DEVELOPMENT OF Q3D-H2D COUPLED MODEL FOR COASTAL INUNDATION ANALYSIS WITH EFFICIENCY

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Recently, quasi 3-Dimensinal (Q3D) ocean models have been utilized for coastal inundation simulations. However, the Q3D models require large computational effort, and are not suitable for large-scale inundation simulation with fine grid resolutions. The main purpose of this study is to develop a Q3D-H2D coupled model, which consists of a quasi-three-dimensional ocean model CCM (Q3D model) and a horizontal two-dimensional inundation model using a CIP method (H2D model), in order to analyze storm surge-induced inundation with efficiency and low computational load. The validity of the coupled model was verified by comparing with the existing numerical results and the experimental ones. As a result, the coupled model was confirmed to be consistent with the existing numerical schemes. Furthermore, the numerical results were found to be in good agreement with the experimental ones, which indicated that the coupled model was capable of analyzing inundation with high accuracy.

Keywords: coupled model; multi-sigma coordinate ocean model; horizontal two-dimensional model; CIP method

INTORODUCTION

Many of great cities in the world are located on low lying flat plains, which are vulnerable to a risk of coastal inundation caused by tsunami, storm surge and so-on. Recently, there is increasing concern about sea level rise and intensification of typhoon, cyclone or tropical storm induced by global warming, which could cause severe flooding due to storm surge. Murakami et al. (2012) predicted a maximum possible storm surge in Ise Bay, Japan under the future metrological condition based on the Special Report on Emission Scenarios (SRES) A1B scenario (Nakićenović et al. 2007), and they suggested that the maximum possible storm surge remarkably exceeds the largest storm surge ever recorded in Japan. It is, therefore, necessary to take effective countermeasures against possible future extreme storm surge and inundation.

Storm surge and coastal inundation had been mainly computed employing a horizontal 2-Dimensional (H2D) model based on a nonlinear long wave theory under the assumptions of hydrostatic approximation and uniform flow in a vertical direction. Since a strong wind in a typhoon, cyclone or tropical storm, in general, induces a three-dimensional flow field, quasi 3-Dimensinal (Q3D) ocean models, such as a Princeton Ocean Model (POM; Blumberg and Mellor 1987), a Finite Volume Coastal Ocean Model (FVCOM; Chen et al. 2003) and a Regional Ocean Modeling System (ROMS; Haidvogel et al. 2008), have been recently used in storm surge calculations. Several studies have been examined the difference between storm surges in a H2D calculation and a Q3D calculation (e.g., Weisberg and Zheng 2008; Shen et al. 2010; Shen and Paramygin 2010). Weisberg and Zheng (2008) conducted storm surge simulation in Tampa Bay, Florida during a hypothetical hurricane like Ivan using the FVCOM, and they revealed that a H2D calculation underestimates storm surge in comparison with a Q3D calculation. Thus, the use of a Q3D model is said to be necessary for simulating storm surge accurately. However, a Q3D model is computationally expensive, and is not suitable for large-scale inundation simulations with fine grid resolutions.

Based on the above-mentioned, the present study aims to develop a Q3D-H2D coupled model in order to analyze coastal inundation with efficiency and low computational load. The validity of the model is examined by applying it to a one-dimensional dam-break problem. Furthermore, the predictive capability of the model against coastal inundation phenomena is demonstrated through comparisons between numerical results and experimental data measured in the hydraulic experiments on run-up bore against seawall (Arimitshu et al. 2013).

DEVELOPMENT OF Q3D-H2D COUPLED MODEL

Model description

A coupled model developed in this study is composed of a quasi three-dimensional Coastal ocean Current Model CCM (Q3D model) and a horizontal two-dimensional inundation model using a Constrained Interpolation Profile (CIP) method (H2D model).

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The CCM was developed by Murakami et al. (2004), which is a primitive coastal ocean circulation model with Boussinesq and hydrostatic approximations. The CCM uses an orthogonal coordinate system in the horizontal direction, while a terrain following multi-sigma coordinate system (Murakami et al. 2008) is used in the vertical direction. The multi-sigma coordinate system can maintain high resolution just below sea surface. Moreover, it can improve computation error in the horizontal pressure gradient near steep topography, which has been confirmed in a traditional sigma coordinate system. The momentum advection terms are discretized with high resolution, fifth-order upwind scheme (Rai and Moin 1991), and a fourth-order central difference scheme is used for the diffusive terms for the accurate calculation. The detailed explanation of the CCM can be found in Murakami et al. (2004, 2008).

