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FRAMEWORK TO ASSESS RISK AND RESILIENCE OF ROAD NETWORKS UNDER SEISMIC AND SUBSEQUENT TSUNAMI HAZARDS

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Abstract

In the 2011 Great East Japan earthquake, seismic ground motion- and/or tsunami-induced damage to road structures caused significant social impacts such as economic losses and delays in the recovery process due to the deterioration of road network functionality. Since road structures play a crucial role in the transportation of emergency goods and materials as well as evacuation of affected people, it is important to estimate the damage level of individual structures considering both seismic ground motion and subsequent possible actions (e.g. liquefaction, tsunami and landslide), and determine the retrofitting prioritization for structures based on not only reliability-based indicators which provide the safety level of individual structures but also social impact and recovery time after an event. In this paper, a framework to assess the risk and resilience of a road network with bridges and embankments subjected to a seismic ground motion and subsequent tsunami is established. Risk and resilience are quantified in terms of the economic loss and recovery of postdisaster road network functionality, respectively. In the proposed methodology, failure probabilities considering uncertainties associated with the fault movement, hazard intensity, and structural vulnerability are computed using Monte Carlo simulation. The effects of ground motion-induced damage to road structures on the deterioration of tsunami capacity are taken into consideration when estimating the structural vulnerability against tsunami. The applicability of the proposed method is demonstrated in an illustrative example of a road network subjected to the anticipated Nankai Trough earthquake. It is expected that the damage to road networks and social impact associated with the recovery process resulting from the anticipated Nankai Trough earthquake would be larger than those resulting from the 2011 Great East Japan earthquake. The estimation results show that the retrofitting prioritization for road structures under both seismic and tsunami hazards due to the anticipated Nankai Trough earthquake can be determined based on the proposed performance indicators (i.e., risk and resilience).

Keywords: seismic hazard; tsunami hazard; risk; resilience; road network

1. Introduction

The damage induced to road structures, such as bridges and embankments, during natural disasters causes significant economic losses and degradation of network functionality. For example, in the 2011 Great East Japan earthquake, many road structures were severely damaged due to the strong ground motions and/or the subsequent tsunami. As a result, approximately 2,300 km of highways were closed due to the damage to road structures [1]. Multiple interacting hazards should be considered to determine the retrofitting prioritization for road structures. Moreover, disaster mitigation measures should be discussed based on not only reliability-based indicators that provide the safety level of structures but also social impacts, such as economic loss, degradation of functionality, and recovery time of road networks.

Risk-based approaches have been used to quantify the social impacts, such as economic loss, number of casualties and required recovery time, caused by natural disasters [2, 3, 4]. These risk-based indicators are useful to make decisions on appropriate disaster mitigation measures. However, considering postdisaster restoration activities, it is important to estimate the resilience, which is a performance indicator associated with recovery process, and to implement disaster mitigation measures for future natural disasters [5]. In general, the resilience is quantified based on the functionality of infrastructure, such as traffic capacity and water service availability, after natural disasters [6, 7, 8]. The disaster countermeasures for mitigating the damage to structures and infrastructure systems are needed to reduce the risk and enhance the resilience.

Risk- and resilience-based indicators can contribute to determining effective disaster mitigation measures. However, in previous studies on risk and resilience assessments, the effects of interacting hazards, such as ground motions and subsequent tsunamis, on structural vulnerability were ignored in reliability assessments for structures. In this paper, a framework to assess the risk and resilience of road networks under seismic and subsequent tsunami hazards is established. In the proposed framework, the risk and resilience are quantified by the economic loss, and postdisaster functionality and recovery time of networks, respectively. Monte Carlo simulation (MCS) is performed to take into account the uncertainties associated with the estimations of fault movement, hazard intensity, and vulnerability of structures. Moreover, the structural vulnerability against tsunamis is estimated considering the effects of ground motion-induced damage on the reduction in tsunami capacity. As an illustrative example, the risk and resilience of a road network, including bridges and embankments, under a ground motion and subsequent tsunami caused by the anticipated Nankai Trough earthquake are evaluated. The analyzed road network is located in Japanese cities where the damage to structures due to the Nankai Trough earthquake would be severe. In the estimations by the Cabinet Office, Government of Japan [9, 10], social impacts associated with the recovery process resulting from the ground motions and/or tsunami caused by the Nankai Trough earthquake would be greater than those caused by the 2011 Great East Japan earthquake. Risk and resilience quantified by the proposed methodology are estimated to determine the retrofitting prioritization for road structures.

