17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

ROAD NETWORK RELIABILITY INFLUENCED BY TSUNAMI FLOATING BODIES ACTING ON A BRIDEGE DECK

X. Liu [(1)], G. Shoji [(2)]

[(1)] *Graduate Student, Department of Engineering Mechanics and Energy, University of Tsukuba, s1820957@s.tsukuba.ac.jp*
[(2)] *Professor, Faculty of Engineering, Information and Systems, University of Tsukuba, gshoji@kz.tsukuba.ac.jp*

Abstract

A tsunami caused by the 2011 off the Pacific coast of Tohoku earthquake hit the Pacific coast of eastern Japan in March of that year. It caused extensive damage to bridge structures, and numerous instances of damage due to tsunami floating bodies (TFBs) were captured on video. A method for evaluating the system reliability of road networks (RNs) during a catastrophic tsunami disaster was proposed based on physical tsunami damage functions for roads and bridges by Ito and Shoji (2018). However, no previous study has dealt with the physical damage done to bridge structures by TFBs. A model for evaluating road system reliability against TFBs was proposed by Liu and Shoji (2019), in which the damage mechanism is based on hydraulic experiments to clarify the relationships among the Froude number F_r, the blockage rate γ_{cv} and the residual rate γ_l. In the present paper, the proposed model is used in case studies involving the RN in the city of Tokushima in Japan, and the system reliability of the RN considering TFB damage is investigated.

The targeted RN in Tokushima City is modelled based on data published by the Geospatial Information Authority of Japan (2006). The start positions are the Tokushima prefectural and city offices, and the end positions are 50 shelters on the targeted RN taken from the Tokushima City Shelters List (2016). In step 2, the link reliability of each road and bridge is calculated separately with different damage functions. The link reliability R_r of roads is computed as $R_r = 1 - P_R(\nu)$ with $P_R(\nu) = e^{-\nu l}(\nu l)^n/n!$, where the damage rate ν is defined using road damage functions from Iitagaki and Maruyama (2016). The bridge reliabilities are calculated separately according to the value of F_r. For $0.24 \leqq F_r \leqq 0.84$, the bridge link reliability $R_b = 1 - \gamma_l$ is applied to the experimental model explaining the relationships between F_r and (i) γ_{cv} and (ii) γ_l, where $\gamma_l = 1/(99.386\gamma_{cv} + 4.925)$ and $\gamma_{cv} = 0.479 F_r^{1.873}$ (Liu and Shoji, 2019). For $F_r > 0.84$, R_b is calculated using the damage function focusing on washed-away bridges by Shoji and Nakamura (2017). In step 3, priority is given to main roads considering temporary recovery routes, for which the shortest routes are calculated. The features of the shortest routes are identified using Dijkstra's algorithm. Finally, the route reliabilities are defined as the route reliability $P_r = \Pi R_r$ of flat roads, the route reliability of $P_b = \Pi R_b$ of bridges and the route reliability $P = P_b \cdot P_r$ considering both bridges and flat roads.

In this paper, the inundation depth is taken with reference to the Investigative Commission focused on the Nankai Trough Earthquake Tsunami (2012), and the tsunami velocity is taken as 2 m/s. The route reliabilities are calculated from the Tokushima prefectural office to the 50 shelters on the targeted RN. In addition, the previous route reliabilities of Ito and Shoji (2018) are analysed regarding only the washed-away bridge damage due to inundation, and these two route reliabilities are compared to clarify the physical damage done to bridge structures by TFBs. The route reliability P decreases with increasing distance from the prefectural office to the 50 shelters. For $0.65 \leqq P \leqq 0.78$, the route reliabilities focusing on only washed-away bridges are smaller than those considering both effects by washed-away bridges and TFBs, which means that inundation is the dominant factor. For $P > 0.78$, the route reliabilities focusing on TFBs are smaller, which means that the effect of inundation is weaker and now TFBs are the main factors regarding bridge damage.

Keywords: tsunami, floating body, road network, route reliability.

1. Introduction

The 2011 off the Pacific coast of Tohoku earthquake (the Tohoku earthquake) occurred at 2:46 PM (local time) on March 11, 2011, with a magnitude of 9.0, causing a massive tsunami in eastern Japan. The tsunami caused extensive damage to the road networks (RNs) in the coastal areas, especially to bridge girders in a wide region of eastern Japan, and this in turn caused great disruption to the post-tsunami rescue and relief activities.

