Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

A QUANTITATIVE FRAMEWORK FOR ASSESSING TSUNAMI VULNERABILITY OF ROAD NETWORKS

GAKU SHOJI[1] and SHIORI ITO[2]

[1] *Faculty of Engineering Information and Systems, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan.*
E-mail:gshoji@kz.tsukuba.ac.jp
[2] *Former Graduate Student, Graduate School of Systems and Information Engineering, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan.*

A framework to evaluate the system reliability of road networks during a catastrophic tsunami disaster was newly proposed based on physical tsunami damage functions of flat roads and bridges, which were both derived by assessment for damage data in the 2011 off the Pacific coast of Tohoku earthquake tsunami. In the framework, the features of shortest routes between targeted substantial public facilities of municipal offices and shelters in a tsunami disaster are identified by using Dijkstra Algorism. In addition, the features of routes between them preferentially passing through main roads are identified. Finally, vulnerable flat roads and bridges on which tsunami countermeasures should be taken and which should be restored preferentially are revealed with the constraints of enhancing system reliability of targeted road networks. This proposed framework was applied to the case studies for the road networks in Tokushima City, Japan, which is anticipated to be suffered greatly from the Nankai megathrust earthquake tsunami disaster, and the possibility of road disruption in a tsunami disaster was investigated.

Keywords: The 2011 off the Pacific coast of Tohoku earthquake, road networks, tsunami, reliability, the Nankai megathrust earthquake.

1 Introduction

The Tohoku earthquake, and the accompanying tsunami, that hit off the Pacific Coast on March 11th 2011, caused immense damage to roads along the Pacific Coast. The national expressways and directly-managed national roads, being cut off in various locations, reduced the functionality of the road network, and had a significant impact on rescue, aid and recovery activities (Ministry of Land, Infrastructure and Transport 2012). Hence, it is extremely important to investigate reduced functionality in road networks as a result of physical damage to roads and bridges from tsunami inundation.

From the perspective of evaluating system reliability against road network function disruption, Nojima and Yamanaka (1998) proposed a method of reliability when evaluating traffic volumes between nodes in road networks during an earthquake disaster in terms of a performance evaluation model, attempting to evaluate the importance of seismic strengthening for roads. Further, Toyota and Shoji (2010), from the perspective of infrastructure system recovery, performed a quantitative evaluation of road traffic disruption resulting from an earthquake that directly hits the capital in Japan, using the seismic intensity exposure distance and degree of congestion in road networks as indicators. As a study based on indicators expressing network shape characteristics, Habuka and Maruyama (2015) investigated how to graph the road network shape based on space syntax theory, and allocate disaster prevention points from the perspective of transfer efficiency by focusing on Kochi for which a particularly significant degree of damage is predicted from a Nankai megathrust earthquake. In these existing studies, attempts are mainly made to evaluate the functional obstacles in road networks based on the physical damage to roads from strong ground motions. However, their investigations into how to evaluate road network function disruption, during times of tsunami disaster, have been somewhat lacking.

Based on the above, in this study, we give consideration to the physical damage to roads from the effect of the tsunami, and propose a method of quantitatively evaluating functional disruption from the perspective of road network system reliability. Additionally, as a case study, we applied the proposed method to the road network in Tokushima City, Tokushima Prefecture, Japan, in order to provide general observations related to the decrease in functionality of road networks from the perspective of reduced reliability in road network links caused by a Nankai megathrust earthquake and tsunami.

2 Framework of the Proposed Method

In Step 1 on the framework of the proposed method, we select the region in which to evaluate functional disruption in the road networks during times of tsunami disaster, and model the target road networks. At this time, the nodes are the road edge points and areas where the route can be changed, and the links are the roads between those nodes.

In Step 2, we apply the damage function to roads and bridges (e.g., Itagaki and Maruyama 2016, Shoji and Nakamura 2017) in regions for which tsunami inundation is forecast. Here, the physical damage to the road caused by the tsunami occurs in the link. Therefore, this study evaluates the reliability of the links. The data related to the inundated regions and inundation depths, for example, from the Nankai megathrust earthquake 11-type tsunami fault model researched by the Cabinet Office (Nankai Trough Earthquake Model Review Committee 2012), envisages cases where the worst possible disaster occurs in the target regions determined in Step 1. At this time, not only is the tsunami height and inundation depth data meshed and used on the Geographic Information System (GIS), but the bridge and flat roads on the road network covering the target regions are extracted as line data, and after confirming both types of data, the damage index is applied to each link of the road network modeled in Step 1, in order to calculate the passable probability of each link as a measure of link reliability.