The H2D model used in this study was developed by Kawasaki et al. (2013), the governing equations of which consist of the continuity equation and the momentum equations based on a nonlinear long wave theory in Cartesian coordinate system. To solve advection terms with a high accuracy, a high-order Godunov scheme known as the CIP method developed by Yabe and Aoki (1991) was employed. The moving boundary treatment proposed by Kawasaki et al. (2004) was utilized to simulate coastal inundation, which is similar to the method developed by Kotani et al. (1998) except that a zero velocity gradient condition was imposed at a wave front boundary. Figure 1 illustrates a schematic of the moving boundary treatment proposed by Kawasaki et al. (2004). If the total depth H_i is smaller than the threshold depth H_s, the grid is regarded as dry. In the figure, the total depth H_i at the grid point i is larger than the threshold depth H_s, and H_{i+1} at the grid point i+1 is smaller than H_s. Hence, the wave front is defined between the grid points i and i+1, and the depth-averaged velocity U_{i+1} at the wave front is set to equal the velocity U_i.

Coupling method

The coupled model makes it possible to continuously simulate coastal flow and flooding by overlapping the two computational domains of the Q3D and H2D models, as shown in Fig. 2. As indicated in Fig. 3, water surface elevation η and depth-averaged velocity U are interactively exchanged between the two models in the overlap region.

The overlap region basically has to be selected as a region where horizontal velocities are vertically almost uniform because the H2D model cannot calculate the vertical distribution of horizontal velocity. It would be, however, difficult to set the overlap region with uniform flow since three-dimensional flow pattern is predominant in real seas. In the present coupled model, the depth-averaged velocity U_c computed by the H2D model is allocated on the base of the vertical distribution of horizontal velocity obtained by the Q3D model, in a similar way to Fujima et al. (2002) and Tomita and Takahashi (2012).

Figure 4 shows a schematic of arrangement of variables in the overlap region. The horizontal velocity $u_{c,n}$ (n = 1 ~ k) at each layer of the connection location is satisfied to the following equation:

$$\sum_{n=1}^{k}\left(u_{c,n}\times\delta_{c,n}\right)=U_c\times H_c \tag{1}$$

where $\delta_{c,n}$ (n = 1 ~ k) is each of the layer thickness of the connection location, and H_c indicates the total

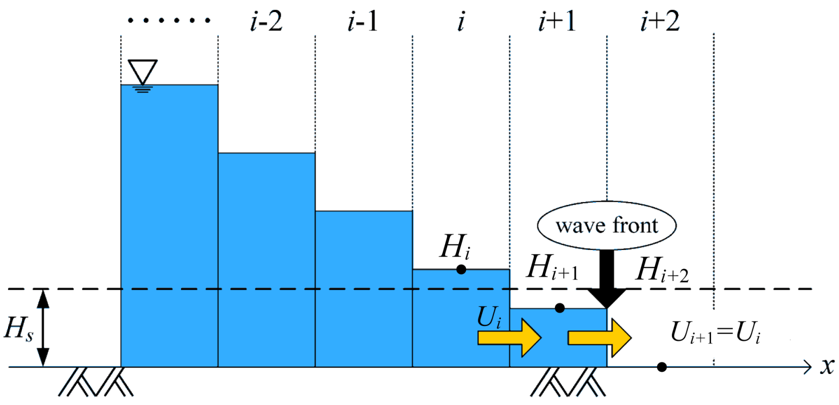


Figure 1. Schematic of the moving boundary method proposed by Kawasaki et al. (2004).