2. Framework to assess risk and resilience of road networks

2.1 Seismic and tsunami hazard assessments

Figure 1 shows the framework to assess the risk and resilience of road networks under both seismic and tsunami hazards. Uncertainties associated with average stress drops in both seismic and tsunami fault models are considered by MCS when assessing seismic and tsunami hazards. The peak ground acceleration (PGA) and tsunami wave height are used as seismic and tsunami hazard intensity measures to estimate hazard and fragility curves when estimating the reliability of individual road structures, respectively. PGA is estimated by using the attenuation relationship provided by Si & Midorikawa [11]. Tsunami wave height is calculated via horizontal 2D tsunami propagation analysis based on nonlinear longwave theory [12].

2.2 Seismic and tsunami fragility analyses

When estimating the seismic fragility curve, many seismic waves with specific seismic intensities are used in the MCS-based seismic response analysis of individual structures. Structural vulnerability against tsunamis is

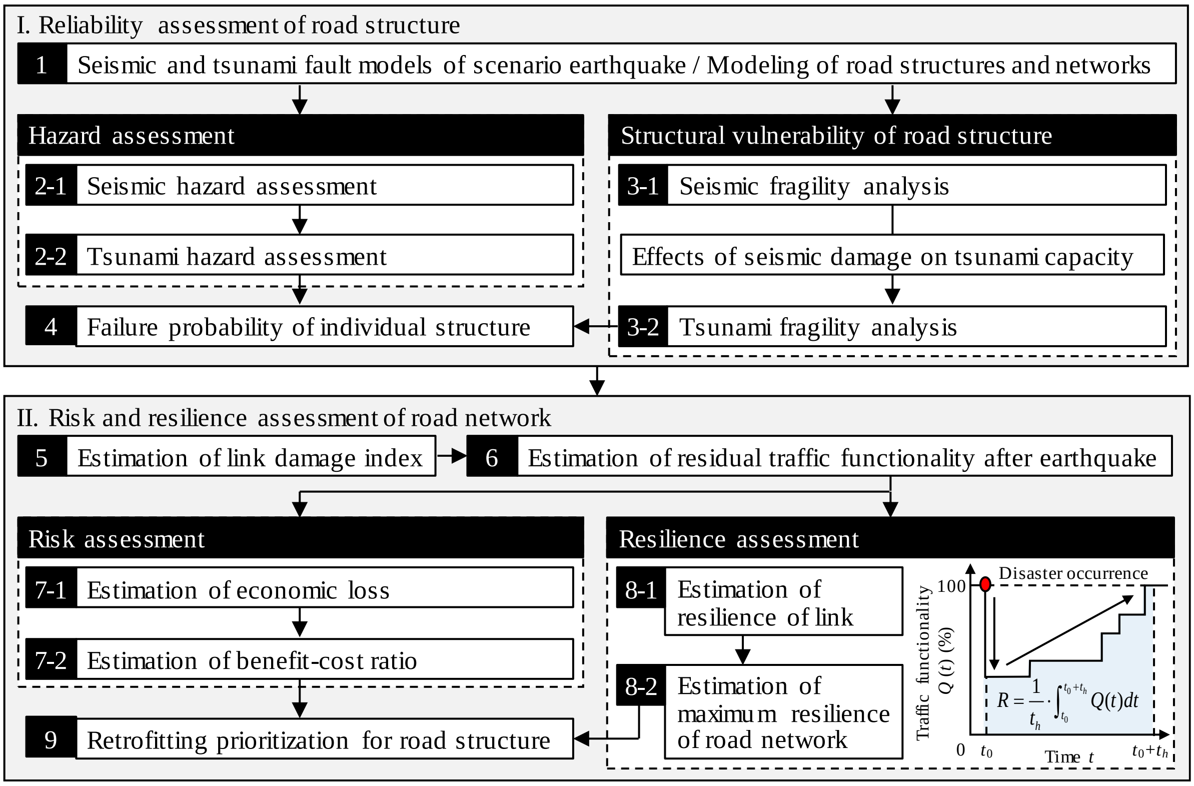

Fig. 1 – Framework to assess risk and resilience of road networks under both seismic and tsunami hazards

evaluated considering the effects of ground motion-induced damage on the reduction in tsunami capacity (i.e., residual displacement and stiffness/strength degradation).

