THE NUMERICAL ANALYSIS OF WAVE OVERTOPPING AND WATER OVERFLOW OVER THE COASTAL LEVEE IN THE STORM CONDITION

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Storm surges and high waves occur at the same time. Due to high tide and waves, water overflow and wave overtopping occur over the coastal levee. Numerical simulation based on the two-dimensional Navier-Stokes equations by using the VOF method, CADMAS-SURF, is applied. The overflow and overtopping calculated by numerical simulation is analyzed, the hydraulic characteristics of flow rate over the coastal levee are clarified.

Keywords: storm surge, high waves, coastal levee, overflow, overtopping, N-S simulation, flow rate

INTRODUCTION

The risk of inundation disaster by storm surge with high waves increases recently with sea level rise and intensified typhoon activity caused by global warming. When typhoons attack on the coast, storm surges and high waves occur at the same time. Due to high tide and waves, water overflow and wave overtopping occur over the coastal levee. At the time of storm surge, the inundation disaster is induced by combination of wave overtopping and water overflow.

Against the overflow and overtopping occur at the same time, it is difficult to measure the flow rate over the coastal levee by hydraulic experiments and field observations. The estimation method of transition process from overtopping to overflow has not been established so far. The applicability of inundation simulations by storm surge depends on the accurate estimation of the flow rate over the coastal levees induced by both overtopping and overflow.

Therefore, numerical simulation based on the two-dimensional Navier-Stokes equations by using the VOF method, CADMAS-SURF, is applied. By this simulation, flow rate over the coastal levee is clarified. The flow rate is compares with the formulas of overflow and overtopping base on the hydraulic experiments. In this study, numerical simulations about water overflow and wave overtopping are performed. The overflow and overtopping calculated by numerical simulation is analyzed, the hydraulic characteristics of flow rate over the coastal levee are clarified.

TRANSITION PROCESS FROM WAVE OVERTOPPING TO WATER OVERFLOW

Fig. 1 is schematic diagrams of the transition process from wave overtopping to water overflow. When $h_c/H_0'>0.5$, overtopping rate can be estimated by using the Goda's diagrams (1975). When $h_c/H_0'<0.0$, $h_c=-h_1$, the water level is slightly higher than the dike crest. Flow rate is underestimated by using the overflow formula. When $-0.5<h_c/H_0'<0.0$, $h_c=-h_1$, the flow rate is combined with wave overtopping and water overflow. When $h_c/H_0'<-0.5$, $h_c=-h_1$, the flow rate is estimated by the overflow formula. Where, h_c is the clearance between water level and dike crest, H_0' is the equivalent deep-water wave height, and h_1 is the water level over dike crest.

In conventional calculation methods, the flow rate over dikes is calculated separately with independent estimations of overtopping rate and overflow flux.

- Overtopping rate is estimated by Goda's diagrams (1975).
- Overflow flux is estimated by the overflow formulas.

The numerical simulations of transition process from wave overtopping to water overflow are performed by using two-dimensional Wave Tank Model. The characteristic of transition process is clarified by the numerical simulation. A new estimation method of the flow rate by combination of wave overtopping and water overflow has been clarified.

CONDITIONS OF NUMERICAL SIMULATION

Wave Tank Model of 2-D Numerical Simulation

When water overflow and wave overtopping occur at the same time, the action of waves influences the flow rate over the coastal levee. This influence is analyzed by the numerical simulation.

