Pre-disaster investment model for strengthening the Chinese railway system under earthquakes

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ABSTRACT

Chinese railway system serves as an important role for the economy of China and the travel needs of its citizens. As China is subject to frequent earthquake events, it is important to investigate how to strengthen the railway system to retain its service after earthquakes. This paper proposes a comprehensive methodology to suggest the optimal investment plan using historical earthquake events data and GIS technology. The proposed optimization model minimizes the expected service loss under future earthquakes subject to an investment budget constraint. The expected service loss is constructed at the service layer of the Chinese railway system that is determined by the damage state of the railway link as well as the function restoration curve at the physical layer. Monte Carlo simulation and Genetic Algorithm are applied to solve the optimization model effectively. Numerical results show that the solution suggested by the proposed optimization model is more responsive to the earthquake impact on the railway system compared with plans suggested by topology-based methods. The proposed methodology can be extended to investigate the investment plans for other transportation systems under threats from natural disasters.
1. INTRODUCTION

Railway transport is one of the most important long-distance transportation modes in many countries. Any disruptions of a railway system caused by natural or man-made disasters can cause seriously economic loss and impair the transport capacity of these countries. Pre-disaster investment in strengthening railway system can mitigate the impact of the unpredictable disruptions and play an essential role in railway system protection. However, the budget for pre-disaster investment is limited. It is not affordable to strengthen the entire railway network, especially for large scale ones such as Chinese railway system (CRS), whose rail mileage is more than 100,000 KM (1). Thus, the challenge faced by decision-makers is how to strengthen a subset of the railway links through investment to retain the railway service after disasters, subject to the limited budget. In this study, we address this pre-disaster investment problem by developing an optimization model.

In the literature, several studies focus on how to enhance the survivability of railway components under earthquakes, such as railway tracks (2, 3) tunnels (4) and bridges (5, 6). These studies analyze the local impacts but ignore the overall railway system performance reduction which is an important measure in investment decision. To overcome this shortcoming, some studies adopt topological metrics in network science to assess the railway system performance at the system level, such as average shortest path length (7), network efficiency (8), size of the giant component and connectivity (9).

Other studies focus on identifying critical components of transportation systems based on network characteristics. Zhang et al. analyze the vulnerability of the high speed railway network in China (10) and the subway network in Shanghai (11) by using transport topological efficiency and connectivity to describe the railway network performance under random and intentional attacks. Liu and Huang adopt the size of giant component to assess system performance and analyze the effect on the security of transportation network of emergency logistics respectively caused by cut vertex attacks, cut edge attacks and avalanche attacks based on complex network theory (12). Ma et al. use degree, shortest path length and betweenness perform causation analysis of railway accident (13). Luo et al. propose an accident causation model based on network efficiency (14). These studies capture the topological characteristics of transportation systems, identify the critical system components, and provide suggestions on vulnerability mitigation strategies from network topology aspects. However, they have four weaknesses in analyzing real transportation systems under natural disasters. First, traffic flow is a key factor to measure transportation system performance and the train flow model is better than the pure
topological models in railway system performance assessment under disasters \(15\). Second, the attack modes based on network topology, such as random attack or critical component attack, cannot capture the characteristics of natural disasters properly, which affect the performance of system components. Third, the damage level of affected system components could vary with probabilities under different natural disaster events, which are simplified as component failure in topology-based models \(7\). Fourth, as railway links usually are widely distributed in a large-scale area with different geographical situations, the geographical information should be considered in system performance assessment \(16\). Chang and Nojima analyze the post-disaster performance of the railway system and highway system under earthquake scenarios in Kobe, Japan and the system performance is evaluated in terms of the distance-based accessibility \(17\). Liu et al. discuss the vulnerability assessment and mitigation of Chinese railway system under floods \(18\). However, these studies do not consider how the pre-disaster investment budget affects the railway system maintenance strategies. To the best of the authors’ knowledge, there is little work on system level pre-disaster investment analysis of railway systems under earthquakes considering the investment budget, especially related to using of real data to study the investment over railway links on a large geographical area.

