13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Life-Cycle Performance Assessment of Road Network Under Multiple Hazards

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ABSTRACT: A procedure for estimating risk and resilience of road networks associated with bridges and embankments subjected to seismic ground motion and subsequent tsunami caused by the anticipated Nankai Trough earthquake is proposed. Since road networks play a crucial role for the transportation system after a natural disaster, it is important to identify the degradation of functionality and economic loss due to damage to structures in networks. In an illustrative example, risk and resilience of road networks in Mie-Prefecture, where the effects of Nankai Trough earthquake would be very intense, are estimated. The numerical results show that the retrofitting prioritization can be determined by comparing the risk and resilience of road networks.

1. INTRODUCTION

Road networks play a crucial role in disaster restoration. Therefore, the need for developing methodologies for the seismic performance assessment of road networks in a life-cycle context is urgent. In the 2011 Great East Japan earthquake, bridges and embankments were severely damaged due to the strong ground motion and/or subsequent tsunami. For this reason, approximately 2,300 kilometers of road networks were closed (Nojima and Kato 2013).

Field investigations after the 2011 Great East Japan earthquake confirmed that many structures were inflicted intense damage by tsunami despite being retrofitted to improve their capacity against the strong ground motion. These damages to structures caused the deterioration of the functionality of networks. For example, although RC bridge piers of Utatsu Bridge on Route 45 were retrofitted by jacketing before the 2011 Great East Japan earthquake, the superstructure was washed away (Kataoka et al. 2013). This caused delays in reconstruction and affected the recovery process significantly.

It is important to consider multi-hazards in a life-cycle context and determine the priority of the retrofit based on not only reliability-based indicators which provide the safety level of structures but also social impacts such as economic losses, and the reduction of the functionality and recovery time due to damage to structures.

In this paper, considering the whole scenario given the occurrence of the anticipated Nankai Trough earthquake, the probabilistic performances of road networks are quantified in terms of the economic loss, functionality loss and recovery time. The methodology to identify the priority for retrofitting networks under the seismic and tsunami hazards by comparing the risk and resilience of networks with and without retrofitting is proposed.