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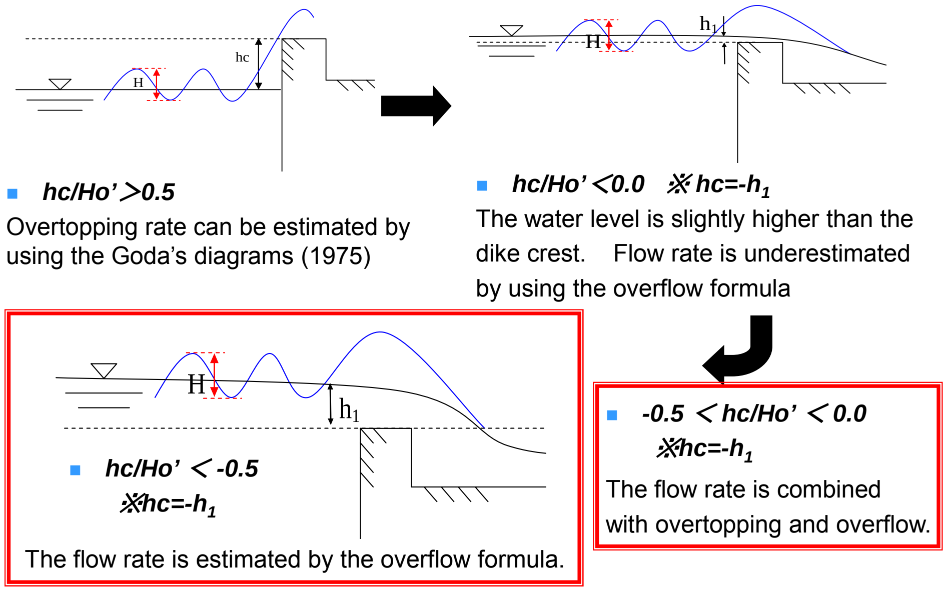
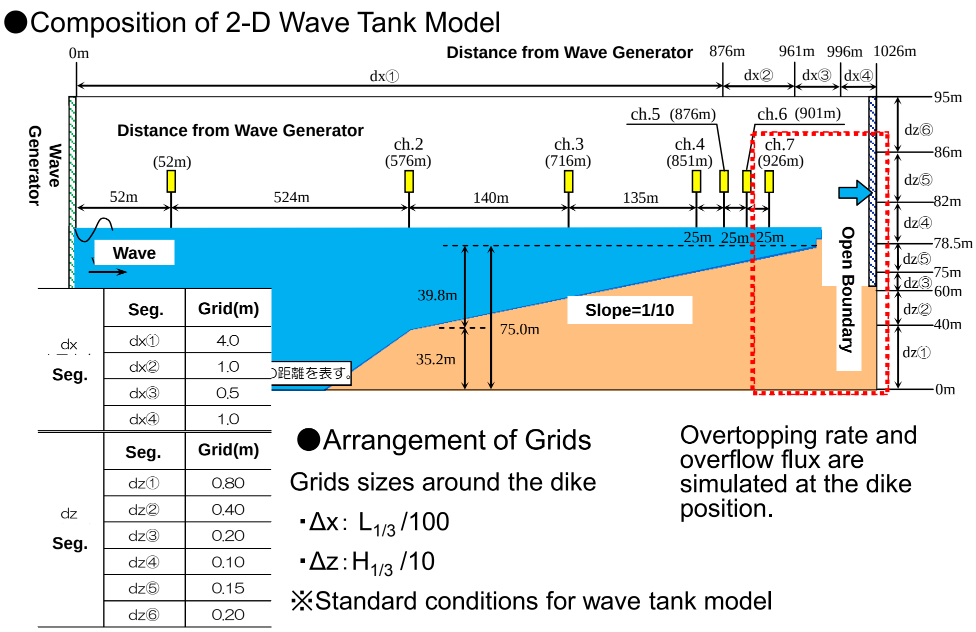


Figure 1. Schematic diagrams of the transition process from wave overtopping to water overflow.

Fig. 2 shows the outline of numerical simulation by using wave tank model. The diagram shows the wave tank condition and red block shows near the coastal dike. Overtopping rate and overflow flux are simulated at the dike position. The table shows the arrangement of horizontal grids along distance from wave generator. The arrangement of vertical grids is shown in this table and right side in the diagram. Standard conditions are shown in the lower of this diagram.

Fig. 3 shows the composition of wave tank model around the coastal dike. The definition of predominant characters around the coastal dike as follows.

- h_c is the clearance between water level and dike crest
- W is dike height and D is dike width.
- H_0' is the equivalent deep-water wave height
- h_1 is the water level over dike crest.



	Seg.	Grid(m)
dx Seg.	dx①	4.0
	dx②	1.0
	dx③	0.5
	dx④	1.0

	Seg.	Grid(m)
dz Seg.	dz①	0.80
	dz②	0.40
	dz③	0.20
	dz④	0.10
	dz⑤	0.15
	dz⑥	0.20

Figure 2. The Outline of Numerical Simulation by using Wave Tank Model, arrangement of grids and position of wave generator and the coastal dike (red block).

The condition of the coastal dike is similar to the fundamental hydraulic experiment that the formulas of overflow were produced. The shape of coastal dike is rectangle. In addition, the sea wall is established at the edge of landside in the waterway model. The water level in the landside of waterway is controlled by this sea wall. The length of the waterway in the landside of waterway is enough. By this length, the water level in the landside is in a steady condition. Furthermore, between the coastal dike and the sea wall, a slope is established. The return flow is controlled in the landside of waterway by this slope.