Although there is little work on pre-disaster analysis of railway systems under earthquakes, there exist several network-based system-level studies on risk analysis of road systems under earthquakes \(19, 20, 21\). Peeta et al. propose a method to decide pre-disaster investment plans for strengthening the highway network under earthquake disasters \(22\). In their work, the system performance is measured by the post-disaster connectivity and traversal costs between the origin and destination under random failure of bridges caused by earthquake. Dong et al. propose a framework for the time-variant sustainability and risk assessment of highway bridges \(23\). The sustainability of the network is quantified in terms of its social, environmental, and economic metrics and the performance of network links is quantified based on individual bridge performance evaluated through fragility analyses. Chen et al. apply finite element model to analyze seismic response of railway bridge system \(24\). Though these studies improve the understanding of pre-disaster investment strategies for highway systems, they cannot be directly applied to railway systems. First, in these studies, links with bridges or tunnels are assumed as the attack objects under earthquake. This may be appropriate for highway systems, because bridges and tunnels are more vulnerable and difficult to recover compared with other types of roads. However, the failure of railway links is more sensitive to the terrain and geological conditions under earthquakes. Second, none of these studies discuss the traffic flow affected by earthquake disasters, which is an important metric to assess the overall system performance. Last, many of
previous studies apply a small region of earthquake scenarios to assess the damage of railway system (25). This is not suitable for large-scale and long-term pre-disaster investment decision that requires a comprehensive assessment of the uncertain occurrence of earthquakes.

To identify the optimal pre-disaster investment plan to strengthen railway system under earthquake, the post-disaster railway system performance under different plans should be addressed and the performance assessment method should contain two main components: the earthquake occurrence model and the railway damage model under earthquake. Probabilistic Seismic Hazard Analysis (PSHA) is a widely used method in earthquake hazard analysis (26) to estimate the site impact by one or more faults. However, it is difficult to apply PSHA to railway systems as the links are widely spread. Monte–Carlo simulation, also known as stochastic modeling, appears to be common in practical analyses (27), in which future earthquake scenarios can be predicted based on historical earthquake data. Based on the predicted scenarios, the expected long-term benefit of pre-disaster investment plans can be estimated. In this paper, Monte-Carlo simulation is adopted as the earthquake occurrence model.

In this study, the proposed methodology advances the research on the pre-disaster investment for railway systems under earthquake in five aspects: (1) To better assess the performance of railway system, a two-layer network representation, including physical layer and service layer, is adopted to model the railway system. The physical layer, consisting of railway tracks and stations, is used to analyze the physical damage of railway components under earthquakes from the engineering point of view; while the service layer, consisting of trains and stops, is used to assess the railway system performance from the perspective of passengers. (2) To assess the effectiveness of pre-disaster investment decisions in a long term, earthquake scenarios are generated based on historical earthquake events data. Geographic Information System (GIS) software is used to analyze historical earthquake events data and predict earthquake scenarios including earthquake location, magnitude and occurrence probability. (3) To assess the damage level of railway links at physical layer, geographical information on railway components is considered in the proposed methodology. The distance between system components and earthquake source is used to estimate the damage state of physical railway systems. (4) The railway component damage model is constructed to decide the damage level of railway links under earthquake. In this study, a railway link is divided into small segments and the probability of each segment damage level is calculated to decide the damage state of the whole link. (5) In the proposed pre-disaster investment model, the system service loss is related to the service recovery duration that is determined by the damage level of railway links.
The remainder of the article is organized as follows. Section 2 introduces the methodology to identify a pre-disaster investment plan for strengthening railway system under earthquake. Section 3 applies the proposed methodology to the pre-disaster investment problem for the Chinese railway system and compares the optimal investment plan with other solutions to investigate the effectiveness of the proposed methodology. Section 4 concludes this study and provides potential directions for future research.