Regarding the RN damage done by tsunami inundation, Ito and Shoji [1] proposed a method for evaluating the system reliability of RNs during a catastrophic tsunami disaster. This proposed framework was applied to case studies involving the RN in Tokushima City, which is expected to suffer greatly in the event of a tsunami caused by a Nankai megathrust earthquake. Based on hydraulic experimental data by Shoji et al. [3] that clarified the damage mechanism of tsunami floating bodies (TFBs) acting on a bridge girder, Liu and Shoji [2] proposed relationships between (i) the Froude number F_r and the blockage rate γ_{cv} of TFBs on a bridge girder and (ii) γ_{cv} and the residual rate γ_l. From the aforementioned studies, an interactive model is proposed for evaluating the functional damage of an RN considering (i) bridge girders being washed away and (ii) blocked or residual of TFBs acting on a bridge girder. The proposed model is then used in a case study of the Tokushima RN to evaluate its link reliability and functioning.

2. Method

2.1 Model of RN

The RN connection reliabilities are evaluated using (i) the modelled network and (ii) inundation depth data analysed by Ito and Shoji [1]. Based on Digital Map 2500 [4] and IPC RN data [5], the national, prefectural and municipal roads are modelled in a 5 km * 5 km area in Tokushima City that includes the prefectural and city offices. As shown in Fig. 1, the total length of the target roads is 411.9 km, and there are 55 bridges. The shortest routes from the prefectural and city offices to 50 shelters intended for a tsunami disaster are identified using Dijkstra's Minimum Cost Path Algorithm. The 50 shelters on the targeted RN were taken from the Tokushima City Shelters List [6]. The data regarding inundation depth were those from the Cabinet Office [7] for Fault Case 3, which assumes a large slip area and a giant slip area from Kii Peninsula to Shikoku Island. The inundation depth data and the RN are shown in Fig. 2.

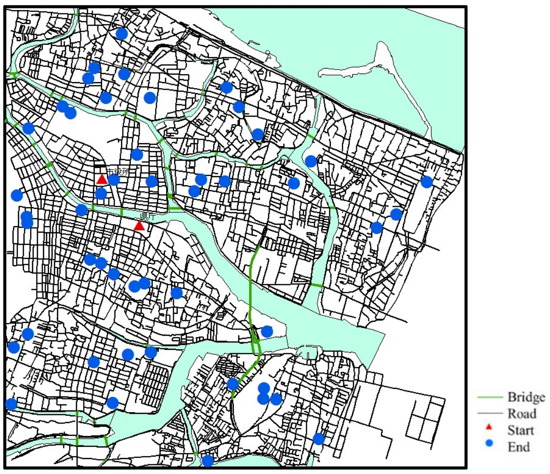


Fig. 1 – Road network (RN)

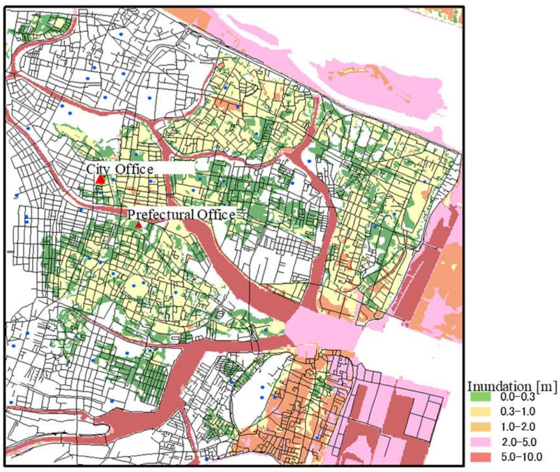


Fig. 2 – RN and tsunami inundation

2.2 Model of damage functions

The link reliabilities of roads and bridges are calculated separately using different damage functions.

1) Flat roads

First, the average inundation depth $\bar{h}$ is defined as

$$\bar{h} = \frac{\Sigma(l_n \cdot h)}{l} \tag{1}$$

where h is the tsunami inundation depth, l is the link length and l_n is the link length corresponding to the inundation depth. Similar to the method applied by Ito and Shoji [1], the damage rate ν [cases/km] of a flat road is defined by Itagaki and Maruyama [8] as

$$\nu = C\Phi(\frac{\ln \bar{h} - \lambda}{\zeta}) \tag{2}$$

where C, λ and ζ are regression constants for geographical features as given in Table 1. In the present study, the geography is defined as being lowland (type IV). The damage probability $P_R(\nu)$ for each flat road is modelled as a Poisson process of the form

$$P_R(\nu) = \frac{(\nu l)^n}{n!} e^{-\nu l} \tag{3}$$

where n is the number of damage occurrences for a road link. Finally, the road link reliability R_r is computed as

$$R_r = 1 - P_R(\nu) \tag{4}$$

with $n = 0$.