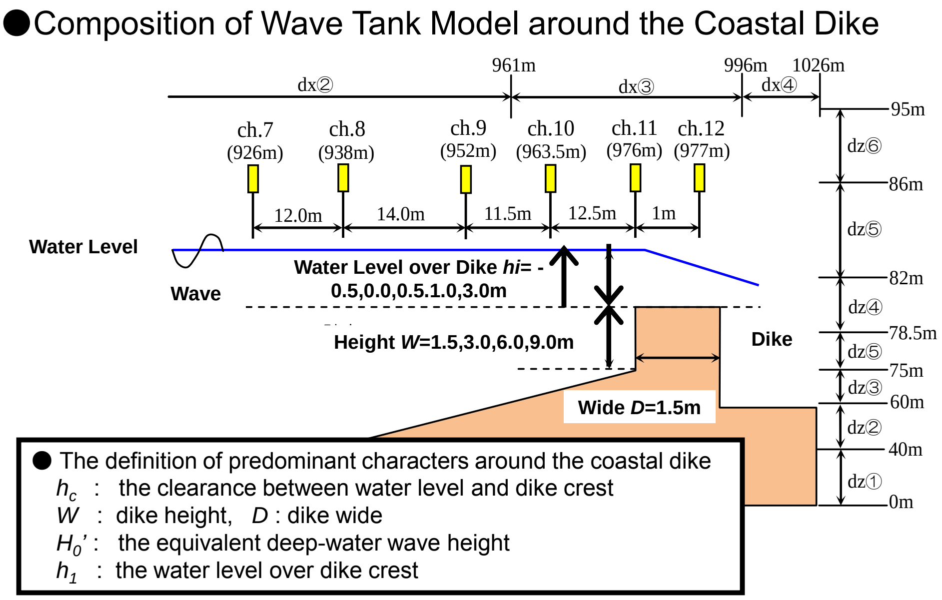


Figure 3. The composition of wave tank model around the coastal dike and the definition of predominant characters around the coastal dike.

Simulation Conditions

Fig. 4 is the sample of Goda's diagram (1975), and red blocks are parameter of diagrams. Parameters of this diagram consist of bottom slope (*tan i*), relative water depth (h/H_0') and relative clearance of dike from water level (h_c/H_0'). The equivalent deep-water wave heights H_0' selected are 1.5, 3.0, 6.0m. They are the typical wave on Japanese coast. Deep-water wave steepness H_0' $/L_0$ is selected a condition for three wave height. 0.017, and H_0'= 1.5, 3.0, 6.0m. During of simulation time is 1,500s that means 150 to 200 wave numbers.

Typical shape of dike is rectangle, dike width is 1.5 and 6.0m, dike height is 1.5, 3.0. 6.0 and 9.0m. Simulation conditions are referred to the Goda's diagrams.

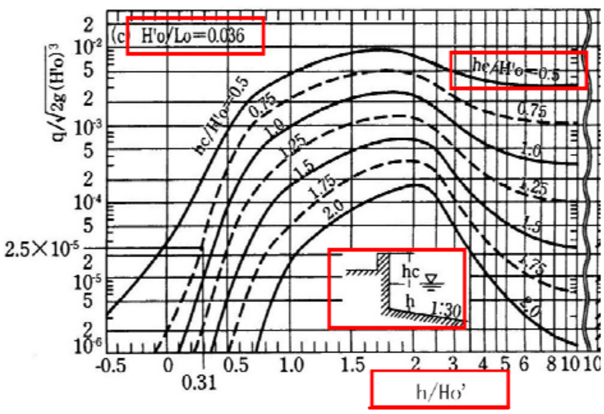


Figure 4. Sample of Goda's diagram (1975) and parameter of diagrams (red block).

Table 1. shows the simulation conditions for wave tank model. Several conditions were already explained. Incident wave at the wave generating point is irregular wave based on the standard frequency spectra proposed by Bretschneider with adjustment of the coefficients by Mitsuyasu.

Fig. 5 shows the time series of incident waves by using wave tank model. Time series of water level is monitored at the wave generator point. Upper time series shows the condition with H_0'=3.0m waves. Lower time series shows the condition without wave.

The ratio of the water level in front of coastal dike and wave height, h_1/H_0 ', is assumed 0.5. On the other hand, the ration of the water level behind the coastal dike and wave height, h_2/H_0 ', are fixed. The condition h_2/H_0 ' of complete overflow is 0.0, and the condition of submerged overflow is 0.47.

Table 1. Conditions of wave simulation by using the wave tank model.

Content of Condition	Setting of Condition
Equivalent wave height (H_0')	0.0, 1.5, 3.0, 6.0m
Deep-water Wave Steepness (H_0'/L_0)	0.017
Bottom Slope	1/10
Dike Height (*W*)	1.5, 3.0, 6.0, 9.0m
Water Level over the Dike (*hi*)	-0.5, 0.0, 0.5, 1.0, 3.0m
Dike Width(*D*)	1.5, 6.0m
Incident wave at the wave generator	Irregular wave based on the standard frequency spectra Proposal by Bretschneider with adjustment of the coefficients by Mitsuyasu
Time length of simulation, time deviation	1,500s, Auto control for stability of simulation

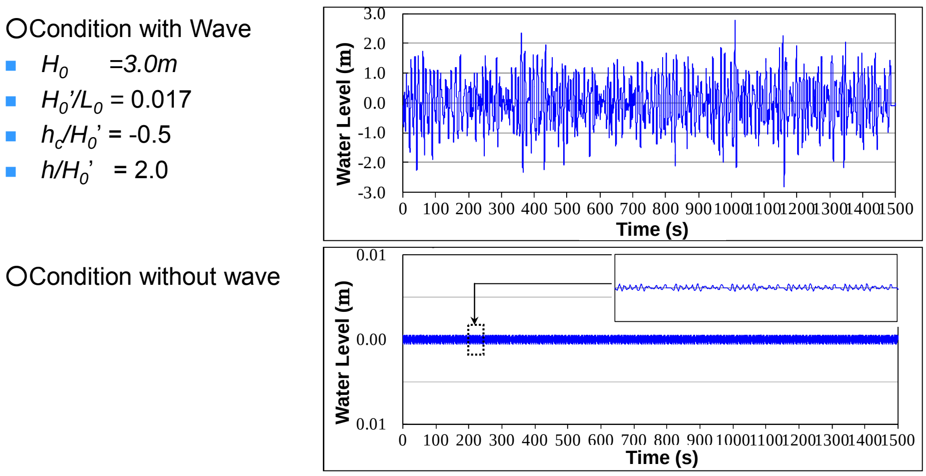


Figure 5. Time series of incident waves at the wave generator points by using wave tank model.

