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EVALUATION OF TSUNAMI FLUID FORCE ACTING ON THE BRIDGE DECK DAMAGED BY THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE TSUNAMI

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Abstract: The 2011 off the Pacific Coast of Tohoku earthquake tsunami caused the catastrophic damage of infrastructures such as coastal structures, utilities and transportation facilities. First we carried out the tsunami flow simulation at the affected five areas such as Rikuzentakata city by using the finite difference method with a staggered leap frog scheme. From the simulation we obtained the inundation heights at the sites where the wash-away nine bridges are located. Second, by using the simulated inundation heights, we estimated the horizontal and vertical hydraulic pressures acting on the bridge decks based on the previously proposed formulas on evaluation of the relationship of the position of a bridge deck to an inundation height with the horizontal and vertical wave pressures acting on a bridge deck.

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku earthquake tsunami caused the catastrophic damage of infrastructures such as coastal structures, utilities and transportation facilities. Among them a bridge structure plays important roles to carry out emergency response by related stakeholders and to support their recovery activities.

The issues are strongly recognized since we experienced the 2004 Indian Ocean tsunami disaster. Since the 2004 tsunami disaster, evaluation of tsunami fluid force acting on a bridge deck is urgently required for designing a tsunami-proof bridge structure, and many academic researchers and practitioners are involved in it. From view of the point of numerical analysis, Yeh (2006) evaluated the tsunami force and velocity in the run-up zone by using the numerical algorithm developed by Carrier *et al*. (2003) based on fully nonlinear shallow-water wave theory. Ikari and Goto (2007) simulated the run-up tsunami wave and the damage of a bridge deck by MPS (Moving Particle Semi-implicit) method, and Shigihara *et al*. (2009) validated the damage of the bridge deck at Sumatra island, Indonesia subjected to the 2004 tsunami by three dimensional numerical fluid analysis by adapting a staggered leap-frog method. However, the effect of tsunami fluid force on the bridge deck damage has not been clarified enough.

From the reason above, we estimate the horizontal and vertical tsunami wave pressures on the wash-away nine bridge decks by combining the previously proposed experimental formulas with the numerical inundation heights. First we carry out the tsunami flow simulation at the affected five areas by using the finite difference method with a staggered leap frog scheme. From the simulation we obtain the inundation heights at the sites where the wash-away nine bridges are located. Second, by using the simulated inundation heights, we estimate the horizontal and vertical hydraulic pressures acting on the bridge decks based on the formulas on evaluation of the relationship of the position of a bridge deck to an inundation height with the horizontal and vertical wave pressures acting on a bridge deck.

2. NUMERICAL SIMULATION OF TSUNAMI WAVE PROPAGATION AND INUNDATION AREAS

2.1 Governing Equations

The tsunami wave propagation is computed by using TSUNAMI-CODE (Tohoku University's Numerical Analysis Model for Investigation of Tsunami). The governing equations are based on shallow water theory as shown in Eq. (1a)-(1c), which are discretized by using the finite difference method with a staggered leap flog scheme (DCRC 2009).

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \qquad (1a)$$

Table 1 Subject Bridges

Group No.	Name of Dameged Bridges	Longtitude	Latitude	Name of Roads	Prefectures
1	Koizumi Long-bridge	141.507	38.769	National Route 45	Miyagi
2	Mizushiri Bridge	141.443	38.673	National Route 45	Miyagi
	Oritate Bridge	141.437	38.648	National Route 398	Miyagi
	Yokotsu Bridge	141.456	38.638	National Route 398	Miyagi
3	Utatsu Bridge	141.524	38.717	National Route 45	Miyagi
4	Shinkitakami Bridge	141.420	38.549	National Route 398	Miyagi
5	Kawaharagawa Bridge	141.630	39.009	National Route 45	Iwate
	Numata Bridge	141.650	39.009	National Route 45	Iwate
	Kesen Bridge	141.622	39.006	National Route 45	Iwate

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)=-gD\frac{\partial \eta}{\partial x}-\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} \quad \text{(1b)}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=-gD\frac{\partial \eta}{\partial y}-\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} \quad \text{(1c)}$$

where η is a tsunami wave height measured from sea surface level, M and N are the discharge fluxs of x-direction and y-direction. D is a total water depth (η+h), h is a water depth, g is the gravitational acceleration, n is the Manning roughness coefficient. n is set as 0.25 in the simulation.

