Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

TSUNAMI DAMAGE ASSESSMENT ON ROAD STRUCTURES IN THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

Gaku SHOJI[1], Tomoharu NAKAMURA[2] and Kazunori TAKAHASHI[3]

[1] Associate Professor, Faculty of Engineering, Information and Systems, University of Tsukuba,
Ibaraki, Japan, gshoji@kz.tsukuba.ac.jp
[2] College of Engineering Systems, University of Tsukuba,
Ibaraki, Japan, s0811237@u.tsukuba.ac.jp
[3] Graduate Student, Graduate School of Systems and Information Engineering, University of Tsukuba,
Ibaraki, Japan, s1120951@u.tsukuba.ac.jp

ABSTRACT: We assess the tsunami damage on road structures due to the 2011 off the Pacific Coast of Tohoku earthquake tsunami. The damage on national roads and expressways at thirteen prefectures of Tohoku and Kanto regions, and the damage on prefectural roads at five prefectures of Tohoku regions are assessed. For related 142 data, we analyzed the damage modes due to tsunami wave loads, and clarified damage ratio R_N^b defined by the value of number of bridge damage points N_d^b divided by total number of exposed bridges N_t^b, focusing on wash-away bridges.

Key Words: The 2011 off the Pacific Coast of Tohoku earthquake tsunami, road structure, bridge, tsunami damage

INTRODUCTION

In the 2011 off the Pacific Coast of Tohoku earthquake (*Mw*=9.0) on March 11, 2011(JMA 2011), extensive damage of road structures located at Tohoku areas such as Iwate, Miyagi and Fukushima prefectures occurred due to the tsunamis. We collect 142 damage data of road structures due to the tsunamis opened at the related web sites for analyses and classify 29 failure modes. For damage assessment of bridges, we obtain the inundation heights at damaged bridges due to the tsunamis by series of tsunami flow simulation based on shallow water theory, which are discretized by using the finite difference method with a staggered leap-flog scheme (DCRC 2009). Finally, we calculate damage ratio R_N^b dependent on an inundation height, which is defined by the value of number of bridge damage points N_d^b divided by total number of exposed bridges N_t^b, focusing on wash-away bridges.

Table 1 Analyzed data of damaged road structures

Road Management Sectors	Damage Information (URL)	Road Management Sectors	Damage Information (URL)
Tohoku Regional Development Bureau Main Office	【Disasiter Prevention Imformation】(Press Release) Tohoku Regional Development Bureau Earthquake Imformation (15th Version) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1110.htm	Kanto Regional Development Bureau Omiya National Road Office	Road Damage Information in the 2011 off the Pacific Coast of Tohoku Earthquake (1st and 3rd Versions) http://www.ktr.mlit.go.jp/oomiya/04data/kisha/h22.htm
Tohoku Regional Development Bureau Iwate River and National Road Office	Earthquake Imformation : Iwate River and National Road Office (2nd and 3rd Versions) http://www.thr.mlit.go.jp/iwate/bousai/bousai/index.htm	Kanto Regional Development Bureau Shuto National Road Office	Damage of National Road No. 298 (18:50 on March 11) http://www.ktr.mlit.go.jp/syuto/index.htm
Tohoku Regional Development Bureau Sanriku National Road Office	Sanriku National Road Office Earthquake Imformation (2nd Version) http://www.thr.mlit.go.jp/sanriku/index.html	Kanto Regional Development Bureau Yokohama National Road Office	Damage Imformation in the 2011 off the Pacific Coast of Tohoku Earthquake (3rd Version) http://www.ktr.mlit.go.jp/yokohama/report/bn2010.htm
Tohoku Regional Development Bureau Sendai River and National Road Office	【Disasiter Prevention Imformation】 (Press Release) Sendai River and National Road Office Disaster Information (3rd, 13th, and 14th Versions) http://www.thr.mlit.go.jp/sendai/index.html	Aomori Prefecture	Disaster Countermeasures Office About the Damage in the 2011 off the Pacific Coast of Tohoku Earthquake (43th Version) http://www.pref.aomori.lg.jp/
Tohoku Regional Development Bureau Yamagata River and National Road Office	【Disasiter Prevention Imformation】 Yamagata River and National Road Office Earthquake Imformation (3rd, 4th, 6th, and 7th Versions) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1106.htm	Iwate Prefecture	Situation of Road Traffic Regulation Management due to the Earthquake in Iwate Prefecture on March 11 (As of 9:30 on August 12) http://www.pref.iwate.jp/list.rbz?nd=2974&ik=1&pnp=2974&of=13
Tohoku Regional Development Bureau Fukushima River and National Road Office	【Disasiter Prevention Imformation】Fukushima River and National Road Office Earthquake Imformation (8th Version) http://www.thr.mlit.go.jp/fukushima/pressedit/disaster_index.html	Akita Prefecture	Imformation Earthquake (2nd, 4th, 5th, 6th, and 9th Versions) http://www.pref.akita.lg.jp/www/genre/0000000000000/1243242791775/index.html
Tohoku Regional Development Bureau Koriyama National Road Office	【Disasiter Prevention Imformation】 Koriyama National Road Office : Emergency System Response in the 2011 off the Pacific Coast of Tohoku Earthquake (2nd, 8th, and 20th Versions) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1117.htm	Miyagi Prefecture	Traffic Regulation in the 2011 off the Pacific Coast of Tohoku Earthquake (As of 16:00 on May 8) http://www.pref.miyagi.jp/road/kiseinow.htm Damag of Public Facility and Emergency Disaster Recovery Situations in the 2011 off the Pacific Coast of Tohoku Earthquake (Updated August 10) http://www.pref.miyagi.jp/doboku/110311dbk_taiou/index.htm
Tohoku Regional Development Bureau Banjyo National Road Office	【Disasiter Prevention Imformation】 Banjyo National Road Office : Road Disasiter Prevention Imformation Earthquake (5th Version) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1132.htm	Yamagata Prefecture	(Press Release) The 2011 off the Pacific Coast of Tohoku Earthquake (3rd and 10th Versions) http://www.pref.yamagata.jp/
Kanto Regional Development Bureau Main Office	Road Division at Kanto Regional Development Bureau Disaster Imformation of National Road in the 2011 off the Pacific Coast of Tohoku Earthquake (15:00 on March 18, 2011) http://www.ktr.mlit.go.jp/saigai/kyoku_dis00000021.html	East Nippon Expressway Company Limited	Damaged Routes and Sections (List) (March 18) http://www.e-nexco.co.jp/whatsnew/h22.html
Kanto Regional Development Bureau Hitachi River and National Road Office	Hitachi River and National Road Office (Press release) : Announcement for the Damage due to the 2011 off the Pacific Coast of Tohoku Earthquake (10:30 on March 12, 2011) http://www.ktr.mlit.go.jp/kisha/index00000022.html	Metropolitan Expressway Company Limited	(Press Release) Influence and Emergency Response due to the 2011 off the Pacific Coast of Tohoku Earthquake and Correspondence (March 14, 2011) http://www.shutoko.jp/
Kanto Regional Development Bureau Utsunomiya National Road Office	Road Damage Information for the 2011 off the Pacific Coast of Tohoku Earthquake (17:00 on March 11, 18:30 on March 11, 12:00 on March 12) http://www.ktr.mlit.go.jp/utunomiya/bousai/old.htm	—	—

