Effect of Breakwaters on Reduction of Fatality Ratio during the 2011 Great East Japan Earthquake and Tsunami

Panon LATCHAROTE¹, Anawat SUPPASRI², Natsuki HASEKAWA³,
Hiroshi TAKAGI⁴ and Fumihiko IMAMURA⁵

¹Member of JSCE, Postdoctoral Researcher, International Research Institute of Disaster Science, Tohoku University
(468-1 Aramaki-aza Aoba, Aoba-ku, Sendai 980-0845, Japan)

E-mail: panon@irides.tohoku.ac.jp

²Member of JSCE, Associate Professor, International Research Institute of Disaster Science, Tohoku University
(468-1 Aramaki-aza Aoba, Aoba-ku, Sendai 980-0845, Japan)

E-mail: suppasri@irides.tohoku.ac.jp

³Member of JSCE, Master Student, International Research Institute of Disaster Science, Tohoku University
(468-1 Aramaki-aza Aoba, Aoba-ku, Sendai 980-0845, Japan)

E-mail: natsuki.hasegawa.s8@dc.tohoku.ac.jp

⁴Member of JSCE, Associate Professor, Graduate School of Science and Engineering, Tokyo Institute of Technology
(2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan)

E-mail: takagi@ide.titech.ac.jp

⁵Member of JSCE, Professor, International Research Institute of Disaster Science, Tohoku University
(468-1 Aramaki-aza Aoba, Aoba-ku, Sendai 980-0845, Japan)

E-mail: imamura@irides.tohoku.ac.jp

Based on lesson learned from the 2011 Great East Japan tsunami, tsunami height is the most influential factor on fatality of people living in coastal area. This paper proposes effect of breakwaters on fatality ratio of people and investigate a reduction of fatality ratio due to the existence of breakwaters. For preliminary study, 24 fishery ports equipped with breakwaters were selected to study how breakwaters affect to loss of fatality ratio along Sanriku ria-coast from Taro to Ishinomaki. The port area behind breakwaters was considered to calculate fatality ratio from number of fatality divided by total number of people and then fatality ratio was linearly correlated with observed tsunami height. In order to estimate fatality ratio in case of ports without breakwaters, simulated tsunami height was calculated by TUNAMI modeling with nesting grids of 1350 m, 450 m, 150 m, and 50 m. For the overall image, breakwaters could reduce fatality ratio of people in the port area with a percentage of reduction approximately 30%. Considering the effect of breakwaters at each port, it was found that fatality ratio of ports equipped with breakwaters is less than those in case of ports without breakwaters for most of ports. In addition to these 24 ports, 18 additional ports equipped with breakwaters were conducted to additional study and compared with 24 ports having no breakwaters. For the overall image, the percentage of reduction became 1%, which is much lower than the reduction in the preliminary study. Focusing on each port, two third of them still provided the reduction of fatality ratio.

Key Words: 2011 Great East Japan tsunami, fatality ratio, breakwaters, tsunami height, loss reduction

1. INTRODUCTION

The 2011 Great East Japan tsunami caused a wide range of devastating tsunami with maximum tsunami height of 40 m and 19,000 casualties along the Tohoku coast¹⁾. Difference in coastal topography, such as Sanriku ria-coast and Sendai plain, leads to a significant difference in tsunami and evacuation characteristics. Considering influential factors on fatality of people, tsunami characteristics is a factor

of tsunami height and tsunami arrival time, while evacuation characteristics is a factor of experience, preparedness, age, gender, and occupation. From past studies, a relationship between fatality ratio and influential factors was proposed based on the surveyed data after the 2011 Great East Japan tsunami and it was found that tsunami height is a major influence on fatality ratio²⁾. After tsunami, breakwaters are important to conduct port operations for immediate disaster relief. However, the major function of

breakwaters is not designed for loss reduction from tsunami. Therefore, this study aims to propose effect of breakwaters on fatality ratio of people living behind ports equipped with breakwaters, which could reduce tsunami intensity during the 2011 tsunami. In addition, this study investigates a reduction of fatality ratio due to the existence of breakwaters.