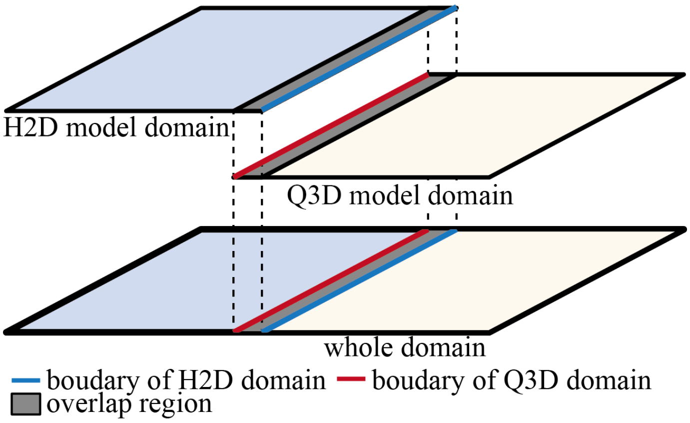


Figure 2. Schematic of computational domain in the H2D-Q3D coupled model.

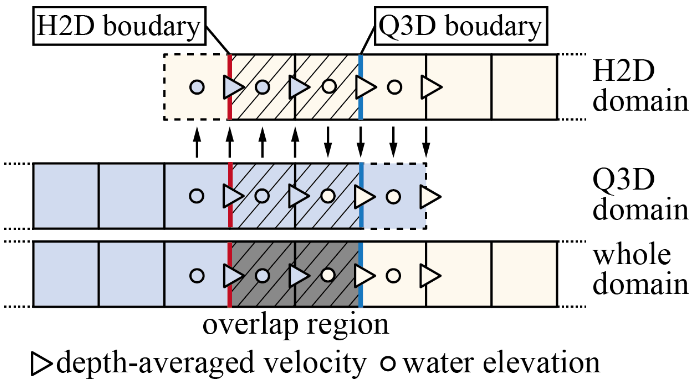


Figure 3. Data exchange schematic between Q3D and H2D models.

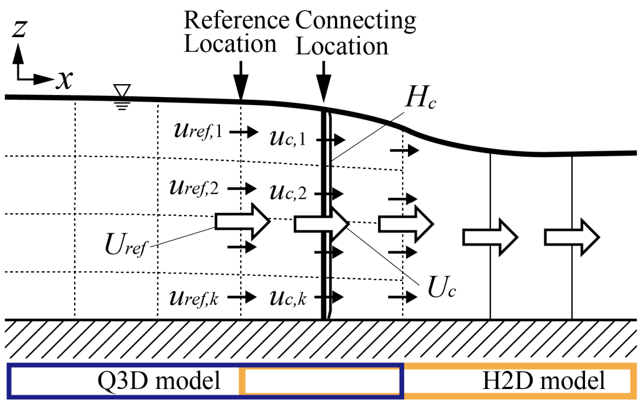


Figure 4. Arrangement of variables in overlap region.

depth of the connection location computed by the H2D model.

Equation (2) is derived with the assumption that a relationship between the horizontal velocity and the depth-averaged velocity is similar at the connection and the reference locations, in a similar way to Tomita and Takahashi (2012).

$$u_{c,n} - U_c = u_{ref,n} - U_{ref} \quad n=1, 2, \cdots k \tag{2}$$

where $u_{ref,\,n}$ ($n = 1 \sim k$) is the horizontal velocity at the reference location computed by the Q3D model, and U_{ref} is the depth-averaged velocity of $u_{ref,\,n}$.

Thus, the horizontal velocity $u_{c,\,n}$ can be expressed by using $u_{ref,\,n}$, U_{ref} and U_c.as follows:

$$u_{c,n} = u_{ref,n} - U_{ref} + U_c \quad n=1,2,3\cdots k \tag{3}$$

However, since the horizontal velocity $u_{c,n}$ obtained by Eq. (3) does not necessarily satisfy Eq. (1), the horizontal velocity is corrected as follows:

$$u'_{c,n} = u_{c,n}\frac{U_c}{U'_c} \quad n=1,2,3\cdots k \tag{4}$$

$$U'_c = \sum_{n=1}^{k}\left(u_{c,n}\times\delta_{c,n}\right)/H_c \tag{5}$$

where $u'_{c,n}$ ($n = 1 \sim k$) is the corrected horizontal velocity, and U'_c is the depth-averaged velocity of $u_{c,k}$. It should be noted that for numerical stability, the velocity correction of Eq. (4) is not performed when the averaged velocity U'_c is much small.