In this study, the damage states of individual structures subjected to a ground motion and subsequent tsunami are divided into three levels: none, moderate, and complete. These damage states are determined according to the degradation of traffic functionality.

2.3 Reliability assessment

The failure probability of a road structure due to a ground motion can be expressed as:

$$P_{fs}(DS_s = ds_i) = \int_0^\infty \left\{ P(DS_s = ds_i \mid \Gamma = \gamma) \cdot \left| -\frac{dF_\Gamma(\gamma)}{d\gamma} \right| \right\} d\gamma \tag{1}$$

where $P_{fs}(DS_s = ds_i)$ is the failure probability that the seismic damage state DS_s becomes ds_i, $F_\Gamma(\gamma)$ is the seismic hazard curve, and $P(DS_s = ds_i \mid \Gamma = \gamma)$ is the conditional failure probability that DS_s becomes ds_i given seismic intensity $\Gamma = \gamma$.

The failure probability of a road structure with damage state $DS_t = ds_j$ due to a tsunami given the seismic damage $DS_s = ds_i$ can be expressed as:

$$P_{ft}(DS_t = ds_j \mid DS_s = ds_i) = \int_0^\infty \left\{ P(DS_t = ds_j \mid H = h, DS_s = ds_i) \cdot \left| -\frac{dF_H(h)}{dh} \right| \right\} dh \tag{2}$$

where $P_{ft}(DS_t = ds_j \mid DS_s = ds_i)$ is the failure probability that the tsunami damage state DS_t becomes ds_j given the seismic damage $DS_s = ds_i$, $F_H(h)$ is the tsunami hazard curve, and $P(DS_t = ds_j \mid H = h, DS_s = ds_i)$ is the conditional failure probability that DS_t becomes d_{sj} given $DS_s = ds_i$ and the tsunami wave height $H = h$.

Finally, the failure probability $P_f(DS = ds_j)$ that the damage state DS becomes ds_j after seismic and tsunami events can be expressed as:

$$P_f(DS=ds_j)=\sum_{i=1}^{j}P_{fs}(DS_s=ds_i)\cdot P_{ft}(DS_t=ds_j\,|\,DS_s=ds_i) \tag{3}$$

2.4 Traffic functionality of a link after an earthquake

The ground motion- and/or tsunami-induced damage to road structures can cause the degradation of postdisaster traffic functionality. The link damage index (*LDI*) is computed as a performance indicator of links after an earthquake in accordance with the methodology proposed by Chang et al. [13]. The postdisaster traffic-carrying capacity and free-flow speed of links are calculated as network functionalities according to the *LDI* provided by Guo et al. [14].

2.5 Risk and resilience assessment

The risk and resilience are quantified by the economic loss and network functionality, respectively. The risk is defined as a sum of direct and indirect losses. The direct loss is the recovery cost for damaged structures. The indirect loss denotes the economic loss due to the increase in running time and travel distance. In this study, the benefit-cost ratio (*BCR*) is used to quantify the economic benefit of retrofitting structures. *BCR* can be calculated by dividing the risk reduction by the retrofitting cost.

The resilience is defined as the normalized integral of link functionality $Q(t)$ in the investigated time horizon t_h, as shown in Figure 1, according to Frangopol & Bocchini [15]. In addition, the maximum resilience of a road network is obtained by comparing the resilience among links in the road network to determine the retrofitting prioritization. Structures on the link with the maximum resilience need to be retrofitted first.

3. Illustrative example

3.1 Analyzed road network

In this illustrative example, the retrofitting prioritization for structures in the road network, shown in Figure 2, under both seismic and tsunami hazards caused by the Nankai Trough earthquake was investigated. The analyzed road network includes girder bridges and embankments. The old and new bridges were designed in accordance with the Japanese seismic specifications published in 1964 and 1996, respectively [16, 17]. The design parameters of the embankments were determined in accordance with Shinoda [18].