2. METHODOLOGY

This paper seeks to identify the optimal investment plan for a railway system to resist earthquake hazards through developing an optimization model to minimize the expected service loss of the railway system. The expected system service loss is assessed at the service layer, which is determined by the damage model constructed at the physical layer of the railway system. The following sections present the graph representation of the railway system, the earthquake damage model, the optimization model, the earthquake scenario generation model, and the solution method to determine the optimal pre-disaster investment plan.

2.1 Network representation of railway system

A railway system can be modeled as two layers, a physical layer and a service layer (28). In the physical layer, railway stations are represented as nodes while railway tracks between stations are represented as links. Without loss of generality, when more than one railway tracks connect two stations, only one link is used to represent these tracks in the physical layer. Differing from the physical layer, links in the service layer represent the train services between stations. If two stations are served by a train without stops in between, there is a link connecting these two stations in the service layer. The physical layer contains the physical topology information (railway stations and tracks) on railway system, while the service layer contains information on how trains serve passengers.

The two-layer network representation is more suitable and flexible in analyzing railway system performance under hazards. The system performance in terms of train service can be quantified at the service layer from passengers’ perspective, while detailed damage information on railway tracks under hazards is assessed at the physical layer. The detail information on the physical layer and the service layer of CRS can be found in the handbook “Chinese railway passenger train handbook” (25), which contains 3,920 passenger trains connecting 2,940 railway stations. The corresponding physical and service layers of the CRS network are shown in Fig 1(a).
and Fig 1(b), respectively. The physical layer of the CRS network consist of 2940 nodes and 3069 links, while the service layer of the CRS network consists of 2940 nodes and 5709 links.

![Physical layer and service layer of the CRS network](image)

(a). The physical layer network of the CRS  
(b). The service layer network of the CRS

Fig 1 Two-layer Chinese Railway System network representation

When an earthquake affects a railway link, a link in the physical layer may be disrupted and passenger trains passing through this link are interrupted. The information on which trains passing through the disrupted link in the physical layer is determined by the mapping from train service in the service layer to railway tracks in the physical layer. Note that the information provided by train schedule handbook is incomplete, becaused the schedule of a train does not contain the stations that the train passes without stops. To establish the mapping from the service layer to the physical layer, trains are assigned to the shortest pathes consisting of railway links connecting adjacent stops.

2.2 Estimation of the CRS service loss under earthquake

In this study, the CRS service loss under earthquake is measured based on the railway train service loss, which is related to not only the number of affected trains but also their service disruption duration. Section 2.2.1 presents the damage estimation model for railway links at the physical layer. Section 2.2.2 presents the calculation of railway service loss at the service layer based on the mapping from physical layer to service layer.

2.2.1 Physical layer damage model

The physical layer damage model is used to estimate the damage of railway link under earthquake. Instead of using a binary indicator for the state of “failure or not”, five damage states are defined to represent railway link damage level according to HAZUS (29): none, minor, moderate, extensive, and complete, denoted by $S = \{s_0, s_1, s_2, s_3, s_4\}$. The damage state of a railway link under earthquake is determined by the peak ground displacement (PGD) value around the link and the earthquake resistance ability of the link. The PGD can be estimated by ground-motion
attenuation relationships (30). As the PGD along a railway link changes with the distance to the epicenter, the PGD value at a point is not appropriate to indicate the damage state of a long railway link. In this study, a railway link is divided into small segments with the same length and the link damage state is the integral of all damage states that are calculated individually based on the segment’s PGD.

Let $E$ denote the set of links in the physical layer and $k$ denote the segment index of a link. Then, a link is the collection of all its segments, i.e., $e = \{e_k\}$, for all $e \in E$. Given an earthquake scenario, the probability of damage state of a segment is determined by the fragility curves of HAZUS model (31), which are modeled as lognormal-distributed functions that give the probability of reaching or exceeding different damage states for a given level of PGD value. Let $\xi_{e_k} \in S$ denote the damage state of segment $e_k$ and $P(\xi_{e_k} \geq s_i | \eta)$ denote the probability that $\xi_{e_k}$ reaches or exceeds $s_i$ under an earthquake scenario $\eta$. Assume that the damage state of each segment is independent. Then, $P(\xi_e \geq s_i | \eta)$ can be calculated by:

$$P(\xi_e \geq s_i | \eta) = 1 - \prod_k (1 - P(\xi_{e_k} \geq s_i | \eta)).$$

(1)