Table 1 – Regression constants [8]

Geographical features	C	λ	ζ
I: Areas with river terraces	1.26	2.17	0.21
II: Ria coast	0.41	0.78	0.28
III: Ria coast with lowland	2.06	1.28	0.41
IV: Lowland	1.87	1.79	0.81

© The 17th World Conference on Earthquake Engineering

2) Bridges

The bridge reliabilities are calculated separately according to the value of the Froude number F_r.

For $0.244 \leqq F_r \leqq 0.844$, the experimental model due to Liu and Shoji [2] is used, which explains the relationships between (i) F_r and the blockage rate γ_{cv} and (ii) γ_{cv} and the residual rate γ_l. First, F_r is calculated as

$$F_r = \frac{v_{ave}^1}{\sqrt{g h_{ave}^1}} \tag{5}$$

where g = 9.8 m/s^2, v_{ave}^1 is the tsunami velocity averaged for 1 s from the peak value and h_{ave}^1[cm] is the 1 s averaged tsunami inundation height computed by adding the 1 s averaged front wave height a_{ave}^1[cm] to the still-water level h_0. Second, the blockage rate γ_{cv} and the residual rate γ_l are defined as

$$\gamma_{cv} = \frac{V_{cv}}{V_f} \tag{6a}$$

$$\gamma_l = \frac{V_l}{V_f} \tag{6b}$$

where V_f is the sum of the volume of all floating bodies used in the hydraulic experiment in Shoji et al .[3], V_{cv} is the sum of the volume of all floating bodies blocked by a bridge girder and V_l is the sum of the volume of all residual floating bodies on a bridge girder.

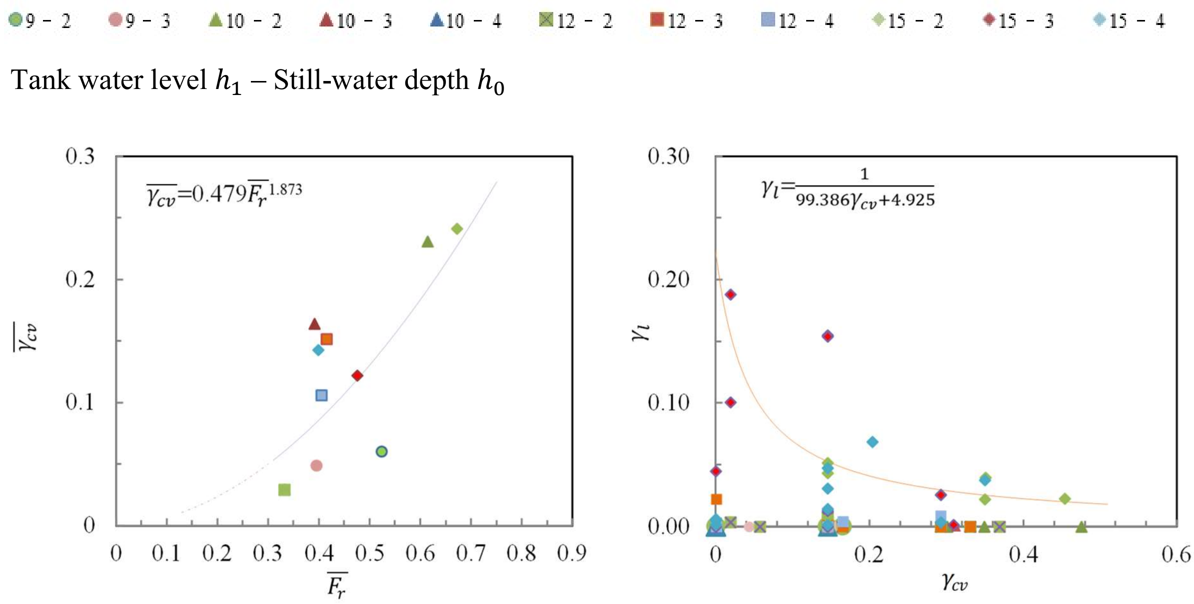


Fig. 3 – Relationship between blockage rate γ_{cv} and residual rate γ_l

© The 17th World Conference on Earthquake Engineering

Then, the models of blockage rate γ_{cv} versus F_r (Fig. 3, left) and residual rate γ_l versus γ_{cv} (Fig. 3, right) are used to evaluate the link reliability of the target RN:

