaps in current methods for emergency restoration scheduling for post-disaster transportation networks through a thorough literature review. Section 3.3 defines the dynamic emergency inspection-routing and restoration-scheduling problem and formulates this problem as a mathematical model. Section 3.4 develops a solution methodology for the proposed mathematical model. Section 3.5 uses an actual highway network to validate the proposed methods. Section 3.6 concludes with research findings and scientific and practical contributions.

3.2 Literature Review

3.2.1 Post-disaster Emergency Restoration Scheduling and Inspection Routing for Transportation Systems

Emergency restoration is time-constrained, and studies on emergency restoration scheduling have focused on quickly satisfying the urgent needs for conducting emergency relief operations. For example, Yan and Shih (2009) optimized the emergency restoration schedule for a post-earthquake roadway network as well as the schedule for relief distributions on the network to minimize the time required for emergency restoration and relief distribution, considering that the recovery of roadways could improve the efficiency of relief distributions. Zhang and Miller-Hooks (2015) optimized the emergency restoration schedules for a railway network to maximize its resilience in terms of traffic capacity, taking into consideration constraints on time and budget. Given that impassable roads may become passable after restoration, and thus routes of restoration teams on the roadway network may change, Li and Teo (2019) investigated both routing and scheduling of emergency restoration activities to support the allocation and delivery of relief supplies. Though differing in various aspects, all these above studies optimized restoration schedules based on the assumption that the actual damages of a transportation system as well as the corresponding restoration methods were fully and immediately understood, and emergency restoration activities could commence in the immediate aftermath of an earthquake. However, in practice, collecting detailed damage information of a highway network for selecting proper restoration methods entirely relies on inspection efforts and may take days or even weeks in a regional highway network, thus leading to the delay in performing emergency restoration activities. Realizing the impact of inspection activities on the restoration time, Lam and Adey (2016) have accounted for such an impact in modeling the recovery process of a damaged roadway network by assuming that inspection should be done prior to restoring a bridge. Then, their model has been applied to the loss assessment of the functionality of roadway networks exposed to different hazards (Lam et al. 2018; Lam et al. 2020). In addition to the impact of inspection activities on the execution of restoration activities, restoration scheduling can also affect inspection routing when emergency inspection and restoration activities are conducted simultaneously on a highway network: bridges undergoing restoration are impassable for inspection teams, and an impassable bridge can be passable after restoration, resulting in the adjustments of routes of inspection teams on the highway network. Therefore, Zhang and Wei (2020) investigated the impact of the inspection-restoration interactions on inspection routing and restoration scheduling by developing a mathematical model to formulate such interactions and concluded that simultaneously performing emergency inspection and restoration activities could lead to significant improvement in system resilience, as compared to general scheduling methods that all inspections were carried out prior to any restoration. In these studies, inspection routes and restoration schedules were optimized based on the estimated damage states of bridges using fragility analysis, and the optimal plans remained unchanged during the execution of emergency inspection and restoration activities. However, the actual damage states of bridges may be dramatically different from the estimated ones due to the uncertainties in the parameters of seismic damage assessment methods, for example, uncertainties associated with ground motion, soil conditions, and construction materials (i.e., concrete and reinforcement) of bridges. Thus, the optimal inspection routes and restoration schedules may become infeasible or suboptimal if significant discrepancies between the actual and estimated damage states of bridges exist. Accordingly, the inspection routes and restoration schedules should be updated in real-time as bridge damage information is revealed gradually by inspection teams, so as to keep the feasibility and optimality of the emergency inspection and restoration plans.

3.2.2 Dynamic Vehicle Routing Problems and Dynamic Scheduling Problems

The proposed dynamic inspection-routing and restoration-scheduling problem shares similar dynamic properties with dynamic vehicle routing problems (DVRPs) and dynamic scheduling problems (DSPs). In the DVRPs, part or all of the input data are unknown and are revealed dynamically during the plan and the execution of the routes. The dynamism in the DVRPs comes from the arrival of new customer demands for services or goods, changes in service time for customers or travel time of vehicles, and availability of vehicles (Attanasio et al. 2004; Haghani and Jung 2005; Pavone et al. 2009; Chen and Miller-Hooks 2012; Kim et al. 2016; Kuo et al. 2016; Ulmer et al. 2017; Bernardo and Pannek 2018). Similarly, prior studies on DSPs have considered numerous real-time events in manufacturing systems, such as machine breakdown, delay in the arrival of materials, job cancellation, rush jobs, and change in job priority (Cowling and Johansson 2002; Ouelhadj and Petrovic 2009). These problem dynamics are commonly addressed using re-optimization approaches, in which a DVRP or a DSP is decomposed into a series of static vehicle routing problems or scheduling problems, and each static problem can be solved using existing algorithms for static vehicle routing problems or scheduling problems (Psaraftis 1980; Yang et al. 2004; Herroelen and Leus 2005; Chen and Xu 2006; Chakrabortty et al. 2016; Sarasola et al. 2016). The re-optimization approaches start with a first optimization to generate an initial route or schedule and then re-optimize the route or schedule either at fixed time intervals (referred to as time slices) or in the presence of real-time events (referred to as decision epochs) (Pillac et al. 2013). In the time slice approach, the total working time is divided into a set of time slices with a fixed duration, and the optimization is executed independently during each time slice. However, the application of such an approach may be limited by the nature of the dynamic events, which are never urgent, because this approach does not deal with the new information obtained during a time slice until the end of the time slice. In contrast, the decision epoch approach that deals with urgent events in a timely manner and updates decisions upon the occurrence of an urgent event is widely used in emergency situations. Given that the real-time bridge damage information obtained from inspection may significantly affect the execution of emergency inspection and restoration activities, such information should be handled in a timely manner. For example, if a bridge that is estimated to be impassable is found to be actually passable, the inspection routes, as well as restoration schedules, should be updated immediately to avoid the delay of inspection and restoration works due to the detour of work teams. Consequently, this chapter uses the decision epoch approach to efficiently deal with the real-time bridge damage information.

In spite of these similarities, the specific characteristics of the proposed dynamic inspection-routing and restoration-scheduling problem increase the complexity in solving such a problem. Specifically, in addition to real-time bridge damage information, the complex real-time interactions between inspection and restoration activities significantly increase its computational complexity. On the one hand, restoration can be conducted to a bridge only after such a bridge has been inspected; on the other hand, restoration works can affect the routes of inspection teams by changing the passability of highways, either from impassable to passable due to the completion of restoring impassable bridges, or from passable to impassable due to the blockage of highways for conducting restoration works. How to handle the real-time bridge damage information during the execution of emergency inspection and restoration activities while accounting for the complex inspection-restoration interactions remains a challenging issue.

3.3 Problem Definition and Formulation

This section formally defines the proposed dynamic inspection-routing and restoration-scheduling problem and introduces the formulation of this problem using the integer programming technique.

3.3.1 Dynamic Emergency Inspection-Routing and Restoration-Scheduling Problem

In the immediate aftermath of an earthquake, some cities are set as the relief command centers. The post-earthquake damage states of bridges, including no damage, slight damage, moderate damage, extensive damage, and complete damage, can be quickly estimated using seismic loss assessment methodology, such as the fragility analysis proposed in (FEMA 2012). In consideration of the misestimates of bridges' damage states, the purpose of emergency inspection in the proposed study is to preliminarily inspect the actual damage states of bridges and provide detailed bridge damage information to the relief command center for selecting proper emergency restoration methods. Moreover, given that emergency restoration aims to partially restore damaged bridges for supporting emergency response activities, the present study assumes that only these bridges in moderate, extensive, or complete damage will obtain emergency restoration, and their damage states decrease to slight damage after emergency restoration. Initial inspection routes and restoration schedules are optimized based on the estimated bridge damage states, with the aim of maximizing highway network resilience, and then work teams start to inspect and restore bridges following the initial plans. Once an inspection team finds that a bridge's actual damage state is different from its estimated damage state (such a bridge is defined as a misestimated bridge in this chapter), the residual inspection routes and restoration schedules for these bridges that have not been inspected and restored will be re-optimized, and work teams will adjust their works based on the updated plans. Such a re-optimization process will be repeated whenever a misestimated bridge is found until reaching the working time limitation.

3.3.2 Definitions of a Highway Network

The definition of a highway system is the same as the definition in Chapter 2, and the notation used within the mathematical formulation in this chapter is listed in Table 3.1 and Table 3.2.

Table 3.1. Notation

Notations	
Sets	
N	set of network nodes, representing cities and bridges
H	set of highway segments
N^b	set of bridge nodes
$N^b_{H_i}$	set of bridge nodes on H_i
N^c	set of city nodes
N^I_t	set of uninspected bridges at time t, $\forall\, t \in \{0,1,\dots,T\}$
N^R_t	set of unrestored bridges at time t, $\forall\, t \in \{0,1,\dots,T\}$
Parameters	
l	length of highway segments
v_0	design speed of highway segments
c_0	traffic capacity of highway segments

BDI_j	bridge damage index of bridge N_j^b, $\forall N_j^b \in N^b$
n_b	number of bridges in the highway network system
n_c	number of cities in the highway network system
n_h	number of highway segments in the highway network system
n_I	number of inspection-crews in the highway network system
n_R	number of restoration-crews in the highway network system
n_I^t	number of bridges that have been inspected at time t, $\forall t \in \{0,1,\dots,T\}$
n_R^t	number of bridges that have been restored at time t, $\forall t \in \{0,1,\dots,T\}$
T	working time limitation
T_j^I	time required for inspecting bridge N_j^b, $\forall N_j^b \in N^b$
T_j^R	time required for restoring bridge N_j^b, $\forall N_j^b \in N^b$

Table 3.2. Decision variables and parameters to be calculated

Notations	
Decision variables	
x_{jkt}	a binary variable to indicate whether inspection crew k starts to inspect bridge N_j^b at time t
y_{jkt}	a binary variable to indicate whether restoration crew k starts to restore bridge N_j^b at time t
α_{ijk}	a binary variable to indicate whether inspection crew k inspects bridge N_j^b in sequence i
β_{ijk}	a binary variable to indicate whether restoration crew k restores bridge N_j^b in sequence i
Parameters to be calculated	
BDI_j^t	bridge damage index of bridge N_j^b at time t, $\forall N_j^b \in N^b, \forall t \in \{0,1,\dots,T\}$
$BDI_{i,j}^t$	bridge damage index of bridge j at time t, $\forall j \in N_{H_i}^b, \forall t \in \{0,1,\dots,T\}$
HDI_i^t	highway damage index of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
R_T	highway system resilience
p_i^t	passability of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
T_{ij}	pre-earthquake shortest travel time between city N_i^c and city N_j^c, $\forall N_i^c, N_j^c \in N^c$
T_{ij}^T	post-earthquake shortest travel time between city N_i^c and city N_j^c at time T, $\forall N_i^c, N_j^c \in N^c$

TR_i^t	travel time on highway segment S_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
c_i^t	residual traffic capacity of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
v_i^t	residual driving speed on highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
f_i^t	traffic flow on highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
t'	identified time
τ_{ij}^t	the shortest travel time between bridge N_i^b and bridge N_j^b at time t, $\forall N_i^b, N_j^b \in N^b$, $\forall t \in \{0,1,\dots,T\}$

3.3.3 Model Assumptions and Formulation

3.3.3.1 Model Assumptions and Notations

The proposed study makes the following assumptions for the simplicity of modeling.

(1) Damages of a highway segment only occur to bridges on it, while links on the highway segment are undamaged.

(2) The inspection and restoration crews work continuously in T without the need to return to the command center to obtain supporting materials, such as fuel, electricity, equipment, and restoration materials, which are provided timely by support teams.

(3) A work team that is inspecting or restoring a bridge cannot move to the next bridge until it has finished its ongoing work.

(4) Bridges in extensive or complete damage states cannot be passed by work teams until these bridges have been restored. Meanwhile, bridges under repair are blocked and

cannot be crossed by work teams, while inspection activities do not lead to the blockage of bridges.

(5) Bridges are not scheduled for restoration until they have been inspected.

(6) Each bridge is inspected at most one time by one inspection team, and each inspected bridge is restored at most one time by one restoration team.

3.3.3.2 Model Formulation

To solve the proposed dynamic inspection-routing and restoration-scheduling problem in the emergency response phase, this chapter adopts the decision epoch approach by decomposing the dynamic problem into a sequence of static inspection-routing and restoration-scheduling problems, in which the estimated damage states of bridges are assumed to be the same as their actual damage states, and then solving these static problems in turn. This approach starts at obtaining the initial inspection routes and restoration schedules by solving the static problem at time $t = 0$ before work teams start to work, and then produces updated inspection routes and restoration schedules by re-solving the static problem whenever a misestimated bridge is revealed. Based on the damage assessment method and the resilience quantification model introduced in Chapter 2, this chapter develops the following integer program (P_0) to obtain the initial inspection routes and restoration schedules at $t = 0$.

(P_0) max R_T (3.3)

subject to

$\sum_{\forall k \in \{1,2,\ldots,n_I\}} \sum_{\forall t \in \{0,1,\ldots,T\}} x_{jkt} \leq 1, \forall j \in N^b$ (3.4)

$\sum_{\forall k \in \{1,2,\ldots,n_R\}} \sum_{\forall t \in \{0,1,\ldots,T\}} y_{jkt} \leq 1, \forall j \in N^b$ (3.5)

$$\sum_{\forall j\in N^b} x_{jkt} \le 1, \forall\, k \in \{1,2,\dots,n_I\}, \forall\, t \in \{0,1,\dots,T\} \tag{3.6}$$

$$\sum_{\forall j\in N^b} y_{jkt} \le 1, \forall\, k \in \{1,2,\dots,n_R\}, \forall\, t \in \{0,1,\dots,T\} \tag{3.7}$$

$$\sum_{\forall j\in N^b} \alpha_{ijk} \ge \sum_{\forall j\in N^b} \alpha_{i+1,jk}\, , \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_I\} \tag{3.8}$$

$$\sum_{\forall j\in N^b} \beta_{ijk} \ge \sum_{\forall j\in N^b} \beta_{i+1,jk}\, , \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{3.9}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} x_{jkt} = \sum_{\forall i\in\{1,2,\dots,n_b\}} \alpha_{ijk}\, , \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\} \tag{3.10}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} y_{jkt} = \sum_{\forall i\in\{1,2,\dots,n_b\}} \beta_{ijk}\, , \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\} \tag{3.11}$$

$$\sum_{\forall j\in N^b} \sum_{\forall t\in\{0,1,\dots,T\}} \alpha_{ijk} x_{jkt} t + \sum_{\forall j\in N^b} \alpha_{ijk} T_j^I +$$
$$\sum_{\forall j\in N^b} \sum_{\forall p\in N^b} \sum_{\forall t\in\{0,1,\dots,T\}} \alpha_{ijk} \alpha_{i+1,pk} x_{pkt} \tau_{jp}^t \le$$
$$\sum_{\forall p\in N^b} \sum_{\forall t\in\{0,1,\dots,T\}} \alpha_{i+1,pk} x_{pkt} t\, , \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_I\} \tag{3.12}$$

$$\sum_{\forall j\in N^b} \sum_{\forall t\in\{0,1,\dots,T\}} \beta_{ijk} y_{jkt} t + \sum_{\forall j\in N^b} \beta_{ijk} T_j^R +$$
$$\sum_{\forall j\in N^b} \sum_{\forall p\in N^b} \sum_{\forall t\in\{0,1,\dots,T\}} \beta_{ijk} \beta_{i+1,pk} y_{pkt} \tau_{jp}^t \le$$
$$\sum_{\forall p\in N^b} \sum_{\forall t\in\{0,1,\dots,T\}} \beta_{i+1,pk} y_{pkt} t\, , \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{3.13}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} x_{jkt}\left(t + T_j^I\right) \le T, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\} \tag{3.14}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} y_{jkt}\left(t + T_j^R\right) \le T, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\} \tag{3.15}$$

$$\sum_{\forall i\in\{1,2,\dots,n_b\}} \sum_{\forall k\in\{1,2,\dots,n_I\}} \alpha_{ijk} \ge \sum_{\forall i\in\{1,2,\dots,n_b\}} \sum_{\forall k\in\{1,2,\dots,n_R\}} \beta_{ijk}\, , \forall\, j \in N^b \tag{3.16}$$

$$\sum_{\forall i\in\{1,2,\dots,n_b\}} \sum_{\forall l\in\{1,2,\dots,n_R\}} \sum_{\forall k\in\{1,2,\dots,n_I\}} \sum_{\forall t\in\{0,1,\dots,T\}} \beta_{ijl} x_{jkt} t +$$
$$\sum_{\forall i\in\{1,2,\dots,n_b\}} \sum_{\forall l\in\{1,2,\dots,n_R\}} \beta_{ijl} T_j^I \le \sum_{\forall k\in\{1,2,\dots,n_R\}} \sum_{\forall t\in\{0,1,\dots,T\}} y_{jkt} t -$$
$$\sum_{\forall i\in\{1,2,\dots,n_b-1\}} \sum_{\forall p\in N^b} \sum_{\forall k\in\{1,2,\dots,n_R\}} \sum_{\forall t\in\{0,1,\dots,T\}} \beta_{ipk} \beta_{i+1,jk} \tau_{pj}^t\, , \forall j \in N^b \tag{3.17}$$

$$x_{jkt}, \alpha_{ijk} \in \{0,1\}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\}, \forall\, t \in \{0,1,\dots,T\}, \forall\, i \in \{1,2,\dots,n_b\}$$