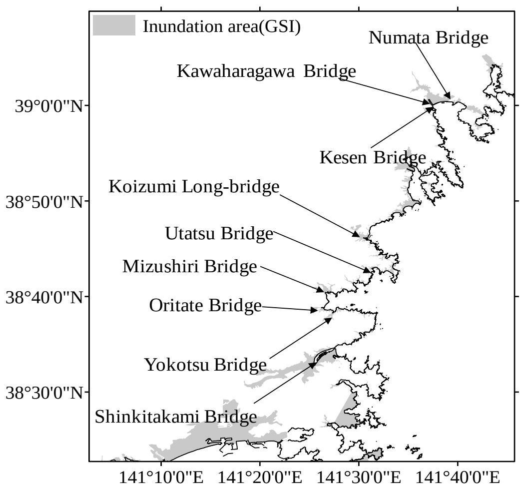

Figure 1 Location of the Bridges

Table 2 Number of Grids for All Groups

Group No.	Region	X-direction	Y-direction	Grid Size[m]
All Group	1	480	720	1350
	2	481	721	450
	3	481	721	150
1, 2, 4	4	541	901	50
3, 5	4	481	721	50
1	5	511	781	16.67(50/3)
	6	781	811	5.55(50/9)
2	5	601	721	16.67(50/3)
	6	811	811	5.55(50/9)
3	5	481	721	16.67(50/3)
	6	721	721	5.55(50/9)
4	5	1090	889	16.67(50/3)
	6	1090	1090	5.55(50/9)
5	5	721	481	16.67(50/3)
	6	931	931	5.55(50/9)

2.2 Details of Computational Data Set

Five affected areas by the 2011 of the Pacific Coast of Tohoku earthquake tsunami are focused for the simulation and totally nine wash-away bridges at the areas are selected for the analysis. Table 1 and Figure 1 show the information

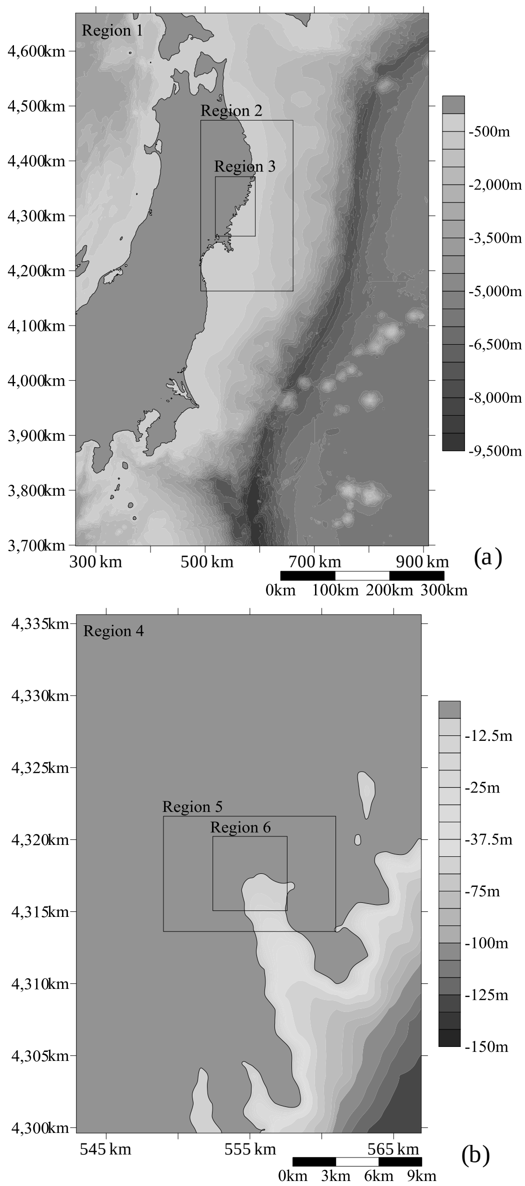

Figure 2 Computatinal Boundary
(a) Region 1 to Region 3, and (b) Region 4 to Region 6

of subject bridges. Six computational regions (Region 1 to Region 6) are used in the nested grid system.