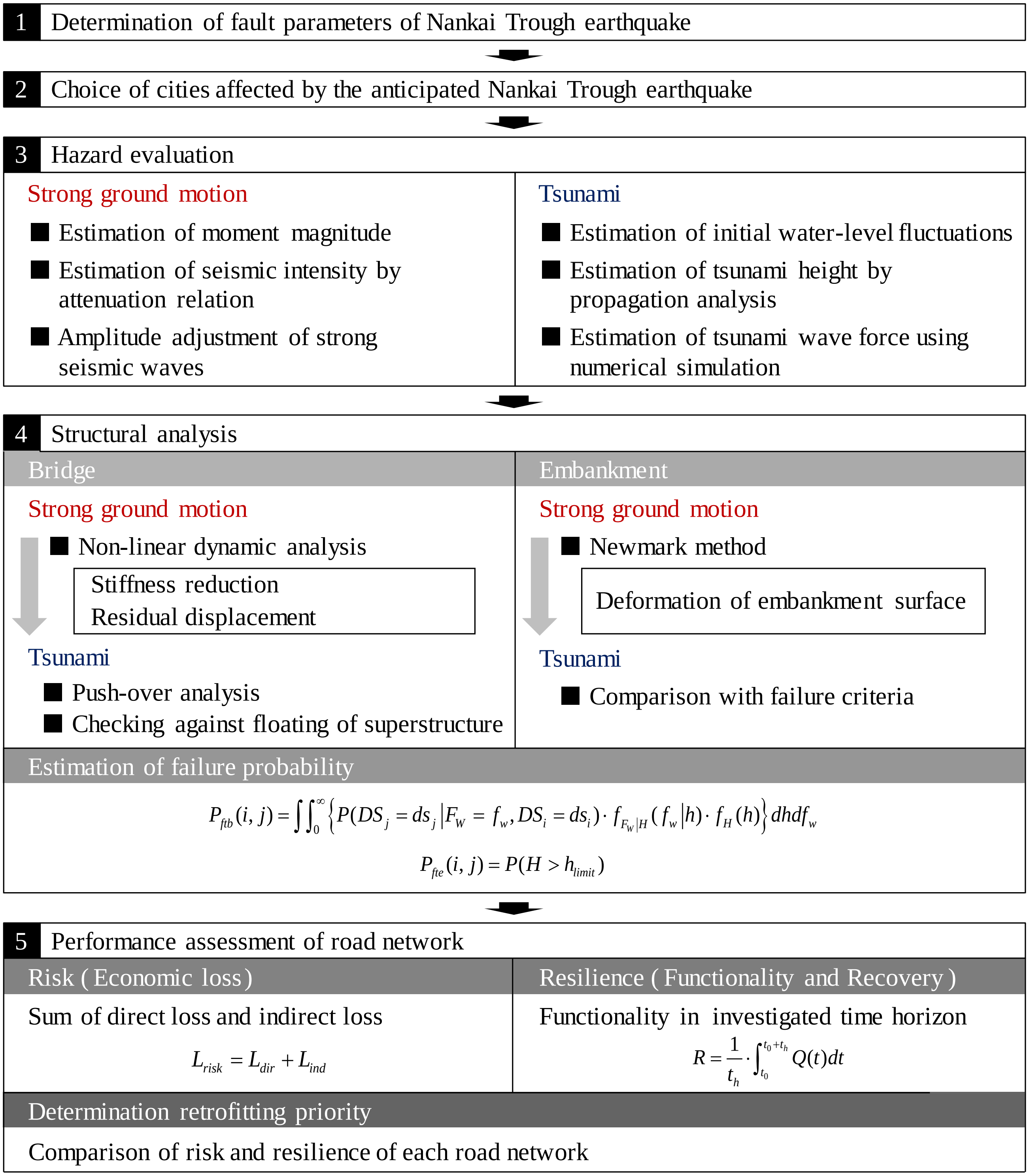

Figure 1: Outline of proposed methodology for performance assessment of road network under multi-hazards

2. RISK AND RESILIENCE EVALUATION OF NETWORK UNDER SEISMIC AND TSUNAMI HAZARDS

Figure 1 shows the outline of the proposed methodology for the performance assessment of a road network under strong ground motion and subsequent tsunami caused by the anticipated Nankai Trough earthquake. The uncertainties associated with the prediction of seismic fault movement are considered. The average stress drop and the slip angle are assumed to be truncated normal variables. Figure 2 shows probability densities of average stress drop associated with seismic and tsunami fault models. The parameters associated with the fault movement are determined based on Central Disaster Management Council (2003).

Strong ground motion and tsunami are treated as a series of external forces. The structural tsunami analysis is conducted considering the damage due to seismic ground motion. In Figure 1, $P_{ftb}(i, j)$ and $P_{fte}(i, j)$ are the probabilities in which the bridge and embankment with ground motion induced-damage state of ds_i becomes damage state of ds_j due to the subsequent tsunami, respectively. $P_{ftb}(i, j)$ and $P_{fte}(i, j)$ can be expressed as

$$P_{ftb}(i,j)=\int\int_0^\infty \left\{P(DS_j=ds_j\,|F_W=f_w,DS_i=ds_i)\cdot f_{F_W|H}(f_w|h)\cdot f_H(h)\right\}dhdf_w \qquad (1)$$

$$P_{fte}(i,j)=P(H>h_{limit}) \qquad (2)$$

where $P\ (DS_j = ds_j\ |F_W = f_w,\ DS_i = ds_i)$ is the conditional probability that DS_j becomes ds_j given $DS_i = ds_i$ and $F_W = f_w$ respectively, $f_{F_W|H}(f_w|h)$ is the probability density function of F_W when tsunami wave height H is equal to h, $f_H(h)$ is the probability density function of H, h_{limit} is the height of embankment necessary to prevent the overflow due to the tsunami.

Seismic waves used in non-linear dynamic analyses of the bridge and embankment are provided by Central Disaster Management Council (2003). The number of seismic waves used in the fragility analysis are 100. The peak ground acceleration (PGA) of each wave is amplified such that PGA is equal to a specified seismic intensity.

In order to conduct tsunami fragility analysis, the hydrodynamic wave force is calculated by CADMAS-SURF/3D (Port and Airport Research Institute 2010). The probability density of tsunami wave heights is evaluated by Monte Carlo-based tsunami propagation analysis (Goto et al. 1997). The vertical wave force applied to the bridge superstructure is also considered. Finally, the damage probabilities $P_{ftb}(i, j)$ and $P_{fte}(i, j)$ are estimated based on the probability densities of seismic and tsunami hazards, and the damage state of structures due to seismic ground motion and subsequent tsunami.

The economic loss L_{risk} is the sum of the direct loss and the indirect loss

$$L_{risk}=L_{dir}+L_{ind} \qquad (3)$$

where L_{dir} is the anticipated direct loss of bridges and embankments in the road network. This direct loss is calculated by multiplying the failure probability and recovery cost. L_{ind} is the indirect loss due to the increase in the running time and the traveling distance. L_{ind} is computed by considering the deterioration of the functionality of the road network. The economic effectiveness of each retrofitting can be evaluated by using the

