Modeling Interaction of Emergency Inspection Routing and Restoration Scheduling for Post-disaster Resilience of Highway-Bridge Networks

Zhenyu Zhang[1]; Hsi-Hsien Wei[2]

Abstract

Post-disaster emergency restoration of damaged highway-bridge networks are crucial to those providing timely emergency assistance to disaster-damaged areas. Ideally, inspection routing and restoration scheduling should well complement each other, such that multiple inspection and restoration crews can operate simultaneously and optimally in the immediate aftermath of disaster events. Therefore, it is necessary to understand the interaction between inspection and restoration in post-disaster emergency-restoration process of highway-bridge networks, as well as such interaction's impacts on the inspection-routing, restoration-scheduling and overall process. This paper proposes an integer program for modeling such inspection-routing and restoration-scheduling problems, accounting for the inspection-restoration interactions, for determining the optimal inspection routes and restoration schedules for damaged highway-bridge networks, with the specific aim of maximizing the networks' travel time as their resilience metric. A hybrid genetic algorithm coupled with an early-termination test is also developed to improve the proposed integer program's computational efficiency. The results of a case study using the proposed method and data from China's 2008 Wenchuan earthquake show that, as compared to a traditional sequential inspection-restoration model, simultaneously and optimally performing inspection and restoration can significantly improve highway-bridge-network resilience.

Keywords: Disaster emergency recovery; Transportation restoration scheduling; Transportation network resilience; Seismic risk

[1] Ph.D. candidate, Department of Building and Real Estate, Hong Kong Polytechnic University ORCID (0000-0003-2167-3303)

[2] Assistant Professor, Department of Building and Real Estate, Hong Kong Polytechnic University (corresponding author); ORCID (0000-0002-7024-0726); hhwei@polyu.edu.hk

Introduction

Highway-bridge networks play a vital role in emergency response for disaster-damaged areas, as damaged networks can disrupt such response by impeding the transportation of rescue crews or humanitarian supplies among the areas that are meant to connect. Post-disaster emergency restoration-scheduling models aimed at maximizing such networks' resilience – specifically, their functionality for emergency-response activities – have been widely studied (Yan and Shih 2009; Miller-Hooks et al. 2012; Faturechi et al. 2014; Zhang and Miller-Hooks 2015; Li and Teo 2019; Liu et al. 2020). Though differing in various respects, the schedules generated by these studies have tended to assume that the actual state of disaster damage to transportation systems and their required restoration facilities are both fully understood in the immediate aftermath of disaster events. Such assumptions can have unfavorable consequences; however, insofar as emergency-restoration activities can be delayed by the weeks or months, it actually takes to inspect all affected bridges for the information of required restoration requirements to restoration crews within a disaster-hit highway-bridge network in real-world scenarios, especially if there is no effective strategy for inspection routing. Ideally, restoration and inspection can be performed simultaneously, with restoration commencing as soon as damage data and decisions about what restoration methods and facilities are required have been obtained via inspection to certain bridges; and such methods and facilities updated when and as further inspections yield new information after inspecting more bridges. This being the case, inspection routing can affect restoration scheduling, because restoring a bridge can only commence after it has been inspected. Conversely, restoration scheduling can also affect inspection routing, since a bridge under restoration will generally be impassable to inspectors' vehicles, among others. Nonetheless, the discussion of this inspection-restoration interaction is generally neglected in current methods for post-disaster emergency restoration scheduling problems, while systematic approaches to post-disaster inspection routing appear to be lacking altogether.

Post-disaster Restoration Scheduling and Inspection Routing for Transportation Systems

The aim of post-disaster scheduling of transportation system restoration is to rapidly recover the damaged systems' functionalities within a limited time. In the specific case of earthquakes, such scheduling can be divided into two general types: emergency (or short-term restoration), and long-term restoration. The former emphasizes the speedy, if partial recovery of damaged transportation systems, primarily in support of emergency-response actions such as rescuing victims from damaged properties, and often should be completed in several days; whereas the latter aims to fully restore the damaged transportation system to its pre-disaster condition, and thus can take months or years (O'Connor 2010; ODOT 2017). Though they differ in terms of their focal system functionalities (e.g., travel distance, traffic time, or accessibility), most long-term restoration studies have shared the general objective of returning the damaged systems' functionalities to their original levels (Bocchini and Frangopol 2012; Chang et al. 2012; Ye and Ukkusuri 2015; Zhang et al. 2017; Twumasi-Boakye and Sobanjo 2019; Liu et al. 2020).

Emergency restoration scheduling studies, on the other hand, have tended to focus on how best to meet victims' urgent needs, such as by maintaining the flow of essential supplies, or performing rescues and evacuations (Tzeng et al. 2007; Hackl et al. 2018); and when cities and transportation systems are severely damaged, such responses can only be achieved after damaged transportation systems have been restored. For example, Yan and Shih (2009) proposed an integer program to optimize the post-earthquake emergency restoration schedules for seriously damaged roadways that would otherwise significantly impede the efficiency of relief distribution, as well as the schedules for such distribution. With the intention of maximizing the traffic capacity of a coupled railway-roadway network during the emergency-response phase following a disaster, Miller-Hooks et al. (2012) proposed an optimization model for the selection of recovery activities, including the restoration of damaged infrastructure, the construction of temporary roadways, and the employment of particular traffic-management strategies. The same model also took account of resource constraints on recovery activities, including the availability of labor and funding. Similarly, with the aim of maximizing the traffic capacity of a rail-based freight-transportation system during emergency response, Zhang and Miller-Hooks (2015) optimized the schedules of emergency-recovery activities, taking resource limitations into consideration. Faturechi et al. (2014) proposed a model for maximizing the post-disaster takeoff and landing capacities of an airport's runway and taxiway network via the optimal allocation of limited emergency resources to response actions. Given that routes impassable to restoration crews may become passable after they are restored, whether fully or partially, Li and Teo (2019) focused on both emergency-restoration schedules and restoration crews' routes for supporting relief activities, including the evacuation of victims and delivery of supplies.

Though differing in various respects, the emergency-restoration scheduling generated in the above-cited studies has tended to proceed from an assumption that the actual state of disaster-related damage to transportation systems and the corresponding essential restoration activities are immediately and completely known, and that restoration commences straightaway after a disaster occurs. In reality, however, information about the damage states of a transportation network's numerous components and what will be required to repair them could only be obtained via a lengthy process of thorough inspection. For instance, the China Ministry of Transport's guidelines for post-earthquake highway bridge inspection allow seven days for the preliminary inspection of those old bridges that have a high possibility of having been severely affected, and one month for the thorough inspection of all bridges in the affected area (MTC 2013). Thus, emergency-recovery activities can be significantly delayed due to restoration not commencing until the actual levels and types of disaster damage to transportation systems and their corresponding restoration requirements are both fully understood – especially if there is no effective strategy for post-disaster inspection routing.

Although in real-world scenarios, inspection reveals a highway-bridge network's overall damage information only gradually, it is nevertheless reasonable to assume that restoration to a given component of the network can commence as soon as the damage information crucial to emergency-recovery activities is obtained via initial inspection. Therefore, assuming a clear division of labor between inspection and restoration crews, all emergency inspections after the first in a series can be performed simultaneously with restoration activities in two or more separate locations. In such a situation, however, interactions between inspection and restoration activities may impact the overall system-recovery process. Taking a highway-bridge network as example, inspection routing can affect restoration scheduling because restoration to a bridge can only be performed after it is inspected, while conversely, restoration scheduling can affect inspection routing because a bridge undergoing restoration will likely be impassable by inspection crews and an impassable bridge after restoration will become passable by inspection crews, thus leading to adjustments in their routes.

It should be borne in mind, however, that inspection crews' physical presence – i.e., generally, arrival at inspection sites in road vehicles – is considered a much more reliable approach than other bridge-damage detection methods that rely on high-resolution satellite imagery or unmanned aerial vehicles, either of which may become impracticable in bad weather (Vigo 2015). It is also noted that while some studies have looked at the optimization of road vehicle-based inspection routing as part of the routine maintenance of bridges within highway-bridge networks that are completely passable (Faber and Sorensen 2002; Yan et al. 2016), their models are not suitable to be directly applied to post-disaster emergency inspection-routing problems, which must account for impassability due to damaged bridges and blockages arising from the aforementioned restoration actions. Lam and Adey (2016) have taken into consideration the impact of inspection activities on the restoration time, assuming that inspection should be done prior to restoration of a bridge, to model the recovery time of a damaged roadway network, and their model has been further applied to assess the functional capacity losses of road networks exposed to time-varying multiple hazards (Lam et al. 2018; Lam et al. 2020). Although these studies have considered the one-way impact of inspection on restoration scheduling, as noted above, restoration scheduling can also conversely affect inspection routing, and a two-way inspection-restoration interaction should therefore be investigated.

Transportation Network Resilience

Resilience was originally defined as the ability of an ecosystem to absorb disturbance from the surrounding environment and still maintain an equilibrium state (Holling 1973).This concept has been extended to the field of infrastructure systems, where it is generally defined as the ability of a system to resist and absorb the impact from disasters (Bruneau et al. 2003) and several studies have been conducted using such definition for the assessment of resilience of transportation systems (Murray-Tuite 2006; Bocchini and Frangopol 2012; Levenberg et al. 2017; Calvert and Snelder 2018). In these studies, various system performance metrics have been used and system resilience can be measured as the temporal change in such performance during the post-disaster. In the quantification of the performance of infrastructure-systems in disaster events, Faturechi and Miller-Hooks (2015) thoroughly reviewed existing quantitative measures and grouped them into two categories: topological and functional. Topological measures, including systems' connectivity, centrality, and betweenness, emphasize the relative locations of nodes and links in a network and are commonly used in the optimization of pre-disaster network planning (Berche et al. 2009; Peeta et al. 2010; Ip and Wang 2011; Reggiani et al. 2015). Functional measures, on the other hand, focus on the inherent serviceability of transportation systems, including travel time, travel distance, traffic capacity, and accessibility, and are often used in the optimization of post-disaster recovery strategies (Vugrin et al. 2010; Frangopol and Bocchini 2011; Chang et al. 2012; Taylor 2012; Zhang and Miller-Hooks 2015). Among these, travel time is the most commonly used indicator in the emergency response phase because travel time is considered the most critical factor affecting the movement of emergency response activities on highway-bridge networks (Orabi et al. 2009). Therefore, the present study adopts travel time as its proxy for system functionality and uses the temporal change in such functionality during the disaster-response phase as its system-resilience metric.