RESULTS AND DISCUSSION

A one-dimensional dam-break problem

A one-dimensional dam-break problem was a traditional test case, and many studies had conducted the dam-break flow simulations for evaluating the accuracy of numerical models. The coupled model was validated by simulating the one-dimensional dam-break flow. The numerical results were compared with those computed by high precision numerical schemes; FDS scheme, TVD-MUSCL scheme, MacCormack scheme, CIP method and a horizontal two-dimensional model using CIP method and SMAC method (Kawasaki et al. 2004).

A schematic of the computational domain is shown in Fig. 5, which is comprised of a 10 m long channel with a flat bottom. The initial water depths are h_1 = 1.0 m for the left half domain and h_2 = 0.4 m for the right half domain. Numerical domain of the H2D model was set from x = 0.00 m to 6.01 m, while numerical domain of the Q3D model was set from x = 5.99 m to 10.00 m. The two regions were overlapped in the range of 5.98 m ≤ x ≤ 6.00 m. The horizontal grid size of Δx = 0.01 m was employed

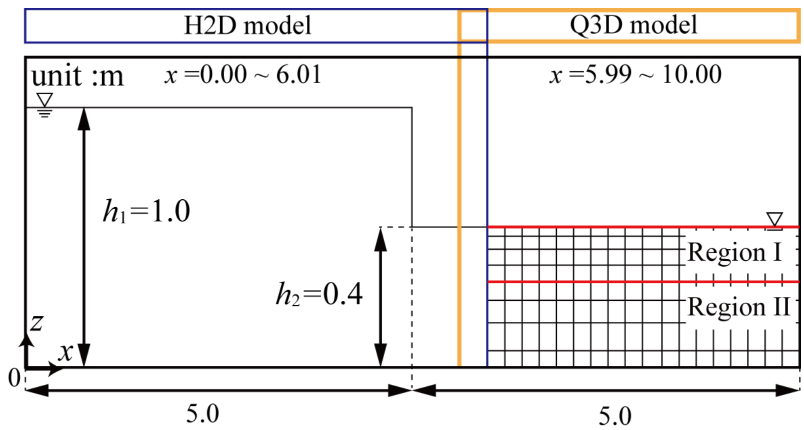
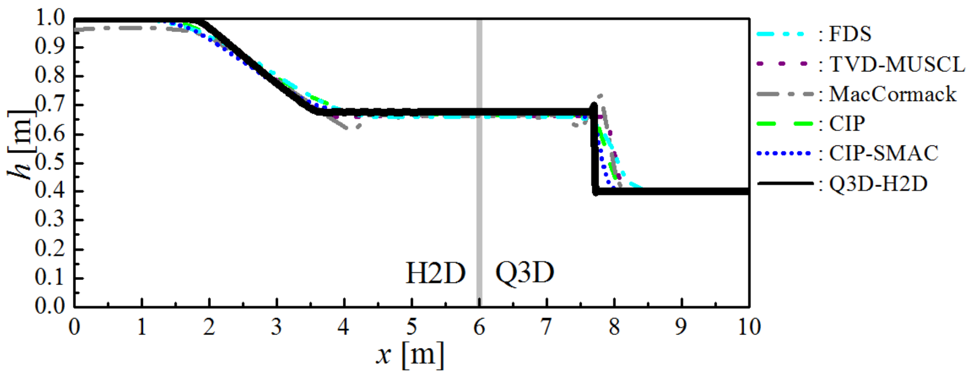


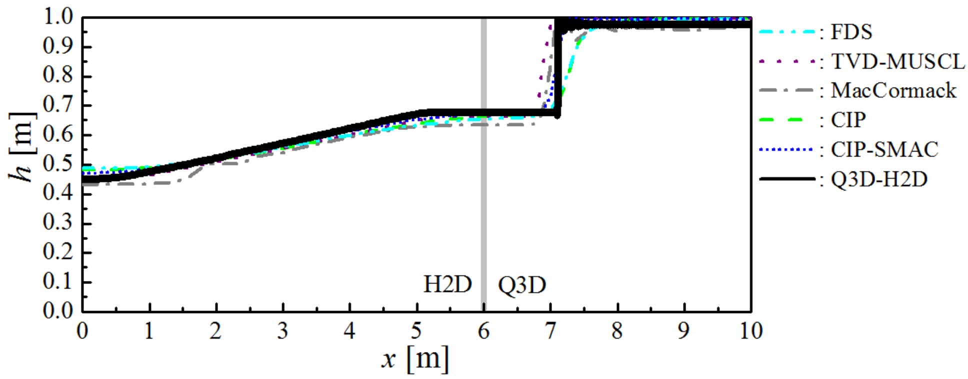
Figure 5. Computational domain for the one-dimensional dam-break flow.