In Step 3, in order to consider the possibility of passing the road after the disaster, cost is set as a variable for analysis, this is added as a weight to the distance for each link, and analysis cases are determined by setting problems related to the usage format when tsunami disasters occur in road networks in the target region. When selecting the route between the initial point and end point on the road network, we can envisage cases in which the shortest route is the actual distance（Case 1） and cases in which a weight is applied to the actual distance in consideration of the road type s（Case 2）.

In Step 4, a probability calculation of the route connectivity reliability is performed for each analysis case. Based on the cost weight set in Step 3, the shortest route between two points is calculated using the Dijkstra method. The link reliability for each link calculated in Step 2 for the desired shortest route is substituted as the cost, and by taking the product, it is possible to calculate the connectivity reliability between any two points and evaluate these as the route reliability.

3 Case Study

3.1 *Road Network Targeted for Analysis*

In case of a Nankai megathrust earthquake tsunami, inundation is forecast over a wide area, mainly along the Pacific Coast. Within this area, Tokushima City in Tokushima Prefecture is made up of 138 large and small rivers, and bridges are commonly seen, making the regional conditions such that traffic could be easily disrupted. Here, we have targeted the road network in a 5 km square range including the central part of Tokushima City, and performed an evaluation of its connectivity reliability in case of a tsunami disaster.

The road data uses the Digital Map 2500 (GSI, MLIT 2006) and considers all national, prefectural and city roads. The extended distance of the target road network is 411.9 km, the number of links is 6,300, the number of nodes is 4,502, and the number of bridges is 55. Established by the Disaster Countermeasures Headquarters, the Tokushima City Hall and Tokushima Prefectural Office, considered to have important functions as bases for recovery, were set as initial nodes, and 50 evacuation points designated by Tokushima City (2016) within the target areas were set as end points, and these were used for route selection.

3.2 *Bridge and Flat Road Link Reliability*

Figure 1 shows the inundation depth distribution and road network for the target area. Here, inundation depth data was used from the fault case 3, set as a large sliding region and ultra-large sliding region from the area off the Kii Peninsula to the area off Shikoku, among the 11 case tsunami fault models shown in Nankai Trough Earthquake Model Review Committee (2012), from which it is envisaged that Tokushima Prefecture will suffer the most severe. In Step 2 on the evaluation framework, the damage function for bridges and flat roads was applied, and the results of calculating link reliability is also shown in Figure 1.

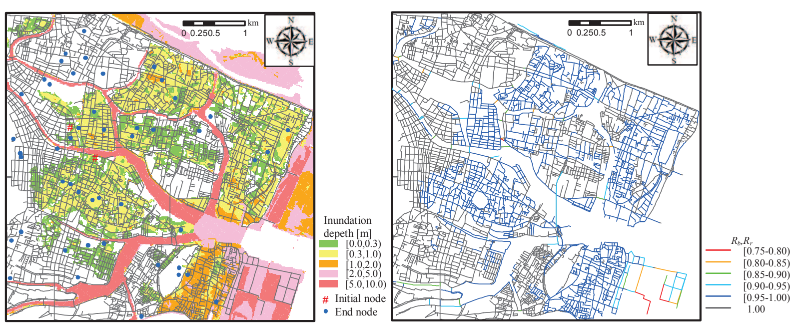
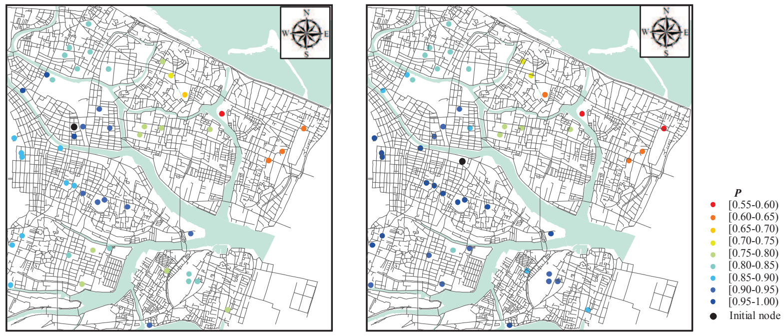


