

# Storm surge disaster of Typhoon 9918 at New Moji District with a distributed runoff model

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**ABSTRACT:** Typhoon 9918 brought wave over topping damage at New Moji District, Kita-kyushu, Fukuoka in 1999. Then the over topping rate was estimated from the tide observation and the ponding state was reproduced with a distributed runoff model. At the south New Moji District, some seawalls collapsed by wave forces in the typhoon invasion. First, the frequency distribution was produced with the joint distribution of wave heights and periods, and the over topping rate was estimated with a weir formula. A two-dimensional unsteady flow model was constructed and the over topping damage was simulated from input data: precipitation, the over topping rate, and a DEM. From the simulation results, over topping rate at collapsed seawalls was 59 times as much as the original at most. Therefore, the seawall collapse might cause the over topping damage at New Moji District at least. A time series of the ponding state was reproduced with the simulation.

## 1. Introduction

Typhoon 9918, on September 24th, 1999, brought damage in various regions in Japan. Its damage increased in Kyushu district because typhoon invaded and high tide occurred at the same time. However the details of the actual flood situation are still unclear because typhoon invasion was from daybreak to early morning, and there is few witness. The over topping rate estimation by the tide observation and submerged situation by a distributed runoff model were reproduced for wave over topping damage at New Moji District, Kita-kyushu, Fukuoka caused by typhoon 9918. The individual wave frequency distribution was estimated by a joint distribution of wave heights and periods, and the over topping rate was estimated by a weir formula. A distributed runoff model was constructed on the assumption that the seawater behavior was two-dimensional flow without a vertical direction velocity change. Flooding simulation was done with DEM, which was made from aerial photos, and an estimated overflow rate.

## 2. Analysis method

### 2.1 Objective area

New Moji District, Kita-kyushu, Fukuoka (Total area 1,806,000m<sup>2</sup>) was the objective area. The New Moji District was landfilled as an industrial site and faced the Sea of Suo. There are the 1st New Moji coastal revetment (814 m length), which was constructed in the north side and the 2nd New Moji coastal revetment (1,171 m length), which was constructed in the south side at the eastern end of the reclaimed land. At the time of typhoon invasion, a wave washed from the eastern edge and wave over topping damage occurred. In addition, the superstructure collapse occurred at five parts of the 1st New Moji coastal revetment (59.9 m length) and at five parts of the 2nd New Moji coastal revetment (96.1 m). In a collapse part, more wave over topping occurred than non-collapse part, and the damage was increased. The New Moji District was indicated in Fig. 1. The coastal revetment was divided every 200 m from the northern end as 0 to 200-m section, 200 to 400-m section, 400 to 600-m section, 600 to 800-m section,



Fig. 1 New Moji district

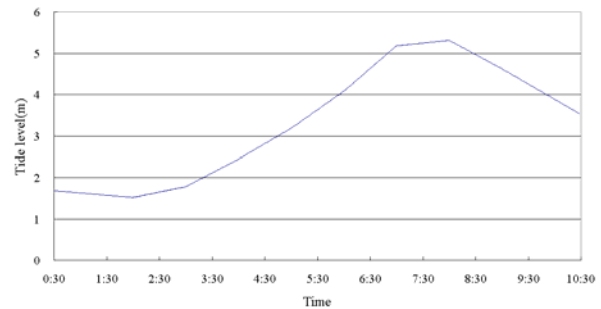


Fig. 2 Tide level fluctuation

800 to 1000-m section, 1000 to 1200-m section, 1200 to 1400-m section, 1600 to 1800-m section and 1800 to 1985-m section. In addition, the ground height, the tide level and the water level were standardized by the chart datum level (CDL) of New Moji District. The CDL of New Moji District was lower 2.14m than the mean Tokyo Bay tidal level.

## 2.2 Typhoon summary

Typhoon 9918 occurred at the eastern sea of Taiwan on September 19th, 1999, and it became strong as it moved to the northward. North Kumamoto was hit at 6:00 a.m. on 24th. Afterward Yamaguchi and Hokkaido were hit, and typhoon invaded in each place. Typhoon brought a total of 36 deceased or missing people, 1,077 injured people and 23,218 flood damages across the country starting with 13 deceased people in Shiranui, Kumamoto. The course and the power of this typhoon resembled typhoon 9119 (the Apple typhoon) that occurred in 1991, but because the former invaded at the time of high tide, the damage increased in Kyushu region.