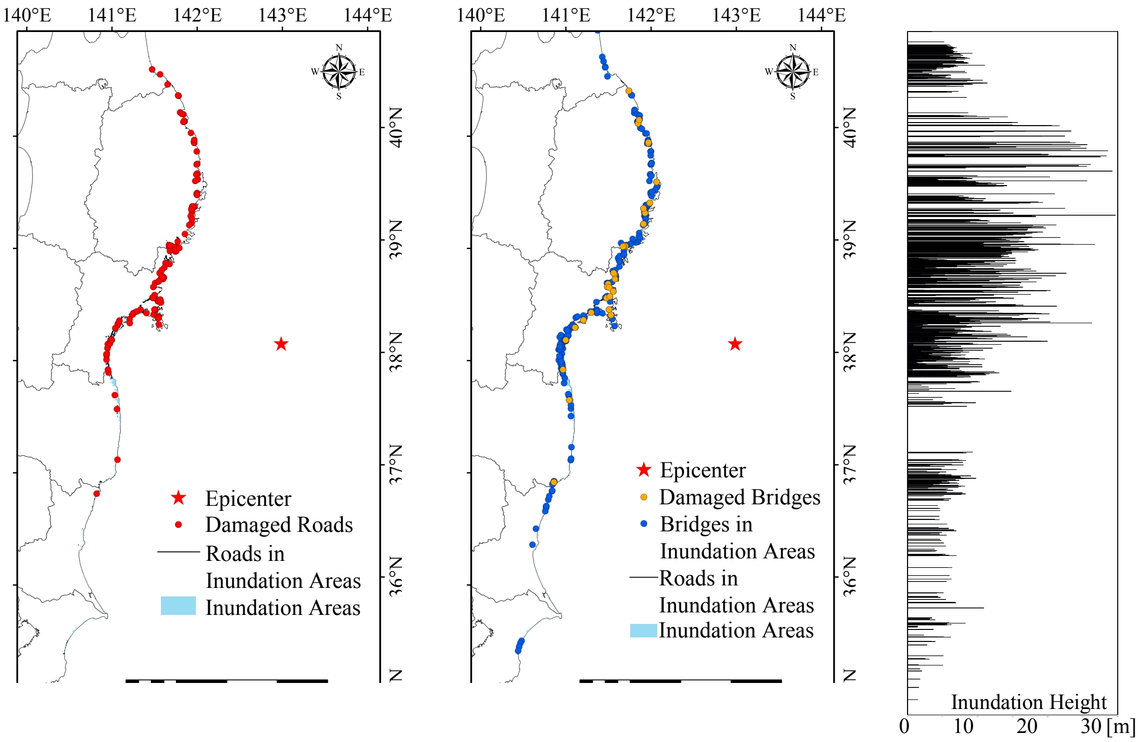
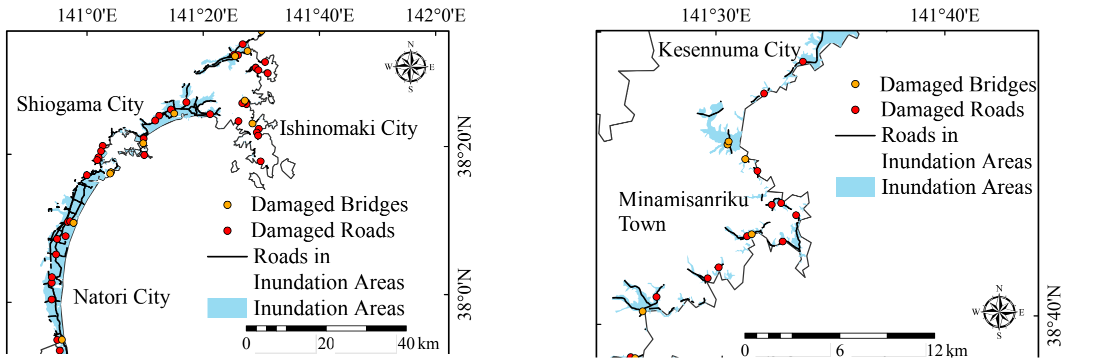