Figure 1. Envisaged inundation depth and link reliability

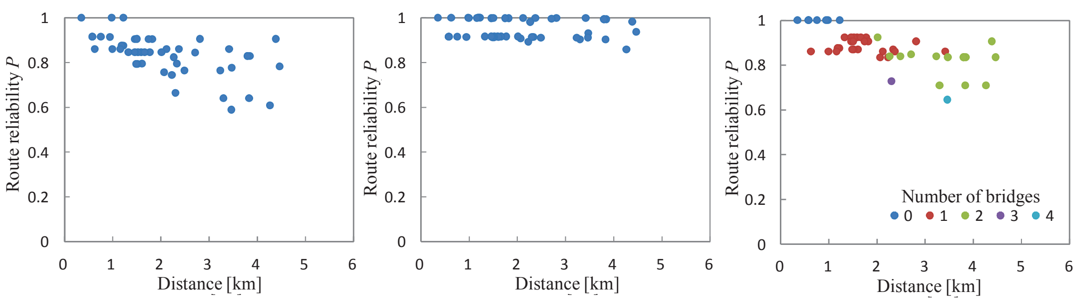
3.3 *Characteristics of Each Case*

In Case 1, the route reliability is calculated in a way that the movement distances between two geographical points is the shortest. Figure 2 shows the route reliability P to each evacuation point when the City Hall and Prefectural Office were used as initial points. For each case, the value of P becomes lower the closer the evacuation point is to the vicinity of the Yoshino river, in the northern area of the target region, and the coastline to the east. The evacuation point in which P was the lowest was the Okinosu area when the Prefectural Office was used as the start point, at P=0.57.



(a) Start point: City Hall (b) Start point: Prefectural Office

Figure 2. Route reliability



(a) Route reliability P for both bridges and flat roads (b) Route reliability P_r for only flat road links (c) Route reliability P_b for only bridge links

Figure 3. Relationship between route reliability and distance for Case 1 where starting point is City Hall

Figure 3 shows the relationship between the distance L, from the initial node to the end node, and route reliability P for Case 1 where starting point is City Hall. We confirmed the three cases of the case of route reliability P, which considers both bridges and flat roads, the case where the flat road link reliability, which considers only the route reliability P_b of bridges is all set to 1.0, and, in the opposite form, where the link reliability for bridge links, which considers only the route reliability P_r of flat roads is set to 1.0.

From Figure 3(a), the route reliability P, with $0<L<1.0$ km, falls to a maximum of P=0.86. Furthermore, when L>2.0 km, $0.59< P <0.99$, and at L=3.47 km, reliability P is at its smallest value. In the same way, in the case where the Prefectural Office is the initial point, when L=3.76 km, P=0.57, which is its smallest value. Hence, where the City Hall and Prefectural Office are initial points, we can understand that the reliability P considering both bridges and flat roads decreases by a maximum of around 60% with the increase in L. On the other hand, from Figure 3(b), whereas a decrease in P_r can be seen with the increase in L within the range L>3.4 km, the values, in general, are distributed around the areas of P_r=1.0 or P_r=0.92. Then, when considering route reliability P_r for flat roads only, we can see that the route reliability P_r is virtually constant regardless of distance L. This suggests that flat road link reliability R_r has virtually little impact on route reliability from the City Hall and the Prefectural Office to the various evacuation points. In contrast to this, from Figure 3(c), when considering the route reliability P_b for bridges only, it is clear that P_b decreases significantly as the number of bridges passed increases. When the number of bridges passed is 0 (zero), route reliability is virtually unaffected, but the route reliability decreases respectively to $0.86<P_b<0.94$ when one bridge is passed and $0.71< P_b <0.92$ when two bridges are passed. In the case in which the Prefectural Office is the initial point, the same tendency is seen, and, in particular, reliability falls significantly to 0.63< P_b <0.84 when 3 bridges are passed.

For Case 2 as well as for Case 1, even in terms of the relationship between the distance L from initial node to end node, and route reliability P, the exact same trends were demonstrated. As for Case 1 in Figure 3, with the route reliability P between two points decreasing as distance L increases, and the route network functionality is clearly highly dependent on the number of bridges passed.

3.4 *Comparison of Case 1 and Case 2*

Figure 4 shows the results of comparing the distance L and route reliability P with the start point of the City Hall, respectively, for Case 1 and Case 2. Compared to Case 1 in which each route between the two points from the City Hall and the Prefectural Office, to 50 evacuation points, is evaluated with the distance l of the links comprising the routes used as the cost as is, to find the shortest route, in Case 2, in which the shortest route is searched for by applying a weighted cost to distance l_s when evaluating so that trunk roads in the emergency road/transport road class are passed as a priority, distance increased by an average of 5.4%. In the case where the City Hall was the initial point, this distance L increased a maximum of 34%, and in the case where the Prefectural Office was the initial point, this increased up to 40%.