To address the aforementioned gaps in existing post-disaster highway-network emergency restoration scheduling methods, the present study proposes an integer program with recursive functions for modeling post-earthquake emergency inspection-routing and restoration-scheduling problems for a highway-bridge network system, with the aim of maximizing that system's resilience, as measured in terms of its travel-time functionality. Unlike traditional emergency restoration scheduling models, which primarily focus on optimizing only restoration schedules, the proposed model is intended to reveal the impacts of the interaction between inspection and restoration on the overall inspection-routing and restoration-scheduling process, by assuming that multiple inspection and restoration crews can operate simultaneously. Additionally, this paper proposes a hybrid genetic algorithm (GA) that combines a heuristic approach with a traditional GA to improve the computational efficiency with which the proposed integer program can be solved efficiently to meet the special need for rapid decision-making in emergency response phase following disasters. Additionally, an early-termination test methodology is designed to resolve possible issues arising from the inspection-routing and restoration-scheduling problems. The proposed model will then be tested using data from the 2008 Wenchuan earthquake in China in three tests based on the same highway-bridge network and earthquake scenario, including a comparison of the network resilience resulted from the proposed inspection-routing and restoration-scheduling model and from a sequential inspection-routing and restoration-scheduling model, a sensitivity analysis of the impacts of the working time as well as the number of work crews on the network resilience, and a comparison of the computational efficiency and accuracy of the proposed early termination test and hybrid GA against a traditional GA without the proposed early termination test. It is hoped that the present research will serve as a basis for further studies of post-disaster emergency inspection-routing and restoration-scheduling problems, with a wider aim of providing support for decision-makers tasked with drafting post-earthquake emergency-response strategies for highway-bridge systems.

Problem Description

This section defines the proposed post-disaster emergency inspection-routing and restoration-scheduling problem for highway-bridge networks and next subsection describes the formulation of this problem by integer program. Firstly, losses need to be estimated by a rapid risk assessment immediately after earthquakes for practical decision-making purposes of emergency response. As such, such near-real-time loss estimation is generally done deterministically (McGuire 2001) and thus a deterministic method is used rather than probabilistic one for risk assessment of the highway-bridge systems in the present study. It is noted that the bridges' actual damage states are assumed to be the same as the estimated damage ones in the present study. Therefore, instead of damage types and levels, the purpose of inspection in the present study is mainly to virtually investigate bridges' actual required restoration activities, and to provide such information for restoration crews.

Also, given that, unlike long-term restoration for restoring all bridges to their pre-disaster conditions, emergency restoration in the present study intends to partially restore damaged bridges primarily in support of emergency-response actions, the present study assumes that only the bridges in moderate, extensive, or complete damage are deemed to be inspected and restored to the level of slight damage as suggested by Bocchini and Frangopol (2012) that slightly-damaged bridges tend to make minimal effect on the traffic function of highway segments, and therefore the bridges in no and slight damage will not be inspected and restored.

In the immediate aftermath of an earthquake, inspection crews start to leave from command centers for inspection and restoration works will leave from command centers and commence once information about required restoration activities of bridges has been collected by inspection crews. Inspection and restoration activities will be performed simultaneously on the network until reaching a given working time.

Network Definition

As shown in Fig. 1, a highway-bridge network system is abstracted as a network graph $G =$

(N, S), consisting of a number of nodes and highway segments, where $N = \{N_1^c, N_2^c, \dots, N_{n_c}^c, N_1^b, N_2^b \dots, N_{n_b}^b\}$ is the set of nodes, including n_c city nodes N_i^c and n_b bridge nodes N_i^b, and $S = \{S_1, S_2, \dots, S_{n_s}\}$ is the set of n_s highway segments S_i between adjacent city nodes, which may include a number of bridges. $l = \{l_1, l_2, \dots, l_{n_s}\}$ is the length of highway segments S; $v_0 = \{v_{0,1}, v_{0,2}, \dots, v_{0,n_s}\}$ is the design speed of S; $c_0 = \{c_{0,1}, c_{0,2}, \dots, c_{0,n_s}\}$ is the traffic capacity of S. Time is discretized into small increments of equal duration, i.e., $t = \{0,1,2, \dots, T\}$. The notation used within the mathematical formulation is listed in Table 1 and Table 2.

<Fig. 1.>

<Table 1.>

<Table 2.>

Seismic-risk Assessment for Highway-bridge Networks

According to the *HAZUS technical manual* (FEMA 2012), the conditional probability of a bridge being in, or exceeding, a particular bridge damage state given a certain intensity of ground motion can be estimated using the bridge's seismic-fragility curve, as shown in Eq. (1),

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

where d_s is the damage state of bridge, DS_k is the designated bridge damage state k, ranging from 1 to 4, representing slight, moderate, extensive, 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.

Following a seismic event characterized by a given ground-motion intensity IM, the probability of a bridge being damaged to each of the five levels can be calculated using Eq. (2),

$$\begin{cases} P(DS_0|IM) = 1 - P(d_s \geq DS_1|IM) \\ P(DS_1|IM) = P(d_s \geq DS_1|IM) - P(d_s \geq DS_2|IM) \\ P(DS_2|IM) = P(d_s \geq DS_2|IM) - P(d_s \geq DS_3|IM) \\ P(DS_3|IM) = P(d_s \geq DS_3|IM) - P(d_s \geq DS_4|IM) \\ P(DS_4|IM) = P(d_s \geq DS_4|IM) \end{cases} \quad (2)$$

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

To convert the probabilistic bridge damage states obtained from the bridges' fragility curves under a given seismic intensity to deterministic damage states, the present study adopts the bridge damage index (BDI) proposed by Dong et al. (2014), which built on the works of Chang et al. (2000) and Gordon et al. (2004). In Dong et al.'s study, the BDI of a bridge in an earthquake can be calculated by summing the product of the probability of all designated bridge's damage levels, as calculated using Eq. (2), and their corresponding BDI_k, expressed in Eq. (3),

$$BDI = \sum_{k=0}^{4} BDI_k \cdot P(DS_k|IM) \quad (3)$$

where BDI_0, BDI_1, BDI_2, BDI_3, BDI_4 are the BDI values corresponding to no, slight, moderate, extensive, and complete damage, and their values are 0, 0.1, 0.3, 0.75, and 1.0, respectively, as suggested by (Chang et al. 2000), in which the values of BDI_k for each of the five bridge damage states were estimated based on the statistical information of bridge damages in the 1994 Northridge Earthquake in the U.S.

Accordingly, a bridge's damage state can be determined by the bridge's BDI obtained by Eq. (3): 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, $0.85 < BDI \leq 1$. The ranges of BDI corresponding to each damage state were suggested by Gordon et al. (2004) based on the statistical data of bridge damages in the 1994 Northridge Earthquake in the U.S.

It is noted that the structure of a highway segment itself is assumed to not be subjected to damage, and the damage of the highway segment is caused and can be estimated by the damage of all bridges on that segment. In other words, bridges within the network are the only elements that can be affected by structural damage and can undergo inspection and repair interventions. As such, this study adopts the link damage index (LDI) proposed by Guo et al. (2017), in which links are equivalent to highway segments in the proposed study, to classify the damage state of highway segments, into one of five levels: no, slight, moderate, extensive, and complete damage. The LDI of a highway segment is determined by the BDI of all bridges along that segment, expressed in Eq. (4),

$$LDI = \begin{cases} \sqrt{\sum_{j=1}^{n} BDI_j^2} & \textit{All bridges on the segment are passable} \\ \infty & \textit{At least one bridge on the segment is impassable} \end{cases} \tag{4}$$

where n is the number of bridges on the highway segment, and BDI_j is the BDI of bridge N_j^b on that segment.

Adopting the same study of Guo et al. (2017), the damage state of a highway segment can then be determined according to the five damage states' corresponding ranges of LDI: no damage ($LDI < 0.5$), slight damage ($0.5 \leq LDI < 1$), moderate damage ($1 \leq LDI < 1.5$), extensive damage ($1.5 \leq LDI < \infty$), and complete damage ($LDI = \infty$). It is noted that Eq. (4) suggests that a highway segment is considered to be complete damage if it contains at least one impassable bridge. Specifically, bridges in extensive or complete damage are deemed to be impassable after earthquakes because such bridges are considered structurally unsafe (FEMA 2012).

Residual Travel Time of Highway-bridge Networks

The present study adopts travel time as the proxy for network functionality and uses the temporal change in such functionality during the disaster-response phase as network-resilience metric. The travel time on highway segment S_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. (5),

$$TR_i^t = \frac{l_i}{v_i^t} \times \left[1 + \alpha \left(\frac{f_i^t}{c_i^t}\right)^{\beta}\right] \tag{5}$$

where l_i is the length of highway segment S_i; v_i^t and c_i^t are the residual driving speed and traffic capacity of S_i at time t; f_i^t is the traffic flow on S_i at time t; the function parameters α and β are 0.15 and 4, respectively. Considering that the residual driving speed

v_i^t and traffic capacity c_i^t of a highway segment will reduce depending on the damage states of the highway segment (i.e., LDI), the present study adopts Guo et al.'s study (2017) for determining v_i^t and c_i^t of highway segments with no, slight, moderate, extensive, and complete damage, being $v_{0,i}$ and $c_{0,i}$, $0.75v_{0,i}$ and $c_{0,i}$, $0.5v_{0,i}$ and $0.75c_{0,i}$, $0.5v_{0,i}$ and $0.5c_{0,i}$, 0 and 0, respectively. Such suggestions on the values of v_i^t and c_i^t can be seen reasonable because they will decrease in line with damage states of the highway segments, as zero values of v_i^t and c_i^t of a highway segment in complete damage indicate that such a highway segment is impassable.