(3.18)

$$y_{jkt}, \beta_{ijk} \in \{0,1\}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\}, \forall\, t \in \{0,1,\dots,T\}, \forall\, i \in \{1,2,\dots,n_b\}$$

(3.19)

$$t_{0,i} = len_{H_i}/v_{0,i} \times \left\{1 + \alpha\left[f_{0,i}/c_{0,i}\right]^{\beta}\right\}, \forall\, i \in H \tag{3.20}$$

$$BDI_j^i = \sum_{k=0}^{4} BDI_k \cdot P_{k|IM}, \forall\, i \in H, \forall\, j \in N_{H_i}^b \tag{3.21}$$

$$HDI_i^t = \begin{cases} \sqrt{\sum_{\forall j \in N_{H_i}^b} {BDI_{i,j}^t}^2} & \forall\, BDI_{i,j}^t \leq 0.525 \\ \infty & \exists\, BDI_{i,j}^t > 0.525 \end{cases}, \forall\, i \in H, \forall\, t \in \{0,1,\dots,T\} \tag{3.22}$$

$$v_i^t = \begin{cases} v_{0,i} & 0 \leq HDI_i^t < 0.5 \\ 0.75 v_{0,i} & 0.5 \leq HDI_i^t < 1.0 \\ 0.5 v_{0,i} & 1.0 \leq HDI_i^t < \infty \\ 0 & HDI_i^t = \infty \end{cases}, \forall\, i \in H, \forall\, t \in \{0,1,\dots,T\} \tag{3.23}$$

$$c_i^t = \begin{cases} c_{0,i} & 0 \leq HDI_i^t < 1.0 \\ 0.75 c_{0,i} & 1.0 \leq HDI_i^t < 1.5 \\ 0.5 c_{0,i} & 1.5 \leq HDI_i^t < \infty \\ 0 & HDI_i^t = \infty \end{cases}, \forall\, i \in H, \forall\, t \in \{0,1,\dots,T\} \tag{3.24}$$

$$p_i^t = \begin{cases} 1 & HDI_i^t < \infty \cap \forall\, j \in N_{H_i}^b \text{ is not under repair at time } t \\ 0 & HDI_i^t = \infty \cup \exists\, j \in N_{H_i}^b \text{ is under repair at time } t \end{cases}, \forall\, i \in H,\ \forall\, t \in$$

$$\{0,1,\dots,T\} \tag{3.25}$$

$$t_i^t = \begin{cases} len_i/v_i^t \times \{1 + \alpha[f_i^t/c_i^t]^{\beta}\}, & p_i^t = 1 \\ +\infty, & p_i^t = 0 \end{cases}, \forall\, i \in H, \forall\, t \in \{0,1,\dots,T\} \tag{3.26}$$

The objective function (3.3) seeks the maximum highway network resilience R_T at the given time horizon T. Constraints (3.4) and (3.5) respectively ensure that each bridge is inspected or restored no more than one time. Constraints (3.6) and (3.7) ensure that a work team can only inspect or restore one bridge at a time. Constraints (3.8) and (3.9) indicate the number of inspection or restoration tasks allocated to a work team. For instance, i bridges are allocated to inspection team k if $\sum_{\forall j \in N^b} \alpha_{ijk} = 1$ and $\sum_{\forall j \in N^b} \alpha_{i+1,jk} = 0$. Constraint (3.10) establishes the relationship between decision variables x_{jkt} and α_{ijk}: if b_j is inspected by inspection team k, $\sum_{\forall t \in \{0,1,\ldots,T\}} x_{jkt} = \sum_{\forall i \in \{1,2,\ldots,n_b\}} \alpha_{ijk} = 1$; otherwise, if b_j is inspected by other inspection teams, $\sum_{\forall t \in \{0,1,\ldots,T\}} x_{jkt} = \sum_{\forall i \in \{1,2,\ldots,n_b\}} \alpha_{ijk} = 0$. Similarly, constraint (3.11) establishes the relationship between y_{jkt} and β_{ijk}. Constraints (3.12) and (3.13) are recursive inequalities to establish the relationship between the start times of two adjacent work tasks of a work team. Constraints (3.14) and (3.15) ensure that all the emergency inspection and restoration works are completed within T. Constraints (3.16) and (3.17) ensure that the restoration of a bridge can only be performed after the inspection of the bridge, formulating the impact of inspection activities on the restoration process. Constraints (3.18) and (3.19) enforce binary-value requirements on these decision variables. Constraints (3.20) to (3.26) are traffic models to calculate pre- and post-earthquake travel time on highway segments. Constraint (3.20) is the Bureau of Public Roads function (Martin and McGuckin 1998) to calculate the pre-earthquake travel time $t_{0,i}$ on each highway segment. The function parameters α and β are 0.15 and 4, respectively. The traffic flow distribution on a highway network is assumed to be user equilibrium, where users choose their routes to minimize their travel time, and the traffic flow distribution on the network can be solved using the Frank-Wolfe algorithm (Florian and Hearn 1995). Constraint (3.21) estimates the post-earthquake damage states of bridges using the bridge damage index (BDI) proposed by (Dong et al. 2014), in which the probabilistic bridge damage states were converted to deterministic values. The values of BDI_k corresponding to no damage ($k = 0$), slight damage ($k = 1$), moderate damage ($k = 2$), extensive damage ($k = 3$), and complete damage ($k = 4$)

are 0, 0.1, 0.3, 0.75, and 1.0, respectively. $P_{k|IM}$ can be calculated using software such as HAZUS based on bridges' seismic fragility curves and the ground motion intensity. Then, the damage state of a bridge can be determined according to the five damage states' corresponding ranges of BDI developed by Gordon et a. (2004): no damage, $0 \leq BDI \leq 0.05$; slight damage, $0.05 < BDI \leq 0.2$; moderate damage, $0.2 < BDI \leq 0.525$; extensive damage, $0.525 < BDI \leq 0.85$; and complete damage, $0.85 < BDI \leq 1$. Based on BDI of bridges on highway segments, constraint (3.22) calculates the highway damage index (HDI) of each highway segment to classify its damage state into no damage ($HDI < 0.5$), slight damage ($0.5 \leq HDI < 1$), moderate damage ($1 \leq HDI < 1.5$), extensive damage ($1.5 \leq HDI < \infty$), or complete damage ($HDI = \infty$) (Guo et al. 2017). Constraints (3.23) and (3.24) establish the relationships between the pre- and post-earthquake traffic speed and traffic capacity of highway segments based on their HDI (Guo et al. 2017). As another part of the inspection-restoration interactions, constraint (3.25) formulates the impact of restoration activities on the subsequent inspection routes and restoration schedules by calculating the passability of each highway segment at each point in time. Specifically, a highway segment that contains bridges in extensive or complete damage or bridges under repair is impassable, and an impassable highway segment becomes passable if all extensively or completely damaged bridges on the segment have been restored. Constraint (3.26) calculates the post-earthquake travel time t_i^t on each highway segment. Specifically, the travel time on an impassable highway segment is infinite. With $t_{0,i}$ and t_i^t of each highway segment, T_{ij} and T_{ij}^t in Eq. (3.2) and τ_{ij}^t in constraints (3.12), (3.13), and (3.17) can be calculated based on t_i and t_i^t of each highway segment using the Dijkstra's algorithm to search for the shortest travel time between nodes.

Other integer programs ($P_1, P_2, ...$) for these static inspection-routing and restoration-scheduling problems at the time when damage states of bridges are found to be misestimated are the same as the above integer program except that 1) the sets of decision variables in these integer programs are dependent on the sets of bridges for emergency inspection and restoration in these problems, and 2) constraint (3.21) is removed, and the estimated BDI values of inspected bridges are replaced by their actual BDI values.

3.3.5 Degree of Dynamism

The number of static problems decomposed from the proposed dynamic problem depends on its dynamism, which is usually characterized by the frequency of changes. The level of dynamism can be varying in different instances of a dynamic problem. For example, using different seismic damage assessment methods may obtain different sets of misestimated bridges in a highway network under the same earthquake scenario, leading to different levels of dynamism. The level of dynamism can be measured by the degree of dynamism dod (Pillac et al. 2013), defined as the ratio between the number of dynamic requests n_d and the total number of requests n_{tot}, as shown in Eq. (3.27):

$$dod = \frac{n_d}{n_{tot}} \tag{3.27}$$

where $dod \in [0, 1]$. A problem is static if $dod = 0$, where all requests are known in advance, while a problem is completely dynamic if $dod = 1$, where no request is unknown in advance. In the proposed dynamic inspection-routing and restoration-scheduling problem, n_d is the number of misestimated bridges, and n_{tot} is the total number of bridges in the highway network, equal to n_b.

3.4 Solution Methodology

3.4.1 The Framework of the Solution Program

As shown in Figure 3.1, the solution program consists of two phases: the initial phase ($t = 0$) before work crews starting to work and the real-time phase ($t > 0$) after work crews starting to inspect and restore bridges. In the initial phase, the solution program initializes the parameters of the integer program P_0, including the number and locations of work crews (n_I, n_R), the damage states of bridges (BDI_j), inspection and restoration time of bridges (T_j^I and T_j^R), and travel demand between cities, and solves the integer program for obtaining the initial inspection routes and restoration schedules using the proposed hybrid GA. Then, the initial plans are executed until an inspection crew has found the actual damage state of a bridge to be misestimated. The inspection crew temporally stops at the misestimated bridge and waits for the next instruction. Meanwhile, the solution program updates the parameters of the integer program ($P_1, P_2, ...$), including locations of work crews, the bridge damage index (BDI_j^t), the sets of uninspected and unrestored bridges (N_t^I and N_t^R), and the restoration time of the misestimated bridge (T_j^R), and reoptimizes the inspection routes and restoration schedules for bridges in N_t^I and N_t^R. Work crews will follow the updated plans after they finish their on-going inspection or restoration works. This program will finally output the actual inspection routes and restoration schedules and the corresponding resilience of the highway-bridge network if the working time limitation is reached.

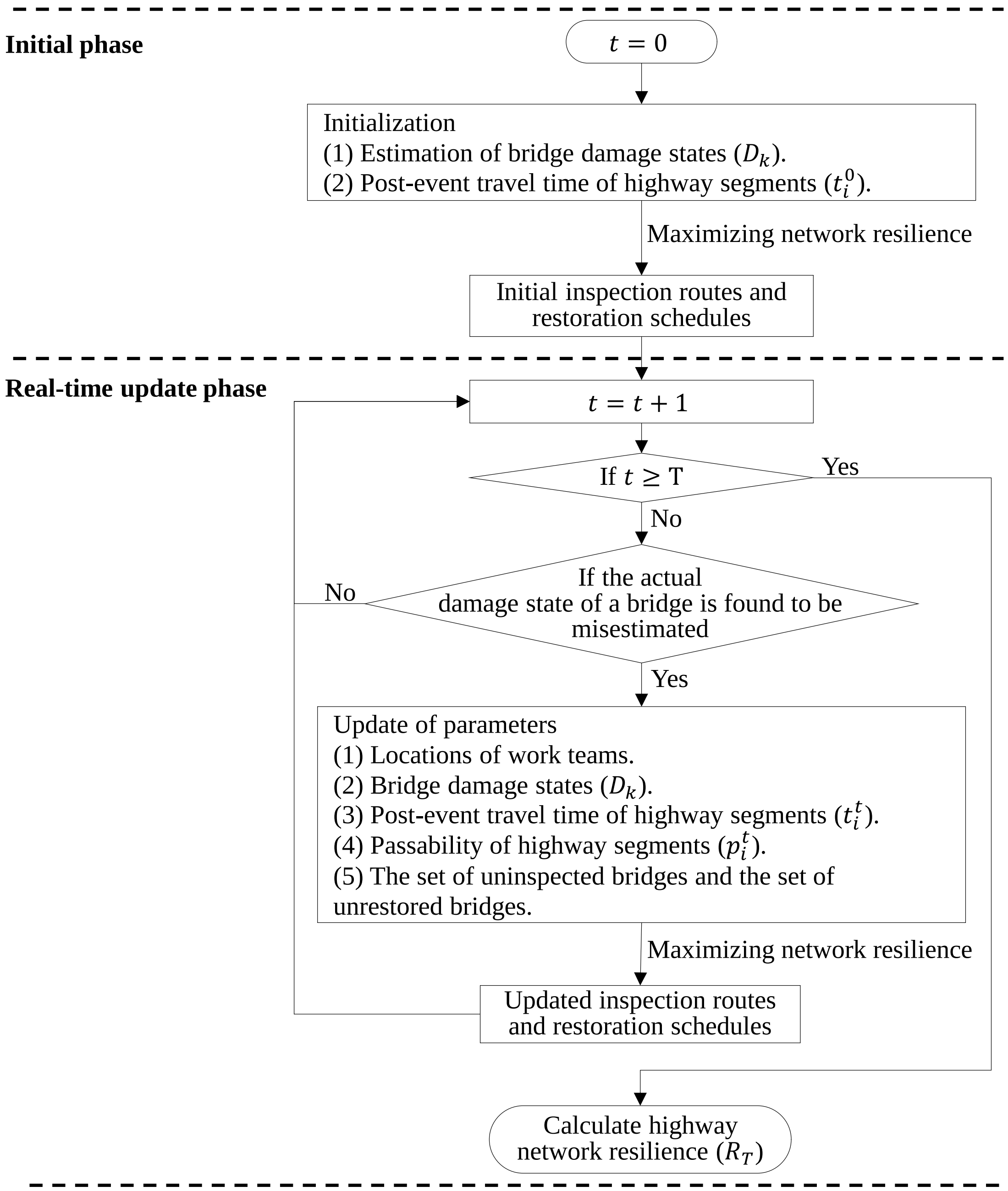


Figure 3.1 Framework of dynamic emergency inspection routing and restoration scheduling

3.4.2 Hybrid Genetic Algorithm

Given that both vehicle-routing and restoration-scheduling problems are characterized as NP-hard problems (Yan et al. 2014; Balcik 2017), and the dynamism as well as inspection-restoration interactions in the proposed problem further increase its computational complexity, optimally solving such a problem on a regional highway network containing dozen of bridges within a limited time is unrealistic. Therefore, this chapter intends to solve the proposed mathematical model using a hybrid GA, which has been proved effective and efficient in solving the integer program for a static inspection routing and restoration scheduling problem (Zhang and Wei 2020). Moreover, the encoding scheme and genetic operations in the hybrid GA are specifically designed to adapt the dynamism in the proposed mathematical model, where the sets of bridges for emergency inspection and restoration change whenever the algorithm updates the inspection and restoration plans. Details of the proposed hybrid GA are explained as follows.

3.4.2.1 Chromosome Encoding and the Fitness Evaluation

A proper chromosome representation approach is one of the critical aspects of the successful implementation of a GA and enables the GA to efficiently solve complex problems. Given that α_{ijk} and x_{jkt}, β_{ijk} and y_{jkt} are non-independent decision variables in the proposed mathematical model, x_{jkt} and y_{jkt} can be calculated using constraints (3.10) through (3.13) if α_{ijk} and β_{ijk} are known. Therefore, the chromosome in this chapter only represents α_{ijk} and β_{ijk} to form candidate routing and scheduling plans for the proposed integer program.

The overview of the proposed encoding scheme for the proposed mathematical model is shown in Figure 3.2. Each chromosome contains two elements: element_1 and element_2, indicating the sequences of bridges for inspection and restoration, i.e., α_{ijk} and β_{ijk}, respectively. Each element consists of n_b genes encoded by non-repeating integer numbers one to n_B, and these two elements are further divided into n_I and n_R sub-elements, respectively, indicating the inspection and restoration sequences of these work teams. Furthermore, each sub-element is divided into two parts to adapt the changes of sets of bridges for emergency inspection and restoration in these integer programs: a fixed part to record bridges that have been inspected or restored, and an alterable part to record bridges to be inspected or restored. When updating inspection routes and restoration schedules, genes on these fixed parts remain fixed, while the sequences of genes on these alterable parts will be rearranged. As more and more bridges have been inspected and restored, the number of genes on fixed parts increases while the number of genes on alterable parts decreases.

The fitness of a chromosome is set as the highway network resilience that is expected to achieve in the time horizon T, and the fitness value is calculated using Eq. (2.6).