2. DATA AND METHOD

(1) Breakwater and fatality data

The locations of ports equipped with breakwaters in **Fig. 1** were selected to study how breakwaters affect to a reduction of fatality ratio for people living behind ports. The data of breakwaters from 24 ports³⁾ with available data of fatality ratio and observed tsunami height were collected along Sanriku ria-coast from Taro to Ishinomaki. The breakwater data contains breakwater location, dimension and damage, including tsunami height at breakwater³⁾. As can be seen in **Fig. 1**, the residential area behind the fishery ports was considered to calculate fatality ratio (FR) from number of fatality (D) divided by total number of people (N) in this port area. For each port area, fatality ratio was investigated using disaster victim database collected by Reconstruction Assistance Research Archive, University of Tokyo. In this study, fatality ratio was linearly correlated with observed tsunami height measured by the 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group.

(2) Numerical simulation and validation

In order to estimate fatality ratio in case of ports without breakwaters, simulated tsunami height was calculated by TUNAMI^{9),10)} modeling with nesting grids of 1350 m, 450 m, 150 m, and 50 m. The finest grid (50 m) of bathymetry and topography data does not include breakwaters. Numerical tsunami simulation was performed to collect tsunami height at port locations without breakwaters inside the finest grid. Initial seafloor deformation was calculated by a rectangular fault model⁴⁾ using the fault parameters of the 2011 Great East Japan earthquake with 55-subfault model⁵⁾.

Validation of the simulation was performed using the Root Mean Square Error (RMSE), and the parameters K and κ proposed by Aida (1978) for reproduction of tsunami height in this study. The simulated tsunami height (h_s) was validated using observed tsunami height (h_o) measured by TTJS of 33 locations of port having no effective breakwaters against tsunami shown in **Fig. 2**. The value of RMSE are 1.07 m. The values of K and κ are 1.05 and 1.12, respectively. The Japan Society of Civil Engineering (JSCE) suggests that $0.95 < K < 1.05$ and $\kappa < 1.45$ is recommended as “Good agreement” in the evaluation of tsunami source and propagation model. The κ value can satisfy the standard, whereas the K value is somewhat acceptable equally to the limited value of the standard. Therefore, this numerical simulation is valid and reliable for reproduction of tsunami height in case of ports without breakwaters.

Fig.1 Location of investigated ports equipped with breakwaters and satellite images of port area (Google Earth).

Fig.2 Comparison of simulated and observed tsunami height at each port having no breakwaters.

(3) Linear regression analysis

The estimated fatality ratio in case of ports without breakwaters was predicted by means of the simulated tsunami height (h_s) and a general estimating equation developed from 13 city data²⁾ by linear regression analysis shown in **Fig. 3**. For this preliminary study, these 13 cities are a large-scale area, not particular in a port area. Therefore, the estimation of fatality ratio in case of ports without breakwaters would be less accuracy because of such a simple assumption. However, more advanced assumption was used for the estimation of fatality ratio in additional study. For fatality ratio and observed tsunami height (h_o) of ports equipped with breakwaters, linear regression analysis was performed to develop a relationship between fatality ratio and tsunami height shown in **Fig. 4**. The regression lines in **Fig. 3** and **Fig. 4** represent the linear estimated fatality ratio at different tsunami height for overall comparison. The estimated fatality ratio at each location in case of ports without breakwaters was calculated by means of the simulated tsunami height and the general estimating equation. The differences (ΔFR) between the estimated fatality ratio and the surveyed data of fatality ratio (FR) at each port are shown in **Table 1**.

Fig.3 Linear regression analysis from 13 city data²⁾.