Table 1. Computational condition for the one-dimensional dam-break flow.

H2D model	Computational domain [m]	x=0.00~6.01
	Horizontal grid size [m]	0.01
	Number of grids	601
	Time increment [s]	0.0005
Q3D Model	Computational domain [m]	x=5.99~10.00
	Horizontal grid size [m]	0.01
	Number of grids	401
	Number of regions in multi-sigma	2
	Number of total layers	8
	Time increment [s]	0.0005



(a) *t* = 1.0 s



(b) *t* = 3.0 s

Figure 6. Comparison between water surface profiles computed by the coupled model and the other high precision numerical schemes.

in whole computational domain, and the time increment Δt was set equal to 0.001 s at every time step so that the Courant condition is always satisfied. The detail of computational conditions was summarized in Table 1.

Figure 6 shows water surface profiles computed by the coupled model and other high precision numerical schemes at times t = 1.0 s and t = 3.0 s, in which black solid lines indicate the numerical results for the coupled model. The water surface profiles of the coupled model are confirmed to vary smoothly around the overlap region (x = 5.98 ~ 6.00 m). It can be seen from Fig. 6 (a) that the water surface profile computed by the MacCormack scheme shows artificial oscillations around x = 4 m and 8 m, while there is little significant difference between the results of other models except for the MacCormack scheme. At time t = 3.0 s when the reflected bore propagates toward the left side, the difference on the water surface profiles between the results of the models appears, as shown in Fig. 6 (b). The water surface profile computed by the coupled model corresponds to the results of the other high precision numerical schemes. Thus, it suggests that the coupled model has comparable computational accuracy with the other schemes.

Simulation of bore runup over a seawall

In order to evaluate the accuracy of the coupled model against overflow and runup phenomena, a hydraulic experiment on bore runup over a seawall implemented by Arimitsu et al. (2012) was simulated. In this study, the three cases in the experiments were considered, as listed in Table 2.

Table 2. Experimental conditions considered in this study.

Land structure	Seawall height H_w (m)	Impoundment depth Δh(m)
absence	0	0.18
absence	0.02	0.18
absence	0.05	0.18

Figure 7 illustrates a schematic of the computational domain. The origin of x axis coincides with the edge of the land, and the positive direction is taken toward the right hand side of the computational domain. In order to meet the experimental condition, an open boundary condition was adopted at the downstream, and a wall boundary was applied at the upstream boundary. A Manning coefficient n was set to 0.005 $m^{-1/3}s$ based on preliminary simulations. The Q3D model was applied on the right region, and the H2D model was used in the left region. The two regions were overlapped in the range of 2.20 m $\leq x \leq$ 2.22 m. Based on the fact that the phenomenon was confirmed to be uniform along the cross-shore direction in the experiments, four grids were used for cross-shore direction in the H2D and Q3D models. The detail of computational conditions was summarized in Table 3.

Figures 8 ~ 10 show the time variations of water surface profile and velocity distribution in the case of the seawall height H_w = 0.00 m (absence of a seawall), 0.02 m and 0.05 m, respectively. Time t = 0 was defined as the time when a bore reached at 2 meters off the seawall (x = 2.0 m) in this study. Just after the initiation of the simulation, the water column causes a bore, which propagates to the left side. As for time t = 2.11 s in Figs. 8 ~ 10, the bore run-up occurs and a reflected wave is generated at the edge of the land. Figures 8 ~ 10 also show that water surface profiles and horizontal velocity vary smoothly around the overlap region throughout the simulations, which implies that the present model can coupled well between the Q3D and H2D models.

Figures 11 (a) and (b) show the time variations of the water surface elevation and the horizontal velocity at x = 1.0 m, respectively. In the figures, although there is a slight difference between the simulation results and the experimental ones around time t = 3.0 s when a reflected wave arrived at x = 1.0 m, the simulation results represent the tendency of the experimental results well.