## 2.3 Data used

### Sea phenomena data

The tide level data, which were observed by Kita-kyushu Port Authority, were used for calculating over topping rate. The average wave height  $\bar{H}$  and the average wave period  $\bar{T}$ , which were required for this simulation, were calculated by Saito (2003) from the equivalent deepwater wave height  $H_0'$  and the representative deepwater wave period  $T$ . The tide level data were indicated in Fig. 2, and the average wave height  $\bar{H}$  and the average wave period  $\bar{T}$  were shown in Table 1. Although the observation data were hourly values, the tide level data were calculated as minute values.

### Topographic data

In simulation, the DEM by Saito (2003) was used as topographic data. The DEM was made by stereo matching for two pieces of aerial photos (photographed on April 27, 1999), which were published by Geographical Survey Institute and the ground control point was given by the field surveying result [1]. The spatial resolution of DEM was 10 m.

Table. 1 Average wave height and average wave period in each section

Section	Time	Average wave height(m)	Average wave period(s)	Section	Time	Average wave height(m)	Average wave period(s)
0-200 m	5:00	1.33	5.17	1000-1200 m	5:00	1.12	5.17
	6:00	1.62	5.75		6:00	1.38	5.75
	7:00	1.89	6.75		7:00	1.62	6.75
	8:00	1.56	6.75		8:00	1.37	6.75
	9:00	1.10	5.25		9:00	0.94	5.25
	10:00	0.55	3.50		10:00	0.47	3.50
200-400 m	5:00	1.30	5.17	1200-1400 m	5:00	1.09	5.17
	6:00	1.58	5.75		6:00	1.34	5.75
	7:00	1.81	6.75		7:00	1.55	6.75
	8:00	1.53	6.75		8:00	1.31	6.75
	9:00	1.07	5.25		9:00	0.90	5.25
	10:00	0.53	3.50		10:00	0.45	3.50
400-600 m	5:00	1.26	5.17	1400-1600 m	5:00	1.02	5.17
	6:00	1.54	5.75		6:00	1.26	5.75
	7:00	1.78	6.75		7:00	1.49	6.75
	8:00	1.52	6.75		8:00	1.28	6.75
	9:00	1.04	5.25		9:00	0.86	5.25
	10:00	0.51	3.50		10:00	0.42	3.50
600-800 m	5:00	1.21	5.17	1600-1800 m	5:00	1.01	5.17
	6:00	1.47	5.75		6:00	1.25	5.75
	7:00	1.73	6.75		7:00	1.47	6.75
	8:00	1.45	6.75		8:00	1.26	6.75
	9:00	1.00	5.25		9:00	0.84	5.25
	10:00	0.50	3.50		10:00	0.42	3.50
800-1000 m	5:00	1.14	5.17	1800-1985 m	5:00	0.98	5.17
	6:00	1.40	5.75		6:00	1.22	5.75
	7:00	1.64	6.75		7:00	1.46	6.75
	8:00	1.39	6.75		8:00	1.24	6.75
	9:00	0.95	5.25		9:00	0.83	5.25
	10:00	0.47	3.50		10:00	0.41	3.50

## 2.4 Joint distribution of wave heights and periods

A joint distribution of wave heights and periods by Longuet-Higgins was used to reproduce the ocean wave situation at the time of a typhoon invasion. It was derived theoretically on the assumption that the spectrum width was narrow in a random wave pattern of the Gauss process, and it was applied to the ocean wave [2]. A joint distribution of wave heights and periods  $P(\tilde{H}, \tilde{T})$  was given by Eq. 1.

$$P(\tilde{H}, \tilde{T}) = \frac{\pi \tilde{H}^2}{4\nu} \exp\left[-\frac{\pi}{4} \tilde{H}^2 \left\{1 + \frac{(\tilde{T} - 1)^2}{\nu^2}\right\}\right] \quad (1)$$

where  $\tilde{H}$  is the dimensionless wave height by the average wave height  $\bar{H}$ ,  $\nu$  is a spectrum width,  $\tilde{T}$  is the dimensionless wave period by the average wave period  $\bar{T}$ . Using this equation, a wave appearance frequency distribution was obtained from each wave height and period.

## 2.5 Over topping rate estimation

An over topping rate was obtained with the weir formula on the assumption that calculated individual waves were a sinusoidal curve. A full width weir formula was used for non-collapse parts, and a rectangle weir formula was used for collapse parts. A flow rate equation is expressed as Eq. 2.

$$Q = CBh^{3/2} \quad (2)$$

where  $Q$  is an overflow rate ( $\text{m}^3/\text{s}$ ),  $C$  is an overflow coefficient,  $B$  is a weir width (m),  $h$  is an overflow depth (m). An over topping rate per unit of the width was obtained as  $B = 1$  m. A full width weir and a rectangle weir had different overflow coefficient. An overflow coefficient  $C_1$  of a full width weir could be obtained by Eq. 3 [3].

$$C_1 = 1.785 + \left(\frac{0.00295}{h} + 0.237 \frac{h}{W}\right)(1 + \varepsilon) \quad (3)$$

$$\text{if } W \leq 1\text{m}, \varepsilon = 0. \text{ if } W > 1\text{m}, \varepsilon = 0.55(W-1).$$

where  $C_1$  is an overflow coefficient of a full width weir,  $W$  is a weir height (m),  $\varepsilon$  is a correction term.