3. RESULTS AND DISCUSSIONS

(1) Preliminary results

Fig. 2 shows a good agreement between the observed tsunami height (h_o) from TTJS group and the simulated tsunami height (h_s) from numerical simulation. For comparison between h_o and h_s in **Table 1**, the simulated tsunami height in case of ports without breakwaters is generally higher than the surveyed data of the observed tsunami height for most of ports, except for Miyako (Sokei), Oura, Ogihama, and Momoura. The observed height of Oura, Ogihama, and Momoura is even higher than tsunami height at breakwater³⁾ which might occur due to reflection wave. In addition, based on past studies, tsunami simulations with and without breakwaters revealed that breakwaters did not noticeably reduce water level in the port area because tsunami entered through opening of breakwaters and filled the port basin within a short time⁸⁾.

Fig. 3 and **Fig. 4** show linear regression analysis resulting in two linear equations of estimated fatality ratio from tsunami height in case of ports without breakwaters and ports equipped with breakwaters, respectively. It was found that the linear estimated fatality ratio in **Fig. 4** is less than that in **Fig. 3** approximately 30% calculated from the slope values of those two linear equations. For the overall image, breakwaters could reduce fatality ratio of people in the port area with a percentage of reduction approximately 30%; nevertheless, it depends on tsunami heights (h_o and h_s). Considering the effect of breakwaters at each port, the differences (ΔFR) between the estimated fatality ratio in case of ports without breakwaters and the surveyed data of fatality ratio (FR) are shown in **Table 1**. Most of them provided a reduction of fatality ratio (Remark +), whereas Miyako (Kuwasaki), Kamishi, Oura, Momoura, and Watanoha did not (Remark -). Although the simulated tsunami height (h_s) is less than the observed tsunami height (h_o) for Miyako (Sokei) and Ogihama, it still could provide the reduction of fatality ratio.

Fig.4 Linear regression analysis from 24 ports equipped with breakwaters.

Table 1 Tsunami height and fatality data of 24 ports equipped with breakwaters.

Port	h_o (m)	h_s (m)	FR	Δ FR	Remark
1) Taro	13.86	14.32	3.92%	2.89%	+
2) Kuwasaki	6.49	7.05	5.08%	-1.73%	-
3) Sokei	8.17	6.57	1.14%	1.98%	+
4) Koyadori	18.66	19.95	5.77%	3.71%	+
5) Funakoshi	13.84	14.37	6.48%	0.35%	+
6) Otsuchi	11.03	11.53	5.01%	0.48%	+
7) Hakozaiki	14.35	15.31	4.96%	2.32%	+
8) Ryoishi	16.33	16.83	4.25%	3.75%	+
9) Kamaishi	8.64	8.79	5.32%	-1.14%	-
10) Osabe	13.71	13.78	4.59%	1.96%	+
11) Wakinosawa	13.88	14.15	2.22%	4.51%	+
12) Shizugawa	14.30	14.56	3.99%	2.94%	+
13) Mitobe	14.62	15.49	5.83%	1.54%	+
14) Aikawa	11.89	12.61	4.49%	1.50%	+
15) Funakoshi	12.45	12.53	4.06%	1.90%	+
16) Oura	11.31	9.65	5.19%	-0.60%	-
17) Onagawa	13.04	13.55	3.40%	3.04%	+
18) Ayukawa	7.51	7.67	1.23%	2.42%	+
19) Kobuchihama	7.52	7.87	1.99%	1.75%	+
20) Fukiura	7.69	8.04	1.46%	2.36%	+
21) Ogihama	8.05	7.70	1.84%	1.82%	+
22) Momoura	10.72	8.94	4.32%	-0.07%	-
23) Watanoha	3.34	3.82	3.16%	-1.34%	-
24) Ishinomaki	6.38	6.60	2.31%	0.83%	+

In addition, it was found that fatality ratio of 24 ports has no relationship with breakwater dimension and damage³⁾.