3.2 Seismic and tsunami hazard assessments

The probability densities of average stress drops associated with seismic and tsunami fault models were determined based on earthquake data provided by the Cabinet Office, Government of Japan [9, 10]. The average stress drops were assumed to be random variables when estimating seismic and tsunami hazards.

The two seismic fault models were used for the seismic hazard assessment. In this illustrative example,

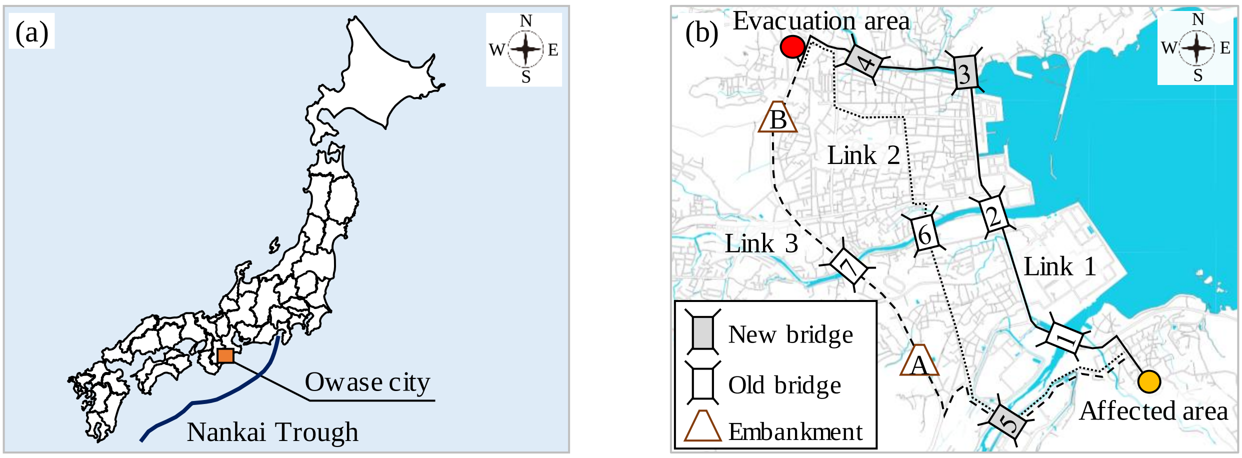

Fig. 2 – Schematic layout: (a) Owase city and (b) investigated road network in Owase city

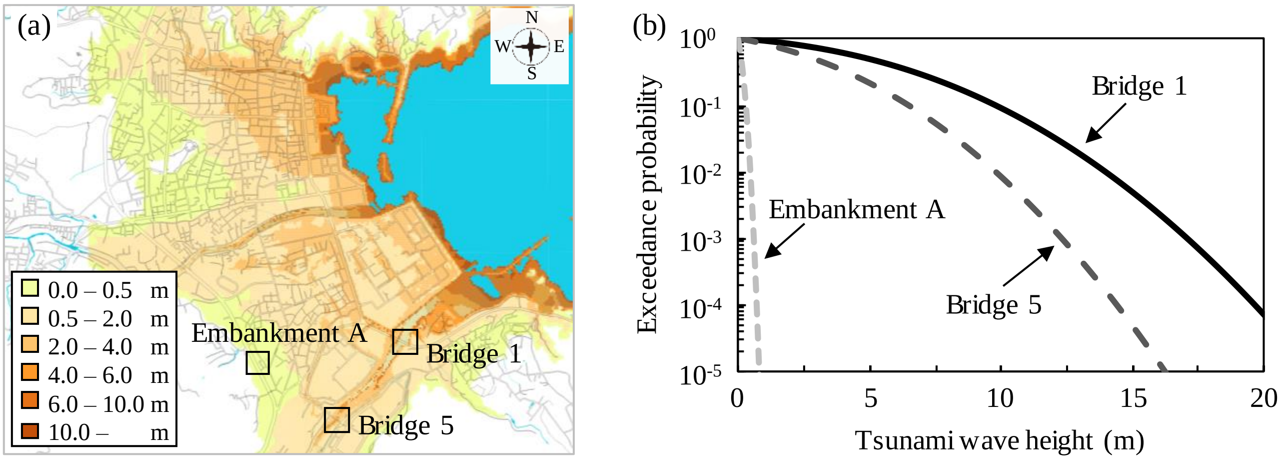

Fig. 3 – Tsunami hazard in Owase city: (a) distribution map of average tsunami wave height and (b) examples of tsunami hazard curves