Under earthquake scenario $\eta$, the probability of link $e$ at damage state $s_i$ is determined by:

$$P(\xi_e = s_i | \eta) = P(\xi_e \geq s_i \cup s_i+1 | \eta) - P(\xi_e \geq s_i+1 | \eta).$$

(2)

Denote the damage state of the physical layer of the CRS as $\xi_E = \{\xi_e | e \in E\}$. A specific realization of $\xi_E$ is denoted by $\xi_E$. The set of all realizations of $\xi_E$ is denoted by $\Xi = \{\xi_E\}_{\eta \in \mathcal{S}}$. Assume that the realization of $\xi_E$ is independent. Then the realization probability of $\xi_E$ under earthquake scenario $\eta$ is determined by:

$$P(\xi_E | \eta) = \prod_{e \in E} P(\xi_e | \eta).$$

(3)

2.2.2 Service layer damage model

The damage at service layer is computed based on the service reduction percentage during a period of time after earthquake, in which the service reduction percentage describes the damage level caused by the earthquake and the service recovery duration concerns about how quick the service is recovered back to the normal level.

In this study, the service reduction percentage is determined by the damage state of physical layer link. The service recovery duration can be obtained from the function restoration curve in HAZUS, which is used to describe the percentage of the component that is operational as a function of time after the earthquake.

Given an earthquake scenario, the impacted links at the service layer are determined by the mapping from physical layer to service layer. Denoted the set of impacted trains as $\Omega_t$, which is determined by the train stop information at the service layer. For a railway link damage state
realization $\xi_e$, the service reduction percentage on the nth day is denoted by $D(\xi_e, n)$, which is
computed based on function restoration curve. Denote $T_w$ as the time period to evaluate the
railway system damage. For each train $t \in \Omega_t$, its damage on nth day is $\max \{D(\xi_e, n) | e \in E_t\}$,
where $E_t$ denotes the set of railway links that train $t$ passes. Denote $f(\xi_E, T_w)$ the service loss of
the railway system under a specific damage state realization $\xi_E$ during $T_w$. Then, we have:

$$f(\xi_E, T_w) = \sum_{n=1}^{T_w} \sum_{t \in \Omega_t} \max \{D(\xi_e, n) | e \in E_t\}. \quad (4)$$

And the expected service loss of the railway system under earthquake scenario $\eta$ is determined by:

$$D(\eta, T_w) = \sum_{\xi_E \in \xi} f(\xi_E, T_w) P(\xi_E | \eta). \quad (5)$$

2.3 Pre-disaster investment optimization model

Applying the service loss estimation model (5), this section proposes an optimization model to
identify the links to be strengthened in a railway system to mitigate future earthquake damage.
Denote $y = \{y_e\}$ as binary decision variables with $y_e = 1$ if railway link $e$ is chosen to be
strengthened; otherwise $y_e = 0$.

Assume that the cost to strengthen a railway link is proportional to its length. Let $c_e$ denote
the cost for strengthening link $e$, and $B$ denote the total budget. Then, the budget constraint is
formulated as:

$$b = \sum_{e \in E} c_e * y_e \leq B. \quad (6)$$

Assume that if a railway link is strengthened, the probabilities of its damage states under
earthquake will decrease. Given an investment plan denoted by $y$, the probability that segment $e_k$
reaches or exceeds damage state $s_i$ can be calculated by:

$$P_y(\xi_{e_k} \geq s_i | \eta) = (1 - \alpha) * y_e * P(\xi_{e_k} \geq s_i | \eta) + (1 - y_e) * P(\xi_{e_k} \geq s_i | \eta), \quad i = 1, 2, 3, 4$$

where $\alpha \in (0,1)$ represents the strengthening intensity. Correspondingly, the probability that
damage state of link $e$ reaches or exceeds $s_i$ under earthquake scenario $\eta$ is calculated by:

$$P_y(\xi_e \geq s_i | \eta) = 1 - \prod_{k} \left(1 - P_y(\xi_{e_k} \geq s_i | \eta)\right) \quad (8)$$