Fig. 1 Locations of damaged road structures and the related inundation height



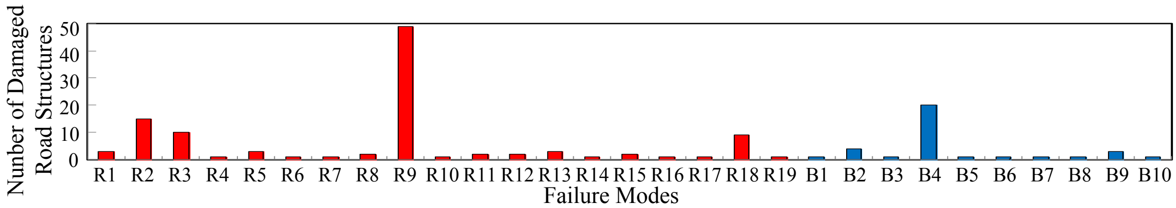
(a) Ishinomaki City, Shiogama City and Natori City

(b) Kesennuma City and Minamisantiku Town

Fig. 2 Locations of damaged road structures in Miyagi prefecture

ANALYZED DATA OF DAMAGED ROAD STRUCTURES

Table 1 shows the information on damaged road structures which is opened at the related web sites by road management authorities and local government sectors. Analyzed road structures are national roads at six prefectures of Tohoku regions, Tokyo metropolitan areas and six prefectures of Kanto regions by Tohoku Regional Development Bureau, Kanto Regional Development Bureau, East Nippon Expressway Company Limited and Metropolitan Expressway Company Limited, and prefectural roads at five prefectures of Tohoku regions without Fukushima prefecture by local government sectors. Total number of data is 680. For selecting 680 data, we remove the damage data to be possibly affected by the ground motions due to the aftershocks after March 11, 2011. Based on the data, first, we identify the locations of damaged road structures. Second, we select 140 data as the data of damaged road structures due to the tsunami waves by comparing the locations of damaged road structures with



Road Damage		Bridge Damage	
R1	Souring	B1	Bridge Bump
R2	Wash-away	B2	Failure of Abutment
R3	Road Failure	B3	Bridge Failure
R4	Subsidence	B4	Falling-down
R5	Collapse	B5	Wash-away of Sidewalk of Bridge
R6	Wash-away of Pavement Slab and Collapse of Road Shoulder	B6	Wash-away of Embankment of Abutment and Falling-down of Service Road Bridge
R7	Wash-away of Road Surface and Collapse of Road Surface	B7	Wash-away of Embankment of Abutment and Falling-down
R8	Collapse of Slope of Embankment	B8	Wash-away of Embankment of Abutment
R9	Deposits	B9	Deposits
R10	Deposits and Road Bump	B10	Wash-away of Pavement Slab and Failure of Handrail
R11	Deposits and Collapse of Road Shoulder		
R12	Deposits and Wash-away of Pavement Slab		
R13	Deposits, Collapse of Road Shoulder and Wash-away of Pavement Slab		
R14	Deposits and Failure of Pavement Slab		
R15	Deposits and Fallen rock		
R16	Deposits, Submergence of Road and Failure of Slope of Embankment		
R17	Deposits and Disruption of Road		
R18	Submergence of Road		
R19	Submergence of Road and Road Failure		

Fig. 3 Failure modes of damaged road structures

estimated inundation areas by GSI (2011) and by considering tsunami failure modes for damaged road structures. We verify all data by checking the locations by GoogleEarth. In addition, we add two damaged bridge data located at prefectural roads, Route 44 in Iwate prefecture to 140 data, by identifying the locations of damaged road structures. Finally, total number of analyzed data is 142. Fig. 1 shows the locations of damaged road structures. Fig. 2 shows the locations of damaged road structures in Miyagi prefecture. 142 data are clarified into two types, road damage and bridge damage. For 109 damaged roads, 55 data are observed in Miyagi prefecture, 46 data in Iwate prefecture, 4 data in Fukushima prefecture, 3 data in Aomori prefecture and 1 data in Ibaraki prefecture. For 33 damaged bridges, 18 data are observed in Miyagi prefecture, 13 data in Iwate prefecture, and 2 data in Fukushima prefecture. We model subject roads and bridges in estimated inundation areas by GSI (2011): by using the digital data of national roads and major prefectural roads in 6 prefectures of Tohoku regions, Tokyo Metropolitan areas and 6 prefectures of Kanto regions offered by National Land Numerical Information Download Service (2011) and by constructing the digital data of other prefectural roads in 5 prefectures of Tohoku regions except Fukushima prefecture by checking GoogleEarth. Total length of subject roads is 518km and total number of subject bridges is 230.