Moreover, the post-earthquake traffic flow distribution on a damaged highway-bridge network is assumed to be user equilibrium, where users choose routes so as to minimize their travel time, and the traffic flow f_i^t on each highway segment can be obtained 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.

Network Resilience

Adapting the transportation network-resilience qualification model proposed 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, the present study defines highway-bridge network resilience R_T as the ratio between the pre- and post-earthquake highway-bridge network functionality (i.e., travel time) at a given working time T, as expressed in Eq. (6):

$$R_T = \frac{1}{2n_P} \sum_{\forall i,j \in N^c, i \neq j} \frac{T_{ij}}{T_{ij}^T} \tag{6}$$

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).

Model Formulation

Model Assumptions

The present study has made several assumptions for the sake of easing the modeling of its focal problem.

(1) A number of cities are set as command centers, where decisions on emergency response are made, and work crews (i.e., inspection crews and restoration crews) depart.

(2) Work crews are assumed to work continuously during time period T and not run out of fuel, electricity, or restoration materials, or require any replacement equipment. Thus, they will not need to visit their own or any other command center for replenishment after their work has started. It is also assumed that restoration scheduling is non–preemptive (i.e., once a restoration crew has begun repair on a given bridge, it must complete its work before moving to another bridge.)

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

(4) The bridges undergoing restoration work will be blocked for repair, and thus they cannot be crossed by any work crew for the duration of that work. However, the bridges undergoing inspection work will not be blocked, and thus they can be crossed if they are not in extensive or complete damage.

Model Formulation

The proposed inspection-routing and restoration-scheduling problem can be formulated as (P): Eqs. (7)-(23)

$$\text{(P)}\ \max\ R_T \quad (7)$$

subject to

$$\sum_{\forall k \in \{1,2,\dots,n_I\}} \sum_{\forall t \in \{0,1,\dots,T\}} x_{jkt} \leq 1, \forall\, j \in N^b \quad (8)$$

$$\sum_{\forall k \in \{1,2,\dots,n_R\}} \sum_{\forall t \in \{0,1,\dots,T\}} y_{jkt} \leq 1, \forall\, j \in N^b \quad (9)$$

$$\sum_{\forall j \in N^b} x_{jkt} \leq 1, \forall\, k \in \{1,2,\dots,n_I\}, \forall\, t \in \{0,1,\dots,T\} \tag{10}$$

$$\sum_{\forall j \in N^b} y_{jkt} \leq 1, \forall\, k \in \{1,2,\dots,n_R\}, \forall\, t \in \{0,1,\dots,T\} \tag{11}$$

$$\sum_{\forall j \in N^b} \alpha_{ijk} \geq \sum_{\forall j \in N^b} \alpha_{i+1,jk}, \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_I\} \tag{12}$$

$$\sum_{\forall j \in N^b} \beta_{ijk} \geq \sum_{\forall j \in N^b} \beta_{i+1,jk}, \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{13}$$

$$\sum_{\forall t \in \{0,1,\dots,T\}} x_{jkt} = \sum_{\forall i \in \{1,2,\dots,n_b\}} \alpha_{ijk}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\} \tag{14}$$

$$\sum_{\forall t \in \{0,1,\dots,T\}} y_{jkt} = \sum_{\forall i \in \{1,2,\dots,n_b\}} \beta_{ijk}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\} \tag{15}$$

$$\sum_{\forall j \in N^b} \sum_{\forall t \in \{0,1,\dots,T\}} \alpha_{ijk} x_{jkt} t + \sum_{\forall j \in N^b} \alpha_{ijk} T_j^I + \sum_{\forall j \in N^b} \sum_{\forall p \in N^b} \sum_{\forall t \in \{0,1,\dots,T\}} \alpha_{ijk} \alpha_{i+1,pk} x_{pkt} \tau_{jp}^t \leq \sum_{\forall p \in N^b} \sum_{\forall t \in \{0,1,\dots,T\}} \alpha_{i+1,pk} x_{pkt} t, \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_I\} \tag{16}$$

$$\sum_{\forall j \in N^b} \sum_{\forall t \in \{0,1,\dots,T\}} \beta_{ijk} y_{jkt} t + \sum_{\forall j \in N^b} \beta_{ijk} T_j^R + \sum_{\forall j \in N^b} \sum_{\forall p \in N^b} \sum_{\forall t \in \{0,1,\dots,T\}} \beta_{ijk} \beta_{i+1,pk} y_{pkt} \tau_{jp}^t \leq \sum_{\forall p \in N^b} \sum_{\forall t \in \{0,1,\dots,T\}} \beta_{i+1,pk} y_{pkt} t, \forall\, i \in \{1,2,\dots,n_b-1\}, \forall\, k \in \{1,2,\dots,n_R\} \tag{17}$$

$$\sum_{\forall t \in \{0,1,\dots,T\}} x_{jkt} \left(t + T_j^I\right) \leq T, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\} \tag{18}$$

$$\sum_{\forall t \in \{0,1,\dots,T\}} y_{jkt} \left(t + T_j^R\right) \leq T, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\} \tag{19}$$

$$x_{jkt}, \alpha_{ijk} \in \{0,1\}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_I\}, \forall\, t \in \{0,1,\dots,T\}, \forall\, i \in \{1,2,\dots,n_b\} \tag{20}$$

$$y_{jkt}, \beta_{ijk} \in \{0,1\}, \forall\, j \in N^b, \forall\, k \in \{1,2,\dots,n_R\}, \forall\, t \in \{0,1,\dots,T\}, \forall\, i \in \{1,2,\dots,n_b\} \tag{21}$$

$$\sum_{\forall i \in \{1,2,\dots,n_b\}} \sum_{\forall k \in \{1,2,\dots,n_I\}} \alpha_{ijk} \geq \sum_{\forall i \in \{1,2,\dots,n_b\}} \sum_{\forall k \in \{1,2,\dots,n_R\}} \beta_{ijk}, \forall\, j \in N^b \tag{22}$$

$$\sum_{\forall i \in \{1,2,\dots,n_b\}} \sum_{\forall l \in \{1,2,\dots,n_R\}} \sum_{\forall k \in \{1,2,\dots,n_I\}} \sum_{\forall t \in \{0,1,\dots,T\}} \beta_{ijl} x_{jkt} t + \sum_{\forall i \in \{1,2,\dots,n_b\}} \sum_{\forall l \in \{1,2,\dots,n_R\}} \beta_{ijl} T_j^I \leq \sum_{\forall k \in \{1,2,\dots,n_R\}} \sum_{\forall t \in \{0,1,\dots,T\}} y_{jkt} t - \sum_{\forall i \in \{1,2,\dots,n_b-1\}} \sum_{\forall p \in N^b} \sum_{\forall k \in \{1,2,\dots,n_R\}} \sum_{\forall t \in \{0,1,\dots,T\}} \beta_{ipk} \beta_{i+1,jk} \tau_{pj}^t, \forall j \in N^b \tag{23}$$

The objective function (7) seeks the maximum resilience R_T that can be achieved within a given time period T. Constraints (8) and (9) ensure that no bridge is inspected or restored more than once. Constraints (10) and (11) ensure that a work crew can commence inspecting or restoring only one bridge at a time. Constraints (12) and (13) indicate the number of bridges that are inspected or restored by a work-crew; 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 crew k is i. Constraint (14) builds the relationship between non-independent decision variables x_{jkt} and α_{ijk}: specifically, if bridge N_j^b is inspected by inspection crew k, $\sum_{\forall t\in\{0,1,\dots,T\}}x_{jkt}=\sum_{\forall i\in\{1,2,\dots,n_b\}}\alpha_{ijk}=1$; otherwise, $\sum_{\forall t\in\{0,1,\dots,T\}}x_{jkt}=\sum_{\forall i\in\{1,2,\dots,n_b\}}\alpha_{ijk}=0$. Similarly, constraint (15) builds the relationship between decision variables y_{jkt} and β_{ijk}. Constraints (16) and (17) are recursive inequalities for establishing the relationship between the start times of two adjacent work tasks performed by the same work crew. For example, for an inspection crew 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 N_p^b and the travel time from N_p^b to N_q^b. Constraints (18) and (19) require that all inspection and restoration works are completed within T, and constraints (20) and (21) enforce binary-value requirements on the decision variables.

As a critical part of this paper's formulation of the interaction between inspection and restoration, constraints (22) and (23) ensure that bridges will be scheduled for restoration only after they have been inspected. Also, because the impacts of bridge-restoration work on subsequently used inspection routes and restoration schedules – i.e., the blocking and eventual unblocking of bridges – can lead to changes in between-bridge travel times, such impacts are captured via a recursive calculation of such travel times, τ_{ij}^t. Specifically, at time t' when a work crew completes the inspection or restoration of a bridge, changes will occur in the network-state-related parameters, which include the set of bridges that have been inspected, the bridge damage index $BDI_j^{t'}$, the link damage index $LDI_i^{t'}$, and the passability of highway segments $S_i^{t'}$. Such change, in turn, affects both $\tau_{ij}^{t'}$ and $TR_i^{t'}$ (Eqs. (4) to (5)). On the other hand, at time t, i.e., during a work crew's inspection or restoration of a bridge $(t\neq t')$, network-state-related parameters remain unchanged. Accordingly, these parameters must be recalculated recursively at each time t', hereafter referred to as the "identified time", to update $\tau_{ij}^{t'}$. The process of updating $\tau_{ij}^{t'}$ is shown in Fig. 2. First, at each identified time t', based on the $BDI_i^{t'}$ of highway bridges, the $LDI_i^{t'}$ of each highway segment is calculated to estimate the residual driving speed $v_i^{t'}$, traffic capacity $c_i^{t'}$, and traffic flow $f_i^{t'}$ of them (Eq. (4)). Next, based on $v_i^{t'}$, $c_i^{t'}$, $f_i^{t'}$, and the travel distance between adjacent nodes, the travel time between each pair of adjacent nodes is calculated using Eq. (5). Meanwhile, the bridges with extensive or complete damage or under restoration are labeled as impassable. Finally, the shortest travel time between bridges ($\tau_{ij}^{t'}$) can be calculated using Dijkstra's algorithm (Hougardy 2010). The proposed optimization model is summarized in Appendix 1.