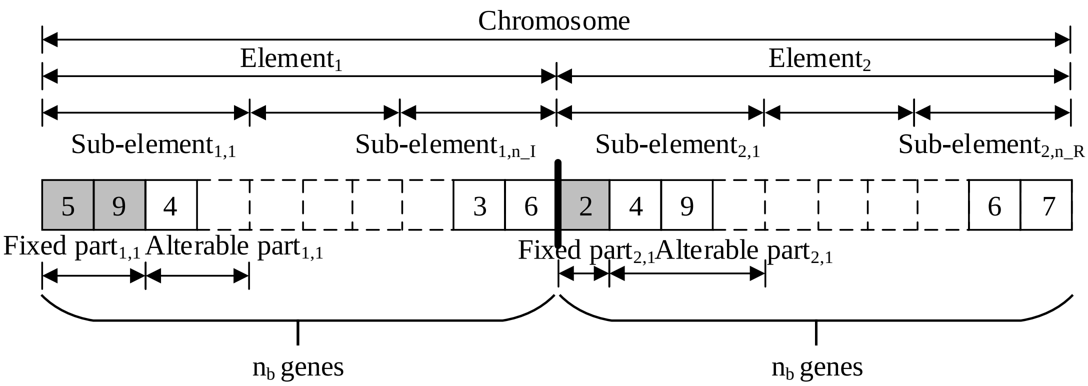


Figure 3.2 Encoding scheme for a chromosome

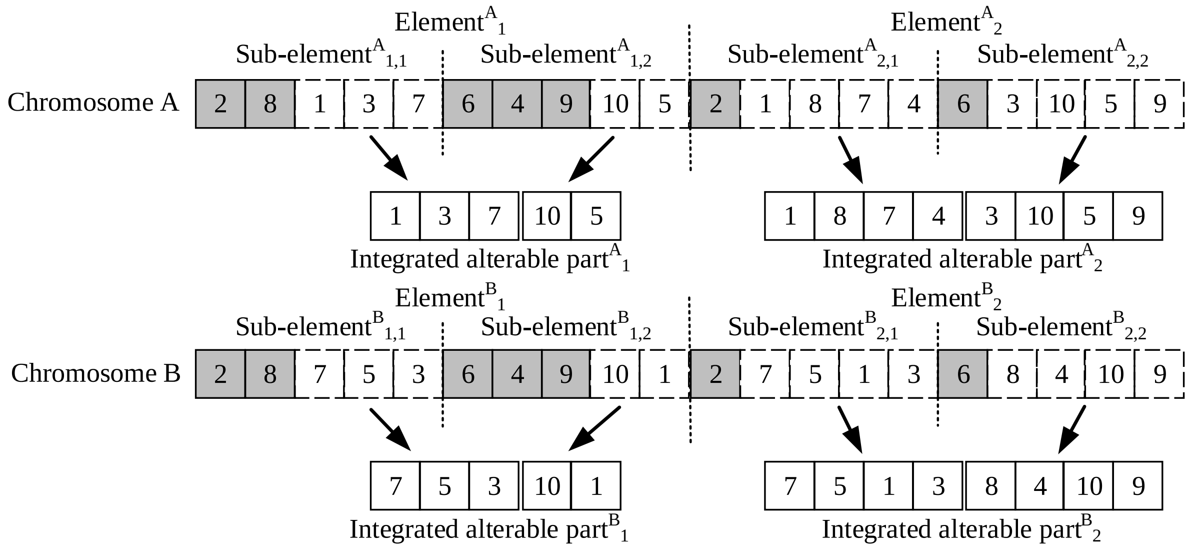
3.4.2.2 Update of Parameters and the Population

Parameters of the proposed mathematical model and the population for the hybrid GA need to be updated before re-optimizing inspection routes and restoration schedules. These parameters include damage states of bridges, locations of work teams, the set of uninspected bridges, and the set of unrestored bridges. The population contains a number of chromosomes, and the fixed parts of these chromosomes are the same, while alterable parts of chromosomes are randomly generated and indicate the inspection routes and the restoration schedules for these two sets of bridges, respectively.

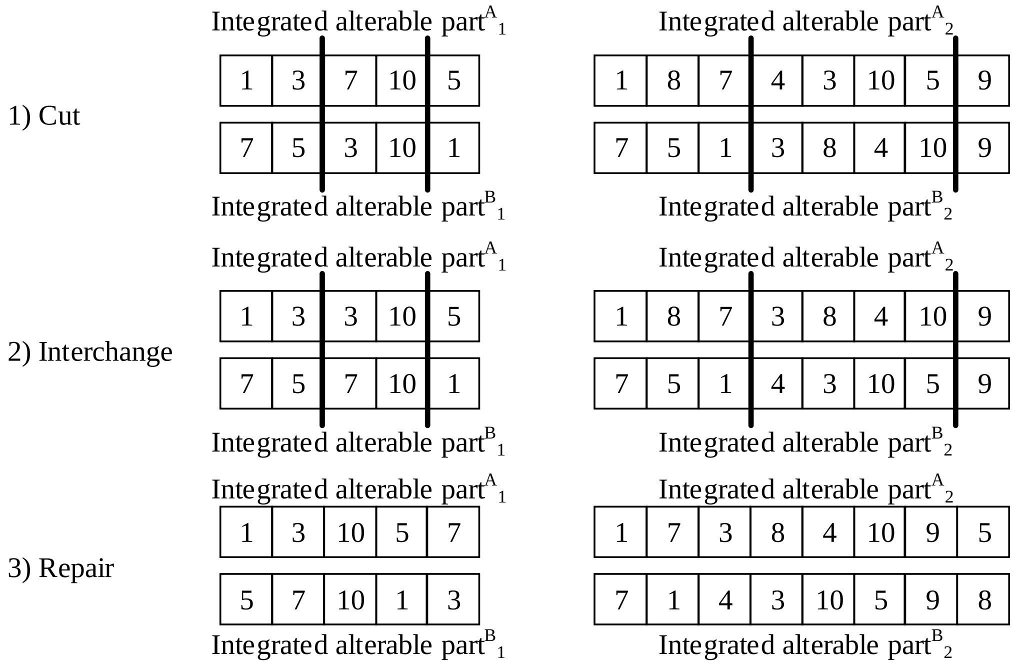
3.4.2.3 Genetic Operations

Genetic operations, including selection, crossover, and mutation, are used to generate new chromosomes to update the population. Elite chromosomes are selected from the initial population for crossover and mutation using the roulette-wheel procedure, which has been proved to be effective in selecting useful chromosomes (Goldberg 1989). Given that the alterable parts of chromosomes change every time the inspection and restoration plans are updated, this chapter proposes the disassembly and assembly methods to effectively conduct crossover and mutation operations.

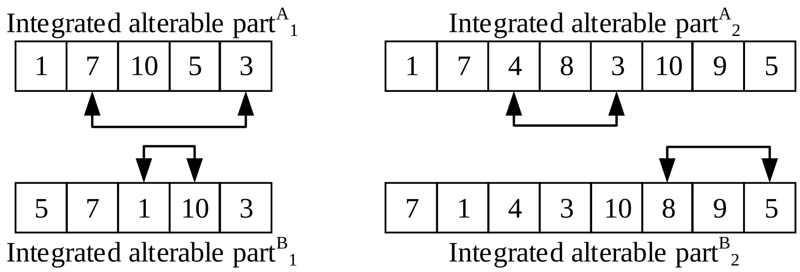
Figure 3.3 illustrates the process of the proposed genetic operations. The elite chromosome A and B indicate that ten bridges are expected to be inspected and restored by two inspection teams and two restoration teams, respectively. The disassembly method cuts off alterable parts from $element_1$ and $element_2$ and gathers the alterable parts that are cut from the same element to form integrated alterable $part_1$ and $part_2$, respectively, representing bridges to be inspected and restored. As shown in Figure 3.3(a), these alterable parts on $element_1$ and $element_2$ of chromosome A and B are cut to form four integrated alterable parts (i.e., integrated alterable $part^A_1$, $part^A_2$, $part^B_1$, and $part^B_2$). Then, the crossover operation is conducted (Figure 3.3(b)): first, two cut points on each pair of integrated alterable parts are randomly selected; second, genes between these two cut points are interchanged; third, these integrated alterable parts are repaired by deleting reduplicate genes and adding missing genes at the end of integrated alterable parts. Next, the mutation operation is conducted by interchanging two genes that are randomly selected on the same integrated alterable part (Figure 3.3(c)). Finally, the assembly method randomly splits integrated alterable part$_1$ and part$_2$ into n_I and n_R alterable parts, respectively, and then assembles these alterable parts with their corresponding fixed parts to form complete chromosomes (Figure 3.3(d)).



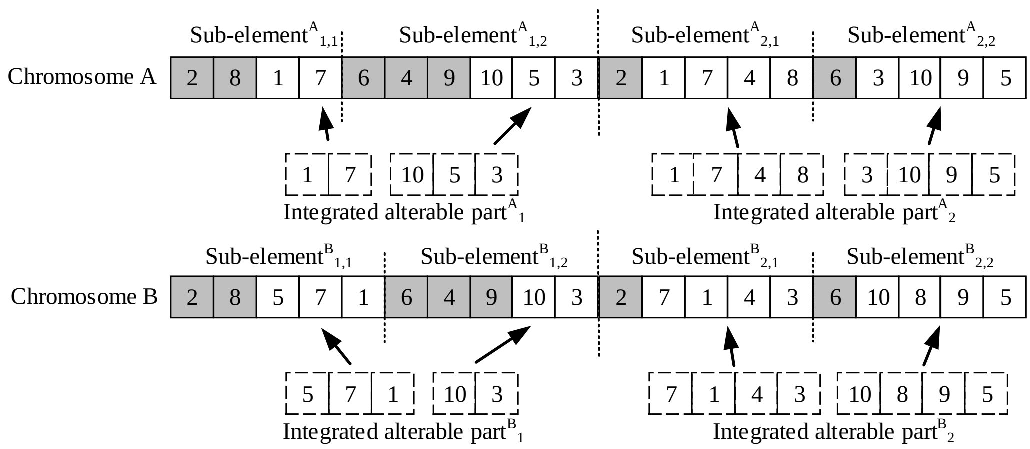
(a) Disassembly



(b) Crossover



(c) Mutation



(d) Assembly

Figure 3.3 Illustration of genetic operations

3.4.2.4 The Early-termination-based Heuristic Approach

The early-termination-based heuristic approach is developed to solve the early-termination problem, which results from the inspection-restoration interactions and the inaccessibility of bridges within highway networks and can lead to the slow evolution of the population's fitness values. Specifically, work teams would terminate their works if bridges to be inspected or restored were inaccessible due to impassable bridges, i.e., bridges in extensive or complete damage, on their ways to these bridges. Details of the early-termination test that is used to check if the early-termination problem occurs to a chromosome are not explained in this chapter since the testing algorithm can be found in Chapter 2. The gene on each alterable part that leads to the early-termination problem is extracted by adopting the early-termination test and is moved to the end of the alterable part, as shown in Figure 3.4.

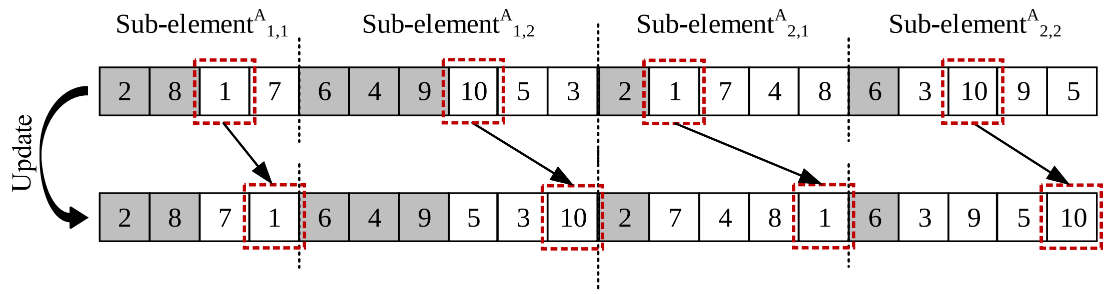


Figure 3.4 The early-termination-based heuristic approach

3.4.3 Performance Evaluation of the Hybrid GA

Evaluating the quality of a heuristic algorithm for a dynamic problem is a difficult task due to the lack of knowledge regarding the optimal solution and the strong upper and/or lower bounds of the solution. A widely accepted way to do such evaluation is the used of the value of information (VoI) defined by Mitrovic-Minic et al. (2004), which gives information on the effectiveness of a heuristic algorithm for solving a dynamic optimization problem without the need to obtain optimal solutions. The VoI establishes comparisons with the solution obtained for the corresponding static instance using the same heuristic algorithm, and the VoI of a heuristic algorithm for a dynamic maximization problem is defined by Eq. (3.28):

$$\mathrm{V}(I_D) = \frac{z(I_S) - z(I_D)}{z(I_S)} \tag{3.28}$$

where $\mathrm{V}(I_D)$ is the VoI on the dynamic instance I_D with information obtained in real-time and ranges from 0 to 1; $z(I_S)$ is the value of the objective function for the static instance I_S with all information obtained in advance ($dod = 0$); $z(I_D)$ is the value of the objective function for I_D. This chapter uses the VoI to evaluate the performance of the proposed hybrid GA in optimizing the highway network resilience of the proposed dynamic problem, and $z(I_D)$ and $z(I_S)$ in Eq. (3.28) are respectively the value of highway network resilience in the proposed dynamic problem and the value in a static problem in which all bridges' damage states are assumed to be correctly estimated. A small value of $\mathrm{V}(I_D)$ indicates the good performance of the hybrid GA in obtaining a high level of resilience, while a large value of $\mathrm{V}(I_D)$ indicates the poor performance of the heuristic algorithm in optimizing highway network resilience.

3.5 Case study

3.5.1 Experimental Design and Parameter Settings

The effectiveness of the proposed mathematical model and the solution methodology were tested in a regional highway network in Sichuan, China, using data on the 2008 Wenchuan Earthquake. The highway network consists of 21 highway segments and 16 cities (Figure 3.5), and attributes of these highway segments, including lengths, design speeds, and traffic capacity, are tabulated in Table 3.3, referring to Zhuang and Chen's report (2012). The case study considered 48 bridges on the highway network for emergency inspection and restoration, and locations of these bridges are shown in Figure 3.5. The data of peak ground acceleration distribution referred to (OSLR 2018), and the fragility curves used in constraint (3.21) for the calculation of BDI adopted the ones in Chen et al. (2012), in which bridges' fragilities curves were established using bridges' damage data in the Wenchuan Earthquake. Due to the lack of information about the location of the relief command center and the number of work teams, we assumed that the relief command center was located in C1 and included four inspection teams and four restoration teams. The average emergency inspection time for a damaged bridge, based on Zhuang and Chen's (2012) report, was 30 minutes. The presumed pre-earthquake travel demand between cities is given in Table 3.4, and the post-earthquake travel demand was set as 12 times of pre-earthquake travel demand based on Li et al.'s study (2008) on the traffic flow after the Wenchuan Earthquake. Moreover, the working time limitation for emergency bridge inspection and restoration was set as 72 hours (i.e., $T = 4320\ minutes$, and $t = \{0,1,2, \dots ,4320\}$ with equal increments of one minute), given that the first 72 hours after an earthquake is considered the "golden hours" for saving human lives (Verma and Chauhan 2015).

Table 3.3 Attributes of highway segments

Highway segment ID	City i	City j	Length (km)	Design speed (km/h)	Traffic capacity (pcu/day)	Bridges on the segment
H1	C1	C2	60	80	115200	B1-B3
H2	C1	C16	48	80	115200	B4
H3	C1	C13	73	80	115200	B5-B7
H4	C2	C3	31	30	16800	B8-B10
H5	C2	C4	25	80	115200	B11-B14
H6	C3	C4	13	40	26400	B15
H7	C4	C5	12	40	26400	B16
H8	C5	C6	25	30	16800	B17-B18
H9	C6	C7	19	30	16800	B19-B21
H10	C7	C8	18	40	24000	B22-B24
H11	C8	C9	62	40	24000	B25
H12	C9	C10	90	40	24000	B26-B31
H13	C10	C11	22	40	24000	B32-B33
H14	C11	C12	43	30	16800	B34
H15	C11	C14	54	40	24000	B35-B38
H16	C12	C13	56	30	16800	B39-B40
H17	C12	C14	53	30	16800	B41
H18	C14	C15	32	40	24000	B42-B43
H19	C13	C15	25	40	24000	B44
H20	C15	C16	32	80	115200	B45-B46
H21	C2	C16	38	40	26400	B47-B48

Table 3.4 Pre-earthquake traffic demands between cities

City N_i^c	City N_j^c	Traffic demand (pcu/day)	City N_i^c	City N_j^c	Traffic demand (pcu/day)	City N_i^c	City N_j^c	Traffic demand (pcu/day)
C1	C2	2000	C1	C12	1500	C5	C8	200
C1	C3	200	C1	C13	1200	C6	C8	200
C1	C4	300	C2	C4	500	C7	C9	300
C1	C5	300	C2	C6	200	C8	C9	500
C1	C8	500	C2	C7	200	C10	C12	200
C1	C9	300	C2	C16	1000	C11	C12	500
C1	C10	500	C4	C5	200	C11	C14	400

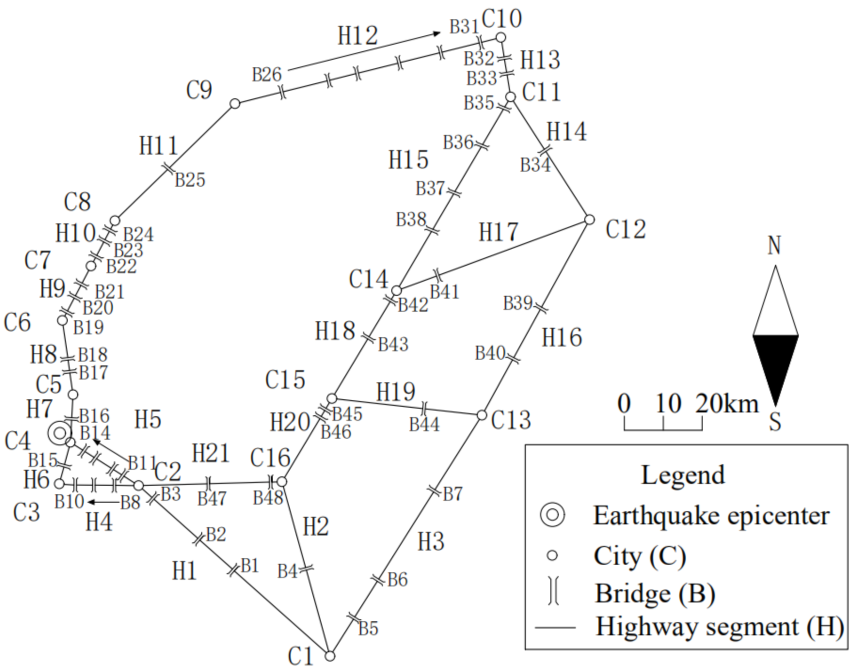


Figure 3.5 A highway network in Sichuan, China

Three sets of tests were performed in the case study based on the same highway system and the same earthquake scenario. First, the system resilience value resulting from the proposed solution methodology for the dynamic model was calculated and compared with the value resulting from a static solution methodology that inspection routes and restoration schedules were not updated. Then, a sensitivity analysis to investigate the impacts of the number of work teams, considered as the resource limitation, on the highway system resilience was conducted. Finally, the impact of the degree of dynamism on the performance of the proposed solution algorithm in optimizing the system resilience was examined. Parameters of the proposed hybrid GA with high computational efficiency for the case study were obtained after conducting extensive experiments: a population size of 100, 10 elite chromosomes, 200 generations, a crossover probability of 0.9, and a mutation probability of 0.2. The mathematical model and the solution algorithm were programmed in MATLAB 2017a, and these tests were executed on a Microsoft Windows 10 desktop computer with an Intel® Core™ i7-7700 CPU (3.6GHz) processor and 32 GB RAM.