FAILURE MODES OF DAMAGED ROAD STRUCTURES

Fig. 3 shows classified 29 failure modes for 109 damaged roads and 33 damaged bridges. 109 data of road damage are classified into 19 failure modes, which are observed in dominantly 50 deposits (R9), 15 wash-aways (R2) and 10 road failures (R3). 33 data of bridge damage are classified into 10 failure modes, which are observed in dominantly 20 falling-downs (B4), 4 failures of abutment (B2) and 2 deposits (B9). From the analysis on above failure modes, we focus on bridge damage in the following section.

Table 2 Subject damaged bridges

Group No.	Name of Damaged Bridges	Longtitude	Latitude	Name of Roads	Failure Modes	No. of the Observetion Sites for Inundation Height
1	Waza Bridge	141.728	40.389	Kadono-hamatamagawa Line of Iwate Prefectural Route 247	B10	2
2	Hirouchi Bridge	141.838	40.126	Noda-osanai Line of Iwate Prefectural Route 268	B3	4
3	Yoneda Bridge	141.826	40.097	National Route 45	B6	14
4	No Name	141.939	39.927	Iwaizumi-hiraga-furai Line of Iwate Prefectural Route 44	B4	6
	No Name	141.939	39.919	Iwaizumi-hiraga-furai Line of Iwate Prefectural Route 44	B4	
5	Mukouwatashi Bridge	142.023	39.573	Omoe-hanto Line of Iwate Prefectural Route 41	B4	4
6	Namiita Bridge	141.937	39.383	National Route 45	B2	2
7	Hinokami Bridge	141.868	39.336	Kamaishi-Tono Line of Iwate Prefectural Route 35	B9	4
8	Toyasaka Bridge	141.884	39.300	National Route 45	B2	10
9	Katagishi Bridge	141.863	39.203	National Route 45	B2	5
10	Kawaharagawa Bridge	141.630	39.009	National Route 45	B4	19
	Numata Overbridge	141.649	39.009	National Route 45	B4	
	Kesen Bridge	141.621	39.005	National Route 45	B4	
11	Koizumi Long-bridge	141.508	38.770	National Route 45	B4	8
	Sodeogawa Bridge	141.507	38.768	National Route 45	B5	
	Nijyuuichihama Bridge	141.520	38.759	National Route 45	B7	
12	Utatsu Bridge	141.523	38.716	National Route 45	B4	8
13	Mizushiri Bridge	141.443	38.674	National Route 45	B4	8
	Oritate Bridge	141.437	38.647	National Route 398	B4	
	Yokotsu Bridge	141.456	38.638	National Route 398	B4	
14	Shin-aikawa Bridge	141.501	38.603	National Route 398	B4	1
15	No Name	141.460	38.558	Kamaya-oosu-ogatsu Line of Miyagi Prefectural Route 238	B8	4
	Shin-kitakami Bridge	141.423	38.547	National Route 398	B4	
16	Onagawa Bridge	141.449	38.447	National Route 398	B4	4
17	Sadakawa Bridge	141.247	38.420	Ishinomakikougyouko-yamoto Line of Miyagi Prefectural Route 247	B4	23
18	Nonohama Bridge	141.470	38.394	Onagawa-oshika Line of Miyagi Prefectural Route 41	B4	6
19	Matsugashima Bridge	141.157	38.354	Okumatsushima-matsushimakouen Line of Miyagi Prefectural Route 27	B4	6
20	Niramori Bridge	141.064	38.290	Shiogama-shichigahama-tagajyo Line of Miyagi Prefectural Route 58	B4	15
21	Hashimoto Bridge	141.061	38.287	Shiogama-shichigahama-tagajyo Line of Miyagi Prefectural Route 58	B4	11
22	Miyashita Bridge	140.955	38.177	Yuriagekou Line of Miyagi Prefectural Route 129	B4	32
23	Takaura Bridge	140.918	37.914	Somawatari Line of Fukushima and Miyagi Prefectural Route 38	B2	24
24	Ootagawa Bridge	140.984	37.643	National Route 6	B9	1
25	Samekawa Bridge	140.801	36.912	National Route 6	B1	4

Table 3 Number of grids for all groups

Region	Group No.	X-direction	Y-direction	Grid Size[m]
1	All Groups	480	720	1350
2	All Groups	481	721	450
3	All Groups	481	721	150
4	8,10	541	901	50
	Others	481	721	
5	8	721	481	16.67(50/3)
	10,15,17, 18,19,20	481	721	
	12	601	601	
	Others	721	721	
6	8	931	931	6.67(50/9)
	12	601	601	
	14,16	621	621	
	15	481	721	
	17	721	481	
	18,19,20	931	481	
	Others	721	721	

DAMAGE ASSESSMENT OF BRIDGES

Analytical framework

We define damage ratio of bridges R_N^b as measure of bridge damage by the tsunamis. R_N^b is the ratio of the number of damaged bridges N_d^b divided by total number of bridges N_t^b,