An overflow coefficient  $C_2$  of a rectangle weir could be obtained by Eq. 4 [4].

$$\begin{aligned}
 \text{if } 0 < h/L \leq 0.1, & \quad C_2 = 1.642(h/L)^{0.022}. \\
 \text{if } 0.1 < h/L \leq 0.4, & \quad C_2 = 1.552 + 0.083(h/L). \\
 \text{if } 0.4 < h/L \leq (1.5-1.9), & \quad C_2 = 1.444 + 0.352(h/L). \\
 \text{if } (1.5-1.9) \leq h/L, & \quad C_2 = 1.785 + 0.237(h/W).
 \end{aligned} \tag{4}$$

where  $C_2$  is an overflow coefficient of a rectangle weir,  $L$  is a weir length (m). An over topping rate per wavelength was obtained by each 0.01-second interval between  $t_1$  and  $t_2$  and summed up the over topping rate each section.  $t_1$  is time when a wave height exceeds the coastal revetment height, while  $t_2$  is time when the wave height becomes lower than the coastal revetment height. The collapse occurred time is unknown, but the calculation was done on the assumption that the collapse occurred at 7:00 a.m. because the ocean wave showed the most intense and there was witness testimony in the reclaimed land.

## 2.6 Construction of a two-dimensional unsteady flow model

Flooding simulation of the seawater, which flooded in the reclaimed land, was done with DEM, which was made by aerial photos, and an overflow rate, which was obtained by a weir equation. The flooding water depth was several meters at most. Thus the change of vertical direction flow velocity was small. Even if the flow was a laminar flow, there was no hydraulics problem. Therefore a two-dimensional unsteady flow model was employed as a model to express the flooding water behavior. An equation of water continuity is shown as Eq. 5. Dynamic equations of  $x$  and  $y$  directions are shown as Eqs. 6 and 7 [5].

$$\frac{\partial h_w}{\partial t} + \frac{\partial u h_w}{\partial x} + \frac{\partial v h_w}{\partial y} = 0 \tag{5}$$

$$\frac{\partial u h_w}{\partial t} = -g \frac{\partial (h_w + H)}{\partial x} - g n^2 u \frac{\sqrt{u^2 + v^2}}{h_w^{1/3}} \tag{6}$$

$$\frac{\partial v h_w}{\partial t} = -g \frac{\partial (h_w + H)}{\partial y} - g n^2 v \frac{\sqrt{u^2 + v^2}}{h_w^{1/3}} \tag{7}$$

where  $h_w$  is a water depth (m),  $u$  is an  $x$ -direction velocity component (m/s),  $v$  is a  $y$ -direction velocity component (m/s),  $H$  is an elevation (m),  $n$  is the Manning roughness coefficient. Finite differences were applied to these partial differential equations with staggered grid. A scalar such as a water depth or a pressure was given the grid center, and the direction velocity component was arranged between the water depths of the next grid. This method easily expressed that the velocity, which was a perpendicular to the surrounding walls, was 0. The grid width was assumed 10 m to adjust DEM resolution, and the time step was assumed 0.1 second.

## 3. Analysis results

### 3.1 Joint distribution of wave heights and periods

Each wave height and wave period's wave frequency in 0 to 200-m section at 7:00 a.m. was shown in Table 2 that was obtained by a joint distribution of wave heights and periods. A vertical axis shows a wave height (m), and a horizontal axis shows a wave period (s). The average height was 1.89 m, and the

average wave period was 6.75 s. The wave with 2.25 m in height and 7.5 s wave period was most frequent in this one hour, and the wave number was 45. In other sections, 1.75 and 2.25 m wave were most frequent in the 1st New Moji coastal revetment, and 1.75 m wave was most frequent in the 2nd New Moji coastal revetment.

Table. 2 Each wave height and wave period's wave frequency in 0 to 200-m section at 7:00 a.m.