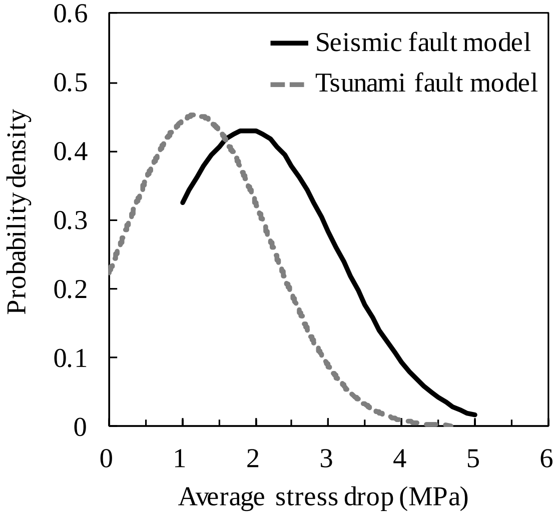

Figure 2: Probability density of average stress drop

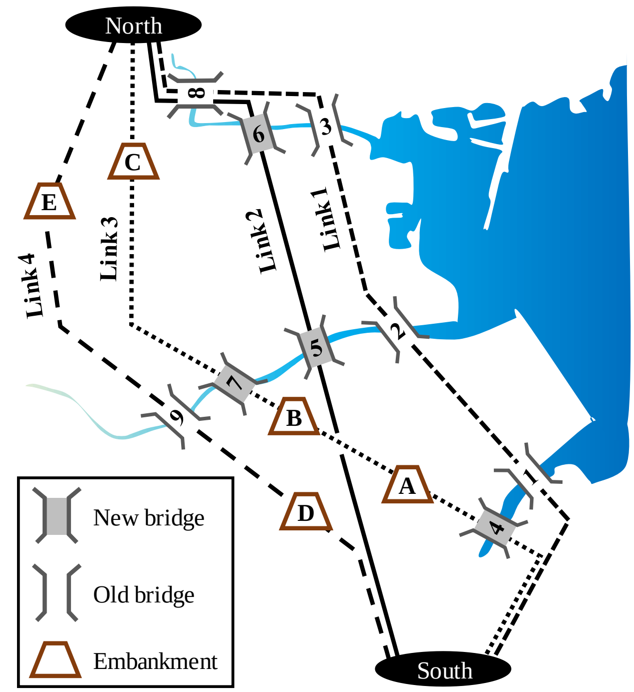

Figure 3: Road network assumed in illustrative example

benefit cost ratio (*BCR*). A retrofitting is efficient if *BCR* is larger than 1.0. In this study, *BCR* is defined as the risk index.

Resilience, *R*, is defined as the normalized integral over time of network functionality *Q*(*t*). As shown in Figure 1, resilience is expressed as

$$R = \frac{1}{t_h} \cdot \int_{t_0}^{t_0+t_h} Q(t)dt \tag{4}$$

where t_0 is the time at which the extreme event occurs, and t_h is the investigated time horizon (Bocchini and Frangopol 2012).

3. ILLUSTRATIVE EXAMPLE

As an illustrative example, risk and resilience of the road network in Owase-City, Mie-Prefecture, Japan under both seismic and tsunami hazards due to Nankai Trough earthquake are estimated based on the procedure shown in Figure 1. Figure 3 shows the schematic layouts of the investigated network in Owase-City. The old and new bridges shown in Figure 3 are designed according to Japanese seismic specification published in 1964 and in 1996, respectively (Japan Road Association 1964, 1996).

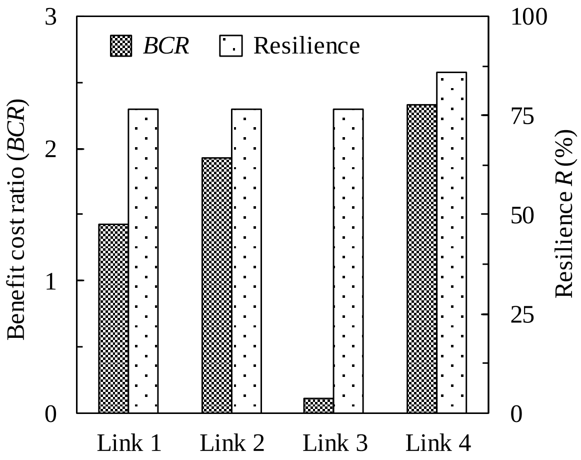

Figure 4: Estimation results of risk and resilience

Figure 4 shows the result of benefit cost ratio (*BCR*) and resilience *R* of each link. The *BCRs* of Links 1, 2 and 4 are greater than 1.0. Retrofitting these Links has benefit in terms of risk. Old bridges which are more vulnerable than new bridges and embankment should be retrofitted first. The quantified resilience of Link 4 is slightly larger than the resilience of other Links. Therefore, it is important to give the highest priority to retrofitting Link 4 in terms of both risk and resilience. This is because tsunami hazard intensity can be smaller with increased distance from the coast.

4. CONCLUSIONS

In this paper, a procedure for estimating risk and resilience of road network subjected to seismic ground motion and subsequent tsunami caused by anticipated Nankai Trough earthquake was proposed. Risk- and resilience-based approaches are useful to make the decision on the retrofitting prioritization.

Further research is needed to enhance the framework for estimating risk and resilience of road networks subjected to multi-hazards. Although bridges and embankments were considered as structures associated with networks in this study, other type of structures such as tunnel structures should be considered. Also, the disaster waste management system must be investigated in terms of resilience and sustainability because a disaster can generate a lot of debris which affects the recovery time. Further studies have to establish risk-, resilience- and sustainability-based design and assessment procedure of infrastructure networks under multi-hazards.

ACKNOWLEDGEMENTS

The authors express sincere appreciation to Dr. Masayuki Yoshimi, National Institute of Advanced Industrial Science and Technology of Japan, for his suggestions related to seismic fault parameters.

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