WAVE AND FLOW SIMULATED BY NUMERICAL SIMULATION

The influence to the overflow with the action of waves is analyzed by numerical simulation.

Fig. 6 is snapshots of velocity field by using the wave tank model. These results are the steady state with waves. Simulation conditions are as follows.

- H_0' = 3.0m, $H_0'/L_0 = 0.017$
- W = 1.5m, D = 1.5m, 6.0m, h_1 = 1.5m
- h_1/H_0' = -0.5

Upper diagram shows the complete overflow with waves. Lower diagram shows the submerged overflow with wave. Simulation reproduces the process of water overflow with waves. In this case, strong velocity is generated by wave breaking over the dike.

Fig. 7 is the snapshots of velocity fields by using wave tank model. These results are the steady state without wave. Simulation reproduces the process of water overflow. Upper diagram shows the complete overflow without wave. Lower diagram shows the submerged overflow without wave.

The flow rate with the action of waves is larger than the one without wave by the wave breaking on the coastal dike.

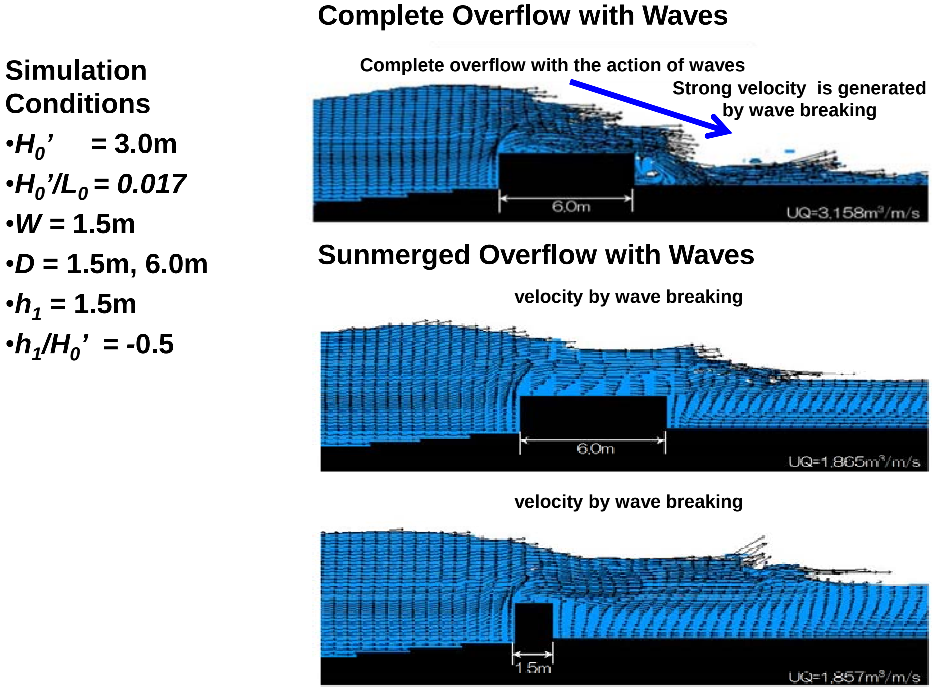


Figure 6. Snapshots of velocity fields with the action of waves by using wave tank model.

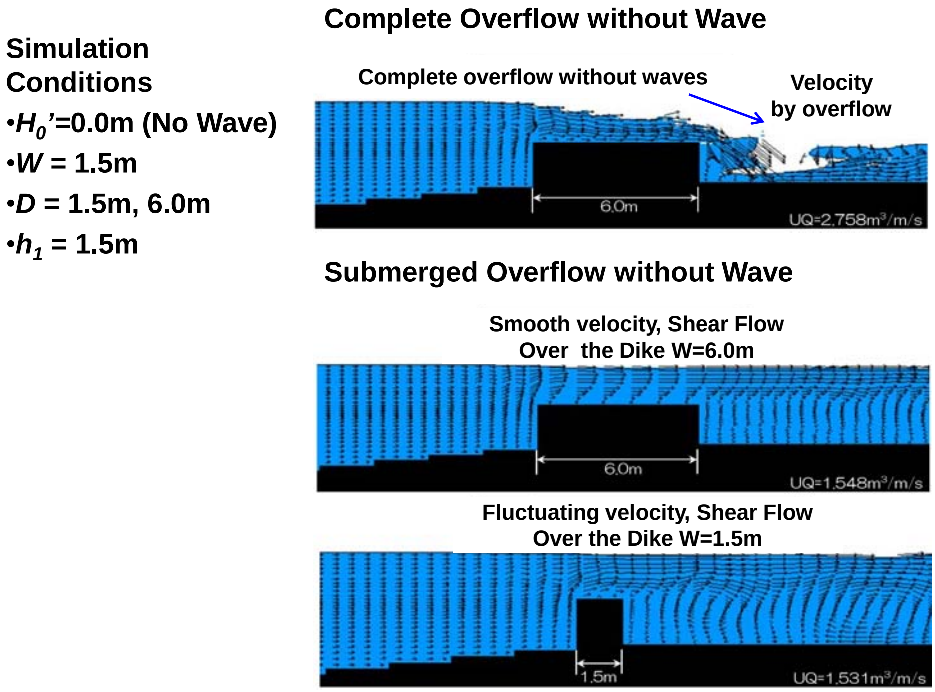


Figure 7. Snapshots of velocity fields without waves by using wave tank model.