Wave period(s)→   Wave height(m)	2.5	5	7.5	10	12.5	15
0.25	2	2	2	2	2	2
0.75	11	14	15	12	9	5
1.25	15	29	32	21	8	2
1.75	10	36	44	19	3	0
2.25	4	32	45	12	1	0
2.75	1	23	37	5	0	0
3.25	0	13	26	2	0	0
3.75	0	6	15	0	0	0
4.25	0	2	8	0	0	0
4.75	0	1	3	0	0	0
5.25	0	0	1	0	0	0
5.75	0	0	0	0	0	0

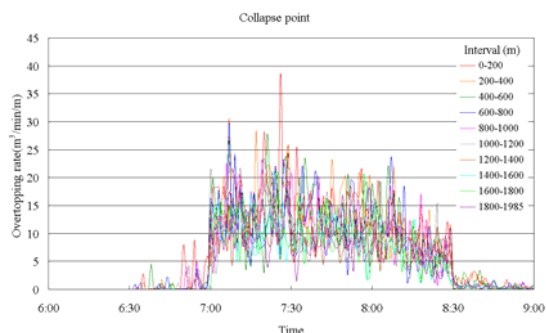


Fig. 3 Over flow rate in collapse section

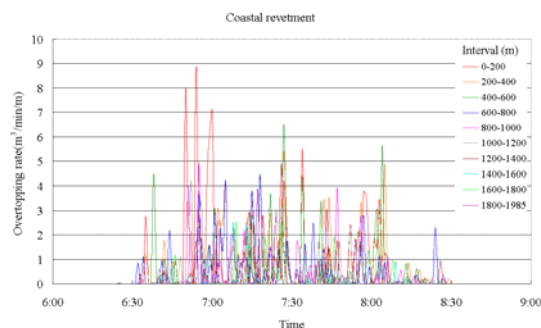


Fig. 4 Over flow rate in non-collapse section

### 3.2 Over topping rate by the weir equation

An over flow rate in the collapse section is shown in Fig. 3 and one in the non-collapse section is shown in Fig. 4. The collapse time is unknown, but the calculation was done on the assumption that the collapse occurred at 7:00 a.m. because the ocean wave was the most intense at that time and there was witness testimony in the reclaimed land. In the collapse section, an over topping rate increased at 7:00 a.m. when the collapse occurred. In particular, the over topping continually occurred during 7:00 a.m. to 8:30 a.m. It is understood that the damage was serious. When an over flow rate in the collapse section and in the non-collapse section were compared, about 59 times differences were estimated at the maximum.

### 3.3 Simulation execution result

A simulation execution screen is shown in Fig. 5. An over topping started from 6:30 a.m., and filling action was in progress where an elevation was relatively low.

## 4. Discussion

An inlet flow into the filled land was obtained from an inlet flow from hinterland and a displacement capacity. Because the torrential rain and high tide by typhoon occurred at the same time, the inlet flow from hinterland exceeded a displacement capacity at 8:00 a.m. When a wave frequency distribution was obtained with a joint distribution of wave heights and periods, it was understood that 1.75 and 2.25-m wave were most frequent in the 1st New Moji coastal revetment, and 1.75 m wave was most frequent in the 2nd New Moji coastal revetment. In this time period, the over topping damage occurred in the non-collapse section because the tide level was about 5 m. In the collapse section where the ground

height was 5.5 m, an over topping rate increased more than non-collapse section because there became a few differences between tide level and ground height and over topping occurred even for a small wave. Flooding simulation was done with DEM, which was made from the aerial photos, and an estimated overflow rate. The seawater, which flooded in the reclaimed land, flowed in relatively a low place as a canal.



Fig. 5 simulation execution screen

## 5. Conclusions

The over topping rate estimation by the tide observation and the submerged situation by a distributed runoff model were reproduced for the wave over topping damage at the New Moji District, Kita-kyushu, Fukuoka caused by Typhoon 9918. Conclusions are shown below.

- 1) An over topping rate was estimated by the weir equation on the basis of the wave frequency distribution. At a collapse section, the frequency of over topping was high, and the over topping continually occurred during 7:00 a.m. to 8:30 a.m. In addition, about 59 times differences occurred at the maximum between the over flow rate in collapse section and in non-collapse section. Therefore, the superstructure collapse was the greatest factor of the over topping damage in the New Moji district.
- 2) A two-dimensional unsteady flow model was constructed, and a flooding simulation was done with rainfall data, DEM, which was made from aerial photos, and an estimated overflow rate as input data. From the simulation result, it was understood that the seawater, which flooded in the reclaimed land, flowed as a canal where an elevation was relatively low.
- 3) Flooding simulation was done by combination of observed sea data, aerial photos, field survey results and two-dimensional unsteady flow model. Various damage assessment could be done different conditions by changing an input parameter. Therefore, this method could be applied to make a disaster master plan.

## References

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