(2) Additional results

In order to improve accuracy of the investigation, **Fig. 5** shows linear regression analysis from the surveyed data of 22 ports having no breakwaters. These data and analysis provided a more realistic linear equations of estimated fatality ratio from tsunami height in case of ports without breakwaters. The observed and simulated tsunami heights (h_o and h_s), total number of people (N), number of fatality (D), and fatality ratio (FR) are shown in **Table 2**. The estimated fatality ratio in case of ports without breakwaters was calculated by means of the simulated tsunami height and the linear equation in **Fig. 5**.

Fig.5 Linear regression analysis from 22 ports having no breakwaters.

In addition to 24 ports equipped with breakwaters in **Table 1**, the surveyed data of 18 additional ports was conducted to develop a relationship between fatality ratio and tsunami height shown in in **Fig. 6**. The differences (Δ FR) between the estimated fatality ratio and the surveyed data of fatality ratio (FR) at each port are shown in **Table 3**.

Table 2 Tsunami height and fatality data of 22 ports having no breakwaters.

Port	h_o (m)	h_s (m)	N	D	FR
1) Yamaguchi	10.00	10.55	251	2	0.80%
2) Yoneaaki	15.82	16.22	472	12	2.54%
3) Asane	4.66	4.27	198	1	0.51%
4) Sakanamachi	5.97	5.65	449	11	2.45%
5) Minatomachi	5.17	4.98	115	4	3.48%
6) Akaiwaminato	7.25	7.02	247	12	4.86%
7) Uoichibamae	6.33	5.54	188	6	3.19%
8) Matsuzakikitasawa	7.25	7.02	201	3	1.49%
9) Matsuzakimaehama	8.97	8.03	301	3	1.00%
10) Saichikawara	7.80	7.53	142	3	2.11%
11) Nagaisofunahara	6.41	6.97	2498	21	0.84%
12) Hajikamiakedo	12.61	9.77	118	8	6.78%
13) Okinoda	11.48	11.56	53	1	1.89%
14) Shirahama	11.06	11.39	3718	199	5.35%
15) Myojin	12.06	11.51	3994	162	4.06%
16) Oyagawahama	17.53	17.30	245	12	4.90%
17) Yagawahama	18.53	18.23	167	8	4.79%
18) Kugunarihama	5.86	6.13	262	5	1.91%
19) Oharahama	8.07	8.78	184	2	1.09%
20) Sato	4.33	4.75	950	11	1.16%
21) Shintona	3.66	3.48	243	7	2.88%
22) Arahama	7.08	7.09	479	12	2.51%

Fig.6 Linear regression analysis from 42 ports equipped with breakwaters.

For the overall image, it was found that breakwaters could reduce fatality ratio of people only 1%, which is much lower than the reduction in the preliminary result, but more accurate. The boundary lines of the scattered points (dashed lines) in **Fig. 5** and **Fig. 6** are similar as same as the proportion of these scattered points over and under the linear lines. Considering the effect of breakwaters at each port, the differences (Δ FR) between the estimated fatality ratio in case of ports without breakwaters and the surveyed data of fatality ratio (FR) are shown in

Table 3. Two third of them (28 ports) provided a reduction of fatality ratio (Remark +), whereas one third of them (14 ports) did not (Remark -).

Table 3 Tsunami height and fatality data of 42 ports equipped with breakwaters.