Given investment plan $y$ and earthquake scenario $\eta$, the probability that link $e$ is in damage state
$s_i$ is computed by

$$P_y(\xi_e = s_i | \eta) = P_y(\xi_e \geq s_i | \eta) - P_y(\xi_e \geq s_{i+1} | \eta) \quad (9)$$

The probability of a specific realization of physical network $\xi_E$ is calculated by

$$P_y(\xi_E | \eta) = \prod_{e \in E} \{y_e * P_y(\xi_e | \eta) + (1 - y_e) * P(\xi_e | \eta)\} \quad (10)$$

The expected service loss of the railway system is formulated as:

$$D_y(\eta) = \sum_{\xi_E \in \xi} f(\xi_E, T_w) P_y(\xi_E | \eta) \quad (11)$$
where $f(\xi_E, T_w)$ is the service loss under a specific realization $\xi_E$ as discussed in section 2.2.

The optimal investment plan $y$ to minimize expected service loss of the CRS under earthquake is the solution of the optimization model:

$$\min_y \text{Exp}_\eta[D_y(\eta)], \quad (12)$$

subject to $\sum_{e \in E} c_e * y_e \leq B$ and $y_e \in \{0,1\}, \forall e \in E$. Note that the objective function in the optimal investment model is considered as the expected service loss over the earthquakes that may occur in a period of time of the future.

### 2.4 Earthquake scenario generation

This study applies historical earthquake events data to generate future earthquake scenarios. The earthquake occurrence probability distribution is estimated for each seismic belt using historical data. If an earthquake occurs in a seismic belt, the occurrence location of the earthquake is randomly selected inside the seismic belt. And the magnitude of earthquake is determined based on the historical distribution of earthquake magnitudes.

![Fig 2 Historical Earthquake events in China from 1898 to 2012](image)

The historical earthquake events data used in this study is downloaded from Advanced National Seismic System (ANSS) catalog from 1898 to 2012 (www.ncedc.org/anss/). The data set includes the location, magnitude and date of each earthquake event. Because some serious earthquakes can influence a large area, a buffer area is set as 100 km from the border of China, as illustrated in Fig 2. In total, 12,750 historical earthquake events with magnitude greater than 4.5 Richter scale are used for earthquake scenario generation.
2.4.1 Earthquake occurrence probability

The Earthquake occurrence is modeled as a Poisson process and the occurrence probability of an earthquake is related with its magnitude and reference time period \( \lambda \). Let \( m \) denote earthquake magnitude and \( T_r \) denote the reference time period. The probability of having at least one earthquake whose magnitude is greater than \( M \) over reference time period \( T_r \) can be calculated by:

\[
P (m \geq M, T_r) = 1 - e^{-\lambda M T_r}
\]

In the equation, the total number of earthquakes \( N \) can be estimated by Gutenberg–Richter law:

\[
\log N = c_1 - c_2 * M
\]

where \( c_1 \) and \( c_2 \) are model parameters that vary among seismic belts. There are 25 main seismic belts in China, illustrated as shaded areas in Fig 2. In this study, the areas that do not belong to any seismic belts are regarded as a special seismic belt. In total, this study considers 26 seismic belts.