$$\overline{\gamma_{cv}} = 0.479\overline{F_r}^{1.873} \quad (7a)$$

$$\gamma_l = \frac{1}{99.386\gamma_{cv} + 4.925} \quad (7b)$$

where $\overline{\gamma_{cv}}$ and $\overline{F_r}$ are the values of γ_{cv} and F_r, respectively, averaged over 10 instances of each experimental case. Finally, once $\overline{F_r}$ is assumed, by computing $\overline{\gamma_{cv}}$ based on Eq. (7a) and substituting $\overline{\gamma_{cv}}$ into Eq. (7b), the bridge link reliability R_b is computed as

$$R_b = 1 - \gamma_l \quad (8)$$

For $F_r > 0.844$, R_b is calculated using the damage function by Shoji and Nakamura [9] for washed-away bridges. First, the dimensionless inundation depth η is defined as

$$\eta = \frac{h}{h_d} \quad (9)$$

where h_d is the bridge girder height. Second, the damage probability is calculated using the standard normal distribution function

$$P_D(\eta) = \Phi(\frac{\ln \eta - 2.69}{1.48}) \quad (10)$$

Finally, the bridge link reliability R_b is computed as

$$R_b = 1 - P_D(\eta) \quad (11)$$

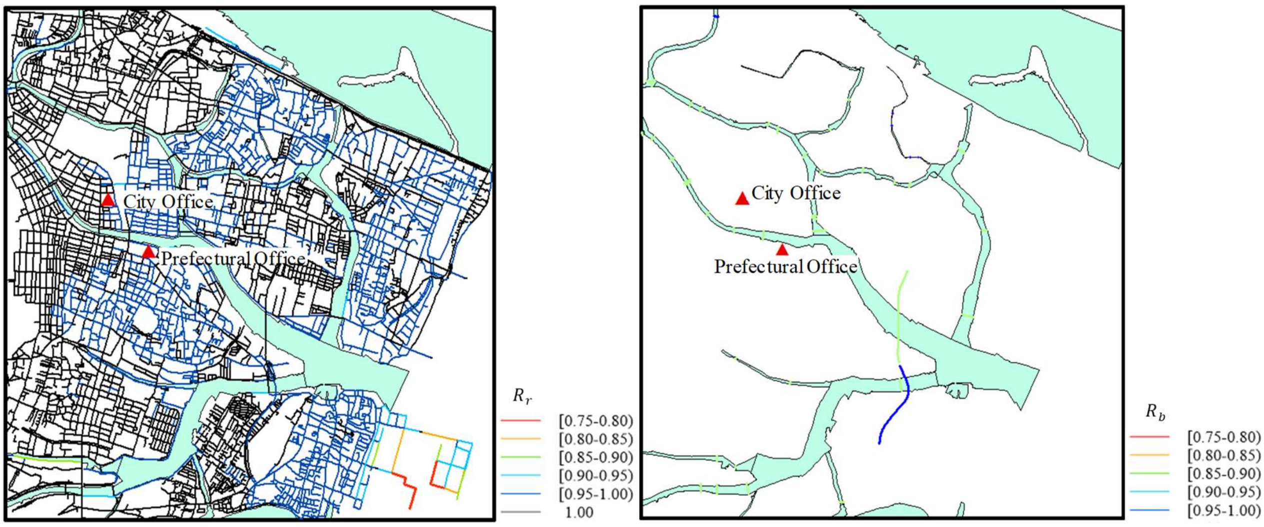
and the calculated link reliabilities for roads and bridges are shown in Fig. 4.

2.3 Setting of analysis case

To consider temporary recovery routes according to road type, priority is given to main roads defined as emergency transportation routes [1]. The weighted distance according to roads type is defined with $s = 1$ for emergency transportation routes (national, prefectural and major regional roads) and $s = 2$ for the others (municipal, agricultural and forest roads):

$$l_s = s \cdot l \quad (12)$$

© The 17th World Conference on Earthquake Engineering



(a) (b)

Fig. 4 – Link reliabilities: (a) road link reliability R_r; (b) bridge link reliability R_b

2.4 Calculation of route reliabilities

The road route reliability P_r, the bridge route reliability P_b and the route reliability P considering both bridges and roads are defined as

$$P_r = \Pi R_r \tag{13a}$$

$$P_b = \Pi R_b \tag{13b}$$

$$P = P_b \cdot P_r \tag{13c}$$

Here, P_r is the road route reliability based on the functional road damage due to tsunami inundation as computed by Ito and Shoji [1], and P_b is the bridge route reliability obtained by multiplying the link reliability R_b shown as Eqs. (8) and (11), which is based on functional damage due to TFBs or washed-away bridges due to inundation calculated separately according to the value of F_r.