<Fig. 2.>

Solution Methodology

Hybrid Genetic Algorithm

In the case of transportation systems, both vehicle-routing and restoration-scheduling problems are usually seen as NP-hard problems (Yan et al. 2014; Balcik 2017). The specific problems to be solved in the present study, which involve accounting for the simultaneous operation within such a network of multiple work crews of two types, are self-evidently more computationally complex than similar problems that involve only one type, and therefore it is impracticable to use traditional GA for achieving the optimal solution on a highway-bridge network consisting of a great number of nodes and links within the limited time. Therefore, this study proposes a hybrid GA to efficiently solve the proposed integer program. As shown in Fig. 3, first, a number of chromosomes, which consist of a set of decision variables and represent a solution for the proposed integer program, are randomly generated to form the initial population. Given that α_{ijk} and $x_{jkt'}$, β_{ijk} and $y_{jkt'}$ are non-independent decision variables, and $x_{jkt'}$ and $y_{jkt'}$ can be calculated using constraints (14) through (17) if α_{ijk} and β_{ijk} are known, a chromosome needs only to include α_{ijk} and β_{ijk} to form candidate routing and scheduling solutions. Additionally, the level of resilience that the network can reach at T via the implementation of such candidate routing and scheduling solutions can be calculated.

A set of chromosomes is then selected from among the initial population as "elite" chromosomes for crossover and mutation, using the roulette-wheel selection method, which has proved effective in selecting useful chromosomes in GA (Goldberg 1989). After applying the chromosome operations, including crossover and mutation, to these elite chromosomes, new offspring will be generated. Next, an early-termination test, a heuristic approach specially designed for the present study's proposed integer program, is applied to accelerate the evolution of chromosomes. Details of this test are provided in the next subsection. After its implementation, the fitness values of the offspring can be obtained, 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 and its corresponding solution.

<Fig. 3.>

Solution Encoding

A chromosome in a GA is considered as a feasible solution for the proposed integer program if it satisfies all constraints. An encoding scheme that allows feasible chromosomes to be created, and chromosomes to be updated while maintaining their feasibility, is critical to efficient computation. The proposed encoding scheme for this study's integer program is shown in Fig. 4. Each chromosome consists of two elements, with element one being the sequence of bridge inspection (i.e., α_{ijk}), and element two, the sequence of bridge restoration (i.e., β_{ijk}). Each element includes n_b genes and is further divided into n_I and n_R sub-elements, which respectively indicate work crews' inspection and restoration sequences. For example, as shown in Fig. 4, the genes on Sub-element$_{1,1}$ indicate the sequence of bridges to be inspected by inspection crew_1, and the genes on Sub-element$_{2,2}$ indicate the sequence of bridges to be restored by restoration crew_2.

<Fig. 4.>

Early-termination Test

The early-termination test is designed to solve possible situations in which all work crews terminate their inspection and restoration activities before reaching working time limitation T and can lead to the slow evolution of the population's fitness. The early-termination problem can result from the inspection-restoration interactions and the inaccessibility of bridges within highway-bridge networks. Specifically, inspection crews would stop working if bridges that they needed to inspect were inaccessible due to some impassable bridges, which are in extensive or complete damage, on the same highway segment that the inspection crews need to pass. Likewise, restoration crews would terminate their works if the bridges they needed to restore were impassable to them (i.e., bridges in extensive or complete damage). As illustrated in Fig. 5, this test begins with inputting a chromosome, whose first identified time t' is 0 when a disaster occurs and all work crews in command centers are ready for work. The following t' is calculated recursively by searching for the earliest end time of the current inspection and restoration works. At t', if the next bridge to be inspected by inspection crew k, e.g., bridge N_i^b, is accessible, the program can move to the next identified time; otherwise, if bridge N_i^b is inaccessible, the end time of ongoing work for inspection crew k is set as infinite, meaning that inspection crew k stays where it is after finishing its current inspection work. Similarly, if the next bridge to be restored by restoration crew k, e.g., bridge N_i^b, is not only accessible but also has been inspected at t', the program can move to the next identified time; otherwise, the end time of ongoing work for restoration crew k is set as infinite. The early-termination test continues until $t' \geq T$. If t' is infinite, early termination is enacted because work crews terminate inspection and restoration works before T is reached; otherwise, the chromosome is deemed normal. For a chromosome with the early-termination problem, the gene on each sub-element that leads to early termination is extracted and moved to the end of that sub-element, deprioritizing the inspection or restoration of the particular bridge associated with that gene (Fig. 6). 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.

<Fig. 5.>

<Fig. 6.>

Illustrative Case Study

A highway-bridge network including 25 cities, 37 highway segments, and 425 bridges in central Sichuan, China, was selected as a case study to illustrate the proposed methodology, as shown in Fig. 1 (it should be noted that only the 115 bridges with moderate, extensive, or complete damage are shown in the figure). The lengths, design speeds, and traffic capacity of this highway segments recorded in Zhuang and Chen's report conducted during the 2008 Wenchuan earthquake (Zhuang and Chen 2012) are shown in Appendix 2. However, due to the lack of real information about the location and number of command centers and work crews, we assumed that three command centers were located in City 1, City 19 and City 21; and that the total number of the inspection crews and restoration crews are six, respectively, in all command centers. The present study adopted 30 minutes as the inspection time for one bridge by one inspection crew as it is the average time spent in inspecting a damaged bridge in the highway system recorded in Zhuang and Chen's same report.

The 2008 Wenchuan earthquake that was selected as the disaster scenario had a magnitude of 8.0, and its peak ground-acceleration distribution data were adopted from (OSLR 2018). The bridges' damage states were accessed using Eq. (3), of which the bridge's fragility curves were adopted the ones developed by Chen et al. (2012) using the bridge damage data surveyed from the 2008 Wenchuan Earthquake (Appendix 3). The restoration time adopted in the present study for Chinese typical bridges can be found in the *Instruction for post-earthquake bridge emergency repair methods and technology* (WCTPMC 2010), which determines the restoration time by accounting for the bridge's type, size, damage state and the repair method to be employed and deemed to partially restore damaged bridges primarily in support of emergency-response actions (Appendix 4). For example, temporarily reinforcement of an extensively damaged girder bridge that contains columns with cracks and distortion using Fiber Reinforce Plastic material can be done in a few hours. The pre-earthquake travel demand between cities were used the data reported in Li et al.'s (2008) study (Appendix 5). The present study set post-earthquake travel demand as 12-time of the pre-earthquake ones based on the suggestion of the same study, which shows that the post-earthquake traffic flow in the emergency-response phase is approximately 12-time to the average daily traffic.

The present study calculated the network resilience and the corresponding optimal inspection route and restoration schedule for the first 72 hours working time after the earthquake occurs, as this time-window is considered the "golden hours" from the point of view of victims' survival (Verma and Chauhan 2015). Three additional tests were also performed, based on the same network and earthquake scenario. These were: 1) a comparison of the network resilience that resulted from the proposed inspection-routing and restoration-scheduling model and from a sequential inspection and restoration model; 2) a sensitivity analysis to investigate the impacts of the working time as well as the number of work crews, considered as resource limitations, on the network resilience; and 3) a comparison of the computational efficiency and accuracy of the proposed early termination test and hybrid GA against a traditional GA without the proposed early termination test. The parameters of the proposed hybrid GA that were found to result in optimal computational efficiency were found to be a population size of 200; 20 elite chromosomes; 200 generations; a crossover probability of 0.9; and a mutation probability of 0.3. The MATLAB 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.

Results and Discussion

The results of the seismic damage assessment show that 167 bridges deemed to have no damage, and 143, 70, 34, and 11 bridges with slight, moderate, extensive, and complete damage, respectively. As previously mentioned, only those bridges with moderate, extensive, or complete damage were deemed to be inspected and restored. As shown in Fig. 7, the network resilience calculated by Eq. (6) dropped to 0.119 in the immediate aftermath of the earthquake, indicating that the travel time of the damaged network was 8.4 times to the pre-earthquake network. It can also be observed that the network resilience returned to 0.537 after 72 hours of the occurrence of the earthquake. During the first 72 hours after the earthquake, 53 bridges were inspected, and 45 of them were restored.

<Fig. 7.>

The optimal inspection routes for each of six inspection crews and the optimal restoration schedules for each of six restoration crews are shown in Fig. 8. The results also show that the inspection-restoration interactions could significantly increase the complexity of inspection routes and restoration schedules, as well as the waiting time of work crews. The inspection and restoration of the bridges (B), B176, B180, B181 on the highway segment S20, and B198 on S22 shown in Fig. 1 are taken as an example to explain such interactions. B176 was in moderate damage, and B180, B181, and B198 were in extensive damage. As shown in Fig. 8(a), the inspection crew (I) 4 traveled from B230 to B180 for inspection. After I4 finished the inspection of B180, it immediately traveled to B176 for inspection, and restoration crew (R) 4 traveled to B180 for restoration after it restored B112 (Fig. 8(b)). After taking 30 minutes to finish the inspection of B176, I4 should have immediately departed to B181; however, the impassability due to extensively-damaged B180 had stopped I4 at B176 for 14.4 hours to wait for the completion of the restoration of B180 by R4. After B180 had become passable after the restoration, I4 departed from B176 to B181 by passing through B180 for inspection, and in the meantime, R4 waited for no time to depart from B180 to B176 for restoration. Similarly, after taking 30 minutes to finish the inspection of B181, I4 should have immediately departed to B198; however, the impassability due to extensively-damaged B181 had stopped I4 at B181 for 4.2 hours to wait for the completion of the restoration of B181 by R4. After B181 had become passable after the restoration by R4, I4 departed from B181 to B198 for inspection, and meanwhile, to restore B198, R4 waited at B181 for 4.2 hours for the completion of the inspection of B198 by I4. It can be observed that the waiting time of work crews due to the inspection-restoration interactions may become significant in the case of bridges in serious damage on the inspection and/or restoration routes.