Port	h _o (m)	h _s (m)	FR	ΔFR	Remark
1) Noda	8.42	10.04	0.58%	2.39%	+
2) Fudaimura	8.47	11.69	0.26%	3.20%	+
3) Omoe	12.96	13.94	2.11%	2.02%	+
4) Taro	13.86	14.32	3.92%	0.32%	+
5) Kuwasaki	6.49	7.05	5.08%	-2.99%	-
6) Sokei	8.17	6.57	1.14%	0.81%	+
7) Takahama	4.76	5.28	0.36%	1.12%	+
8) Sakaida	6.31	6.20	1.05%	0.79%	+
9) Dai13Chiware	10.01	11.52	2.06%	1.35%	+
10) Koyadori	18.66	19.95	5.77%	0.13%	+
11) Funakoshi	13.84	14.37	6.48%	-2.23%	-
12) Otsuchi	11.03	11.53	5.01%	-1.59%	-
13) Kirikiri	14.44	13.63	5.83%	-1.79%	-
14) Hakozaiki	14.35	15.31	4.96%	-0.42%	-
15) Ryoishi	16.33	16.83	4.25%	0.73%	+
16) Kamaishi Bay	8.32	9.84	0.64%	2.27%	+
17) Kamaishi	8.64	8.79	5.32%	-2.72%	-
18) Yunagomae	7.53	8.52	0.53%	2.00%	+
19) Takonoura	8.64	10.11	2.25%	0.75%	+
20) Okirai	10.45	11.04	2.78%	0.49%	+
21) Osabe	13.71	13.78	4.59%	-0.51%	-
22) Otomo	14.16	15.23	2.72%	1.79%	+
23) Hirota	10.70	11.62	1.09%	2.35%	+
24) Wakinosawa	13.88	14.15	2.22%	1.97%	+
25) Sodehama	13.53	14.24	3.99%	0.23%	+
26) Shizugawa	14.30	14.56	3.99%	0.33%	+
27) Mitobe	14.62	15.49	5.83%	-1.24%	-
28) Aikawa	11.89	12.61	4.49%	-0.76%	-
29) Funakoshi	12.45	12.53	5.83%	-1.24%	-
30) Oura	11.31	9.65	4.06%	-0.35%	-
31) Onagawa	13.04	13.55	3.40%	0.61%	+
32) Ayukawa	7.51	7.67	1.23%	1.04%	+
33) Kobuchihama	7.52	7.87	1.99%	0.34%	+
34) Fukiura	7.69	8.04	1.46%	0.92%	+
35) Yoriisohama	15.70	12.21	2.43%	1.18%	+
36) Kitsunozaki	8.21	7.60	2.03%	0.22%	+
37) Ogihama	8.05	7.70	1.84%	0.44%	+
38) Momoura	10.72	8.94	4.32%	-1.68%	-
39) Watanoha	3.34	3.82	3.16%	-2.03%	-
40) Ishinomaki	6.38	6.60	2.31%	-0.35%	-
41) Shiogama	4.65	5.47	1.60%	0.02%	+
42) Hanabushi	6.67	7.20	1.20%	0.93%	+

4. CONCLUSIONS

Fatality data of people during the 2011 Great East Japan tsunami in Iwate and Miyagi were used to calculate fatality ratio of ports equipped with breakwaters and estimate fatality ratio in case of ports without breakwaters. For preliminary study, the relationship between fatality ratio and tsunami height in 24 fishery ports was developed based on the surveyed data after the 2011 tsunami. In addition, the estimated fatality ratio in case of ports without breakwater was calculated by simulated tsunami height to study the effect of breakwaters on fatality ratio of people living in the port area. The reduction

of fatality ratio was examined by the differences between fatality ratio in case ports equipped with and without breakwaters. From the simple assumption, the percentage of reduction was approximately 30% calculated from the difference of the slope values between two linear equations for the overall image. Focusing on each port, most of ports provided the reduction of fatality ratio. Although the simulated tsunami height is less than the observed tsunami height for some ports, it still could provide the reduction of fatality ratio. However, there are still some limitations that should be concerned for these preliminary results. First, the number of breakwaters used in this study is limited to 24 port locations. Second, the general estimating equation is limited to fatality data of 13 city¹, not particular in port area having no breakwater. In addition, it was found that fatality ratio of 24 ports has no relationship with breakwater dimension and damage.

Additional study was conducted to improve accuracy of the investigation by adding more 18 ports equipped with breakwaters and comparing with fatality data of 24 ports having no breakwaters. From the more advanced assumption, the percentage of reduction became 1%, which is much lower than the reduction in the preliminary study. Focusing on each port, two third of them provided a reduction of fatality ratio, whereas one third of them did not.