3.5.2 Results and Discussions

3.5.2.1 Post-earthquake Damage States of the Highway Network

In the immediate aftermath of the earthquake, 5, 32, 7, and 4 bridges in Figure 3.5 were in slight, moderate, extensive, and complete damage, respectively, as recorded in (Zhuang and Chen 2012), and the highway system resilience dropped to 0.331, indicating that the travel time on the damaged highway network was around three times the travel time on the pre-earthquake highway network. The results of the seismic damage assessment (constraint (3.21)) show that the damage states of 12 bridges were misestimated. The actual and estimated damage states of these 48 bridges and their emergency restoration time, which could be determined by taking into account bridges' types, sizes, damage states, and emergency restoration methods (WCTPMC 2010), are tabulated in Table 3.5.

Table 3.5 Bridge damage states and emergency restoration time

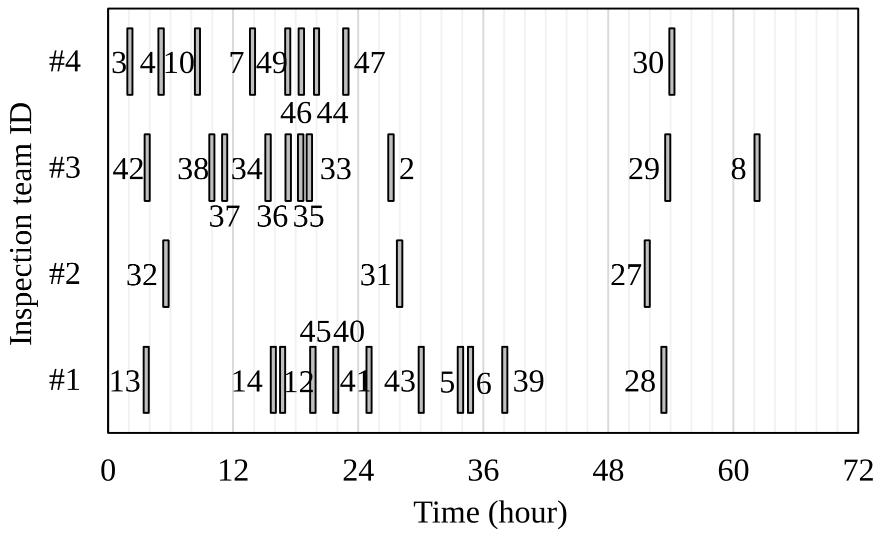
Bridge ID	Damage state		RT	Bridge ID	Damage state		RT
	Actual	Estimated	(hours)		Actual	Estimated	(hours)
B1	MD	MD	9	B25	MD	MD	9
B2	MD	MD	8	B26	MD	MD	9
B3	MD	MD	8	B27	MD	ED	13
B4	MD	MD	8	B28	MD	MD	6
B5	MD	MD	6	B29	MD	MD	9
B6	SD	MD	-	B30	MD	MD	10
B7	SD	MD	-	B31	MD	ED	21
B8	MD	MD	6	B32	ED	ED	16
B9	MD	MD	6	B33	MD	MD	8
B10	ED	ED	23	B34	MD	MD	5
B11	MD	MD	9	B35	ED	MD	19
B12	MD	MD	8	B36	MD	ED	10
B13	SD	ED	8	B37	ED	ED	9
B14	ED	CD	24	B38	MD	MD	10
B15	CD	CD	840	B39	SD	MD	-
B16	CD	CD	480	B40	SD	MD	-
B17	CD	CD	312	B41	MD	MD	7
B18	CD	CD	576	B42	ED	ED	23
B19	ED	ED	35	B43	MD	MD	6

B20	MD	MD	8	B44	MD	MD	8
B21	MD	ED	8	B45	MD	MD	7
B22	MD	ED	6	B46	MD	MD	7
B23	MD	MD	5	B47	MD	MD	14
B24	MD	MD	6	B48	MD	MD	9

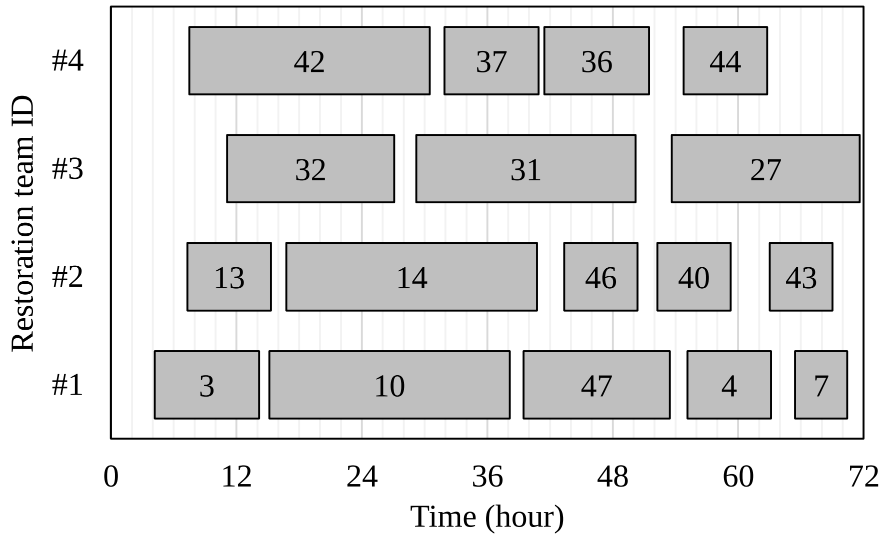
Note: RT = emergency restoration time; SD = slight damage; MD = moderate damage; ED = extensive damage; CD = complete damage.

3.5.2.2 Optimal Inspection Routes and Restoration Schedules

Based on the estimated bridge damage states, the initial inspection routes and restoration schedules for these work teams were obtained by solving the integer program P_0, as shown in Figure 3.6. The results indicate that inspection-restoration interactions could considerably increase the complexity of inspection routes and restoration schedules. Taking the inspection and restoration of three extensively damaged bridges, i.e., B27 and B31 on the highway segment H12, and B32 on H13 in Figure 3.5, as an example to explain such interactions. Immediately after the earthquake, inspection team_2 traveled from the relief command center (C1 in Figure 3.5) to B32 for inspection, as shown in Figure 3.6(a). Once inspection team_2 finished the inspection of B32, it should have moved to B31 immediately; however, the impassability of B32 had stopped inspection team_2 at this bridge for 21 hours to wait for the restoration of B32. After B32 had been inspected, restoration team_3 moved to this bridge for restoration (Figure 3.6(b)). Once B32 had been restored and became passable, inspection team_2 immediately departed from B32 to B31 for inspection. Meanwhile, restoration team_3 should have immediately moved to B31 for restoration; however, restoration team_3 had to stop at B32 and waited for one hour because B31 was uninspected. After inspection team_2 finished the inspection of B31, it stopped at this impassable bridge for 22 hours, and restoration team_3 moved to this bridge for restoration. Similarly, once B31 had been restored, restoration team_3 stopped at this bridge, and inspection team_2 traveled from B31 to B27 for inspection. Finally, restoration team_3 moved to B27 for restoration after inspection team_2 finished the inspection of this bridge. It is clear that inspection-restoration interactions could lead to significant waiting time of work teams if the routes of inspection/restoration teams contain impassable bridges.



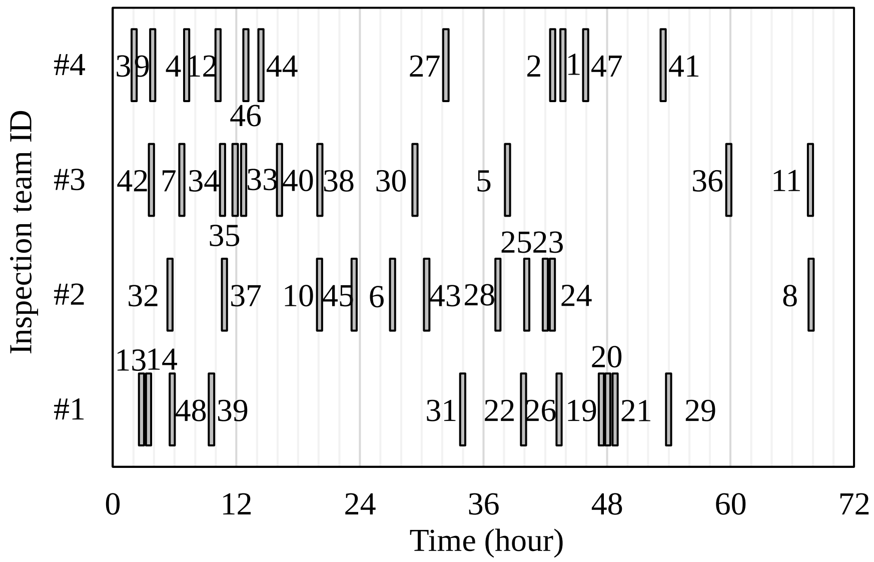
(a) Initial inspection routes



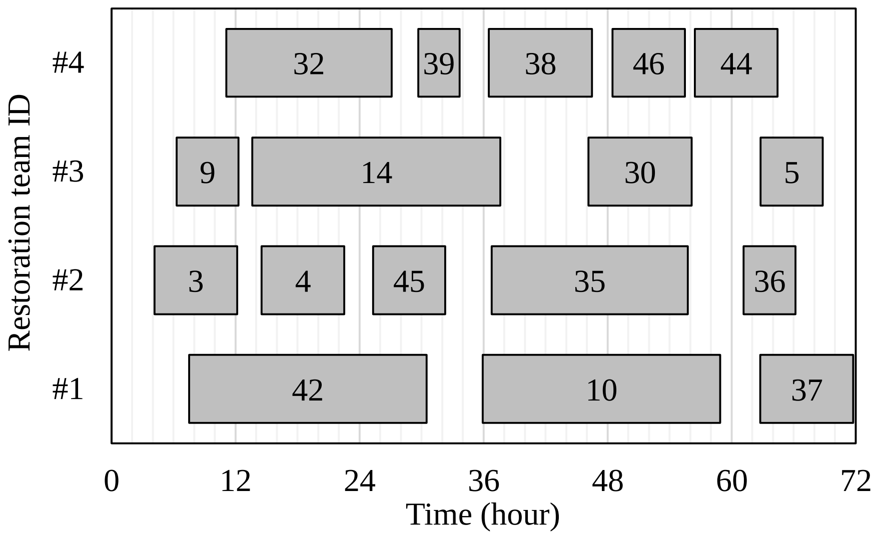
(b) Initial restoration schedules

Figure 3.6 Initial inspection routes and restoration schedules

In the real-time update phase, with the initial inspection and restoration plans, inspection teams left the relief command center to the bridges they intended to inspect. After inspection team_4 inspected B3 at time $t = 140\ minutes$, it found that B3 was in moderate damage, rather than in extensive damage as estimated, and H1 was actually passable. With such information, the relief command center could update the post-earthquake travel time of H1 using constraints (3.22) to (3.26). Meanwhile, inspection team_1, inspection team_2, and inspection team_3 were on their ways to B13, B32, and B42 for inspection at $t = 140\ minutes$, and these three inspection teams should finish the inspection of these bridges before following the updated inspection routes, whereas no restoration team left the relief command center for restoration at that time. Therefore, the locations of these four inspection teams for updating the inspection routes were B13, B32, B42, and B3, respectively, while all these four restoration teams were in C1. Finally, the set of uninspected bridges included all damaged bridges except B3, B13, B32, and B42, and the set of unrestored bridges included all 48 bridges. With all above updated parameters, the relief command center could update the optimal inspection routes and restoration schedules. This update process would be repeated whenever a misestimated bridge was found until reaching the working time limitation. The final inspection routes and restoration schedules at $t = 4320\ minutes$ are shown in Figure 3.7 and are significantly different from the initial optimal plans in Figure 3.6. The results demonstrate that taking into consideration the real-time bridge damage information can lead to dramatic changes in the optimal inspection routes and restoration schedules.



(a) Updated inspection routes



(b) Updated restoration schedules

Figure 3.7 Updated inspection routes and restoration schedules

3.5.2.3 Optimal Highway System Resilience

In the first 72 hours, the system resilience could be improved to 0.705 using the proposed dynamic model, where inspection routes and restoration schedules were updated in real-time. Moreover, the highway network resilience of the dynamic problem was also calculated using a static routing and scheduling method proposed by Zhang and Wei (2020), in which inspection routes and restoration schedules were fixed in the first 72 hours. The results show that, compared with the static method, the system resilience could be improved by 64%, from 0.430 to 0.705, by updating the inspection routes and restoration schedules in real-time. Thus, it is safe to say that taking into account the real-time bridge damage information and updating inspection routes and restoration schedules in real-time are critical to achieving a high level of highway system resilience.

Meanwhile, to explore the upper bound of the system resilience in the proposed real-time optimization model, an upper-bound model that the estimated damage states of bridges were assumed to be consistent with their actual damage states (i.e., $n_d = 0$ and $dod = 0$ in Eq. (3.27)) was conducted. Under such a condition, the highway system resilience was 0.739 at the 72-hour mark. The value of information $\mathrm{V}(I_D)$ of the proposed hybrid GA for the proposed dynamic problem was 0.046 (Eq. (3.28)), and therefore, the proposed solution algorithm can be seen as an effective approach to solve dynamic inspection-routing and restoration-scheduling problems.

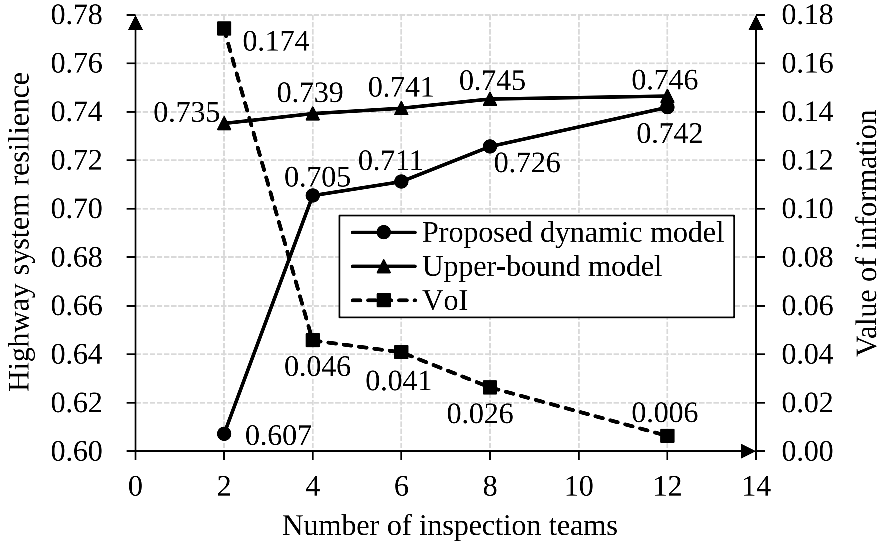
3.5.2.4 Effect of the Number of Work Teams

The sensitivity of the system resilience to the number of work teams to respond to a disaster was investigated via two tests, T1 and T2 (Table 3.6). In T1, the number of inspection teams increased from two to 12, while the number of restoration teams remained four. A sharp increase in highway system resilience, from 0.607 to 0.705, could be observed if the number of inspection teams increased from two to four (Figure 3.8(a)). Then, the highway system resilience increased steadily from 0.705 to 0.742 if the number of inspection teams increased from four to 12. The results are significantly different from the results in the upper-bound model, where increasing or decreasing the number of inspection teams could only slightly increase or decrease the highway system resilience. Meanwhile, $\mathrm{V}(I_D)$ decreased gradually from 0.174 to 0.006 as more inspection teams were available. The results indicate that a high level of system resilience and a good performance of the proposed solution algorithm could be gained by increasing the number of inspection teams to quickly collect real-time bridge damage information.