ANALYSIS OF OVERFLOW AND OVERTOPPING

Hydraulic Characteristics of Combined Overflow and Overtopping

Fig. 8 shows a comparison of the flow rate over the coastal dike between the different wave conditions. One is the action of waves, *Hs*=3.0m, and the other is without waves. Under diagram shows the horizontal distribution of mean water level.

The flow rate with the action of waves increases than the one without waves. The mean water level in front of the coastal dike is not influenced with the wave conditions. On the other hand, the mean water level behind the coastal dike rises about 5cm by the action of the waves. This characteristic is confirmed on the two types of overflow, complete and submerged. Increase of the flow rate is related to the water level rise behind the coastal dike.

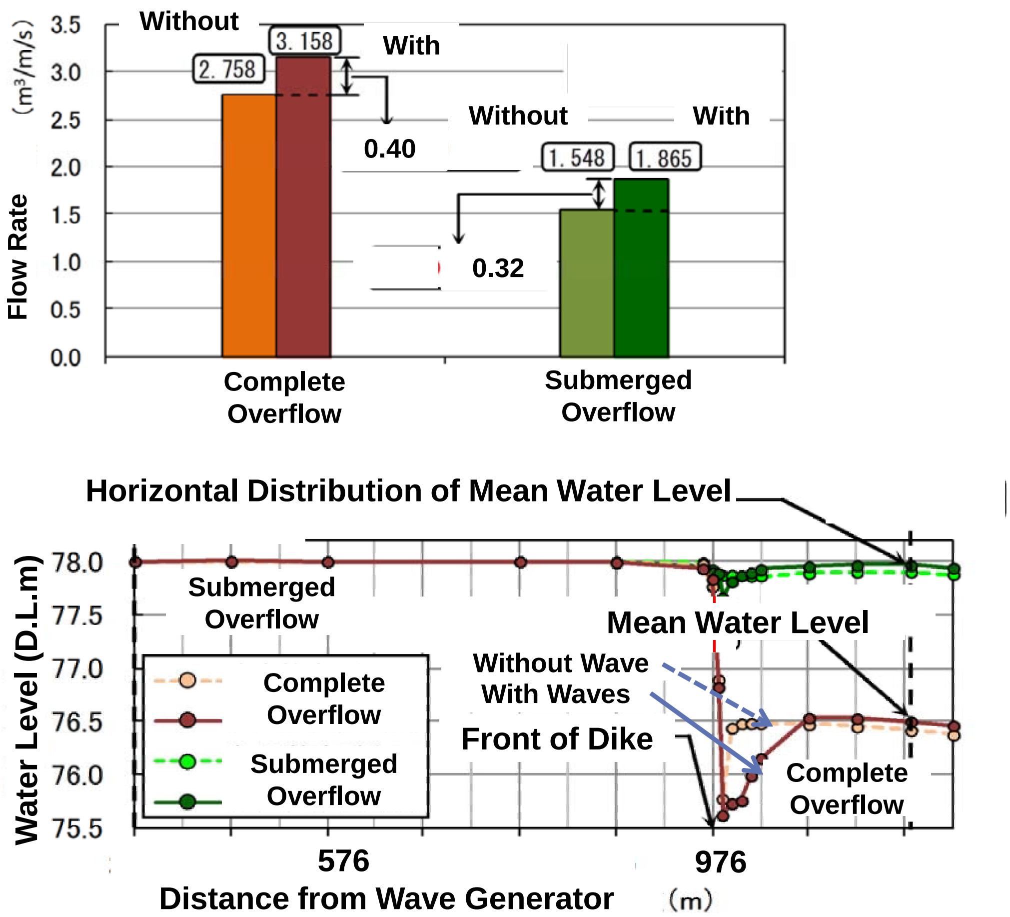


Figure 8. The comparisons of the flow rate over the coastal dike and the horizontal distribution of mean water level between the different wave conditions.

Fig. 9 shows the vertical distribution of the mean velocity at the point, the sea edge of the coastal dike. At the deep water area, large mean velocity generates near the water surface by the action of waves. The constant mean velocity produces under 5m depth.

The mean velocity with the action of waves is larger than without wave at the sea edge of the coastal dike. The large mean velocity directs to behind the coastal dike near the water surface by the wave breaking. When waves act, water falls down behind the coastal dike by wave breaking on the coastal dike. The one directional flow near the sea surface is generates by the wave breaking. By this condition, the flow rate increased.