This study suggested that the existence of breakwaters can reduce fatality ratio of people due to the 2011 tsunami for most of ports. The results of loss reduction can support future construction and strengthening of breakwaters, which provide extra benefit apart from fishery, even though most breakwaters are not designed for loss reduction from tsunami. These findings can partially prove a significance of the existence of breakwaters on the reduction of fatality ratio and will be important for disaster mitigation planning against future large tsunami. For further improvement, the parameter of influential factors should not be limited to only tsunami height and nonlinear regression analysis should be performed in the future attempt.

ACKNOWLEDGMENT: The authors would like to thank the 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group for providing the surveyed data of tsunami height. We appreciate the fatality data provided by Reconstruction Assistance Research Archive, University of Tokyo.

This research was funded by the Willis Research Network (WRN) under the Pan-Asian/Oceanian tsunami risk modeling through the International Research Institute of Disaster Science (IRIDeS) at Tohoku University.

APPENDIX A

Table 4 Location and fatality data of 24 ports equipped with breakwaters.

Port	Lat	Long	N	D
1) Taro	39.73269167	141.9748222	3062	120
2) Kuwasaki	39.64166944	141.9747528	197	10
3) Sokei	39.62810556	141.9721940	263	3
4) Koyadori	39.42526670	142.0132806	381	22
5) Funakoshi	39.42449722	141.9782611	694	45
6) Otsuchi	39.34927778	141.9323361	799	40
7) Hakozaki	39.32566111	141.9143250	1311	65
8) Ryoishi	39.30491667	141.8941083	636	27
9) Kamaishi	39.27065000	141.9040806	188	10
10) Osabe	38.99316111	141.2595560	566	26
11) Wakinosawa	39.00454167	141.6577139	225	5
12) Shizugawa	38.67291944	141.4502222	8180	326
13) Mitobe	38.64336944	141.4607389	2350	137
14) Aikawa	38.60229167	141.5024500	3896	175
15) Funakoshi	38.53505833	141.5088639	3994	162
16) Oura	38.45463611	141.4954111	231	12
17) Onagawa	38.40266389	141.5047972	294	10
18) Ayukawa	38.29473056	141.5066806	1462	18
19) Kobuchihama	38.32439722	141.4664444	753	15
20) Fukiura	38.35182778	141.4467750	137	2
21) Ogihami	38.37542500	141.4474611	163	3
22) Momoura	38.39713889	141.4309000	185	8
23) Watanoha	38.40719722	141.3658444	7157	226
24) Ishinomaki	38.40664440	141.3315722	130	3

APPENDIX B

Table 5 Location and fatality data of additional 20 ports equipped with breakwaters.

Port	Lat	Long	N	D
1) Noda	40.11532220	141.83449440	4632	27
2) Fudaimura	40.01135556	141.90707500	3088	8
3) Omoe	39.57582100	142.03014300	1186	25
4) Takahama	39.60144400	141.95239900	841	3
5) Sakaida	39.46223400	141.95739800	410	37
6) Dai 13 Chiwari	39.41873100	141.98358700	97	2
7) Kirikiri	39.37278400	141.94662900	635	37
8) Kamaishi Bay	39.25794722	141.93086110	3751	24
9) Yunagomae	39.03667800	141.72240200	568	3
10) Takonoura	39.03590300	141.73668200	267	6
11) Okirai	39.11335600	141.81825600	288	8
12) Otomo	38.98311700	141.70988600	1911	52
13) Hirota	38.95372300	141.68988800	457	5
14) Sodehama	38.67312800	141.46552100	8180	326
15) Yoriisohama	38.38842100	141.52485700	411	10
16) Kitsunozaki	38.34957222	141.41880830	148	3
17) Shiogama	38.26643889	141.05140280	2813	45
18) Hanabushi	38.30608600	141.08245100	416	5

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(Received March 16, 2016)