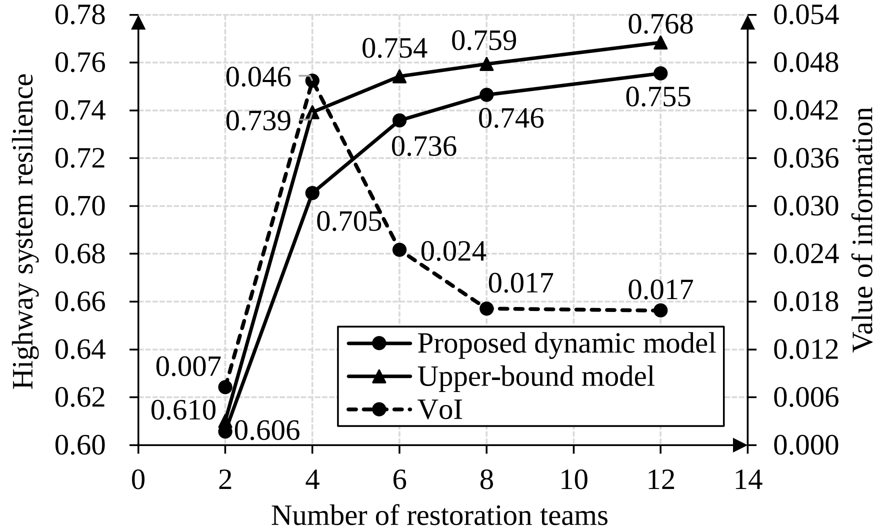
In T2, the number of restoration teams increased from two to 12, while the number of inspection teams remained four. The results show that the highway system resilience increased by 24.6%, from 0.606 to 0.755, and $V(I_D)$ fluctuated between 0.007 and 0.046 (Figure 3.8(b)). These two tests indicate that both inspection and restoration capacities can significantly affect highway system resilience in the proposed dynamic problem, and the results can help decision-makers to optimally allocate work teams to meet their specific requirements on the level of system resilience.

Table 3.6 Number of work teams in experiments

Experiment ID	Number of inspection teams	Number of restoration teams	Highway network resilience		Value of information
			Upper bound	Real-time	$V(I_D)$
	2	4	0.716	0.607	0.152
	4	4	0.726	0.705	0.028
T1	6	4	0.729	0.7118	0.025
	8	4	0.735	0.726	0.013
	12	4	0.746	0.742	0.006
	4	2	0.653	0.635	0.027
	4	4	0.726	0.705	0.028
T2	4	6	0.735	0.731	0.006
	4	8	0.746	0.731	0.020
	4	12	0.759	0.755	0.004



(a) Results of T1 (with four restoration teams)



(b) Results of T2 (with four inspection teams)

Figure 3.8 Impact of the number of work teams on highway system resilience

3.5.2.5 Effect of the Degree of Dynamism

Additionally, three levels of dynamism (i.e., low, medium, and high) were considered to examine the impact of the degree of dynamism on the performance of the proposed hybrid GA in solving the proposed dynamic problem. The aforementioned case that included 12 misestimated bridges was considered as the case of low degree of dynamism ($dod = 0.25$), while 24 and 36 misestimated bridges were considered in the cases of medium ($dod = 0.5$) and high ($dod = 0.75$) degree of dynamism, respectively. As shown in Figure 3.9, $V(I_D)$ of the proposed solution algorithm increased from 0.046 to 0.162 as the degree of dynamism increased, leading to a decrease in highway system resilience. This indicates that the degree of dynamism can affect the performance of the proposed hybrid GA in optimizing highway system resilience, and decreasing the degree of dynamism of the problem by reducing the number of misestimated bridges can contribute to good performance of the hybrid GA.

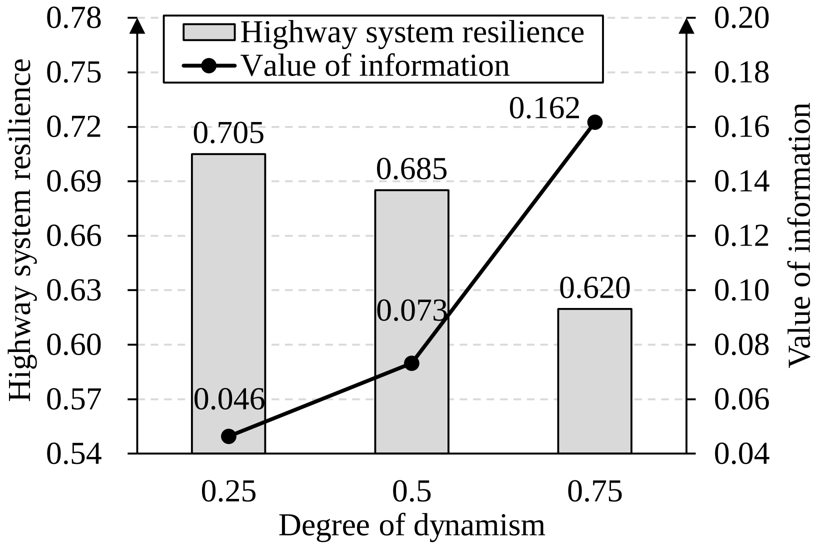


Figure 3.9 Impact of the degree of dynamism on the performance of the Hybrid GA

3.6 Conclusions

3.6.1 Research Findings

Existing studies on post-earthquake emergency bridge inspection routing and restoration scheduling were not able to take advantage of the real-time bridge damage information obtained via inspection activities; however, the results of the proposed study proved the benefits of doing so. To address the real-time information in the proposed dynamic inspection-routing and restoration-scheduling problem, this chapter has developed a mathematical model using the integer programming technique for such a problem by first decomposing the dynamic problem into a sequence of static inspection-routing and restoration-scheduling problems and then formulating these problems as integer programs, with the aim of maximizing highway system resilience. Furthermore, a hybrid GA that integrated a heuristic approach into a GA that was specifically designed for adapting the dynamisms in the proposed mathematical model was developed to effectively solve these integer programs.

The proposed mathematical model and solution methodology were applied to a highway system in Sichuan, China, adopting the data from the 2008 Wenchuan Earthquake. The results show that inspection-restoration interactions could significantly increase the complexity of inspection routes and restoration schedules, and the real-time bridge damage information could considerably affect the optimal inspection and restoration plans. By comparing the system resilience calculated by the proposed solution methodology against the resilience calculated by a static routing and scheduling method, it became clear that dynamically updating inspection routes and restoration schedules by taking into consideration real-time bridge damage information led to significant improvement in highway system resilience, as compared to fixed inspection routes and restoration schedules. Moreover, the results of the sensitivity analysis on the number of work teams demonstrate that both of the inspection and restoration capacities could significantly affect the level of highway system resilience, while increasing the number of inspection teams to quickly collect bridge damage information could improve the performance of the proposed hybrid GA. Finally, the investigation on the degree of dynamism suggest that the performance of the hybrid GA in optimizing highway system resilience could be improved by decreasing the degree of dynamism of the proposed problem.

3.6.2 Scientific and Practical Significance

The proposed techniques can provide real-time decision support to decision-makers in charge of deploying work teams for emergency bridge inspection and restoration after an earthquake. By considering the inherent dynamism of a post-earthquake highway network and the complex interactions among inspection and restoration activities, and by further employing real-time communications between on-site bridge inspectors and decision-makers in updating the routing and scheduling of inspection and restoration activities, the resulting decisions can aid work teams in efficiently recovering the functionality of highway networks, and thus, maximizing highway network resilience. Moreover, the proposed tools that can be used to plan real-time, interacting emergency bridge inspection and restoration activities provide the basis for further research on simultaneously planning recovery strategies for multiple infrastructure systems, such as electric power systems and telecommunication systems, given that planning such strategies involve both real-time information and interactions among different response and recovery activities.

CHAPTER 4 SCHEDULING LONG-TERM BRIDGE RESTORATION ACTIVITIES BY ACCOUNTING FOR THE RESTORATION-DOWNTIME IMPACT

4.1 Introduction

Highway networks play vital roles in the post-earthquake recovery of communities by transporting reconstruction materials and equipment, and supporting commercial activities as well as people's daily lives. However, the damage or destruction of highway bridges can lead to the disruption of highways, thereby hindering the recovery of communities. Therefore, establishing optimal restoration schedules for damaged bridges in a highway network is of critical importance to promote the efficient recovery of highway networks to their pre-earthquake conditions.

A general objective of scheduling restoration activities for transportation networks is to maximize transportation network resilience (Ip and Wang 2009; Frangopol and Bocchini 2011; Chen and Miller-Hooks 2012; Zhang and Wang 2016). A widely accepted method for quantifying transportation network resilience in the recovery phase is the use of network functionality curves, and network resilience is defined as the post-disaster cumulative functionality in a time horizon (Bruneau et al. 2003; Frangopol and Bocchini 2011). After a disaster, a transportation system's functionality drops to a low level and will recover gradually with the implementation of restoration activities until reaching its pre-disaster level. Prior studies commonly used monotonically increasing functions to define transportation networks' functionality curves (Bocchini and Frangopol 2012; Ye and Ukkusuri 2015; Twumasi-Boakye and Sobanjo 2018; Zhang et al. 2018; Li et al. 2019); however, highway networks' functionality, instead of increasing monotonically, may temporarily drop due to the blockage of highways for the restoration of bridges on them. For example, if some highways that were passable after a disaster were blocked for the restoration of bridges on them, the functionality of the highway network would temporarily decrease during the restoration downtime of these highways. Accordingly, failing to account for the impact of restoration downtime on network functionality may overestimate highway network resilience, and thereby, the inaccurate calculation of objectives can lead to inefficient bridge restoration strategies.

Given that well-designed network functionality is the key to explicitly appraise network resilience, this chapter develops a novel functionality recovery model for highway networks to address the above issue by taking into account the impact of restoration downtime on highway networks' functionality in scheduling post-earthquake bridge restoration activities. Moreover, the proposed bridge restoration-scheduling problem is formulated as an integer program with recursive functions to capture the fluctuation of highway network functionality over time. The proposed functionality recovery model will then be validated using a highway network in Sichuan, China. With the proposed mathematical tool for solving this problem, decision-makers are able to obtain optimal bridge restoration schedules for post-earthquake highway networks.

This chapter is organized as follows. Section 4.2 thoroughly reviews the existing methods for the quantification of transportation network resilience and reveals shortages of these methods. Section 4.3 presents definitions and assumptions of the bridge restoration-scheduling problem and develops the mathematical model for the problem. Section 4.4 designs specific solution algorithms to efficiently solve the proposed mathematical model. Section 4.5 uses an actual highway network to investigate the effectiveness of the proposed methodology. Section 4.6 concludes with research findings and significance.

4.2 Literature Review

The definition of resilience dates back to 1973 when Holling (1973) first defined the resilience of an ecological system as a measure of the system's ability to absorb disturbance and still maintain an equilibrium state. Adopting in the field of infrastructure systems, researchers have developed different conceptual definitions of resilience (Zhou et al. 2010; Miller-Hooks et al. 2012; Zhang and Wang 2016; Levenberg et al. 2017; Zhang et al. 2017; Calvert and Snelder 2018; Wan et al. 2018). A widely accepted definition of infrastructure system resilience was proposed in Bruneau et al. (2003), where resilience consists of four properties: robustness (the ability to resist disasters and still operate a service), redundancy (the number of substitutable components to keep the system's serviceability), resourcefulness (the capability to identify problems, establish priorities, and allocate resources after a disaster), and rapidity (the recovery time of the investigated system from a disaster to its normal level of performance). Based on such a definition, Bruneau et al. (2003) further developed a quantification method for infrastructure system resilience by proposing the "resilience triangle". As shown in Figure 4.1(a), after a disaster at time t_0, the functionality of the infrastructure system drops down to the lowest level, $F(t_0)$, and the level of such a drop indicates the robustness and redundancy of the system. Then the functionality starts to ascend monotonically and approximately linearly once the system receives restoration activities until the functionality recovers to its pre-disaster level at time $t_0 + T$. The recovery path reflects the resourcefulness and rapidity of the system. The resilience triangle is the shaded area above the recovery path, representing the resilience loss. The resilience triangle establishes the relationship between resilience and system functionality and has been widely used in quantifying resilience losses of infrastructure systems, such as power supply systems and medical facilities (Bruneau 2006; Bruneau and Reinhorn 2006; Bruneau and Reinhorn 2007). Furthermore, alternative analytical definitions of resilience have been developed based on the concept of resilience triangle to quantify the resilience of highway networks, rather than their resilience losses. Bocchini and Frangopol (2012) defined resilience as the area below the functionality curve $F(t)$ in a time horizon T, as shown in Figure 4.1(b). Such a definition takes into account the shape of the recovery path and can be used to optimize disaster management strategies, such as restoration scheduling, given that different strategies may result in different recovery paths. However, expressed in units of time, resilience values calculated by this method can be challenging to be understood by decision-makers (Bocchini and Frangopol 2011). For such a reason, the resilience value is normalized into 0 to 1 using Eq. (4.1) (Cimellaro et al. 2010; Frangopol and Bocchini 2011):

$$R = \frac{\int_{t_0}^{t_0+T} F(t)dt}{T} \tag{4.1}$$

where the numerator is the area underneath the post-disaster functionality $F(t)$ between t_0 and $t_0 + T$, and the denominator is the area underneath the pre-disaster functionality between t_0 and $t_0 + T$ when its value is 1 (i.e., $1 \cdot T = T$) (Figure 4.1(b)).

Furthermore, recently, there is an emerging consensus that step functions can more practically reflect the recovery paths of highway networks than continuous functionality curves because the recovery of a highway network's functionality is actually a discrete process rather than a continuous process (Ye and Ukkusuri 2015; Twumasi-Boakye and Sobanjo 2018; Zhang et al. 2018; Li et al. 2019). As shown in Figure 4.1(c), the functionality of a highway network remains unchanged during the restoration of damaged bridges on it and jumps to a higher level once damaged bridges are restored. Accordingly, network resilience can be calculated by discretizing Eq. (4.1) to Eq. (4.2):

$$R = \frac{\sum_{t=t_0}^{t_0+T} F(t)\Delta t}{T} \tag{4.2}$$

All above studies utilized monotonically increasing functions to measure networks' functionality because these studies held the idea that a network's functionality would increase gradually along with the recovery of the network's physical damages directly caused by disasters. In practice, however, the loss of network functionality results from not only physical damages but also restoration activities required to address physical damages. For instance, the restoration of bridges will block highways that are still in service for supporting the movement of people and goods following a disaster, and thus the functionality of the highway network may decrease during the restoration downtime of these highways. Accordingly, the failure to be aware of the restoration-downtime impact (i.e., highways are blocked during restoration downtime) on the network functionality can lead to the overestimation of highway network resilience. Given that maximizing highway network resilience is a general objective for studies on optimizing restoration strategies (Ip and Wang 2009; Frangopol and Bocchini 2011; Chen and Miller-Hooks 2012; Zhang and Wang 2016), the inaccurate quantification of resilience can thereby lead to inefficient bridge restoration strategies. To bridge the above research gap, this chapter develops a novel functionality recovery model for explicitly quantifying highway network resilience and optimally scheduling bridge restoration activities.

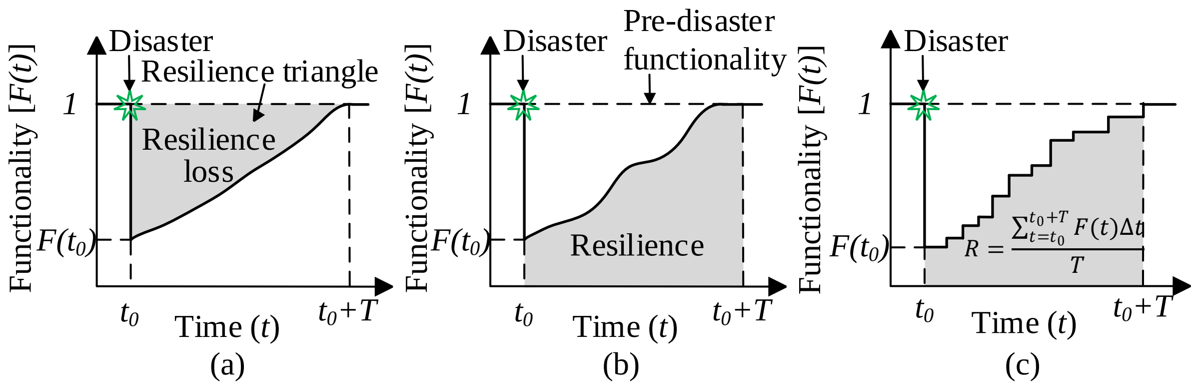


Figure 4.1 Resilience models: (a) resilience triangle defined in (Bruneau et al. 2003); (b) resilience of a bridge network defined in (Bocchini and Frangopol 2012); (c) stepped recovery path of a highway network's functionality (Ye and Ukkusuri 2015; Twumasi-Boakye and Sobanjo 2018; Zhang et al. 2018; Li et al. 2019)

4.3 Mathematical Model

4.3.1 Definitions and Notations

The definition of a highway system is the same as the definition in Chapter 2, and the notation used within the mathematical formulation in this chapter is listed in Table 4.1 and Table 4.2.