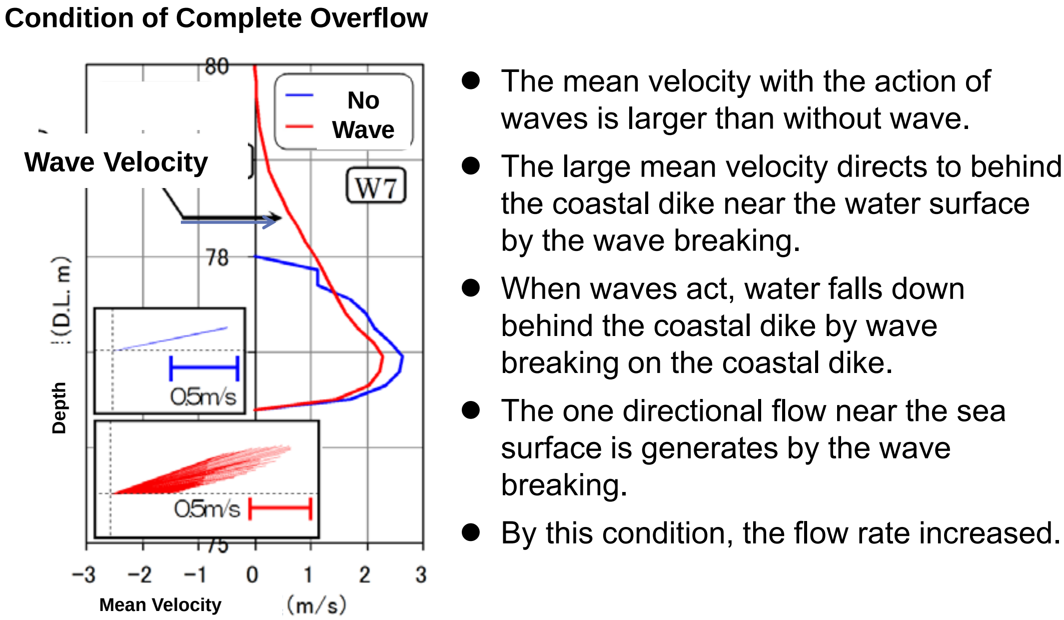


Figure 9. The vertical distribution of the mean velocity at the sea edge of the coastal dike.

Simulation Accuracy of Overflow Phenomena

The estimation of overflow rate is used the Honma's formulas (1985). Eq. 1 and Eq. 2 are selected by the types.

: the complete overflow $Q = 0.35 h_1 \sqrt{2gh_1}$ (1)

: the submerged overflow $Q = 0.91 h_2 \sqrt{2g(h_1 - h_2)}$ (2)

Where, g is the acceleration of gravity, h_1 is the water level in front of coastal levee, and h_2 is the water level behind of the coastal levee. Two water levels are estimated over the top of the coastal levee. The flow rate over the coastal levee calculated by the numerical simulation is compared with the estimation value based on the overflow formulas. The flow rate calculated by the numerical simulation reproduces the one estimated by the overflow formulas.

Honma's formulas Eq. 3 cannot estimate the dike width D. The estimation of overflow rate uses the following formulas produced by Rao and Muralidhar (1963). Eq. 4 is selected by the ratio between the water level over the dike crest and the dike wide. The parameters in equations are that h_1 is water level over the dike crest, D is width of dike, and W is height of dike.

$$Q = 0.35\,h_1\sqrt{2gh_1} \qquad C = 1.550 \qquad (3)$$

$$Q = Ch_1^{3/2}$$

$$\begin{array}{ll} 0 < h_1/D \leqq 0.1 & C = 1.642\left(h_1/D\right)^{0.022} \\ 0.1 < h_1/D \leqq 0.4 & C = 1.552 + 0.083\left(h_1/D\right) \\ 0.4 \leqq h_1/D \leqq \left(1.5\sim1.9\right) & C = 1.444 + 0.352\left(h_1/D\right) \\ \left(1.5\sim1.9\right) \leqq h_1/D & C = 1.785 + 0.237\left(h_1/W\right) \end{array} \qquad (4)$$

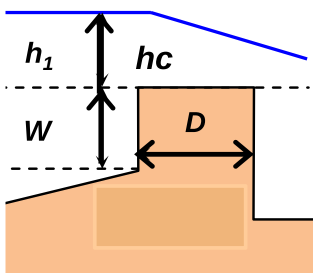


Fig. 10 shows the comparisons of the flow rate estimated over the coastal dike, Left bar is based on the Honma's formulas, center bar is based on the Rao & Muralidhar formulas, and right bar is simulated by the wave tank model. These bar graphs show about the complete overflow. The conditions is h_1=1.5m, D=1.5m. The simulation result reproduces the estimation based on the overflow formulas produced by Rao & Muralidhar. When the condition is D=1.5m, simulation result is larger than estimation based on the Honma's formulas.