3. Discussion

Assuming a tsunami velocity of 2 m/s, the calculated route reliabilities P from the prefectural office to 50 shelters in Tokushima City are shown in Fig. 5, where P by Eq. (13) considers both the functional damage due to TFBs by Eq. (8) and tsunami inundation by Eqs. (4) and (11).

Ito and Shoji [1] calculated the route reliability P_b regarding only tsunami inundation by multiplying the link reliability R_b as shown in Eq. (11). However, the present study considers not only the washed-away bridges due to inundation calculated by Eq. (11) but also the functional damage due to TFBs by Eq. (8). To clarify the differences between the TFB damage and the washed-away damage on bridge girders, and damage mechanism of RNs about especially the bridge girders during tsunami disasters, the calculated route reliabilities P_b and P are compared in Fig. 6 with those due to Ito and Shoji [1]. Both results of the relations between the route reliability P_b and P with distance L from the prefectural office to 50 shelters are shown in these figures.

© The 17th World Conference on Earthquake Engineering

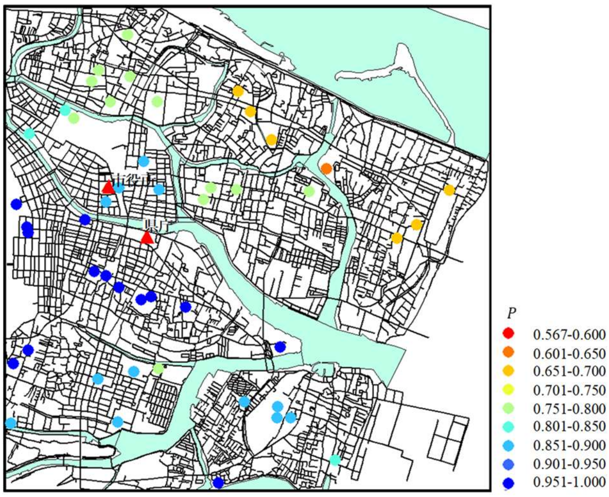
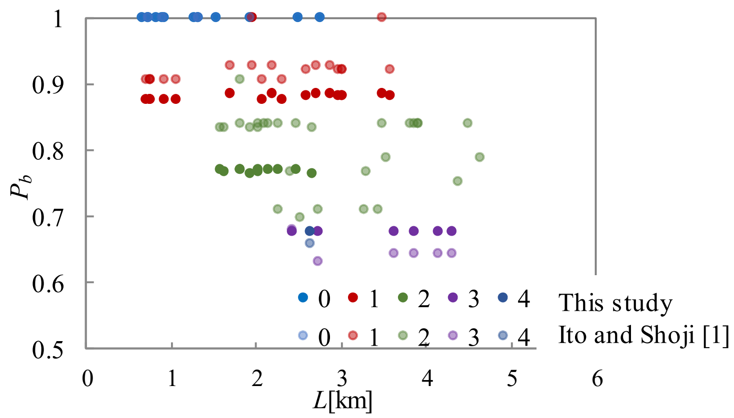
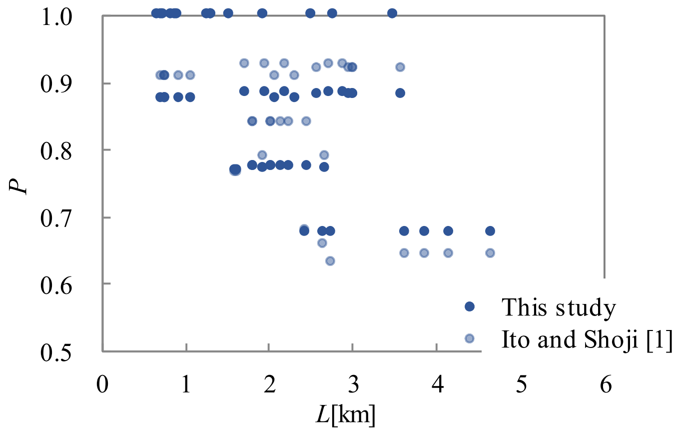


Fig. 5 – Route reliability



(a)



(b)

Fig. 6 – Relationships between route reliability and distance L: (a) route reliability P_b versus L; (b) route reliability P versus L

In Fig. 6(a), there is a clear trend of decreasing reliability P_b with increasing distance L. The number of bridge crossings is presented with different colours. As shown in Figs. 6(a) and 6(b), the relationships between the distance L and the route reliabilities P_b and P can explain the same mechanism, and among them, the relationship between P and L is judged to be the most explanatory.