Table 4.1 Sets and parameters

Notations	Description
Sets	

H	set of highway segments
N	set of nodes
N^b	set of bridges in the highway network
N^c	set of cities in the highway network
$N^b_{H_i}$	set of bridges on highway segment H_i
Parameters	
c_0	pre-earthquake traffic capacity of H
v_0	design speed of H
l	length of H
n_b	number of damaged bridges in the highway network
n_c	number of cities in the highway network
n_h	number of highway segments in the highway network
n_R	number of restoration teams
T	time horizon
T^R_j	time required for restoring N^b_j
t_0	the time when an earthquake occurs

Table 4.2 Decision variables and time-dependent parameters

Notations	Description
Decision variables	
x_{jkt}	A binary variable to determine whether restoration team k starts to restore bridge N^b_j at time t
α_{ijk}	A binary variable to determine whether restoration team k restores bridge N^b_j at sequence i

Parameters to be calculated

BDI_j^t	bridge damage index of N_j^b at time t
$BDI_{i,j}^t$	bridge damage index of bridge j at time t, $\forall j \in N_{H_i}^b, \forall t \in \{0,1,\dots,T\}$
HDI_i^t	highway damage index of highway segment H_i at time t, $\forall H_i \in H$, $\forall t \in \{0,1,\dots,T\}$
c_i^t	post-earthquake traffic capacity of H_i at time t
$f_{0,i}$	pre-earthquake traffic flow on H_i
f_i^t	post-earthquake traffic flow on H_i at time t
p_i^t	a binary parameter to indicate whether H_i is passable at time t; 1 represents passable, and 0 represents impassable
HDI_i^t	high damage index of H_i at time t
T_{ij}	pre-earthquake shortest travel time between N_i^c and N_j^c
T_{ij}^t	post-earthquake shortest travel time between N_i^c and N_j^c at time t
TR_i	Pre-earthquake travel time on H_i
TR_i^t	Post-earthquake travel time on H_i at time t
v_i^t	Post-earthquake traffic speed on H_i at time t

4.3.2 Highway Network Resilience

The proposed post-earthquake recovery model of a highway network is shown in Figure 4.2. An earthquake occurs at time $t_0 = 0$, and the highway network functionality $F(t)$ drops to a low level due to the damages of highway bridges. The network functionality may fluctuate during the recovery process: the functionality will drop if highway segments that are still passable after the earthquake are blocked for the restoration of bridges, remain unchanged during the conduction of restoration works, or jump to a high level after finishing the restoration of bridges and reopening these blocked highway segments. This chapter uses normalized travel time as the measure of the highway network functionality to reflect the change of functionality curves over time during the recovery process. The functionality is formulated by Eq. (4.3):

$$F(t) = \frac{1}{2n_P} \sum_{\forall i,j \in N^c, i \neq j} \frac{T_{ij}}{T_{ij}^t} \tag{4.3}$$

where T_{ij} is the pre-earthquake shortest travel time between city N_i^c and city N_j^c ; T_{ij}^t is the post-earthquake shortest travel time between N_i^c and N_j^c at time t; n_P is the total number of the shortest paths between n_c cities in the network, and its value is $\frac{n_c \cdot (n_c - 1)}{2}$. $F(t)$ ranges from 0 to 1, where the value 1 means that travel time on the highway network has been recovered to the pre-earthquake level, while a low value of $F(t)$ indicates that users on the highway network spend much time traveling between cities comparing to pre-earthquake conditions. Adapting the resilience model in (Frangopol and Bocchini 2011) to the proposed stepwise functionality, this chapter calculates the highway network resilience using Eq. (4.4):

$$R_T = \frac{\sum_{\forall t \in \{0,1,\ldots,T\}} F(t)}{T} \tag{4.4}$$

where R ranges from 0 to 1, and a large value of R indicates efficient recovery of the highway network.

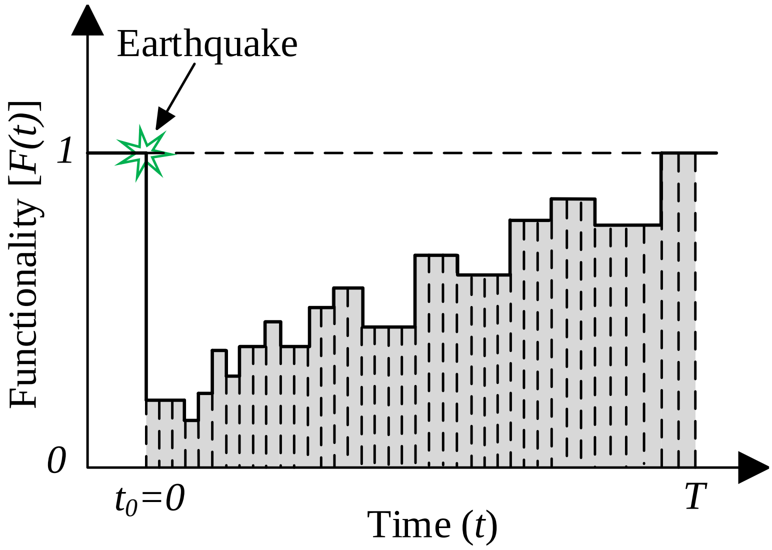


Figure 4.2 The proposed post-earthquake recovery model of highway network functionality

4.3.3 Model Assumptions

For the sake of simplicity, this chapter makes the following assumptions:

(1) Detailed damage information of bridge and their restoration methods are fully understood prior to conducting long-term restoration activities.

(2) Highway segments containing either extensively damaged bridges or completely damaged bridges are impassable until all of these bridges have been fully restored.

(3) A highway segment is blocked if some bridges on it are under repair, and daily traffic cannot pass such a segment. A blocked highway segment will be unblocked if all restoration works on it has been finished and it contains no bridge in extensive or complete damage state.

(4) A damaged bridge is restored by a single restoration team. Once a restoration team starts to restore a damaged bridge, it must finish the current restoration work prior to restoring the next bridge.

(5) Travel demand between cities within the highway network remains fixed in the investigated time horizon.

4.3.4 Optimization Model

In this section, mathematical models for the optimization of bridge restoration schedules are developed, taking into account the restoration-downtime impact on network functionality. Accordingly, the model for the bridge restoration-scheduling problem is formulated as follows.

$$\max\ R_T \tag{4.5}$$

subject to

$$\sum_{\forall k\in\{1,2,\dots,n_R\}}\sum_{\forall t\in\{0,1,\dots,T\}} x_{jkt} = 1, \forall\, j \in N^b \tag{4.6}$$

$$\sum_{\forall i\in\{1,2,\dots,n_b\}}\sum_{\forall k\in\{0,1,\dots,n_R\}} \alpha_{ijk} = 1, \forall\, j \in N^b \tag{4.7}$$

$$\sum_{\forall j\in N^b} x_{jkt} = 1, \forall\, t \in \{0,1,\dots,T\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{4.8}$$

$$\sum_{\forall j\in N^b} \alpha_{ijk} = 1, \forall\, i \in \{1,2,\dots,n_B\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{4.9}$$

$$\sum_{\forall t\in\{0,1,\dots,T\}} x_{jkt} = \sum_{\forall i\in\{1,2,\dots,n_b\}} \alpha_{ijk}\,, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\} \tag{4.10}$$

$$\sum_{\forall j\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}} \alpha_{i+1,jk}x_{jkt}t - \sum_{\forall j\in N^b}\sum_{\forall t\in\{0,1,\dots,T\}} \alpha_{ijk}x_{jkt}t - \sum_{\forall j\in N^b} \alpha_{ijk}T_j^R = 0, \forall\, i \in \{1,2,\dots,n_B-1\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{4.11}$$

$$TR_i = \frac{l_i}{v_{0,i}} \times \left[1+\alpha\left(\frac{f_{0,i}}{c_{0,i}}\right)^{\beta}\right], \forall\, i \in H \tag{4.12}$$

$$TR_i^t = \begin{cases} \frac{l_i}{v_i^t} \times \left[1+\alpha\left(\frac{f_i^t}{c_i^t}\right)^{\beta}\right], & p_i(t)=1 \\ +\infty, & p_i(t)=0 \end{cases}, \forall\, i \in H \tag{4.13}$$

$$c_i^t = \begin{cases} c_{0,i}, & 0 \leq HDI_i(t) < 1.0 \\ 0.75c_{0,i}, & 1.0 \leq HDI_i(t) < 1.5, \forall\, i \in H \\ 0.5c_{0,i}, & 1.5 \leq HDI_i(t) < \infty \end{cases} \tag{4.14}$$

$$v_i^t = \begin{cases} v_{0,i}, & 0 \leq HDI_i(t) < 0.5 \\ 0.75v_{0,i}, & 0.5 \leq HDI_i(t) < 1.0\,, \forall\, i \in H \\ 0.5v_{0,i}, & 1.0 \leq HDI_i(t) < \infty \end{cases} \tag{4.15}$$

$$HDI_i^t = \begin{cases} \sqrt{\sum_{j \in N_{H_i}^b} {BDI_{i,j}^t}^2} & \forall BDI_{i,j}^t < 0.75 \\ +\infty & \exists BDI_{i,j}^t \geq 0.75 \end{cases}, \forall\, i \in H \tag{4.16}$$

$$p_i^t = \begin{cases} 1 & HDI_i^t < +\infty \cap \nexists\, j \in N_{H_i}^b \text{ is under repair at time } t \\ 0 & HDI_i^t = +\infty \cup \exists\, j \in N_{H_i}^b \text{ is under repair at time } t \end{cases}, \forall\, i \in H \tag{4.17}$$

$$x_{jkt}, \alpha_{ijk} \in \{0,1\}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\}, \forall\, t \in \{0,1,\dots,T\}, \forall\, i \in \{1,2,\dots,n_b\} \tag{4.18}$$

The objective function (4.5) aims to obtain the maximum highway network resilience R_T in the investigated time horizon T. Constraints (4.6) and (4.7) ensure that each bridge is restored by one restoration team within the time horizon T. Constraints (4.8) and (4.9) ensure that each restoration team can only restore one damaged bridge at any time. Constraint (4.10) establishes the relationship between these independent decision variables x_{jkt} and α_{ijk}. Constraint (4.11) builds the relationship between the start time of two adjacent restoration tasks of a restoration team. This constraint is formulated based on the assumption (4) that a restoration team must finish its current restoration work prior to moving to the next bridge. Constraint (4.12) is the Bureau of Public Roads function used for the estimation of travel time on an pre-earthquake highway segment, where parameters α and β in the function are 0.15 and 4, respectively (Martin and McGuckin 1998). The traffic flow distribution on a highway network is assumed to be user equilibrium (UE), where users choose their routes with the aim of minimizing their travel time (Chang et al. 2012). Therefore, traffic flow on highway segments can be estimated using the Frank-Wolfe algorithm (Florian and Hearn 1995). Constraints (4.13) to (4.16) are recursive functions to re-calculate TR_i^t at each discrete time t. Constraint (4.13) estimates the post-earthquake travel time of highway segments containing damaged bridges (Chang et al. 2000; Dong and Frangopol 2017; Guo et al. 2017). This chapter assumes that UE on a post-earthquake highway network is formed immediately once a segment is blocked or unblocked. Constraints (4.14) and (4.15) respectively present the relationships between the pre- and post-earthquake traffic capacity and traffic speed of a highway segment based on its damage state. The post-earthquake damage state of a highway segment can be quantitatively described by the highway damage index (HDI): a highway segment is in no damage, slight damage, moderate damage, extensive damage, or complete damage if $HDI < 0.5$, $0.5 \leq HDI < 1.0$, $1.0 \leq HDI < 1.5$, $1.5 \leq HDI < \infty$, or $HDI = \infty$, respectively (Guo et al. 2017). HDI of a highway segment can be calculated using constraint (4.16) according to the damage states of bridges on the segment. In order to quantify the damage state of a bridge, the bridge damage index (BDI) is developed: $BDI = 0.10$ if a bridge is in slight damage; $BDI = 0.30$ if a bridge is in moderate damage; $BDI = 0.75$ if a bridge is in extensive damage; $BDI = 1.00$ if a bridge is in complete damage state (Chang et al. 2000). The HDI_i of a passable highway segment H_i that contains neither extensively damaged bridges nor completely damaged bridges is the square root of the squared sum of BDI_j^i of all bridges on H_i; otherwise, HDI_i is infinite if H_i contains bridges in either extensive damage or complete damage state (Guo et al. 2017). Constraint (4.17) determines if a highway segment is passable at time

t: H_i is passable on condition that its HDI_i^t is finite and none of these damaged bridges on the segment is under repair at time t; otherwise, H_i is impassable if HDI_i^t is infinite or at least one damaged bridge on the segment is under repair at time t. After obtaining TR_i and TR_i^t of each segment, T_{ij} and T_{ij}^t in Eq. (4.3) can be calculated using Dijkstra's algorithm (Hougardy 2010), which has been proved to be efficient in searching for the shortest paths between node pairs within a network. Finally, constraint (4.18) ensures the values of decision variables to be binary.

4.4 Solution Methodology

Scheduling problems are NP-hard problems (Yan et al. 2014; Balcik 2017), which means that optimally solving the proposed problem on a real highway network containing dozens or even hundreds of bridges within a limited time is unrealistic. Therefore, this chapter designs a heuristic algorithm that integrates a genetic algorithm (GA) with the Frank-Wolfe algorithm (Florian and Hearn 1995) for solving the UE to efficiently obtain a good solution for the proposed problem. In the GA, decision variables are encoded as chromosomes, indicating bridge restoration schedules. In this chapter, if the bridge restoration sequence α_{ijk} is known, the time to start the restoration of each bridge x_{jkt} can be calculated based on constraints (4.10) and (4.11). Therefore, only α_{ijk} is encoded in chromosomes to form candidate solutions, using the traditional encoding approach for scheduling problems (Zhang and Miller-Hooks 2015; Zhang et al. 2017). The damage states of bridges BDI_j^t at each time can be obtained according to these chromosomes, and thus, the rest time-dependent parameters at each time, including TR_i^t, f_i^t, c_i^t, v_i^t, HDI_i^t, p_i^t, and T_{ij}^t, can be calculated using constraints (4.13) to (4.17).

The framework of the solution methodology for the proposed mathematical model is illustrated in Figure 4.3. First, the initial population is formed by randomly generating a number of chromosomes. Then, the fitness values of these chromosomes, which are used for selecting elite chromosomes for genetic operations, are calculated following the steps in the shaded area in Figure 4.3: 1) calculate c_i^t, v_i^t, and p_i^t of each highway segment at each point in time t, and then assign traffic demands on the highway network using the Frank-Wolfe algorithm; 2) calculate the network functionality $F(t)$ from $t = 0$ to $t = T$; 3) calculate the fitness of a chromosome, i.e., the value of highway network resilience R, using Eq. (4.4). Elite chromosomes are selected from the population, based on chromosomes' fitness values, for crossover and mutation to generate new offspring. This chapter uses the roulette-wheel approach as the selection method, where chromosomes with high fitness values are associated with high probabilities of being selected (Goldberg 1989). The fitness values of the new offspring are calculated, and then the population is updated by deleting those chromosomes with low fitness values while keeping the population size fixed. Finally, the algorithm outputs the optimal bridge restoration sequence α_{ijk} and its corresponding R when meeting the stopping criterion, i.e., the number of generations.