2.4.2 Earthquake occurrence location and magnitude

Due to the lack of geological details, this study assumes that any location in a seismic belt has the same earthquake occurrence probability. The set of earthquake events is denoted by \( H = \{\eta\} \). According to Kolmogorov-Smirnov test result, Johnson SB distribution is selected to fit the historical magnitude distribution. Johnson SB distribution is a bounded distribution with shape parameters \( \gamma \) and \( \delta \), location parameter \( \mu \), and scale parameter \( \sigma \). The probability density function and cumulative distribution function are:

\[
f(x) = \frac{\delta \sigma e^{-\frac{1}{2}(\gamma+\delta \ln(\frac{x-\mu}{\mu+\sigma-x}))^2}}{\sqrt{2\pi}(x-\mu)(\mu+\sigma-x)}, \mu < x < \mu + \sigma
\]

\[
F(x) = \Phi(\gamma + \delta \ln \frac{1}{1-z}), \text{ where } z = \frac{x-\mu}{\sigma}.
\]

Earthquake magnitude is generated by inverse function:

\[
x = \frac{\sigma \exp(\frac{\phi^{-1}(U)-\mu}{\delta}) + \mu}{1 + \exp(\frac{\phi^{-1}(U)-\gamma}{\delta}) + \mu}
\]

where \( \Phi(*) \) is cumulative distribution function of standard normal distribution and \( U \) is a random number generated from the standard uniform distribution.

2.5 Solution method

As the formulation of objective function (12) relies on the earthquake scenario generation model that depends on the seismic belts, Monte Carlo simulation and Genetic Algorithm are applied to identify the optimal investment plan. A set of earthquake scenarios are generated based on the method presented in section 2.4, and used to investigate the expected railway service loss under a specific investment plan. The investment plan \( y \) is presented as a set of binary variables.
that are coded as genes in Genetic Algorithm. The solution method used to solve the optimal investment plan is summarized as the following steps:

**Step 1** Generate earthquake scenarios of 20 years based on the approach presented in Section 2.4. Each scenario includes the location and the magnitude of the earthquake.

**Step 2** Compute the PGD of the affected railway links that are within the 100km range from epicenter of the earthquake location.

**Step 3** According to the PGD, compute the probabilities of different damage state realizations for each railway link. Then, roulette-wheel selection is performed to decide the damage state of each railway link.

**Step 4** Identify the optimal investment plan by applying Genetic Algorithm

- **Step 4.1** Generate an initial population of investment plans. All investment plans must satisfy the budget constraint.
- **Step 4.2** Based on the investment plans, adjust the failure probabilities of the railway links.
- **Step 4.3** Apply roulette-wheel selection to decide the damage state for each link.
- **Step 4.4** Estimate the service loss of the CRS. Search the service layer links (i.e. trains) that pass through the damaged railway links, then use the value of influenced trains weighted by the function-disturbed percentage as service loss.
- **Step 4.5** Estimate the fitness function that has the service loss as arguments. If the number of generations is greater than 40, stop; otherwise, go to next iteration.
- **Step 4.6** Select the investment plans whose corresponding service losses are lower than the lowest loss of ancestor as next generation population. The initial lowest loss is set as the loss of CRS without any investment.
- **Step 4.7** Implement mutation and crossover on the selected investment plans and check whether the investment plan satisfies the budget constraint. If an investment plan is infeasible, then it is deleted from the solution set. Add the feasible investment plans to the next generation population. Go to Step 4.2

In genetic algorithm, each chromosome contains 3069 bits of binary genes, which has the same number of links in the physical layer of the CRS.

### 3. NUMERICAL ANALYSIS AND RESULTS

This section applies the proposed methodology to identify the optimal investment plan for the CRS. In one simulation run, earthquake scenarios in 20 years are generated based on the method proposed in section 2. Each earthquake scenario has its own location and magnitude. We perform 100 simulation runs in Monte Carlo simulation. The investment budget is set from 5000 km to 15000 km with a step of 2000 km, and the strengthening intensity is set from 0.1 to 0.4 with a step of 0.1.
3.1 Experiment results

Fig 3 illustrates the convergence process of CRS damage under different settings of investment budget and strengthening intensity. In Fig. 3, the expected service loss becomes stable after 40 generations in most cases. If the investment budget is small, for example 5000 km, then the improvement in terms of expected service loss reduction is limited, even when the strengthening intensity increases to 0.4.