The time variations of the inundation depth and the horizontal velocity at x = -1.0 are shown in Fig. 12. It can be seen from Fig. 12 (a) that there are good agreement on the inundation depth between numerical and experimental results for all the three cases. As for the horizontal velocity shown in Fig. 12 (b), the simulation results also agree well with the experimental results, but the maximum velocity appearing at the leading edge is overestimated. This is probably because a rapid increase in the horizontal velocity was not measured in the hydraulic experiments due to the limitation of propeller current meters which are not suitable for highly fluctuating velocities. The validity of the coupled

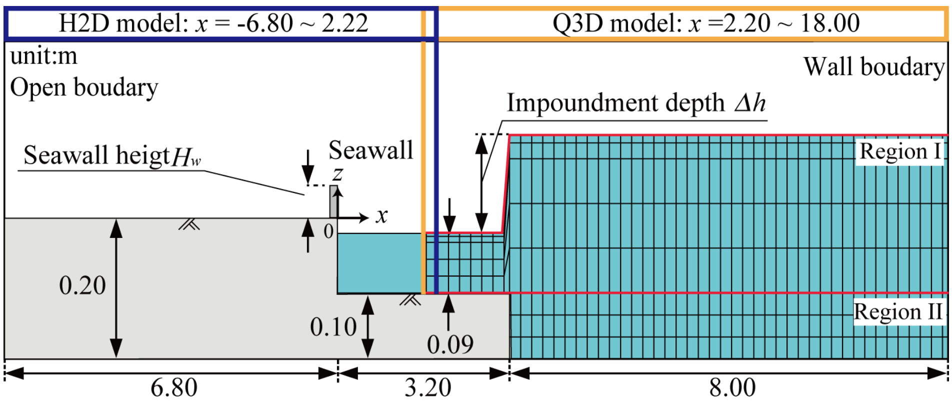


Figure 7. Computational domain for the simulation of bore runup over seawall.

Table 3. Computational condition for the simulation of bore runup over seawall.

H2D model	Computational domain [m]	x = -6.80 ~ 2.22
	Horizontal grid size [m]	0.01
	Number of grids	401
	Time increment [s]	0.0005
Q3D Model	Computational domain [m]	x = 2.20 ~ 11.20
	Horizontal grid size [m]	0.01
	Number of grids	601
	Number of regions in multi-sigma	2
	Number of total layers	8
	Time increment [s]	0.0005

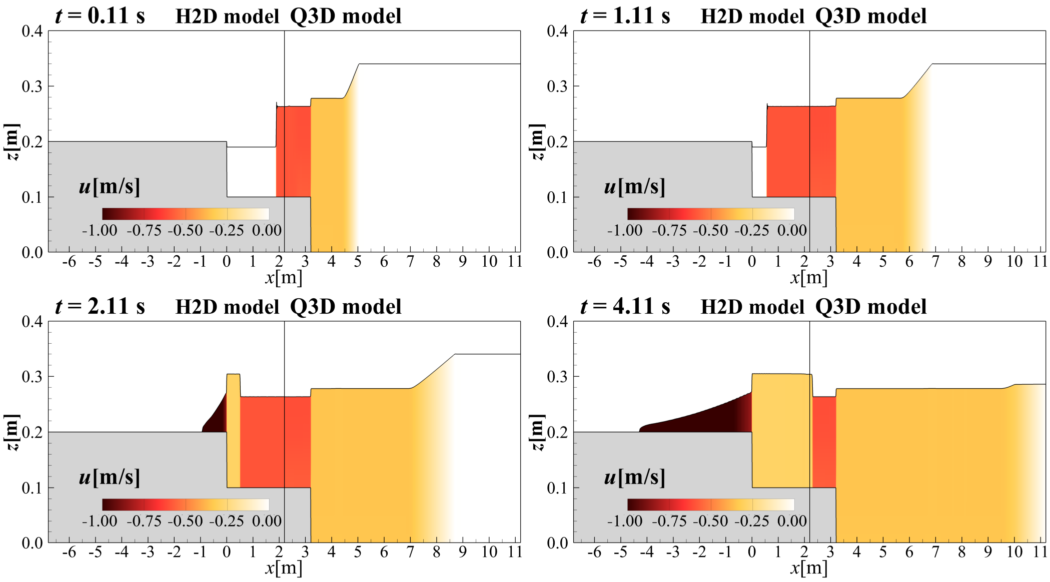


Figure 8. Temporal and spatial distributions of water surface profile and horizontal velocity in the case of H_w = 0.00 m (absence of a seawall).