Region 1 is used together in five groups. Region 2, Region 3, and Region 4 are used together in Group 1, Group 2 and Group 4. Region 2, Region 3, and Region 4 are used together in Group 3 and Group 5. Region 5 and Region 6 are for each group separately. 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 bathymetry with 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. Figure 2 (a) shows the computational area of Region 1, Region 2, and Region 3 for Group 5. Figure 2 (b) shows the computational area of Region 4, Region 5, and Region 6 for Group 5. Table 2 shows the number of grids in *x*-direction and *y*-direction in WGS-1984-UTM-54-N coordinate system. The time step for computation is 0.15 second, and total computational time is 120 minutes for all groups.

2.3 Tsunami Source Model

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). Figure 3 shows the initial water elevation for the tsunami simulation.

3. COMPARISON OF SIMULATED INUNDATION DATA WITH OBSERVED DATA

By the limitation of paper lengths, we show the results from the typical simulation to validate the simulated inundation data with observed data.

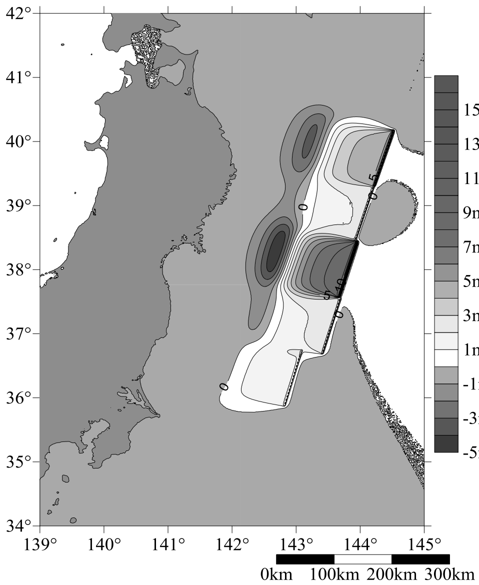

Figure 3 Initial Water Level
(Tohoku University Model Ver1.1)

Figure 4 shows the elevation from the topography and bathymetry data used for the Group 5 simulation. It also shows the positions of subject three bridges and the related twenty three observation sites for twenty inundation heights and three run-up heights with reliability A and B, by the

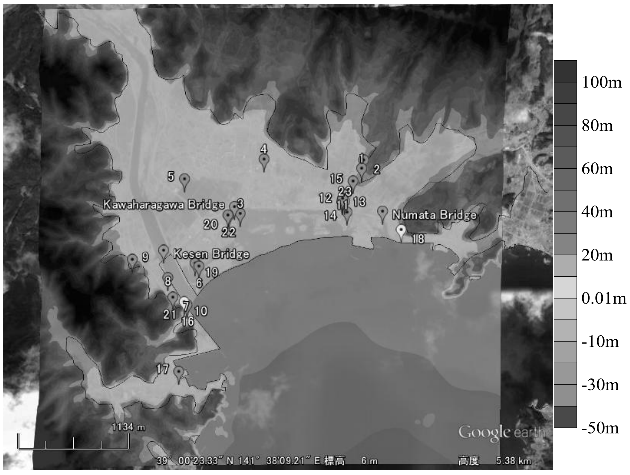

Figure 4 Elevation for Group 5 Simulation
(Red denotes the positions of subject bridges, blue denotes the positions of observation sites for inundation height, yellow denotes those for runup heights)

Figure 5 Inundation Areas for Group 5 Simulation
(Red, blue and yellow dots denote same meanings as those in Figure 4)

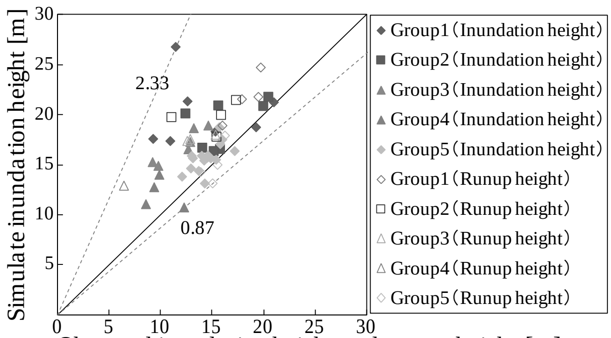

Figure 6 Comparison of Observed Inundation Heights and Run-up Heights with Simulated Results