<Fig. 8.>

Network resilience was also calculated from a sequential inspection and restoration model in which the restoration of bridges commenced after all accessible bridges had been inspected by one of these six inspection crews, where the optimal inspection routes were first obtained using the proposed hybrid GA with the objective of minimizing the inspection time and then the optimal restoration scheduling was also solved using the proposed hybrid GA, with the objective of maximizing the network resilience. As shown in Fig. 7, the result shows that it took about 36 hours for all accessible bridges to be inspected, and after the network resilience started to increase when the first bridge was restored at the 38-hour, the resilience finally reached to 0.324 at the 72-hour mark. This result indicates that network resilience can be 65.7% higher within the golden 72 hours if the proposed model rather than the general inspection and restoration model is used. Thus, it is safe to say that simultaneously performing inspection and restoration can significantly improve network resilience, as compared to commencing restoration only after all accessible bridges have been inspected.

Additionally, to explore the upper bound of network resilience in the proposed model, a test was conducted based on the assumption that complete information about all bridges' damage levels and required restoration methods and facilities were known immediately after the earthquake, and that only emergency restoration activities were performed (i.e., a "zero-time" assumption was made regarding inspection). Under such conditions, as shown in Fig. 7, network resilience was 0.641 at the 72-hour mark. Thus, the network resilience resulting from the proposed model, 0.537, was approximately 83.8% of the upper bound, and the proposed model can, therefore, tentatively be seen as an effective approach to inspection-routing and restoration-scheduling problems.

Additional runs were conducted to investigate the impact of the working time on the network resilience. As shown in Fig. 9, as the working time increasing from 24 hours (1 day) to 120 hours (5 days) with an increment of 24 hours, the network resilience increased from the value of 0.119 at the 0-hour mark to 0.327, 0.456, 0.537, 0.589, and 0.625 respectively. In other words, the network resilience is increased by 0.208, 0.337, 0.418, 0.470, and 0.506 at the end of Day one to five, respectively. This indicates that emergency inspection and restoration in the first 24 hours following an earthquake may play a disproportionate role in emergency response. One explanation of this result is that our model was able to prioritize the inspection and restoration of those bridges critical to network resilience in the working time limitation.

It can also be observed that even in the case of 120-hour working time, there was no bridge with complete damage that was restored, but only the ones with moderate or extensive damage were restored. Under such conditions, parts of the network remained disconnected and could not be reached during the first 120 hours after the earthquake. For example, C5 was disconnected and could not be reached due to completely-damaged bridges B63 on S7, and B73 and B74 on S8. This case is consistent with the actual situation as the Caopo city had been disconnected for 60 days from the highway-bridge network due to several completely-damaged bridges on the city's both two highway segments connecting to the main network after the Wenchuan Earthquake (OSLR 2018).

<Fig. 9.>

Sensitivity analysis of the impacts on network resilience of the numbers of work crews, considered as resource limitations, proceeded via two tests, as shown in Table 3. The impact of the number of inspection crews on network resilience was investigated in the first test, which included three scenarios: S1 (i.e., the scenario used in the aforementioned discussion) with a total of six inspection crews; S2, in which there were three; and S3, in which there were nine. In each of these three scenarios, the number of restoration crews remained unchanged at six. Comparison of network resilience at the 72-hour mark under all three scenarios showed that adding three inspection crews (i.e., S3 vs. S1) only increased such resilience by 1.1%, from 0.537 to 0.542; whereas network resilience was only decreased by 1.3%, from 0.537 to 0.530, if the number of inspection crews was decreased by three (i.e., S2 vs. S1) (Fig. 10). This indicates the relative unimportance to network resilience of the sheer number of inspection crews, as against restoration crews: a result that has important implications for decision-makers seeking to optimally allocate inspection crews to achieve specific network -resilience outcomes.

Test two also comprised three scenarios: S1 with a total of six restoration crews, S4 with three, and S5 with nine, in all of which the number of inspection crews was held steady at six. As compared to S1, network resilience at the 72-hour mark was higher by 12.0%, i.e., 0.537 vs. 0.602, when the number of restoration crews was increased by three (i.e., in S5); and it decreased by 26.9%, from 0.537 to 0.393, when the number of restoration crews was reduced by three (in S4) (Fig. 10). This further confirms that the key to sharp increases in resilience is restoration capacity rather than inspection capacity, and again has important implications for decision-makers.

<Table 3.>

<Fig. 10.>

Fig. 11 depicts network resilience at T of 72 hours along with numbers of generations, as per both the proposed hybrid GA and a traditional GA that does not incorporate the proposed heuristic approach. As this figure indicates, the maximum network resilience of 0.537 calculated by the proposed hybrid GA converges at 110 generations, as compared to a network resilience of 0.459 and around 160 generations in the case of the traditional GA. In other words, the proposed hybrid GA's performance is superior to traditional GA in terms of computational efficiency, i.e., 1.45 times faster, as well as providing a better solution to the problem.

<Fig. 11.>

Conclusion

Post-earthquake restoration scheduling for highway-bridge networks has generally not incorporated parallel scheduling or routing of inspections, but the results of the present study clearly demonstrate the benefits of doing so. To understand the impacts of inspection-restoration interactions on post-disaster emergency inspection and restoration prioritization problems, this paper has proposed an integer program for such problems by modeling such interactions in the case of earthquake-damaged bridges, with the aim of maximization of highway-network resilience. Additionally, it reported on the development of a hybrid GA that combines a traditional GA with a specially designed heuristic approach to improve the integer program's computational efficiency.

The proposed methodology was tested using detailed data about a highway-bridge network in central Sichuan, China, and the effects of the 2008 Wenchuan earthquake on it. By comparing the network resilience calculated via the proposed inspection-routing and restoration-scheduling model against that from a sequential inspection and restoration model in the present case study, it became clear that parallel inspection and restoration work led to significant improvement in network resilience, which increased by 65.7% at the 72-hour, as compared to a sequential schedule in which all inspections are carried out prior to any restorations. It can also be observed that the waiting time of work crews due to the inspection-restoration interactions may become significant in the case of bridges in serious damage on the inspection and/or restoration routes. Based on the results of sensitivity analysis of the impacts of the number of work crews on the network resilience, one can conclude that the number of restoration crews, as against inspection, is the key influence on increases or decreases in network resilience. Finally, the present case study shows that the proposed hybrid GA had 1.45-time faster computational efficiency than a traditional GA and also provided a better optimal solution.

Though it is hoped that the present study will serve as a basis for further research on post-disaster inspection routing and restoration scheduling for highway-bridge systems, it has some limitations that should be acknowledged. First, a deterministic optimization program was proposed in the present study; however, a stochastic program could be conducted to address the uncertainty associated with certain parameters (e.g., restoration time) in support of more comprehensive recovery decision-making purposes. Second, the bridges' actual damage states are assumed to be the same as the estimated damage ones in the present study; however, in real-world scenarios, the damage states may differ from the estimated ones, and thus a model capable of modifying the damage states in real time could be developed. Finally, given that the proposed hybrid GA may not be able to obtain a global optimum solution, and thus the deviation from the exact solution was unknown, more advanced solution methods that may lead to higher computational accuracy, such as penalty function approach, could be devised.

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Appendix

<Appendix 1.>

<Appendix 2.>

<Appendix 3.>

<Appendix 4.>

<Appendix 5.>

Data Availability Statement

Data of complete parameters of highway segments of this study are available from the corresponding author upon reasonable request.

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Table List

Table 1. Notation

Notations	
Sets	
N	set of network nodes, representing cities and bridges
S	set of highway segments
N^b	set of bridge nodes
N^c	set of city nodes
Parameters	
l_i	length of highway segment $S_i, \ \forall S_i \in S$
$v_{0,i}$	design speed of highway segment $S_i, \ \forall S_i \in S$
$c_{0,i}$	traffic capacity of highway segment $S_i, \ \forall S_i \in S$
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-bridge network system
n_c	number of cities in the highway-bridge network system
n_s	number of highway segments in the highway-bridge network system
n_I	number of inspection-crews in the highway-bridge network system
n_R	number of restoration-crews in the highway-bridge 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. 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, $\forall N_j^b \in N^b$, $\forall t \in \{0,1,\dots,T\}$
LDI_i^t	link damage index of highway segment S_i at time t, $\forall S_i \in S$, $\forall t \in \{0,1,\dots,T\}$
R_T	highway system resilience
S_i^t	passability of highway segment S_i at time t, $\forall S_i \in S$, $\forall t \in \{0,1,\dots,T\}$
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, $\forall S_i \in S$, $\forall t \in \{0,1,\dots,T\}$
c_i^t	residual traffic capacity of highway segment S_i at time t, $\forall S_i \in S$, $\forall t \in \{0,1,\dots,T\}$
v_i^t	residual driving speed on highway segment S_i at time t, $\forall S_i \in S$, $\forall t \in \{0,1,\dots,T\}$
f_i^t	traffic flow on highway segment S_i at time t, $\forall S_i \in S$, $\forall t \in \{0,1,\dots,T\}$
t'	identified time
τ_{ij}^t	the shortest travel time between bridge N_i^b and bridge N_j^b at time t, $\forall N_i^b, N_j^b \in N^b$, $\forall t \in \{0,1,\dots,T\}$