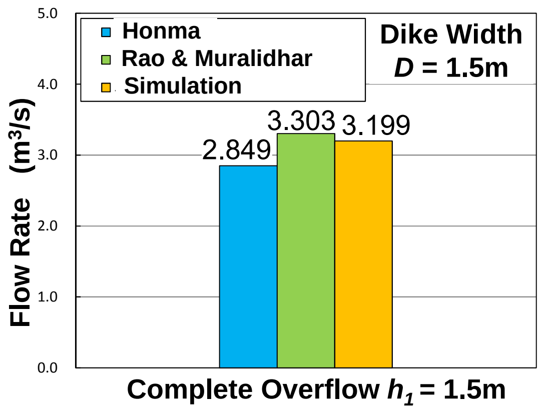


Figure 10. The comparisons of the flow rate estimated over the coastal dike.

Fig. 11 shows the comparison with simulation results and overflow formula. In this diagram, red and blue curve lines are the characteristic lines calculated by overflow formulas, and the marks are the simulation results in several conditions.

When the water level is slightly higher than the dike height, -0.5<h_c/H_0'<0.0, h_1>0.0, the flow rate by using overflow formula is underestimated because of neglect of wave overtopping. When the water level is higher than the dike height, h_c/H_0'<-0.5, h_1>2.0, the flow rate is equivalent to the estimated value by using overflow formula produced by Rao and Muralidhar (1963).

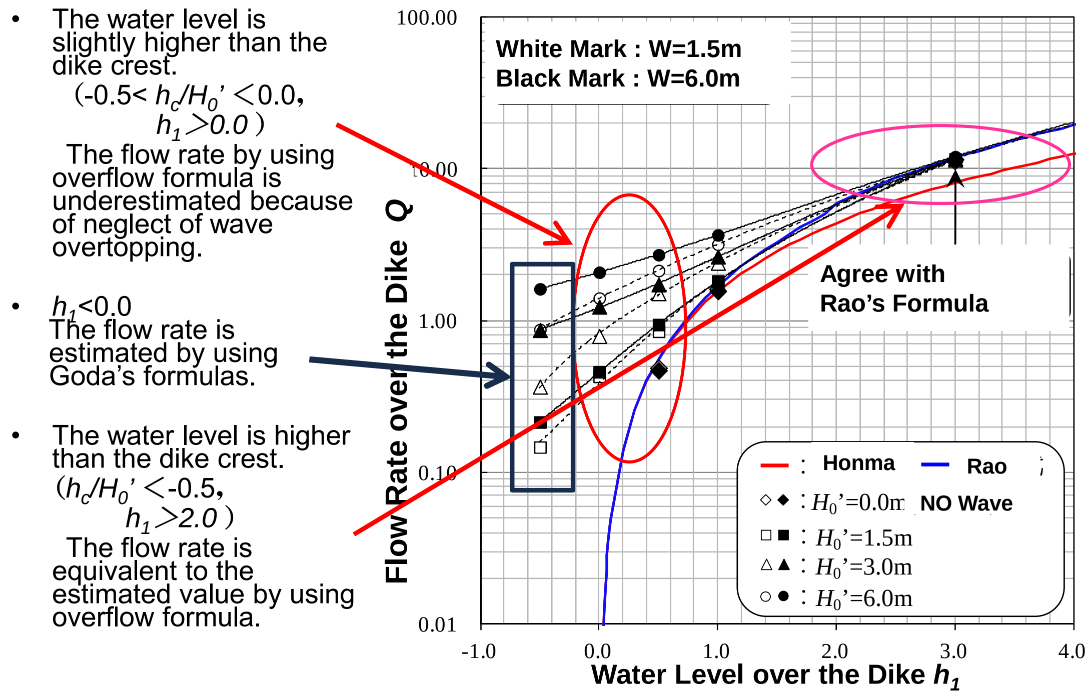


Figure 11. The comparison with simulation results and overflow formula.

Estimation Method of Flow Rate

Formulation of estimation method of flow rate combined with overtopping and overflow is applied. The Eq. 5 refers to the Goda's formula (1975). Calculation method of overtopping rate for irregular wave contains parameters *a*, *b*, *c*. that each value is given to these parameters.

$$\frac{q_{\exp}}{\sqrt{2g\left(H_O'\right)^3}} = \int_0^\infty q^*(x)p(x)dx$$

$$q^* = \frac{q(x)}{\sqrt{2g\left(H_O'\right)^3}} = A_0\left(\frac{K}{1+K}\right)^{3/2} x^{3/2}\left[1-\frac{h_C}{H_O'}\bullet\frac{1}{Kx}\right]^{5/2} \qquad (5)$$

$$K = \frac{\eta_C}{H} = \min\left\{\left[1.0 + a\frac{xH_O'}{h} + \frac{b}{K_{sb}}\left(\frac{xH_O'}{h}\right)^2\right], c\right\}$$

Where a is parameter related with relative water depth, b is parameter related to wave shoaling and wave breaking and c is parameter obtained wave height and water depth at the breakwater point. When the overtopping rate estimates for the rectangle dike, parameter *a* is 1.0, *b* is 0.8, and *c* is 0.0.