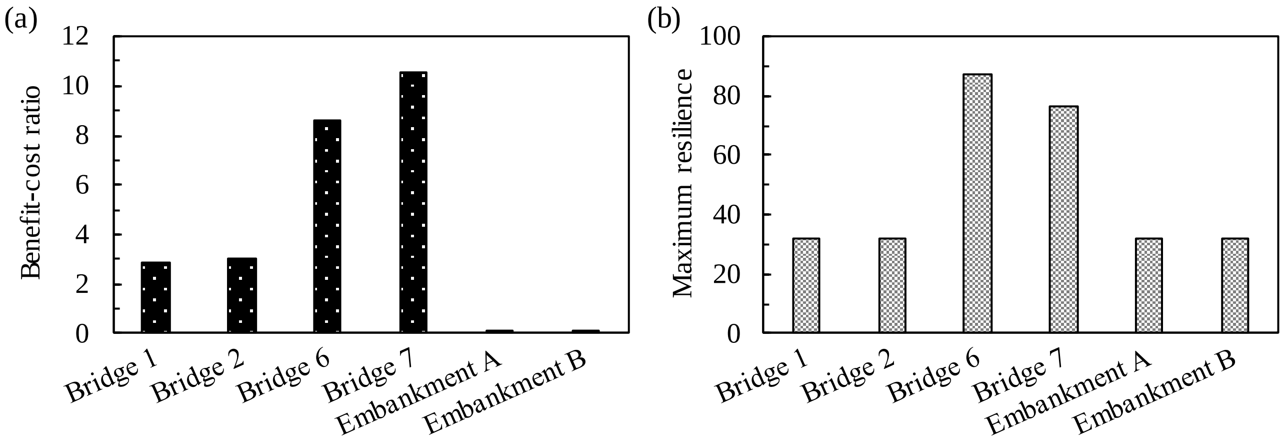

Fig. 4 – Estimation results: (a) risk and (b) resilience

all structures in the road network analyzed are assumed to have the same seismic hazard since the equivalent hypocentral distances were approximately equal over the network.

15 tsunami fault models were used for the MCS-based tsunami propagation analyses. Figure 3 shows the distribution map of average tsunami wave height and examples of tsunami hazard curves in Owase city. The tsunami hazard curves depend on the distance from the coast and the geographical conditions.

3.3 Seismic and tsunami Fragility analyses

Using a total of 100 seismic waves estimated by the Cabinet Office, Government of Japan [9], nonlinear dynamic analysis and the Newmark method were performed to obtain seismic fragility curves of bridges and embankments, respectively. Tsunami fragility curves of the bridges were estimated by pushover analyses using hydrodynamic forces. In addition, vertical wave forces were calculated to ensure the floating resistance of bridge superstructures. When estimating the structural vulnerability of the embankments, the threshold of the overflow depth was determined in accordance with Shuto [19].

3.4 Risk and resilience of a road network

In this illustrative example, the benefit-cost ratio and maximum resilience were estimated under the assumption that only one old bridge or embankment is retrofitted. Figure 4 shows the result of risk and resilience estimations of the analyzed road network. As shown in Figure 4, retrofitting Bridge 7 can bring the significant economic benefits. Regarding the resilience, the maximum resilience can be increased by retrofitting Bridge 6 efficiently. These results demonstrate that stakeholders can make decisions on the retrofitting prioritization for road structures using the risk and resilience as performance indicators.

4. Conclusion

A framework to assess the risk and resilience of road networks subjected to a seismic ground motion and subsequent tsunami is established. As an illustrative example, the proposed methodology was applied to a road network in Japan, including bridges and embankments, under both seismic and tsunami hazards caused by the anticipated Nankai Trough earthquake. Risk- and resilience-based approaches, as described in [20-24], can contribute to making decisions on the retrofitting prioritization of the road structures.

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