Fig 3 Convergence of the solution method under different values of strengthening intensity

Fig 4 illustrates the locations of railway links to be strengthened based on the optimal solution when the investment budget is 5000 km and strengthening intensity is 0.1. In Fig. 4, many links to be strengthened are located close to several big cities of China, such as Beijing, Shanghai, and Zhengzhou, which are the busiest railway hubs. In addition, the locations of these links are close to seismic belts as illustrated in the Fig. 4.

The western China is an area with low railway mileage and sparse population. However, these areas are earthquake prone. Once earthquake occurs, all trains traveling toward these areas
are affected. Thereby, the optimization model also suggests several links in western China to be strengthened.

Fig 4 The railway links to be strengthened

3.2 Comparison with topology-based investment plans

Topological metrics are usually used to identify critical components in network science. We compare the optimal investment plan shown in the previous section with the plans based on two topological metrics in complex network theory: degree and betweenness. Here, degree of node $i$ is defined as the total number of nodes connecting to node $i$, and betweenness of node $i$ is defined as the number of shortest paths that pass through node $i$. The investment plans based on degree and betweenness analyses are shown in Fig 5.

(a) Investment plan based on degree analysis          (b) Investment plan based on betweenness analysis

Fig 5 Investment plans based on topology analysis
The strengthened links based on degree analysis, shown in Fig 5(a), are distributed in southeast of China and most of them are connected to several big cities. The strengthened links based on betweenness analysis are shown in Fig 5(b). These links are connected to or nearby the south-north railway corridor of the CRS.

Table 1 Expected service loss reduction percentage compared with topological metric

<table>
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<tr>
<th>Budget (km)</th>
<th>5,000</th>
<th>7,000</th>
<th>9,000</th>
<th>11,000</th>
<th>13,000</th>
<th>15,000</th>
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<tr>
<td>Betweenness</td>
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<td>1.0%</td>
<td>1.0%</td>
<td>1.5%</td>
<td>2.0%</td>
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<tr>
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The investment plans determined by the optimization model (12) and topological methods show different characteristics. The optimization model selects over the whole network concerning the impacts from future earthquakes. The optimization model applies train service information to choose better investment plans. By contrast, the topological methods select links based on the characteristics of the network, without consideration of the impact from earthquakes on railway service.

The expected service loss reduction percentages of the investment plans suggested by different methods are summarized into Table 1. For the investment plans suggested by the optimization model, the expected service loss reduces with the increase of strengthening intensity. And the strengthening intensity becomes more effective if the investment budget is larger. In addition, the plans suggested by the proposed optimization model perform better than those based on topological metrics in most cases, especially when the strengthening intensity is low. It demonstrates the benefit of considering the impact of earthquake on train flow in the proposed model.

4. CONCLUSIONS

This paper proposes an optimization model to determine the optimal pre-disaster investment plan for strengthening the Chinese railway system under earthquakes. The proposed model selects the
investment links to minimize the expected service loss that is constructed at the service layer of
the railway network. The expected service loss is estimated based on the future earthquake events
whose locations and magnitudes are predicted using historical data. Monte Carlo simulation and
Genetic Algorithm are applied to solve the optimization model effectively. Numerical analyses
illustrate that the proposed optimization model is able to identify an investment plan more
responsive to the earthquake impact on the railway system than those suggested by the
topological metrics. The comparison between the results suggested by optimization model and by
topology-based methods demonstrates the importance of modeling the service interruption
probability that should be not handled as random attacks.

In this study, the effect of pre-disaster investment plan is modeled as a reduction of the
probability of damage level. The improvement of service restoration speed has not been modeled.
Meanwhile, the budget constraint is modeled as the total railway length allowed to be
strengthened. In the real world, strengthening railway links relies on various types of resources,
all of which have budgets. In addition, the expected service loss under earthquakes may be
associated with influences on passengers or local GDP. These factors can be considered in the
modeling process. The proposed methodology can also be extended to investigate the investment
plans for other transportation systems under threats from natural disasters.

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