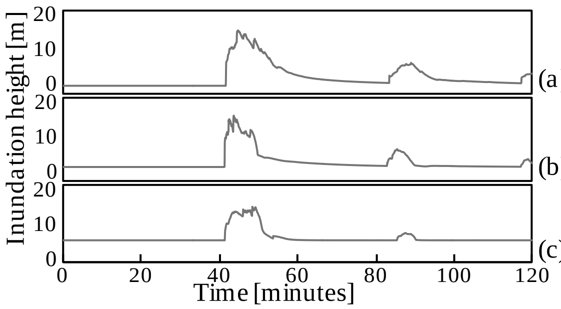

Figure 7 Time Series of Inundation Heights at Subject Bridges for Group5 Simulation
(a) Kawaharagawa Bridge,
(b) Numata Bridge, and (c) Kesen Bridge

2011 Tohoku Earthquake Tsunami Joint Survey Group (2011). Figure 5 shows the inundation areas by Group 5 simulation. The elevation data at point 11 is estimated possibly to have the difference with the real value since point 11 is located near the steep slope.

From the results by the Group 5 simulation for Rikuzentakata city, simulated inundation heights show the values of 11.15m to 18.87m, which have the differences by -3.04m to 3.04m compared with observed values. It indicates that simulated inundation heights become 0.82 to 1.22 times ones compared with the observation data.

Figure 6 shows the relationship between the simulated inundation data from the Group 1 to Group 5 simulations and the related observation data. We validate the simulated inundation heights with seven points for Group 1, seven points for the Group 2, six points for the Group 3, and four points for Group 4. We validate the simulated run-up heights with five points for Group 1, four points for the Group 2, three points for the Group 3, and one point for Group 4. From Figure 6, the magnification factors of simulated inundation data with observed data are 0.84 to 2.33. Based on this validation, we use the simulated inundation heights data at subject bridges as input tsunami waves acting on their bridge decks in consideration of accuracy for simulated results as shown in Figure 6. In addition, we obtain time series of inundation heights at subject bridges for the Group 5 as shown in Figure 7.

4. ESTIMATION OF TSUNAMI WAVE PRESSURES ON THE WASH-AWAY BRIDGE DECKS

We estimate tsunami wave pressures on the wash-away nine bridge decks by applying the following experimental formulas by Shoji *et al.* (2011) to the simulated data. These formulas are for surging breaker bores (SBB) and plunging breaker bores (PBB).

$$\kappa = 1.54 - 0.69\eta^{8.38} \quad :\text{SBB (2a)}$$

$$\lambda = -1.73\times10^{3} + 1.74\times10^{3}\eta^{3.77\times10^{-4}} \quad :\text{SBB (2b)}$$

$$\kappa = 1.73 - 0.63\eta^{5.42} \quad :\text{PBB (2c)}$$

$$\lambda = -1.56\times10^{3} + 1.56\times10^{3}\eta^{3.64\times10^{-4}} \quad :\text{PBB (2d)}$$

Table 3 shows inundation heights and elevation at subject bridges, and η, κ, λ, $\overline{F_x}/A_s$, $\overline{F_z}/A_b$ defined as the following equations. Figure 8 shows also the wash-away bridge data in the relationships of κ-η and λ-η.

Table 3 Wave Pressures Act on Subject Bridges
(a) For Surging Breaker Bores, and (b) For Plunging Braker Bores

Group No.	Name of Dameged Dridge	Inundation Height [m]	Elevation [m]	η	κ	λ	F_X/A_s [kN/m^2]	F_Z/A_b [kN/m^2]
1	Koizumi Long-bridge	18.27	6.53	0.64	1.53	0.21	279.97	38.72
2	Mizushiri Bridge	19.97	7.17	0.64	1.53	0.21	306.11	41.92
	Oritate Bridge	20.27	7.09	0.65	1.52	0.22	310.29	44.48
	Yokotsu Bridge	17.43	1.58	0.91	1.23	0.44	215.91	76.64
3	Utatsu Bridge	17.35	2.04	0.88	1.30	0.42	226.95	72.87
	Utatsu Bridge by Secondary Wave	13.76	2.04	0.85	1.36	0.39	188.50	54.57
4	Shinkitakami Bridge	9.38	7.29	0.22	1.54	-0.48	145.39	-45.28
5	Kawaharagawa Bridge	15.375	1.81	0.88	1.30	0.42	201.10	64.56
	Numata Bridge	15.75	3.179	0.80	1.44	0.35	227.63	55.77
	Kesen Bridge	14.576	5.757	0.61	1.53	0.17	224.38	25.10

(a)