© The 17th World Conference on Earthquake Engineering

In Fig. 6(b), if the route reliability is relatively high at $P > 0.78$, then P calculated by Eq. (13) considering both the functional damage due to TFBs and washed-away damage of bridge girders is lower than P due to only washed-away damage of bridge girders by Ito and Shoji [1]. The reason for this is considered to be that the impassable impact of residual floating bodies acting on the bridge girders to the link reliability is greater than that caused by washed-away bridge girders due to tsunami inundation. At that time, the impact γ_l of residual floating bodies on the bridge girders by Eq. (7) is larger, in which case the bridge link reliability R_b by Eq. (8) is lower. Conversely, Fig. 6(b) also shows that with increasing distance L, the route reliability P decreases to around 0.65. For the $0.65 < P \leq 0.78$ case, the route reliability P is lower, the damage probability $P_D(\eta)$ by Eq. (10) is larger, R_b by Eq. (11) is lower, whereupon P becomes lower.

4. Conclusions

In this paper, an interactive model is proposed for evaluating the functional damage of an RN considering both washed-away bridge girders and blocked or residual of TFBs acting on a bridge girder. The proposed model is used in a case study of the Tokushima RN, and the following conclusions are drawn.

When the effect of bridge girders washed away by tsunami inundation is not significant and the only dominant effect is that of floating bodies acting on bridge girders, the route reliability P is greater than 0.78. At that time, the impact γ_l of residual floating bodies acting on bridge girders is larger, whereupon the bridge link reliability R_b is lower.

5. Acknowledgements

The Nankai Trough Giant Earthquake Tsunami Model Study Group provided the tsunami inundation data, and Prof Yoshihisa Maruyama of Chiba University provided the basic road network data. We would like to thank all those involved here. The support by JSPS KAKENHI Grant Number JP 17H01287 is gratefully acknowledged. The authors would like to thank MARUZEN-YUSHODO Co., Ltd. (https://kw.maruzen.co.jp/kousei-honyaku/) for the English language editing.

6. References

[1] Ito S, Shoji G (2018): Evaluation framework of foundation disruption of road network during a tsunami disaster, *Journal of Japan Society of Civil Engineers A1*, **74**(4), 120-130 (In Japanese).

[2] Liu X, Shoji G (2019): Modeling of tsunami floating bodies acting on a bridge deck. *Proceedings of the 9th Symposium on Disaster Mitigation and Resilience of the Infrastructures and Lifeline Systems*, *Journal of Japan Society of Civil Engineers*, 113-118, University of the Ryukyus, Japan (In Japanese).

[3] Shoji G, Liu X, Iidaka N (2019): Experimental study associated with tsunami floating bodies acting on a bridge deck, *Journal of Japan Society of Civil Engineers A1*, **75**(4), 639-656 (In Japanese).

[4] GSI (2006): Digital Map 2500 (Spatial Data Infrastructure).

[5] Orkney Inc (2009): IPC Road Network Data (Nationwide) Fall 2009.

[6] List of evacuation shelters in Tokushima City (2016): https://www.city.tokushima.tokushima.jp/anzen/shoubo_bousai/hinanjo_list/ichiran.html.

[7] Nankai Trough Giant Earthquake Model Study Group (2012): Nankai Trough Giant Earthquake Model Study Group (Second Report, Tsunami Fault Model Edition), Cabinet Office, Government of Japan.

[8] Itagaki O, Maruyama Y (2016): Damage Ratio of Regional Road due to the 2011 off the Pacific coast of Tohoku Earthquake Tsunami, *Journal of Japan Society of Civil Engineers A1 (Structure and Earthquake Engineering)*, **72**(4), 82-89 (In Japanese).

[9] Shoji G, Nakamura T (2017): Damage assessment of road bridges due to the 2011 off the Pacific coast of Tohoku earthquake tsunami, *Journal of Disaster Research*, **12**(1), 79-89.

© The 17th World Conference on Earthquake Engineering