A_{i0} is coefficient of overflow, 0.10, $x=H/H_0'$ is non-dimensional wave height, $p(x)$ is probability density function of *x*, $K_{sb}=H_{1/3}\ /H_0'$ is the changing rate of significant wave height by non-linear shoaling and wave breaking, *K* is ratio of wave level to wave height and *min{A,B}* is smaller value.

Fig. 12 shows comparison with simulation results and diagram of overtopping. Red lines are the characteristic line obtained by Goda and the marks are the simulation results in several conditions. On the overtopping condition, h_c/H_0'>0.5, Simulation results reproduce the characteristic curves in the diagram proposed by Goda. On the condition of water level rise, h_c/H_0'<0.5, simulation results over the coastal dike are increase with water level rising. In this condition, the flow rate is estimated by using Goda's formila (1975).

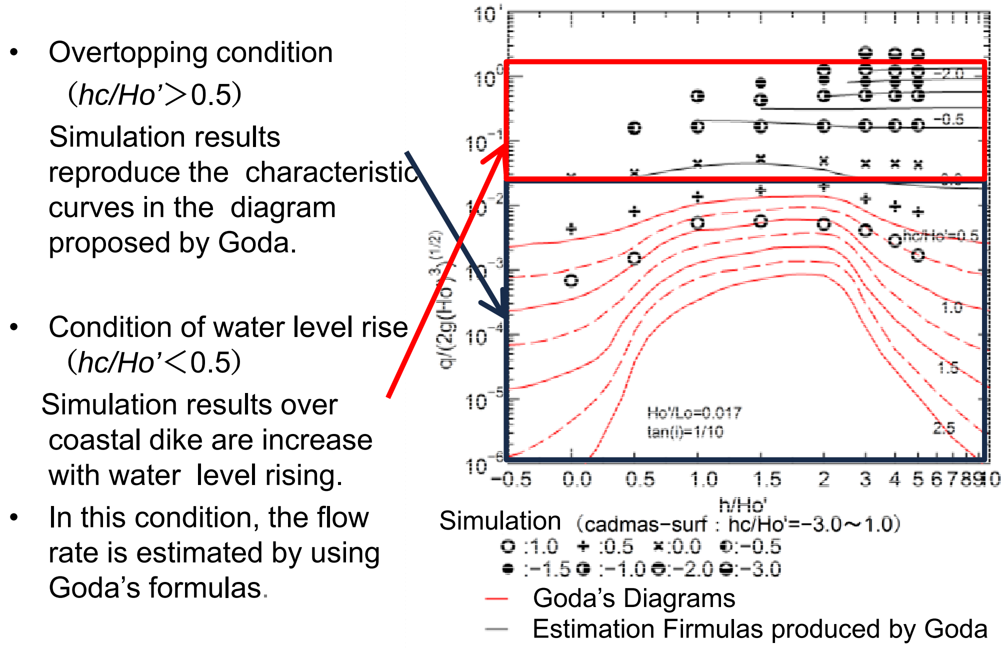


Figure 12. Comparison with simulation results and diagram of overtopping, red lines are the characteristic lines obtained by Goda and the marks are the simulation results in several conditions.

The method of estimation for the flow rate combined with overtopping rate and overflow flux is summarized as follows.

When dike crest is higher than the half of incident wave height, *hc/Ho' ＞0.5, t*he rate of overtopping can be estimated by using the Goda's diagrams. The formulation method Eq.5 reproduces the Goda's diagrams. When dike crest is smaller than the half of incident wave height or the water level is slightly higher than the dike crest, *-2.0＜hc/Ho'＜0.5,* the formulation method is able to calculate the flow rate over the dikes. Estimation method by using Goda's formulas is performed to the transition process from over topping to overflow over the dikes (Fig. 12). When the water level is higher than the dike crest, *hc/Ho'＜-2.0,* h_1 *＞0.0,* the flow rate is equal to estimation by using overflow formula by Rao and Muralidhar (Fig. 11).

CONCLUSIONS

When storm surge and high waves occur at the same time, the phenomena with overflow and overtopping over the coastal dike is generated. The characteristics of these phenomena are analyzed by using the numerical simulation. The two-dimensional N-S equations by the VOF method, 2-D wave tank model, are applied.

The numerical simulations are performed to calculate the flow rate over the coastal dike with the two conditions. One is the action of waves and the other is without wave. The complete overflow and submerged flow are assumed. The flow rate over the coastal dike increases with the action of waves. The increasing of flow rate is induced by the strong velocity toward landside generated with the wave breaking on the coastal levee. Furthermore, the increasing of flow rate in the condition of complete overflow is larger than the one in the condition of submerged overflow.

Flow rate induced by transition process from overtopping to overflow is performed by the 2-D wave tank model. The estimation method is based on the formulation proposed by Goda (1975) and produced by Rao & Muralidhar (1963). Several parameters in the Goda's formula are defined by numerical wave simulations of the process combined with overtopping and overflow. According to these simulation results, flow rates over the coastal dikes are estimated accurately during the time of storm surge.

Future study is to up-grade the estimation method applying to any other shapes of dike, and several wave conditions should be adapted to wave simulations.

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