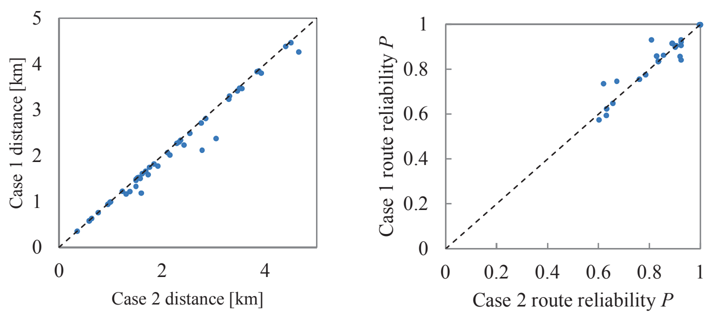


Figure 4. Comparison of distance and route reliability between Case 1 and Case2 where starting point is City Hall

Despite the fact that the distance L generally increased between two points, for routes to a total of 29 evacuation points in Figure 4 where the City Hall was the initial point, and for routes to a total of 24 evacuation points where the Prefectural Office was the initial point, reliability P increased, providing the result that route selection using the trunk road was preferable. On the other hand, in the case of Figure 4 where the City Hall was the initial point, for the 3 routes in which the number of bridges passed increased compared to Case 1, the result was that route reliability P was greatly reduced compared to Case 2. In the same way, even in the case where the Prefectural Office was the starting point, for the two routes in which the number of bridges passed increased and the one route where the distance L became 17% longer, a major decrease was seen in route reliability P.

4 Conclusions

We have proposed a method of quantitatively evaluating the functional disruption on a road network from the perspective of physical damage to bridges and flat roads in case of a tsunami disaster and so forth. In reality, as it is also feared that a Nankai megathrust earthquake will occur with a high degree of probability, we used the road network situated in Tokushima City, Tokushima Prefecture, which would be expected to suffer significant damage from a tsunami, as a case study. We clarified the features of route reliability between the two points of the City Hall or the Administrative Office, and 50 evacuation points, and learned the following things.

- The route reliability of road networks with flat roads with low link reliability and bridges were greatly affected, and in some cases the values decreased by up to 60%.
- Based on the proposed method, it is possible to identify regions that can easily become isolated from the perspective of functional disruption at the time of tsunami disasters on road networks.
- The route reliability of the road network may suddenly decrease due to an increase in distance between two geographical points. This trend is particularly strong when there is an increase in the number of bridges crossed.
- Route selection of trunk roads, such as emergency traffic roads and transport roads, that are key at times of tsunami disasters give better overall results from the perspective of route reliability, but it is important to note that where the connecting roads to these trunk roads are weakened due to the effect of the tsunami, the route reliability may in fact decrease.

Acknowledgments

We received data on tsunami height and inundation depths during a Nankai megathrust earthquake from the Nankai Trough Earthquake Model Review Committee. We also carry out the road network modeling from valuable supports by Professor Y. Maruyama at Chiba University .We would like to take this opportunity to deeply express our gratitude to all involved.

References

Geospatial Information Authority of Japan, Ministry of Land, Infrastructure, Transport and Tourism, Digital Map 2500 (National Geospatial Framework), 2006.

Habuka, Y. and Maruyama, Y., Proper Location of Disaster Response Base in Kochi Prefecture with Emphasis on Accessibility, *Journal of JSCE, Division A: Structural Engineering/Earthquake Engineering*, 71(4), I_257-I_264, 2015.

Itagaki, O. and Maruyama, Y., Damage Ratio of Regional Road due to the 2011 off the Pacific Coast of Tohoku Earthquake Tsunami, *Journal of JSCE, Division A: Structural Engineering/Earthquake Engineering*, 72(4), I_82-I_89, 2016.

Ministry of Land, Infrastructure and Transport, *Record of the Great East Japan Earthquake-Disaster Response*, Mar 11, 2012. Available on Mar 7 2018: http://www.mlit.go.jp/common/000208803.pdf

Nankai Trough Earthquake Model Review Committee, *Secondary Report, Tsunami Fault Model Edition - Tsunami Fault Model and Wave Height/Inundation Areas*, 2012. Available on Mar 7 2018: http://www.bousai.go.jp/jishin/nankai/model/

Nojima, N. and Yamanaka, T., Performance-Based Prioritization in Upgrading Seismic Reliability of Road Network, in *Proceedings of the 10th Japan Earthquake Engineering Symposium*, no.J-12, 3205-3210, Tokyo, Japan, 1998.

Shoji, G. and Nakamura, T., Damage Assessment of Road Bridges Subjected to the 2011 Tohoku Pacific Earthquake Tsunami, *Journal of Disaster Research*, 12(1), 79-89, 2017.

Tokushima City Official Website, List of Tokushima City Evacuation Points (Evacuation Points at Time of General Disasters or Earthquake Disasters), 2016. Available on Mar 7 2018: https://www.city.tokushima.tokushima.jp/anzen/shoubo_bousai/hinanjo_list/ichiran.html

Toyota, A. and Shoji, G., The Relation between the Function on Emergency Road Networks and the Efficiency of Local Assistance during the Post-Earthquake Restoration Process of Lifeline Systems, *Journal of JSCE, Division A: Structural Engineering/Earthquake Engineering*, 66(1), 317-327, 2010.