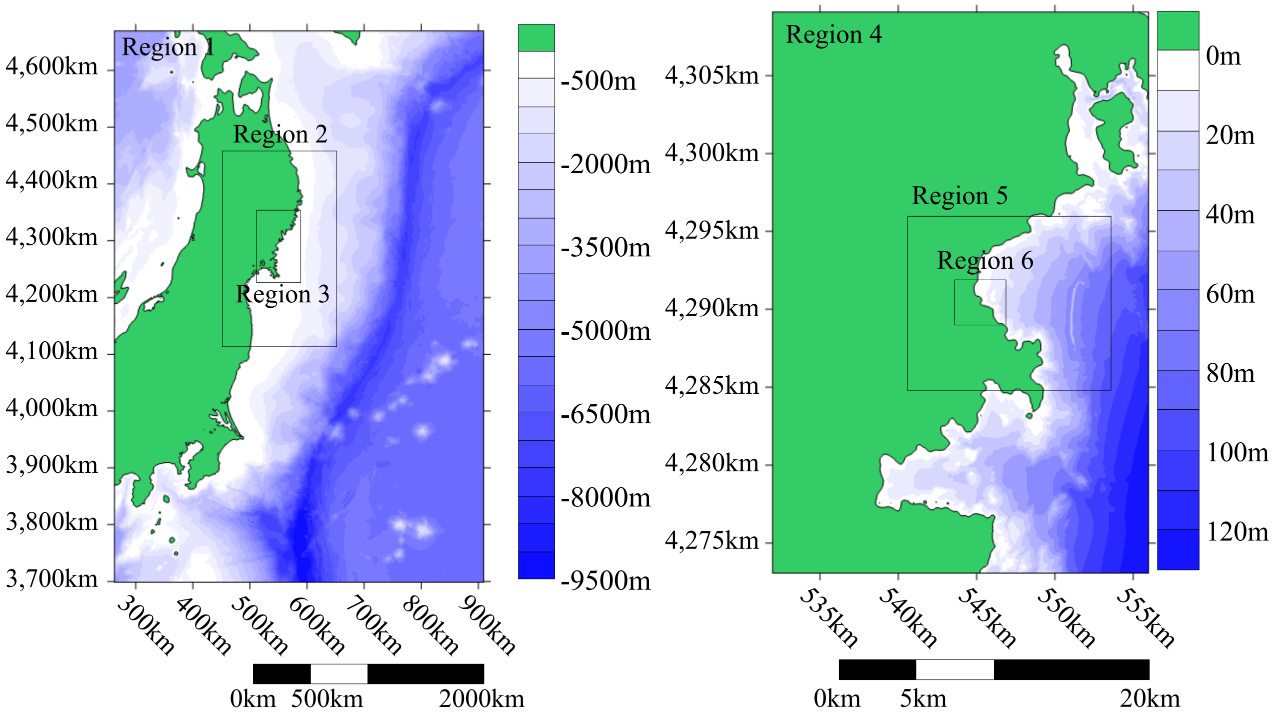
$$R_N^b = \frac{N_d^b}{N_t^b} \tag{1}$$

For the following analyses in calculating the number of damaged bridges N_b^d at a 2.0m interval of inundation heights, we use the simulated data for the corresponding inundation heights at damaged bridges from numerical simulation as described in the following subsection. And in calculating the number of non-damaged bridges (N_t^b-N_d^b) at a same class of inundation heights, we use the observed data for the corresponding inundation heights at non-damaged bridges with reliability level A and B by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (2011), which are measured in the closest site from subject non-damaged bridge. When we select the corresponding observed data, if the distance from a non-damaged bridge site to the observation site becomes more than 250m, we consider that we do not have the reasonable corresponding observed data for an inundation height at a non-damaged bridge and we remove the data for the analyses.

Finally, we use 33 simulated data for the inundation heights at damaged bridges and 91 observed data for inundation heights at non-damaged bridges.

Numerical simulation for calculating inundation heights at damaged bridges

Table 2 shows subject damaged bridges with failure modes of B1 to B10 in Fig. 3 and corresponding classification of simulation groups for Group 1 to Group 25. For each simulation group, the tsunami wave propagation is computed by using TSUNAMI-CODE (Tohoku University's Numerical Analysis Model for Investigation of Tsunami), and the corresponding inundation heights at subject damaged bridges are computed. The governing equations are based on shallow water theory, which are discretized by using the finite difference method with a staggered leap-flog scheme (DCRC 2009). We set the value of Manning roughness coefficient n as 0.025 for all groups. For each simulation group,



(a) Region1 to Region3 (b) Region4 to Region6

Fig. 4 Computational boundary for Group 11 simulation

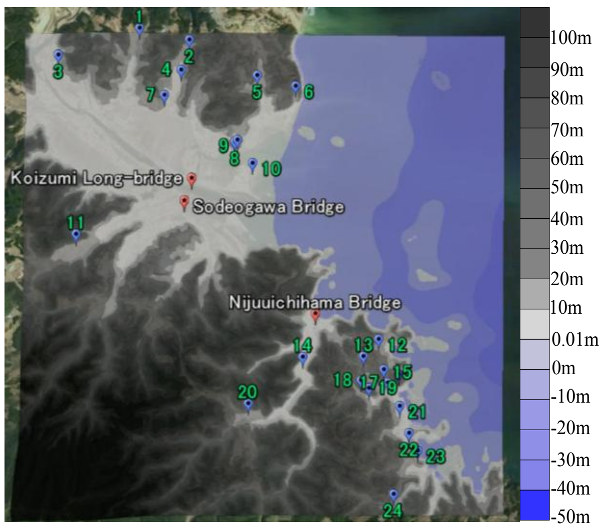


Fig. 5 Elevation for Group 11 simulation (Red denotes the positions of subject bridges, blue denotes the positions of observation sites for inundation heights.)