Table 3. Numbers and locations of work crews

Test	Command centers location	Number of inspection crews	Number of restoration crews	Inspection crew ID	Restoration crew ID
S1	City 1	3	3	1,2,3	1,2,3
	City 19	2	2	4,5	4,5
	City 21	1	1	6	6
S2	City 1	1	3	1	1,2,3
	City 19	1	2	2	4,5
	City 21	1	1	3	6
S3	City 1	3	3	1,2,3	1,2,3
	City 19	3	2	4,5,6	4,5
	City 21	3	1	7,8,9	6
S4	City 1	3	1	1,2,3	1
	City 19	2	1	4,5	2
	City 21	1	1	6	3
S5	City 1	3	3	1,2,3	1,2,3
	City 19	2	3	4,5	4,5,6
	City 21	1	3	6	7,8,9

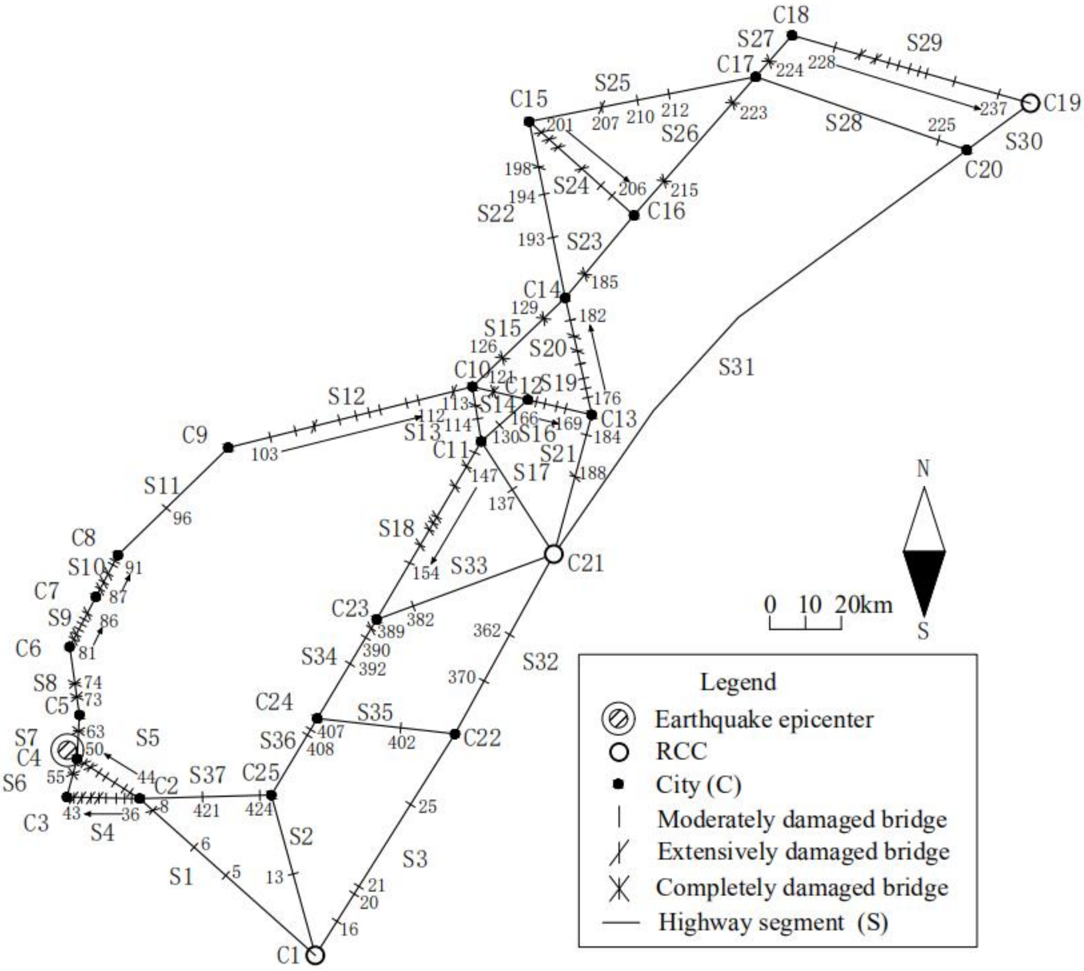


Fig. 1. The post-earthquake highway-bridge network system in central Sichuan, China