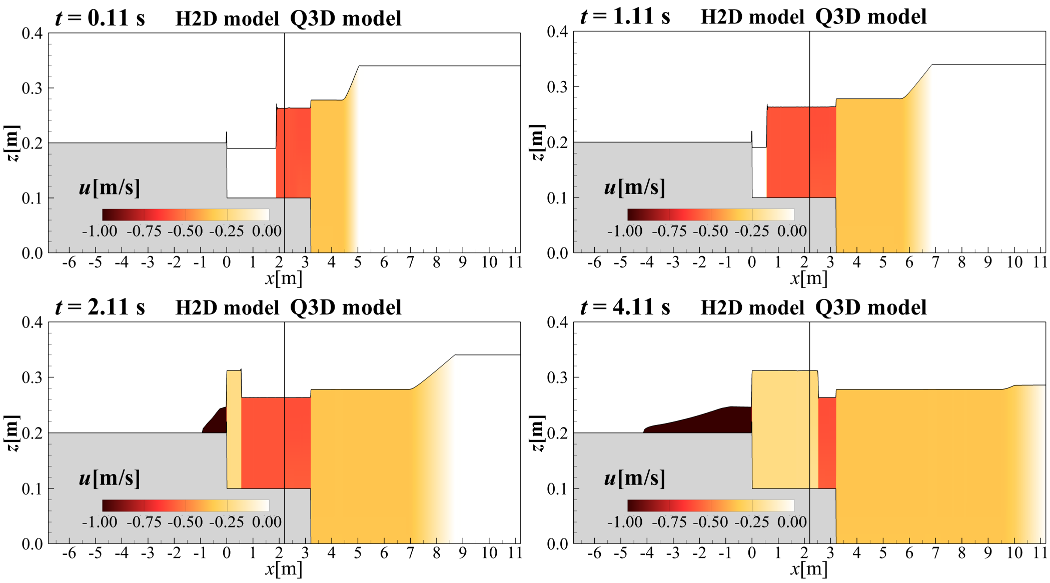


Figure 9. Temporal and spatial distributions of water surface profile and horizontal velocity in the case of H_w = 0.02 m.

model was, therefore, verified for simulating coastal flooding.

CONCLUSION

The Q3D-H2D coupled model, which consists of a quasi three-dimensional Coastal ocean Current Model CCM (Q3D) and a horizontal two-dimensional inundation model (H2D) with a high accuracy advection scheme, has been developed in this study so as to analyze coastal inundation, such as storm surge-induced flooding, with efficiency and low computational load. The validity of the model was confirmed through the comparison with the existing numerical results and experimental ones, which implied that the coupled model was capable of analyzing coastal inundation with good accuracy. In the future, the applicability of the coupled model on storm surge simulation in real seas would be examined.