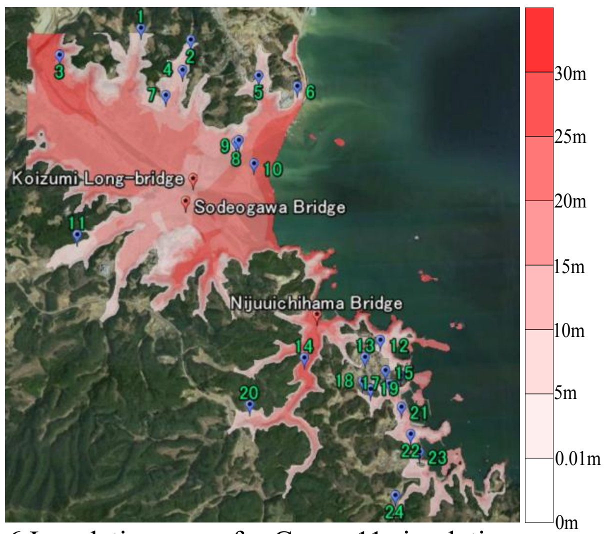


Fig. 6 Inundation areas for Group 11 simulation (Red and blue dots donate same meanings as those in Fig. 5)

six computational regions (Region 1 to Region 6) are used in the nested grid system. Table 3 shows the number of grids in x-direction and y-direction for each simulation group in WGS-1984-UTM-54-N coordinate system.

Region 1 is used together in all groups. Region 2, Region 3, and Region 4 are used together in Group 10 and Group 12. Region 2, Region 3, and Region 4 are also used together in Group 13 and Group 15. Other Regions are used separately for each simulation group. Region 1 is generated by using GEBCO 30 second data with the grid size of 1,350m. Region 2, Region 3, and Region 4 are generated by using GEBCO 30 second data for topography and JHA 1m-increment-line data for with

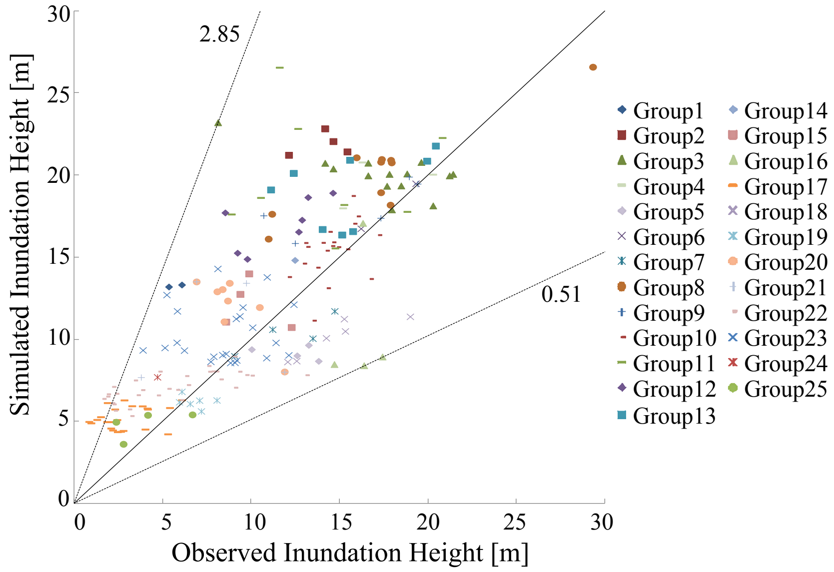
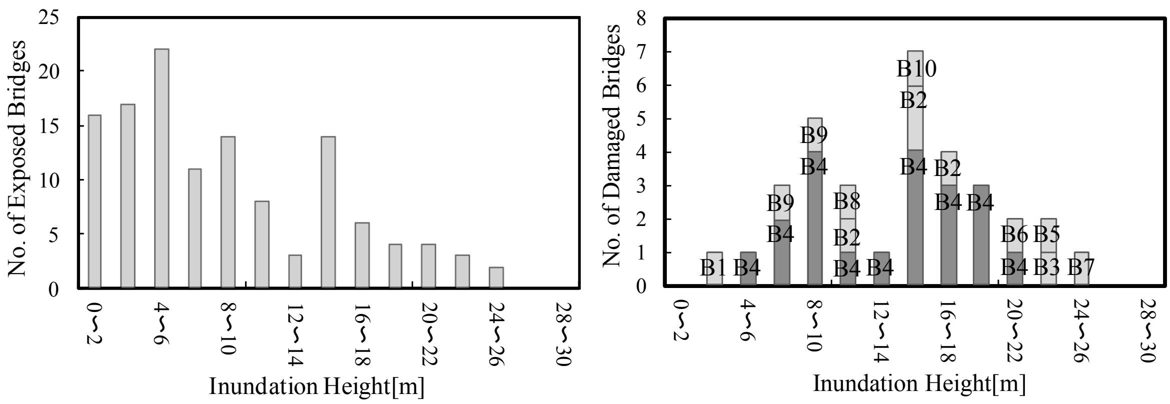