Group No.	Name of Dameged Bridge	Inundation Height [m]	Elevation [m]	η	κ	λ	F_X/A_s [kN/m^2]	F_Z/A_b [kN/m^2]
1	Koizumi Long-bridge	18.27	6.53	0.64	1.67	0.25	306.89	45.56
2	Mizushiri Bridge	19.97	7.17	0.64	1.67	0.25	335.64	49.45
	Oritate Bridge	20.27	7.09	0.65	1.67	0.25	339.77	51.88
	Yokotsu Bridge	17.43	1.58	0.91	1.36	0.45	237.28	78.04
3	Utatsu Bridge	17.35	2.04	0.88	1.41	0.43	246.03	74.71
	Utatsu Bridge by Secondary Wave	13.76	2.04	0.85	1.47	0.41	202.77	56.45
4	Shinkitakami Bridge	9.38	7.29	0.22	1.73	-0.35	162.99	-33.36
5	Kawaharagawa Bridge	15.375	1.81	0.88	1.41	0.43	218.00	66.19
	Numata Bridge	15.75	3.179	0.80	1.55	0.37	244.41	58.78
	Kesen Bridge	14.576	5.757	0.61	1.69	0.21	247.22	31.31

(b)

$$\eta = \frac{\bar{a} - h_c}{\bar{a}} \tag{3a}$$

$$\kappa = \frac{\bar{F}_x / A_s}{\rho g \bar{a}} \tag{3b}$$

$$\lambda = \frac{\bar{F}_z / A_b}{\rho g \bar{a}} \tag{3c}$$

η is the ratio of bridge deck position from a still wall level h_c by an averaged wave height $\bar{a}$ from a still water level. κ is defined as the ratio of $\bar{F}_x/A_s$ with an averaged horizontal wave force $\bar{F}_x$ and projected area of a bridge deck A_s, by hydraulic static pressure $\rho g \bar{a}$. λ is also defined as the ratio of $\bar{F}_z/A_b$ with an averaged vertical wave force $\bar{F}_z$ and area of bottom of a bridge deck A_b, by hydraulic static pressure $\rho g \bar{a}$. In the following analysis, we assume a wave height $\bar{a}$ to be the simulated inundation height, and h_c to be the value of elevation as shown in Figure 9.

By focusing on the Group 5 simulation results, from Table 3 and Figure 8 for plunging breaker bores, Kawaharagawa Bridge decks with η=0.88 are estimated to be affected by κ=1.41 and λ=0.43 tsunami wave pressures, which are $\bar{F}_x/A_s$ of 218.07kN/m^2 and $\bar{F}_z/A_b$ of 66.21kN/m^2. It is possible that Kawaharagawa Bridge is affected by simultaneously strong horizontal wave pressure and uplift vertical wave pressure. Numata Bridge decks with η=0.80 are estimated to be affected by κ=1.55 and λ=0.37 tsunami wave pressures, which are $\bar{F}_x/A_s$ of 244.41kN/m^2 and $\bar{F}_z/A_b$ of 58.58kN/m^2. Kesen Bridge decks with η=0.61 are estimated to be affected by κ=1.69 and λ=0.21 tsunami wave pressures, which are $\bar{F}_x/A_s$ of 247.22kN/m^2 and $\bar{F}_z/A_b$ of 31.31kN/m^2. At Numata Bridge and Kesen Bridge, higher horizontal pressure and lower uplift vertical pressure act on their bridge decks compared with those at Kawaharagawa Bridge.

From the similar analyses, we find that the mechanism of horizontal and vertical wave pressures on the wash-away nine bridge decks are classified into three categories : relatively lower κ and higher positive λ acts at Yokotsu Bridge, Kawaharagawa Bridge and Utatsu Bridge, relatively middle κ and positive λ acts at Numata Bridge, Oritate Bridge, Koizumi Long-bridge, Mizushiri Bridge and Kesen Bridge, and relatively higher κ and negative λ acts at Shinkitakami Bridge.