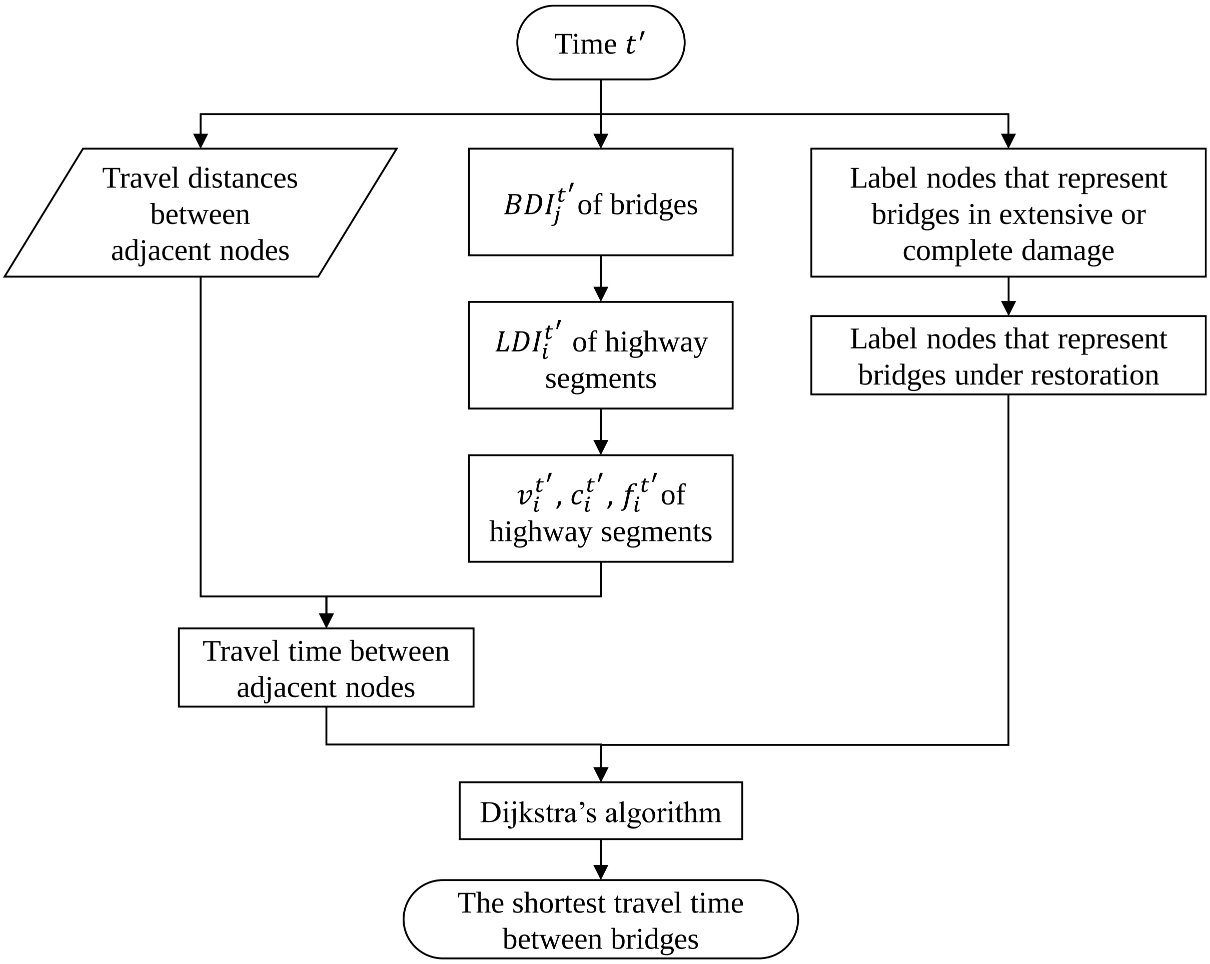


Fig. 2. Calculation of the shortest travel time between bridges

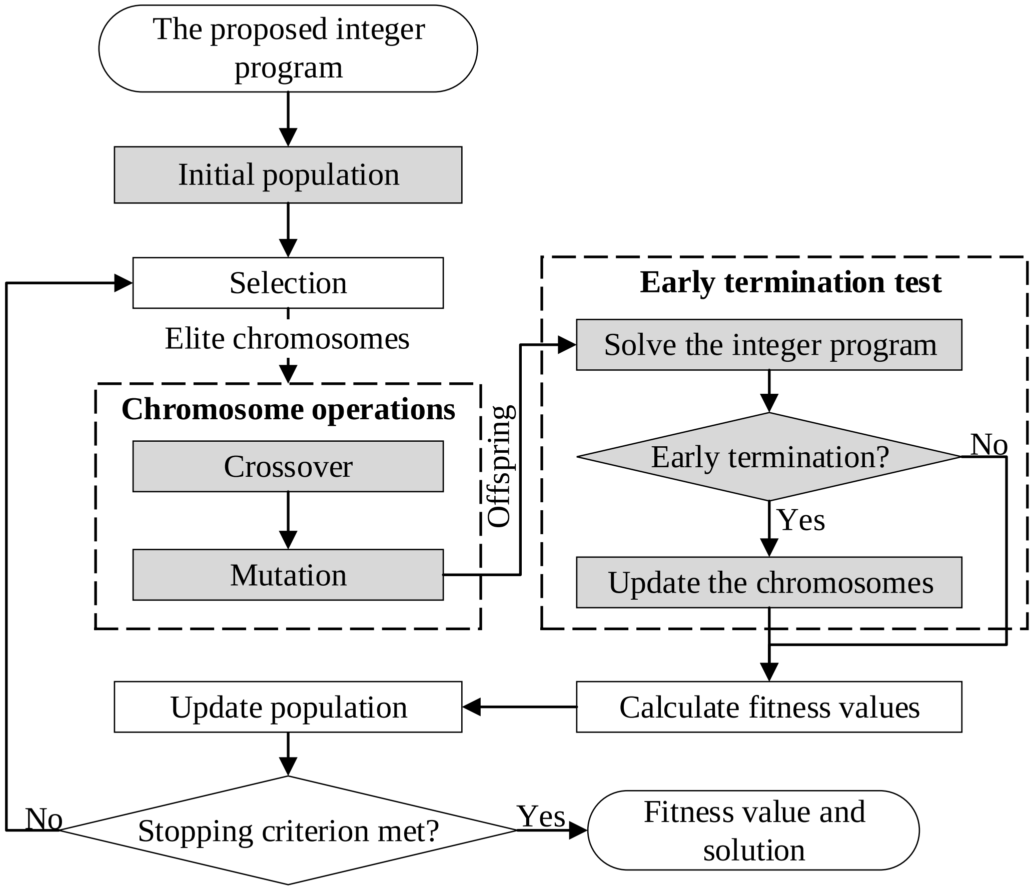


Fig. 3. Process of the proposed hybrid genetic algorithm

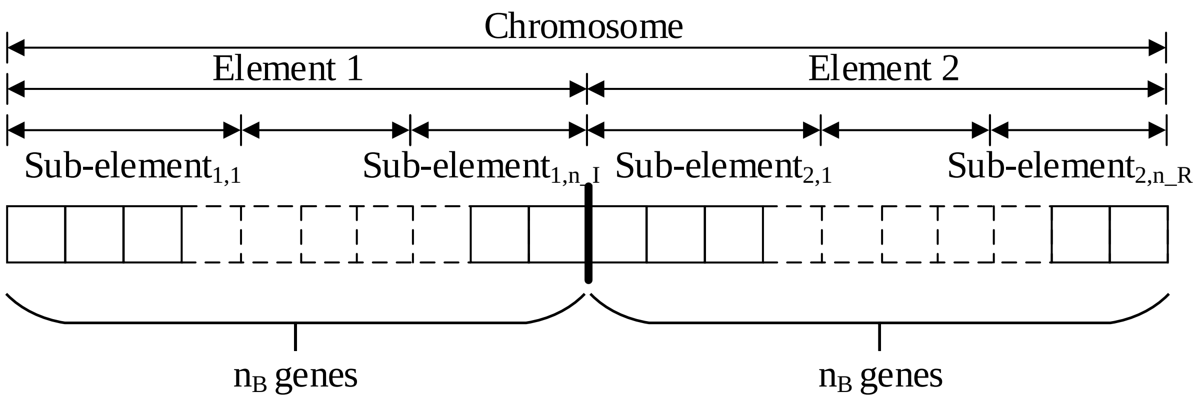


Fig. 4. Encoding scheme for a chromosome

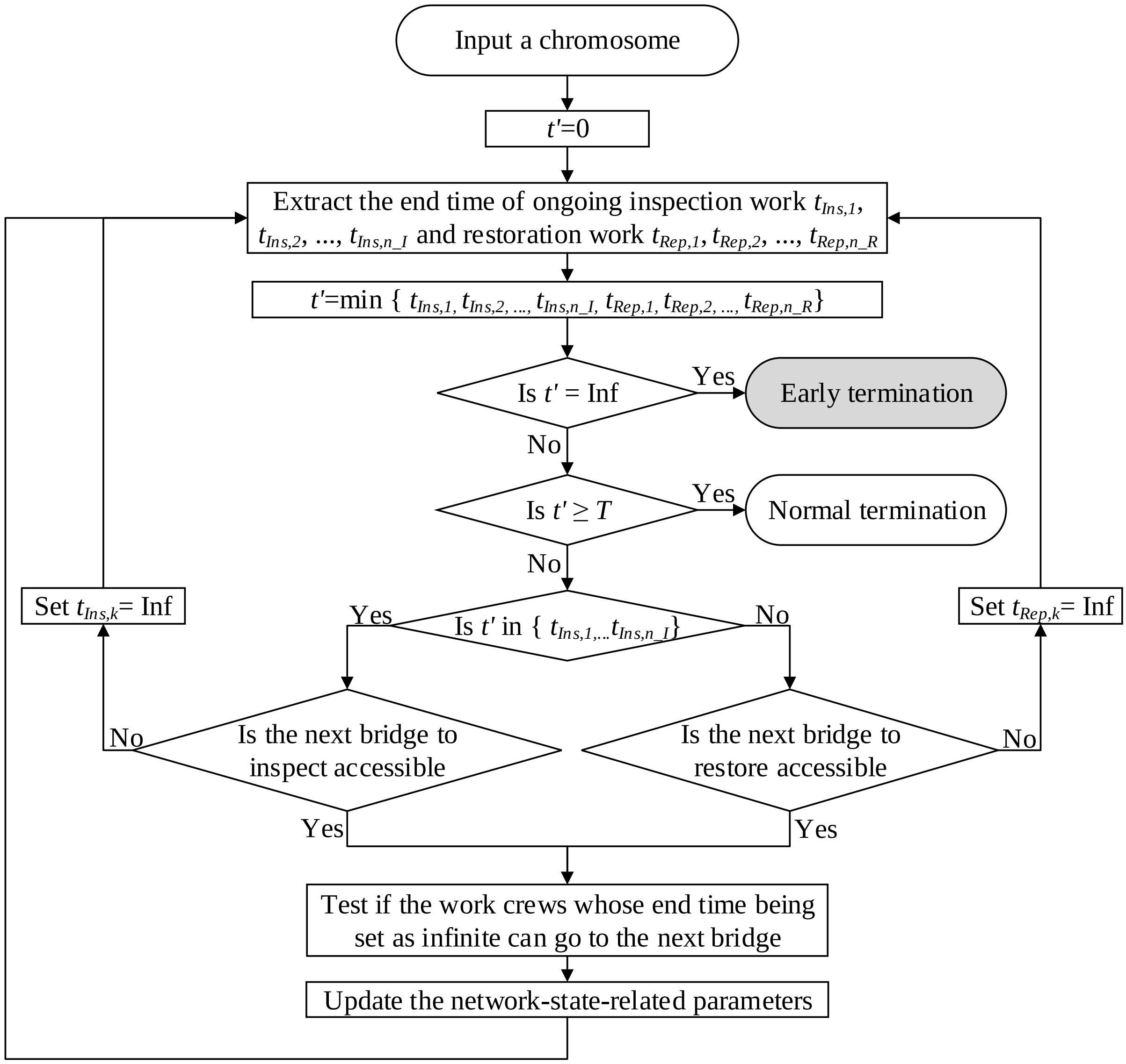


Fig. 5. Process of the early-termination test

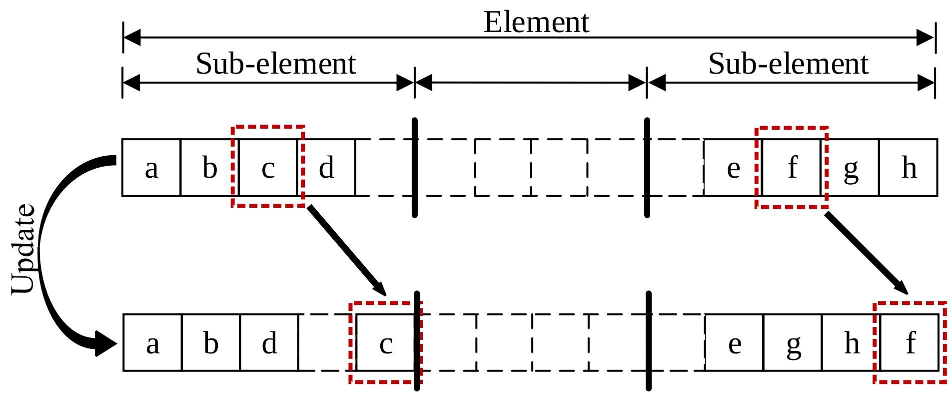


Fig. 6. Updating of a chromosome terminated early

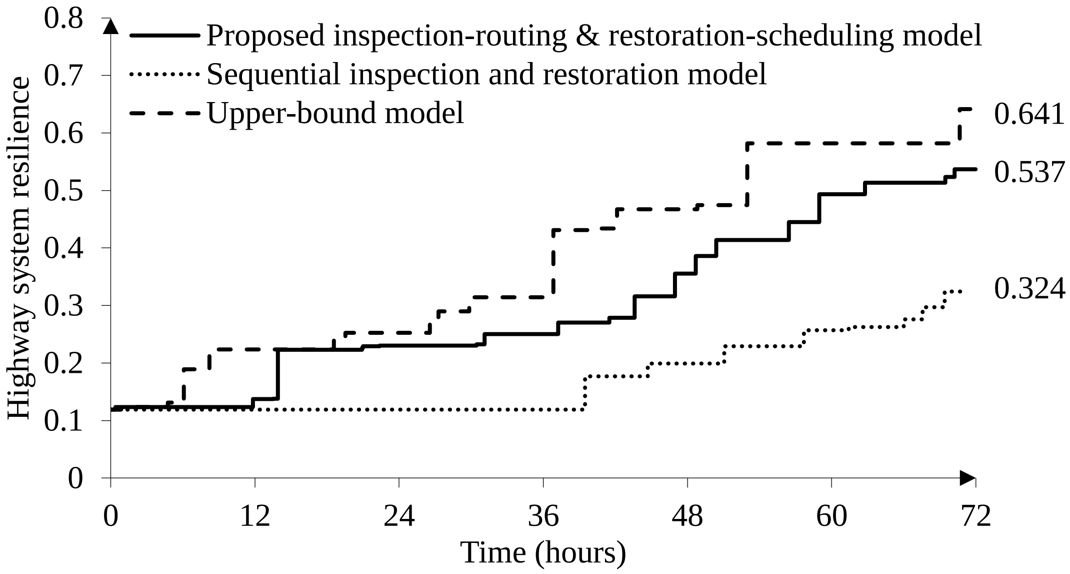
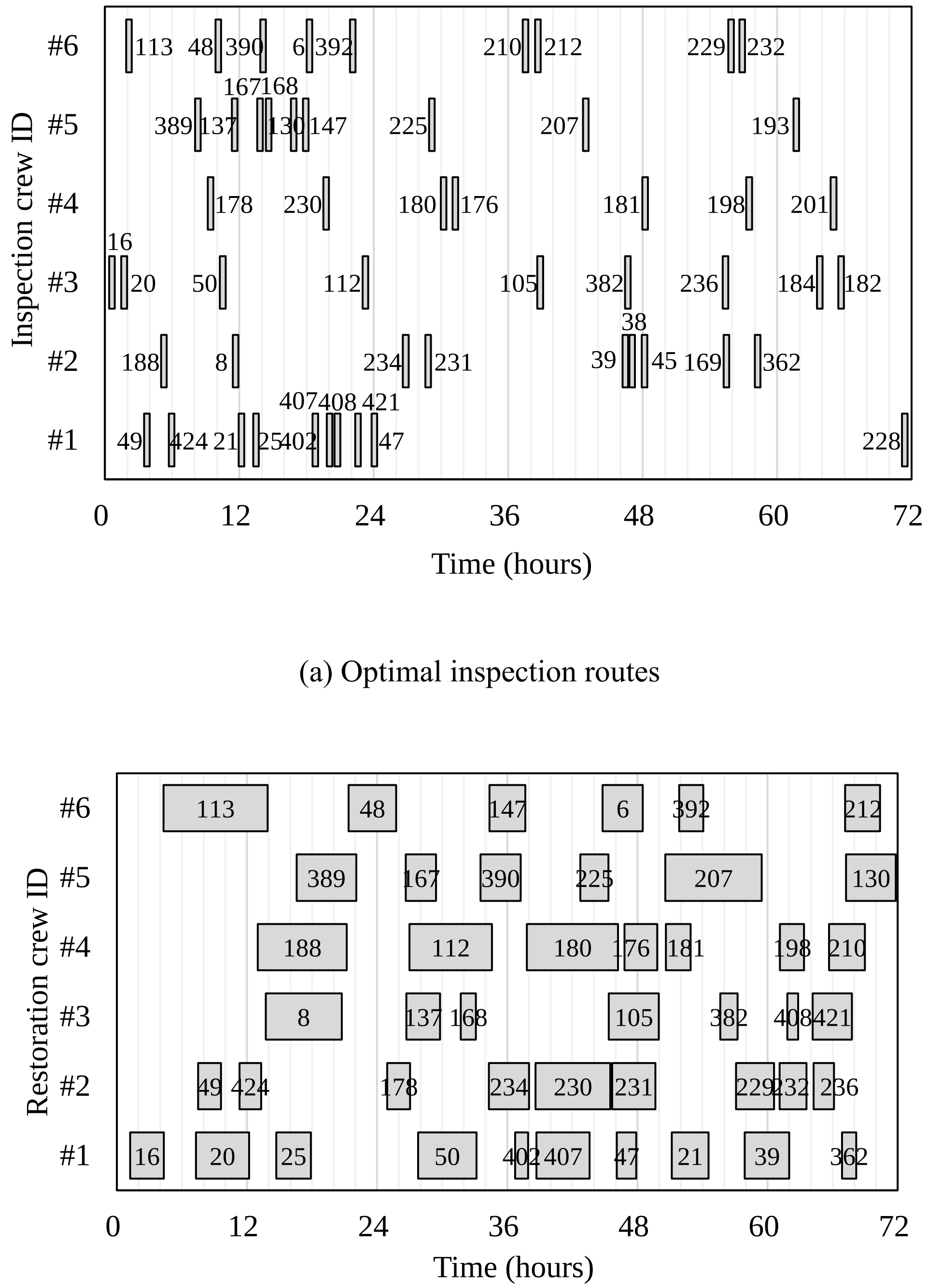


Fig. 7. The highway system resilience over time



(a) Optimal inspection routes

(b) Optimal restoration schedules

Fig. 8. Optimal results for inspection routes and restoration schedules (the numbers on the bars are bridge IDs, and the length of a bar represents the inspection/restoration time)