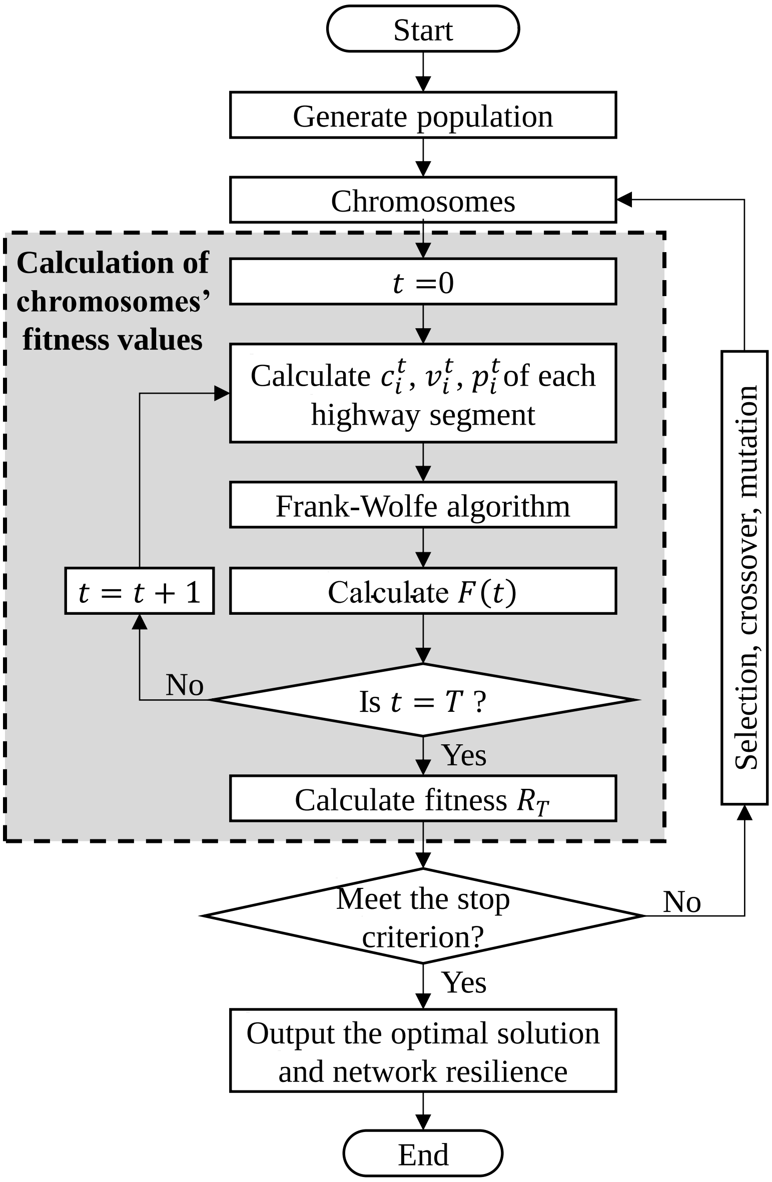


Figure 4.3 Workflow of the solution methodology

4.5 Case Study

4.5.1 Experimental Design and Parameter Setting

The proposed methodology was applied to a real highway network in Sichuan, China, which consists of 19 cities and 27 highway segments, using data from the 2008 Wenchuan Earthquake in China (Figure 4.4). Table 4.3 shows attributes of these highway segments, including their locations (N_i^c and N_j^c, indicating the two city nodes connected by a segment), lengths (l), design speed (v_0), and traffic capacity (c_0). The daily travel demand between city nodes under normal conditions is tabulated in Table 4.4. The earthquake occurred at $t_0 = 0$ and damaged 112 bridges in the highway network. The damage states of these bridges and their restoration time, which could be determined by taking into account bridges' types, sizes, and damage states (FEMA 2003), are listed in Table 4.5. Due to the lack of information about the number of work teams, this chapter assumes that ten restoration teams are available for the restoration of these bridges. The time horizon T was set as 1600 days (i.e., $T = 1600\ days$, and $t = \{0,1,2,\dots,1600\}$ with equal increments of one day) based on the results of preliminary experiments that the restoration of all damaged bridges in the highway network could be finished within 1600 days. Moreover, after extensive experiments for calibration, the parameters of the proposed GA that were found to be computationally efficient in solving the mathematical model were: a population size of 100, 20 elite chromosomes, 200 generations, a crossover probability of 0.8, a mutation probability of 0.2.

Next section solved the optimization for the proposed mathematical model. The highway network resilience values with and without considering the restoration-downtime impact were calculated, respectively, so as to validate the superiority of the proposed functionality recovery model in explicitly quantifying highway network resilience and in efficiently scheduling bridge restoration activities. Moreover, the sensitivity analysis on the impact of the number of restoration teams, considered as resource limitations, on the highway network resilience was also investigated. The algorithms were coded in MATLAB 2017a, and these codes were conducted on a desktop computer with an Intel® Core™ i7-7700 CPU (3.6GHz) with 32 GB RAM in the environment of Microsoft Windows 10.

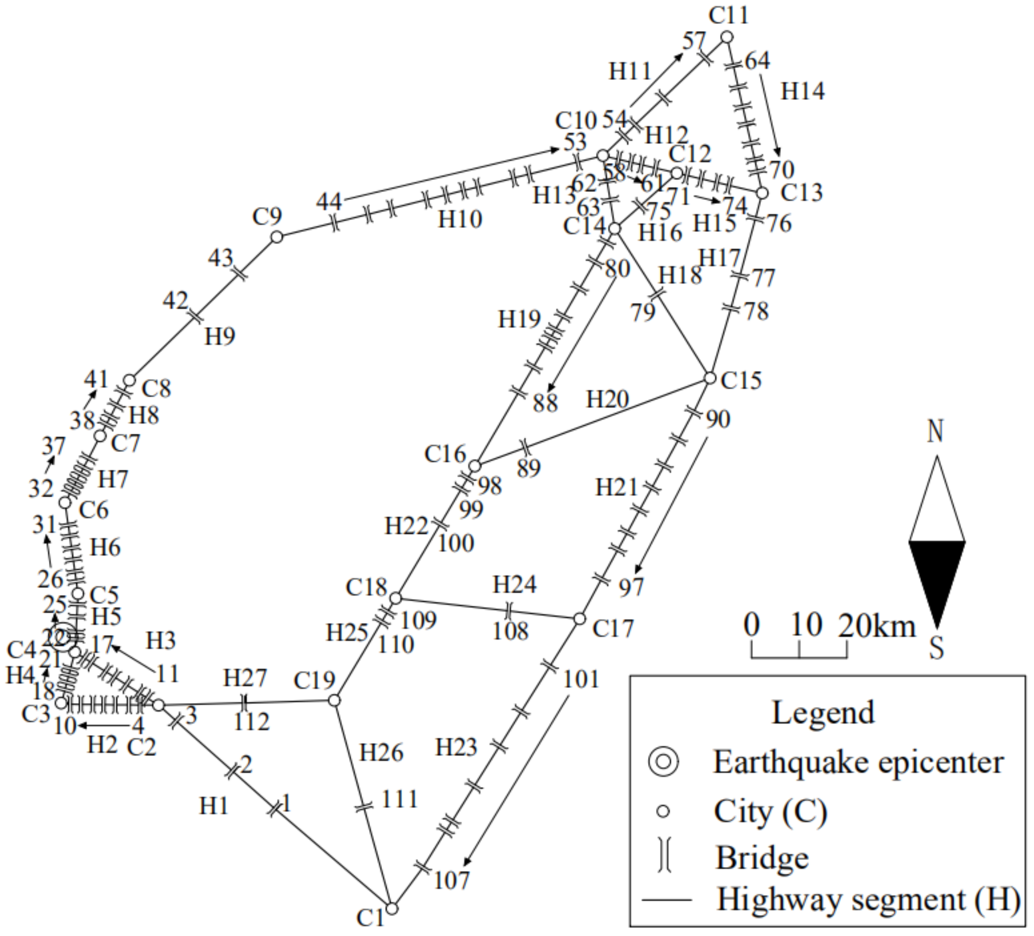


Figure 4.4 A highway network in Sichuan, China

Table 4.3 Attributes of highway segments

Highway segment H_i	N_i^c	N_j^c	l (km)	v_0 (km/hour)	c_0 (pcu/day)	Bridges on H_i
H1	C1	C2	60	80	115200	1-3
H2	C2	C3	27	30	16800	4-10
H3	C2	C4	23	80	115200	11-17
H4	C3	C4	13	40	26400	18-21
H5	C4	C5	12	40	26400	22-25
H6	C5	C6	27	30	16800	26-31
H7	C6	C7	20	30	16800	32-37
H8	C7	C8	21	40	24000	38-41
H9	C8	C9	51	40	24000	42-43
H10	C9	C10	90	40	24000	44-53
H11	C10	C11	24	40	26400	54-57
H12	C10	C12	30	40	26400	58-61
H13	C10	C14	19	40	24000	62-63
H14	C11	C13	49	40	24000	64-70
H15	C12	C13	24	30	16800	71-74
H16	C12	C14	25	40	24000	75
H17	C13	C15	45	30	16800	76-78
H18	C14	C15	53	30	16800	79
H19	C14	C16	61	40	24000	80-88
H20	C15	C16	68	30	16800	89

H21	C15	C17	68	30	16800	90-97
H22	C16	C18	31	40	24000	98-100
H23	C1	C17	48	80	115200	101-107
H24	C17	C18	27	40	24000	108
H25	C18	C19	38	80	115200	109-110
H26	C1	C19	48	80	115200	111
H27	C2	C19	73	40	26400	112

Table 4.4 Pre-earthquake travel demand between cities

City nodes (N_i^c N_j^c)	Travel demand (pcu/day)	City nodes (N_i^c N_j^c)	Travel demand (pcu/day)
C1, C2	2000	C7, C9	300
C1, C3	200	C8, C9	500
C1, C4	300	C9, C10	500
C1, C8	500	C10, C11	200
C1, C9	300	C10, C12	300
C1, C10	500	C10, C13	600
C1, C13	200	C10, C14	300
C1, C15	1500	C11, C13	500
C1, C16	1500	C12, C13	400
C1, C17	1200	C12, C14	300
C1, C18	1000	C13, C15	500

C1, C19	1800	C14, C15	500
C2, C3	400	C14, C16	400
C2, C4	500	C15, C16	800
C2, C5	300	C15, C17	1000
C2, C6	200	C16, C17	1400
C2, C7	200	C16, C18	800
C4, C5	200	C17, C18	2300
C5, C8	200	C18, C19	1800
C6, C8	200		

Table 4.5 Bridge damage states and long-term restoration time

Bridge N_i^b	Damage state	Restoration time (day)	Bridge ID	Damage state	Restoration time (day)
1	MD	45	57	MD	79
2	MD	149	58	ED	144
3	MD	168	59	CD	285
4	MD	198	60	CD	199
5	MD	50	61	ED	183
6	MD	187	62	ED	66
7	ED	121	63	MD	68
8	ED	101	64	MD	105
9	ED	79	65	ED	144
10	ED	226	66	ED	156

11	SD	41	67	MD	83
12	MD	133	68	MD	34
13	MD	190	69	MD	186
14	MD	54	70	MD	128
15	MD	173	71	MD	90
16	ED	209	72	MD	166
17	ED	187	73	MD	182
18	MD	192	74	MD	91
19	ED	200	75	MD	125
20	CD	215	76	MD	50
21	ED	110	77	ED	219
22	CD	195	78	SD	26
23	CD	100	79	MD	108
24	ED	114	80	MD	35
25	ED	208	81	ED	68
26	CD	164	82	ED	248
27	CD	163	83	SD	123
28	ED	232	84	ED	183
29	ED	247	85	ED	196
30	ED	205	86	ED	187
31	CD	102	87	ED	104
32	ED	141	88	MD	33
33	ED	63	89	MD	146
34	MD	75	90	SD	88

35	MD	93	91	SD	82
36	MD	96	92	SD	97
37	ED	149	93	MD	97
38	ED	244	94	SD	67
39	ED	111	95	SD	149
40	ED	182	96	MD	150
41	MD	106	97	SD	36
42	MD	150	98	MD	176
43	SD	65	99	MD	177
44	MD	67	100	MD	193
45	MD	122	101	SD	69
46	ED	232	102	MD	91
47	MD	21	103	SD	141
48	MD	180	104	SD	90
49	MD	49	105	MD	158
50	MD	68	106	MD	113
51	MD	115	107	MD	125
52	MD	120	108	MD	101
53	ED	65	109	MD	143
54	CD	153	110	MD	23
55	CD	294	111	MD	30
56	ED	95	112	MD	110

Note: SD = slight damage; MD = moderate damage; ED = extensive damage; CD = complete damage

4.5.2 Results and Discussion

4.5.2.1 The Impact of Restoration Downtime on Highway Network Resilience

The highway network functionality following the earthquake was 0.648, calculated using Eq. (4.3). The case study examined the impact of restoration downtime on the highway network resilience via two experiments, E1 and E2, where E1 adopted the proposed recovery model that took into consideration the restoration-downtime impact, while E2 used a traditional recovery model, i.e., the model in Figure 4.1(c), without considering the restoration-downtime impact. The maximum highway network resilience in 1600 days in E1 and E2 were 0.825 and 0.932, respectively, indicating that neglecting the restoration-downtime impact can lead to the overestimation of the optimal resilience value of the investigated highway network by 13.0%. Such overestimation resulted from the neglect of functionality drops during the restoration downtime of highways. As shown in Figure 4.5, curve 1 and curve 2 are the optimal functionality recovery paths generated in E1 and E2, respectively. As shown in Figure 4.5, when bridge restoration works began at $t = 0$, the highway network functionality in E1 (i.e., curve 1) sharply dropped from 0.648 to 0.536 because of the blockage of H1, H22, and H23 for the restoration of bridge B2, B3, B98, B103, B104, and B105 on these highway segments. Moreover, the blockage of H22, H23, and H25 for the restoration of bridge B90, B91, B102, B107, and B110 on them at around day 600 also led to a dramatic decrease in highway network functionality (Figure 4.5).

On the other hand, the network functionality in E2 (i.e., curve 2 in Figure 4.5) increased monotonically during the recovery process. Although all restoration works were finished in 1543 days in E2, the network functionality recovered to its pre-earthquake level at day 942 because the rest-unrestored damaged bridges were unlikely to impede the traffic function of the highway network. However, the restoration-downtime impact could lead to significant losses of functionality in the period from day 942 to day 1543, which was neglected in curve 2.

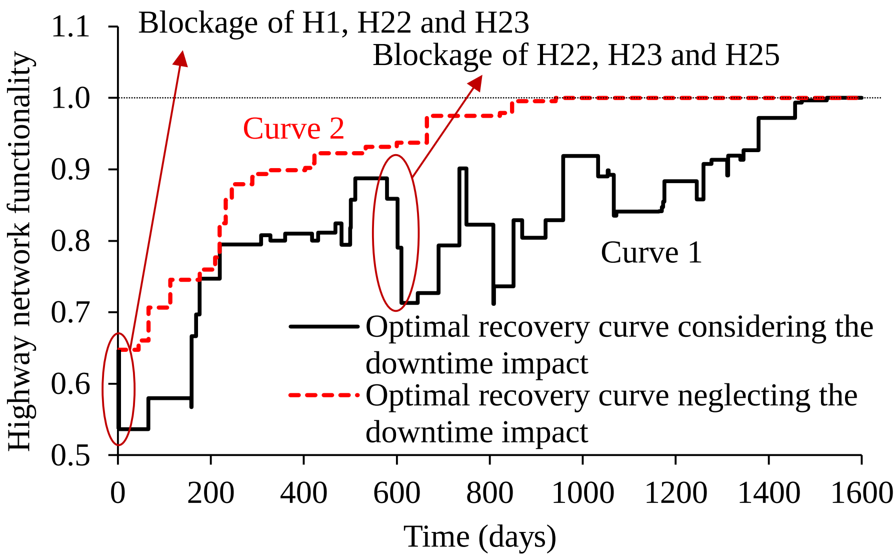
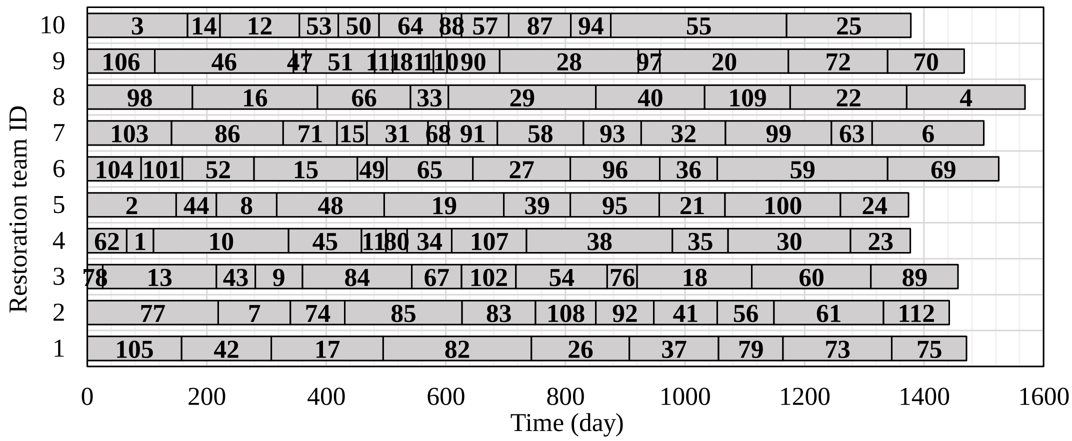


Figure 4.5 Optimal recovery paths of the highway network functionality

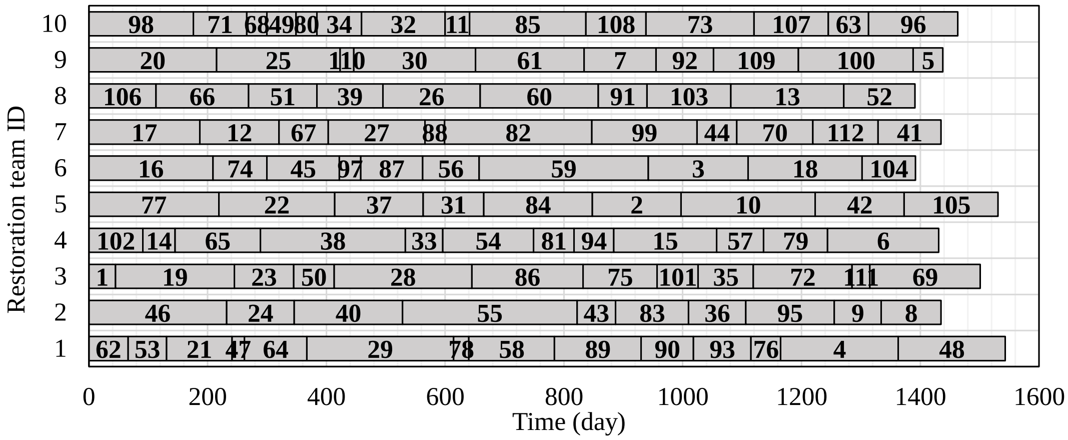
4.5.2.2 Optimal Restoration Schedules

Furthermore, traditional recovery models could result in inefficient restoration schedules due to significant restoration downtime of highway segments in these schedules. The optimal bridge restoration schedules with and without considering the restoration-downtime impact, namely schedule 1 and schedule 2, are shown in Figure 4.6. When adopting the proposed functionality recovery model, the highway network resilience under schedule 1 (i.e., 0.825) was 11.0% higher than the highway network resilience under schedule 2 (i.e., 0.734) because the restoration downtime of highway segments in schedule 1 is shorter than the downtime in schedule 2. This chapter takes the restoration of B1, B2, and B3 on H1 as an example to illustrate the advantage of the proposed functionality recovery model in reducing the restoration downtime of highway segments. As shown in schedule 1 (Figure 4.6(a)), the restoration downtime of H1 was 168 days, equal to the restoration time of B3 because B1 and B2 were restored during the restoration of B3. However, the restoration downtime of H1 in schedule 2 (Figure 4.6(b)) was 307 days, i.e., 139 days longer than the restoration downtime in Figure 4.6(a), because these three bridges were restored in different periods. Similarly, the restoration downtime of H23 in schedule 1 was 284 days, while the restoration downtime of the same highway segment in schedule 2 was 608 days. Accordingly, the proposed recovery model that takes into account the restoration-downtime impact on highway network functionality can enhance highway network resilience in terms of resourcefulness by identifying efficient bridge restoration schedules that could reduce the negative impact of restoration downtime on network functionality.