5. CONCLUSIONS

We estimated the horizontal and vertical tsunami wave pressures on the wash-away nine bridge decks due to the 2011 off the Pacific Coast of Tohoku earthquake tsunami by combining the previously proposed experimental formulas with the simulated inundation heights. First we carried out the tsunami flow simulations at the affected five areas (Group 1 to Group 5) by using the finite difference method with a staggered leap frog scheme, and we obtained the inundation heights at the sites where the wash-away nine

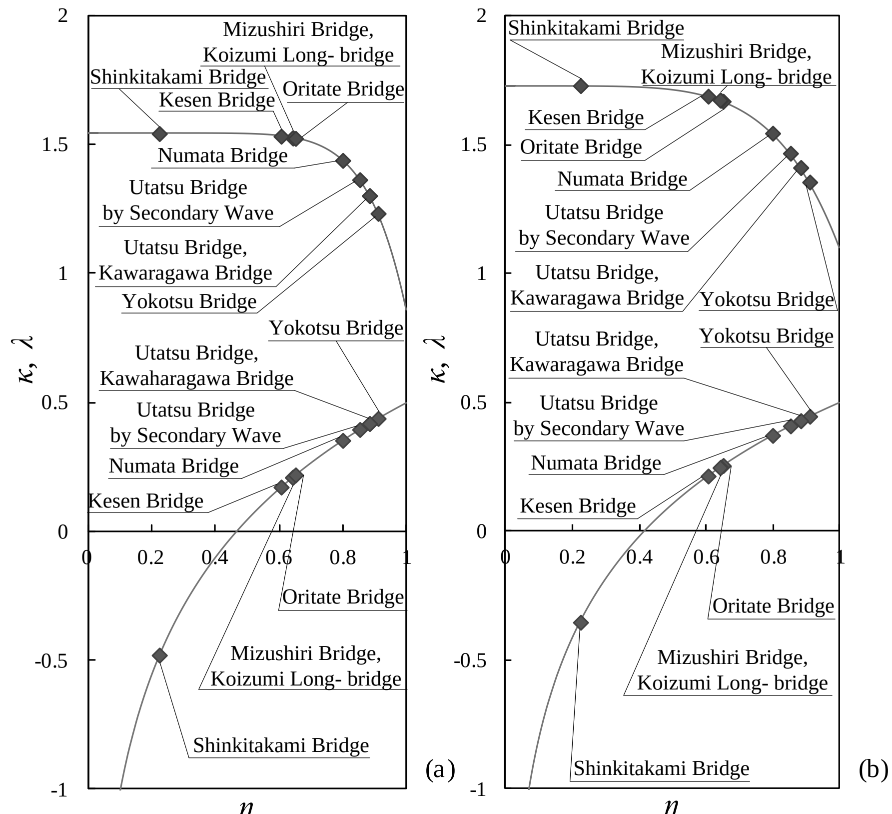

Figure 8 Wash-away Bridge Decks Data in the Relationship of κ-η, λ-η
(a) For Surging Breaker Bores, and (b) For Plunging Braker Bores

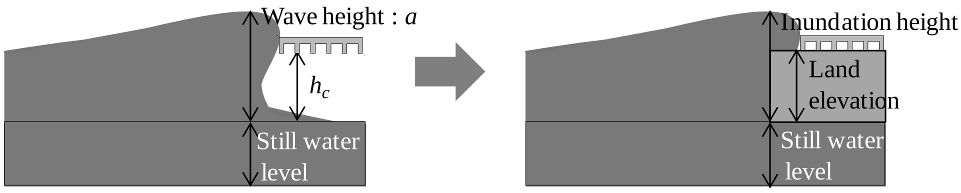

Figure 9 Correspondence of Parameters in Experimental Formulas with Simulated Data

bridges are located. Second, by using the simulated an inundation heights, we estimated the horizontal and vertical hydraulic pressures acting on the bridge decks based on the formulas on evaluation of the relationship of the position of a bridge deck η to a inundation height with the horizontal and vertical wave pressures acting on a bridge deck κ and λ. Following conclusions are deduced.

(1) We validated the simulated inundation heights with the simulated inundation data of 44 inundation heights and 16 run-up heights with observation data. Among the data simulated inundation heights for Group 5 with highest accuracy show the values of 11.15m to 18.87m, which have the differences by -3.04m to 3.04m compared with observed values. In contrast, the data simulated inundation heights for Group 1 with relatively lowest accuracy show the values of 17.37m to 26.76m, which have the differences by 0.24m to 15.28m compared with observed values.

(2) The mechanism of horizontal and vertical wave pressures on the wash-away nine bridge decks are classified into three categories : relatively lower κ and higher positive λ acts at Yokotsu Bridge, Kawaharagawa Bridge and Utatsu Bridge, relatively middle κ and positive λ acts at Numata Bridge, Oritate Bridge, Koizumi Long-bridge, Mizushiri Bridge and Kesen Bridge, and relatively higher κ and negative λ acts at Shinkitakami Bridge.

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