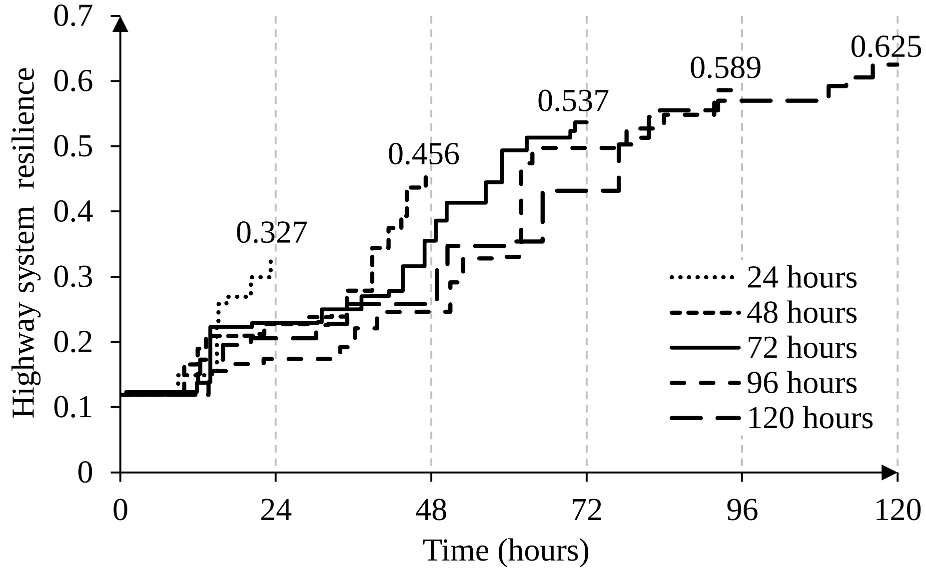


Fig. 9. The impact of working time on highway system resilience

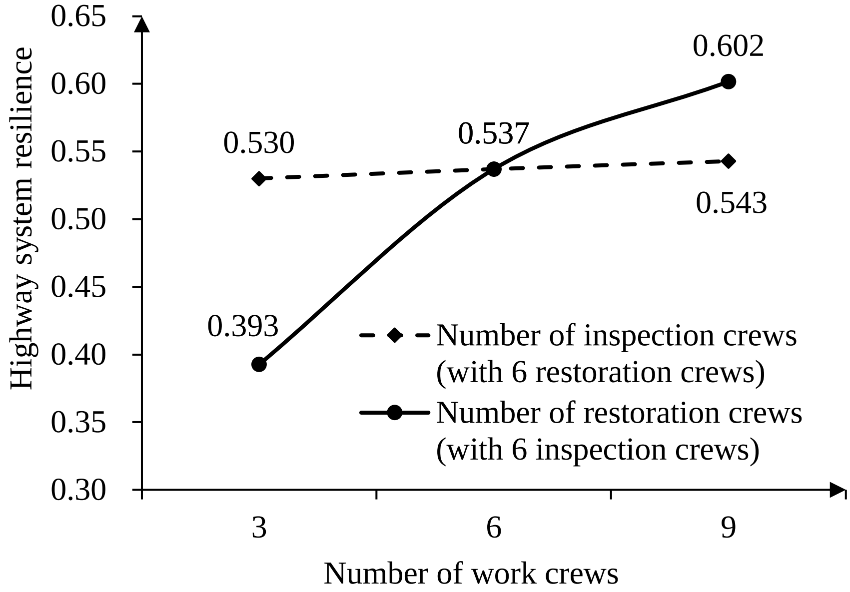


Fig. 10. The impact of the number of work crews on highway system resilience

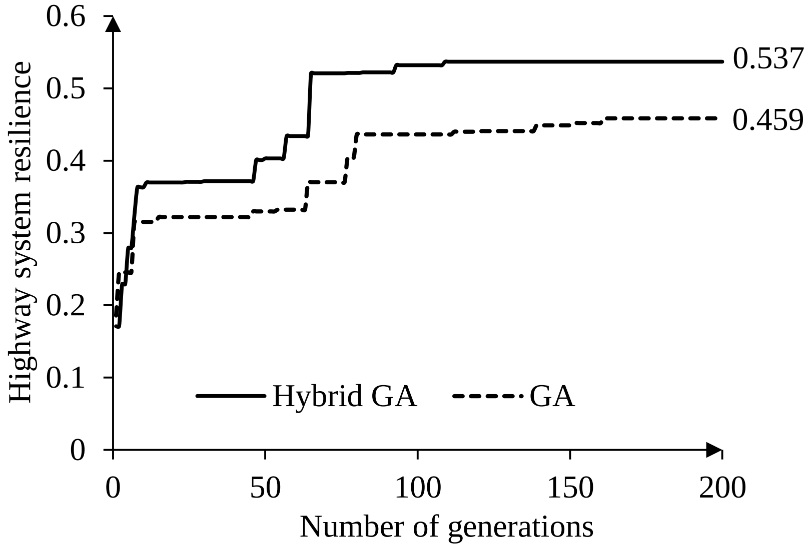


Fig. 11. Evolution of resilience values across generations

Figure Captions List

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Fig. 2. Calculation of the shortest travel time between bridge

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Fig. 6. Updating of a chromosome terminated early

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Fig. 9. The impact of working time on highway system resilience

Fig. 10. The impact of the number of work crews on highway system resilience

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