Moreover, the results also show that the traditional recovery model could also lead to the overestimation of highway network resilience for certain restoration schedules. The resilience values for schedule 1 and schedule 2 were calculated using the proposed recovery model and the traditional recovery model, respectively. As shown in Figure 4.7, the resilience values calculated using the traditional recovery model for these two schedules were respectively 7.2% and 27.0% higher than the resilience values calculated using the proposed model. The results also indicate that the impact of restoration downtime on network resilience in schedule 2 was more significant than the impact in schedule 1. Therefore, the impact of restoration downtime on highway network resilience can vary under different schedules.



(a) Schedule 1 (the optimal schedule considering the restoration-downtime impact)



(b) Schedule 2 (the optimal schedule without considering the restoration-downtime impact)

Note: The length of a bar indicates the duration of restoring a bridge, and integers on these bars are bridge IDs.

Figure 4.6 Optimal bridge restoration schedules

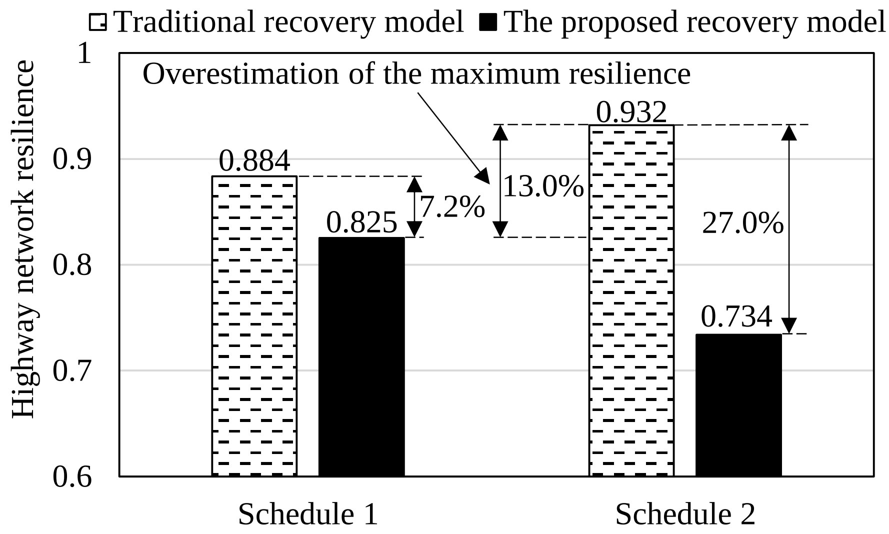


Figure 4.7 Highway network resilience under the optimal schedules calculated using different recovery models

4.5.2.3 Effect of the Number of Restoration Teams

Additionally, to assess the impact of the number of restoration teams, as the resource limitation, on the maximum highway network resilience, six more experiments with the number of restoration teams being 5, 15, 20, 30, 50, and 80, respectively, while keeping other parameters constant, were designed. The results are shown in Figure 4.8. First, if the number of restoration teams increased from five to 30, the maximum resilience value increased from 0.809 to 0.895, by 10.6%, and the total restoration time drastically decreased by 2520 days, from 3036 days to 516 days. This indicates that adding more restoration teams can significantly improve highway network resilience and decrease the total restoration time of the highway network. On the other hand, if the number of restoration teams exceeded a certain level, the marginal benefit of increasing restoration teams decreased rapidly. For example, further increase of the number of restoration teams from 30 to 80 only slightly improved the highway network resilience by 0.9%, from 0.895 to 0.903, and reduced the total restoration time by 222 days, from 516 days to 294 days. Therefore, insufficient resources can lead to the delay of the recovery of a highway network, while abundant resources result in the low efficiency of resource usage with a minor improvement on highway network resilience. The proposed study can be used to investigate resource assignment plans in actual restoration projects for highway networks and help decision-makers to achieve a certain level of highway network resilience with high resource usage efficiency.

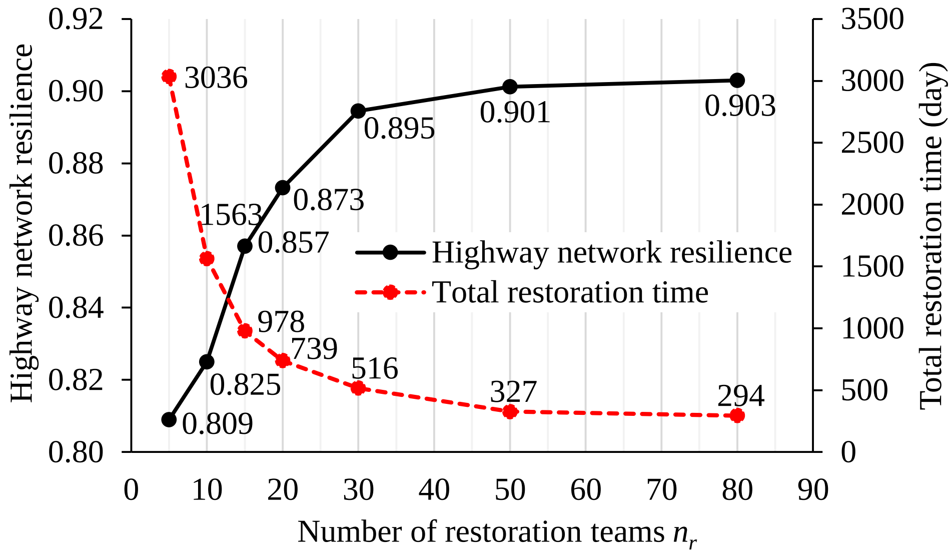


Figure 4.8 Impact of the number of restoration teams on highway network resilience

4.6 Conclusions

4.6.1 Research Findings

The present study optimized the long-term bridge restoration schedule in a post-earthquake highway network aiming at maximizing highway network resilience in the recovery phase. Specifically, the proposed functionality recovery model that took into account the impact of restoration downtime on highway network functionality could aid in the explicit appraisal of highway network resilience and obtaining efficient bridge restoration schedules with short restoration downtime of highways. An integer program for the bridge restoration-scheduling problem was developed, and recursive functions were employed in the integer program to capture the restoration-downtime impact on the highway network functionality. Moreover, a solution algorithm that integrated a genetic algorithm with the Frank-Wolfe algorithm for the assignment of traffic flow on the highway network was developed to solve the proposed mathematical model.

The proposed model was applied to a post-earthquake highway network in Sichuan, China, which consists of 19 cities, 27 highways, and 112 damaged bridges. The results show that neglecting the restoration-downtime impact on decreasing highway network functionality could lead to the overestimation of highway network resilience, while taking into account such an impact could enhance the resilience of a highway network in terms of resourcefulness by establishing efficient bridge restoration schedules that could reduce the negative impact of restoration downtime on highway network functionality. Moreover, insufficient restoration teams could delay the restoration of highway networks, while overmany restoration teams could lead to low efficiency of resource usage with only slight improvement on highway network resilience. Accordingly, involving a proper number of restoration teams in a restoration project can not only promote the rapid recovery of a highway network from disasters but also aids in the efficient use of resources.

4.6.2 Scientific and Practical Significance

The present study that initially examines the restoration-downtime impact on the quantification of highway network resilience and the optimization of bridge restoration schedules has both scientific and practical contributions. In theory, given that the widespread restoration downtime can significantly affect civil infrastructure systems' functionality, such as the power supply capacity of electric power systems, this chapter can serve as a basis for further research on developing practical and accurate functionality recovery models for these systems and thereby explicitly appraising their resilience. In terms of practical applications, the proposed mathematical tool can generate the optimal restoration schedule for bridges in a highway network and suggest decision-makers with the proper number of resources for the restoration works while avoiding overlong recovery time of the highway network and low efficiency of resources usage.

CHAPTER 5 CONCLUSIONS AND EXTENSIONS

5.1 Conclusions

Damaged bridges in post-earthquake highway networks can significantly delay emergency response and recovery activities by hindering the movement of people and goods on the network. Therefore, this thesis aims at promoting the efficient recovery of post-earthquake highway networks by developing mathematical models to optimize post-earthquake bridge restoration strategies. Three objectives have been proposed to accomplish this aim. The first objective is to understand the impact of inspection-restoration interactions on the optimal emergency bridge inspection routes and restoration schedules. The second objective is to dynamically update emergency bridge inspection routes and restoration schedules by accounting for the real-time bridge damage information revealed by inspection teams. The third objective is to investigate the impact of restoration downtime on highway network resilience and the optimal long-term restoration schedules. These objectives have been achieved by developing a set of mathematical models using the integer programming technique. Moreover, specific hybrid GAs have been designed to efficiently solve these models. The proposed mathematical models and solution methodologies were validated using highway networks in Sichuan, China, and data from the 2008 Wenchuan Earthquake. This thesis concluded with five key findings.

First, simultaneously performing emergency inspection and restoration activities could lead to significant improvement in highway network resilience, and inspection-restoration interactions could considerably increase the complexity of the emergency inspection routes and restoration schedules. Specifically, the waiting time of work teams resulting from the inspection-restoration interactions could be significant on condition that a highway network contained many impassable bridges.

Second, updating the emergency inspection routes and restoration schedules in real-time by taking into consideration the real-time bridge damage information obtained via inspection efforts could ensure the effectiveness and efficiency of emergency inspection and restoration activities, thereby achieving a high level of highway network resilience.

Third, taking into account the restoration-downtime impact on decreasing the highway network functionality could help to explicitly and practically appraise highway network resilience and thereby establish efficient long-term bridge restoration schedules with short restoration downtime of highways.

Fourth, the impacts of inspection and restoration capacities on highway network resilience in these problems were different. Specifically, the restoration capacity, rather than inspection capacity, could significantly affect highway network resilience in the static emergency inspection-routing and restoration-scheduling problem, while the inspection capacity could greatly affect the level of highway network resilience in the dynamic problem by affecting the speed of bridge damage information collection. Moreover, in the long-term restoration-scheduling problem, insufficient restoration teams could lead to the delay of restoration works, while a large number of restoration teams could decrease the efficiency of resource usage with only minor improvements on highway network resilience.

Fifth, the proposed hybrid GAs were efficient in solving these proposed problems and could generate better solutions with less computational time, comparing with traditional genetic algorithms.

5.2 Extensions

Though it is hoped that the present thesis will serve as a basis for further research on optimizing post-disaster management strategies for highway networks, it has some limitations that should be acknowledged, and extensions of this study are suggested to overcome these limitations.

First, this thesis optimized the emergency restoration schedules and the long-term restoration schedules independently and neglected the impact of emergency restoration activities on the conduction of long-term restoration activities. For example, some impassable bridges in extensive damage could become passable after emergency restoration, as explained in chapter 2 and chapter 3, whereas such bridges were still considered impassable when scheduling long-term bridge restoration activities in chapter 4. In practice, the functionality of a highway network can be partially recovered with the implementation of emergency restoration activities, and long-term restoration activities are conducted based on a partially restored highway network (Li et al. 2019). Neglecting the impact of emergency restoration efforts on networks' functionality in the long-term restoration scheduling method could lead to the waste of restoration resources and affect the appraisal of highway network resilience in the recovery phase. Accordingly, a more general long-term scheduling method that could take into consideration the impact of emergency restoration activities on the conduction of long-term restoration activities could be developed in the future.

Second, this thesis estimated bridge damage states using deterministic approaches; however, the use of a deterministic seismic damage assessment method in the dynamic scenario led to the misestimation of a quarter of these 48 bridges' damage states.

Therefore, probabilistic damage assessment methods could be conducted to address uncertainties associated with bridges' damage states. Given that Bayesian methods are able to continuously update the probability distributions of parameters with uncertainties as new information is available and have been used in real-time post-disaster damage assessment of infrastructure systems (Bensi et al. 2011; Bensi et al. 2013; Gehl et al. 2018), Bayesian methods could therefore be adopted to dynamically update the damage probability distributions of bridges on a highway network based on the evolving damage information of bridges, thereby aiding in the improvement of understanding of bridges' post-disaster damage states.

Third, this thesis assumed that bridges' actual damage states remained unchanged after an earthquake, and each bridge could only be inspected and restored at most one time in the emergency response phase; however, in real-world scenarios, aftershocks may significantly change the damage states of bridges – for example, the aftershocks in the Wenchuan Earthquake aggravated the damage states of a number of bridges (Zhuang and Chen 2012). Consequently, the bridges that have been inspected or restored require to be re-inspected and restored in the emergency response phase if an aftershock occurs. A dynamic model capable of handling the dynamism in terms of the changes of bridges' actual damage states resulted from aftershocks could be developed to broaden the scope of the application of the proposed dynamic mathematical model.

Fourth, this thesis assumed that emergency inspection could correctly obtain bridges' actual damage information; however, emergency inspections may yield inaccurate results if only cursory or visual inspection are performed (Bensi et al. 2011). The misinformation on bridges' damages could affect the efficiency of the proposed inspection-routing and restoration-scheduling methods. Therefore, a next step to support emergency bridge inspection and restoration operations through optimization could involve the study of the role of misinformation in solution performance and the required accuracy level of information.

Fifth, this thesis assumed that the inspection time and restoration time for a damaged bridge were deterministic, and the inspection and restoration of each damaged bridge could be finished on time. However, in actual conditions, inspection time and restoration time of bridges are likely to be uncertain due to various reasons, such as the change of work proficiency of laborers, the unpredictable weather conditions, the fluctuation of equipment and funds, etc. Consequently, uncertainties in these parameters could eventually lead to highway network resilience uncertain. Accordingly, the proposed deterministic models could be extended to probabilistic models to address uncertainties associated with inspection time and restoration time and to investigate the impacts of such uncertainties on the assessment of highway network resilience, as well as the optimization of inspection routes and restoration schedules.

Sixth, if uncertainties are considered in the future study, the proposed hybrid GAs for deterministic inspection routing and restoration scheduling problems may not be efficient to solve stochastic problem. Therefore, other solution methods for stochastic problems, such as the reinforcement learning technique, could be developed to solve the stochastic inspection routing and restoration scheduling problems, given that the reinforcement learning technique has been proven to be efficient in solving complex, large-scale, and stochastic problems.

Seventh, although this study focused on bridge damages, the proposed mathematical framework could be adapted to accommodate the analysis covering the damage of highways by using reinforcement learning technique to address the multiplied intensity of computation efforts due to a huge amount of damage information.

Eighth, although this thesis used travel time as the resilience measure to optimize emergency response and recovery strategies, a future study may develop other resilience measures for the optimization of pre-disaster mitigation strategies, such as reinforcement of bridges in the design stage. Specifically, resilience measures can be used to rank the highway segments in the network, and the highway segments with higher rankings play vital roles in supporting emergency response and recovery activities. Accordingly, the bridges on the highway segments with higher ranking should be designed with higher reliability so as to maintain the functionality of these highway segments after disasters.

Finally, this study assessed the damage of a bridge from the system-level; however, a more detailed bridge damage assessment method that can assess the damage state of each component of a bridge could be adopted to the proposed framework to promote the efficiency in properly selecting emergency restoration methods for each bridge.

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