Fig. 7 Comparison of observed inundation heights with simulated results



(a) Number of exposed bridges (b) Number of damaged bridges

Fig. 8 Frequency of subject bridges by an inundation height

the grid size of 450m, 150m, and 50m, respectively. Region 5 and Region 6 are generated by using GSI DEM 10m-point data for topography and JHA 1m-increment-line data for bathymetry with the grid size of 16.67 (50/3) m and 5.56 (50/9) m. Fig. 4(a) shows the computational boundary of Region 1, Region 2, and Region 3 for Group 11 simulation. Fig. 4(b) shows the computational boundary of Region 4, Region 5, and Region 6 for Group 11 simulation. The time step for computation is 0.15 second, and total computational time is 120 minutes for all groups. The tsunami source model proposed by Imamura et al. (2011) is used for the simulation. We give the initial water level based on the tsunami source model by using Okada's method (Okada 1985).

By the limitation of paper lengths, we show the results for the typical simulation to validate the simulated inundation data with observed data. Fig. 5 shows the elevation from the topography and bathymetry data used for Group 11 simulation. It also shows the positions of subject three bridges and the related twenty four observation sites for inundation heights with reliability A and B, by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (2011). Fig. 6 shows the inundation areas for Group 11 simulation. From the results by Group 11 simulation for Koizumi Long-bridge areas, simulated inundation heights show the values of 8.92m to 20.83m, which have the differences by -1.06m to 14.94m compared with observed values. It indicates that simulated inundation heights become 0.94 to 2.28 times compared with the observation data.

Fig. 7 shows the relationship between the simulated inundation data from Group 1 to Group 25

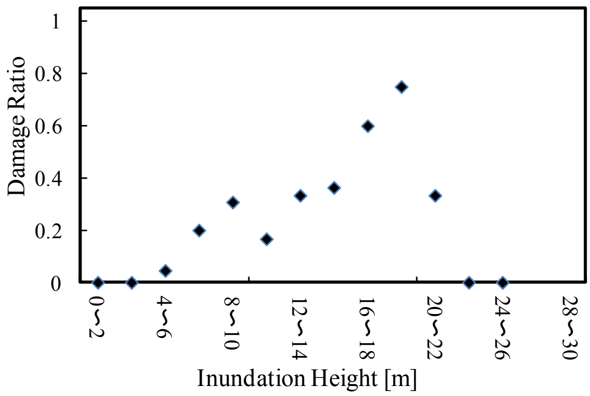


Fig. 9 Relation between damage ratio R_N^b and inundation heights for wash-away bridges

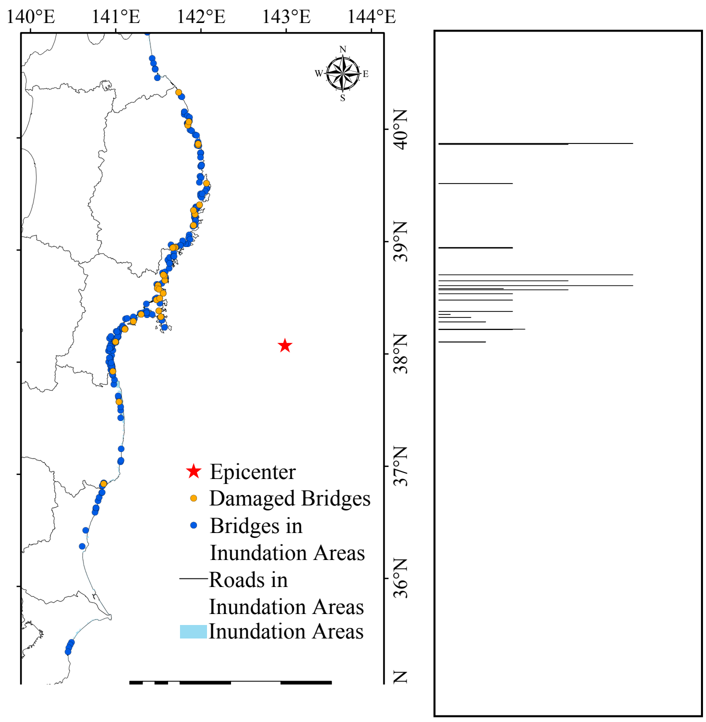


Fig. 10 Spatial distributions of damage ratio R_N^b

simulations and related observation data. Group 6 simulation data show 1.00 times to 1.03 times inundation heights compared with the related observed data and give relatively higher accuracy than other simulation data. In contrast, Group 3 simulation data show 0.93 times to 2.85 times inundation heights compared with the related observed data and show relatively lower accuracy than other simulation data. The magnification factors of total simulated inundation data with observed data vary from 0.51 to 2.85. Based on this validation, we use the simulated inundation heights data at subject damaged bridges as input inundation heights acting on their bridges in consideration of accuracy for simulated results as shown in Fig. 7.

Damage ratio of wash-away bridges

Fig. 8(a) shows the frequency of the number of exposed bridges N_t^b by an inundation height, including non-damaged bridges and damaged bridges. These data are classified in a 2m-interval inundation height. N_t^b with inundation heights of 4.0m to 6.0m shows the largest value of 22. Fig. 8(b) shows the frequency of the number of damaged bridges N_d^b by an inundation height, in which includes all failure modes of bridge damage of B1 to B10 denoted in Fig. 3. These data are also classified in a same interval. N_d^b with inundation heights of 14.0m to 16.0m shows the largest value of 7.

We calculate bridge damage ratio R_N^b at a 2.0m interval of inundation heights based on Eq. (1) by selecting falling-down failure mode (B4). Fig. 9 shows the relation between the damage ratio R_N^b and inundation heights. Fig. 10 shows the spatial distributions of damage ratio R_N^b. From Fig. 9, R_N^b with inundation heights of 0.0m to 4.0m show zero, R_N^b with inundation heights of 4.0m to 6.0m increases slightly to 0.04, R_N^b with inundation heights of 6.0m to 16.0m increases to the values of 0.18 to 0.33, R_N^b with inundation heights of 16.0m to 18.0m increases to the large value of 0.5, and R_N^b with inundation heights of 18.0m to 20.0m shows the largest value of 0.75. From Fig. 10, highest R_N^b is observed at Motoyoshi Town, Kesennuma City, Miyagi Prefecture for Koizumi Long-bridge areas (Group 11) and Tanohata Village, Iwate Prefecture for No-name bridge (Group 4).

CONCLUSIONS

We assessed the tsunami damage on road structures due to the 2011 off the Pacific Coast of Tohoku earthquake tsunami. We collected 142 damage data of road structures due to the tsunamis opened at the related web sites for analyses and classified 29 failure modes. For damage assessment of bridges, we obtained the inundation heights at damaged bridges due to the tsunamis by series of tsunami flow simulation based on shallow water theory, which are discretized by using the finite difference method with a staggered leap-flog scheme (DCRC 2009). Finally, we calculated damage ratio R_N^b dependent on an inundation height, which is defined by the value of number of bridge damage points N_d^b divided by total number of exposed bridges N_t^b, focusing on wash-away bridges.

(1) For 109 damaged roads, failure modes are classified into 19 types, which are observed in dominantly 50 deposits, 15 wash-aways and 10 road failures. For 33 damaged bridges, failure modes are classified into 10 types, which are observed in dominantly 20 falling-downs, 4 failures of abutment and 2 deposits.

(2) Simulated inundation heights at 33 damaged bridges are verified by comparing these related data with observed data by the 2011 Tohoku Earthquake Tsunami Survey Group (2011). The magnification factors of total simulated inundation data with observed data varied from 0.51 to 2.85.

(3) R_N^b with inundation heights of 0.0m to 4.0m show zero, R_N^b with inundation heights of 2.0m to 4.0m increases slightly to 0.04, R_N^b with inundation heights of 6.0m to 16.0m increase to the value of 0.18 to 0.33, R_N^b with inundation heights of 16.0m to 18.0m increases to the large value of 0.5 and R_N^b with inundation heights of 18.0m to 20.0m shows the largest value of 0.75. Highest R_N^b is observed at Motoyoshi Town, Kesennuma City, Miyagi Prefecture for Koizumi Long-bridge areas and Tanohata Village, Iwate prefecture for No-name bridge areas.

ACKNOWLEDGEMENTS

The authors acknowledge valuable supports for numerical simulation for calculating inundation heights at subject bridges from Disaster Control Research Center, Tohoku University (Professor F. Imamura and Professor S. Koshimura). The authors also appreciate valuable cooperation for calculating inundation heights at damaged bridges from Mr. Y. Hiraki and Mr. Y. Ezura at University of Tsukuba.

REFERENCES

Disaster Control Research Center, Tohoku University. “Tohoku University’s Numerical Analysis Model for Investigation of Tsunami.” TUNAMI-CODE.

Geospatial Information Authority of Japan (GSI). “Digital Elevation Model.” http://www.gsi.go.jp/kiban/etsuran.html.
Imamura, F., Koshimura, S., Murashima, Y., Akita, Y. and Aratani, Y. (2011). “The tsunami simulation for The 2011 off the Pacific Coast of Tohoku earthquake tsunami, Tohoku University Model (version1.1).” Disaster Control Research Center(DCRC), 1-6.
Japan Hydraulic Association (JHA). “Digital Topography of Ocean Floor M7000 Series.”
National Land Numerical Information Download Service. “Digital Road Data.” http://nlftp.mlit.go.jp/ksj/.
Okada, Y. (1995). “Surface deformation due to shear and tensile faults in a half-space.” *Bull. Seismol. Soc. Am.*, Vol. 75, 1135-1154.
The 2011 Tohoku Earthquake Tsunami Joint Survey Group. “Result of tsunami surveys.” http://www.coastal.jp/tsunami2011/index.php.
The General Bathymetry Chart of the Oceans (GEBCO). http://www.gebco.net/.