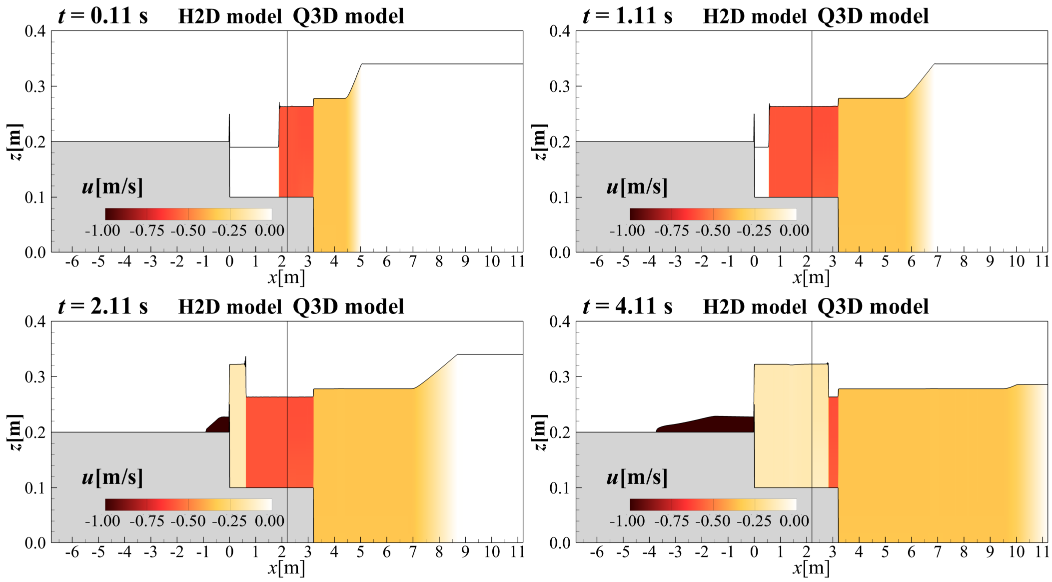


Figure 10. Temporal and spatial distributions of water surface profile and horizontal velocity in the case of H_w = 0.05 m.

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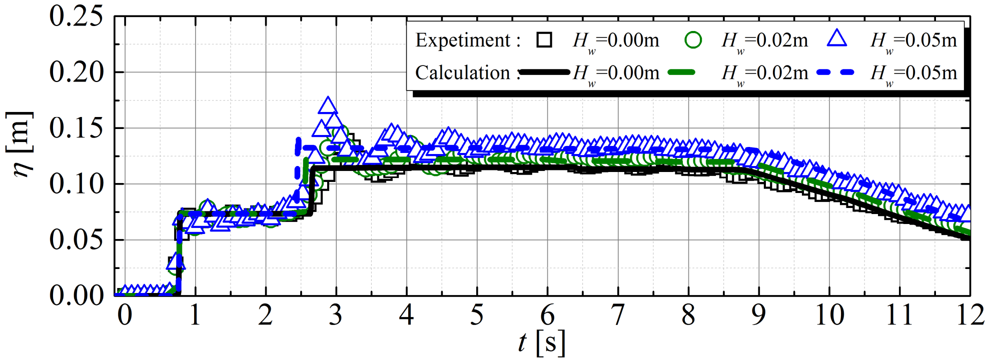
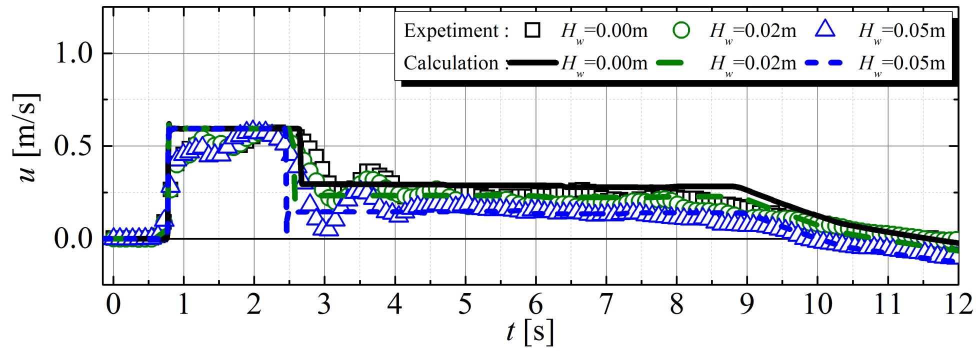
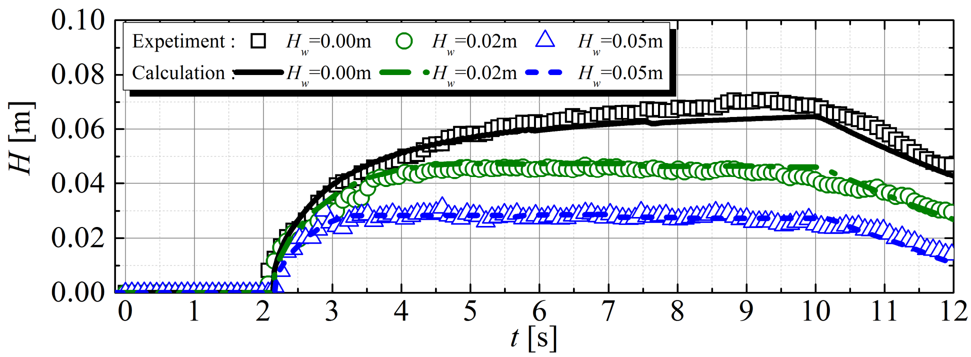


(a) Water surface elevation

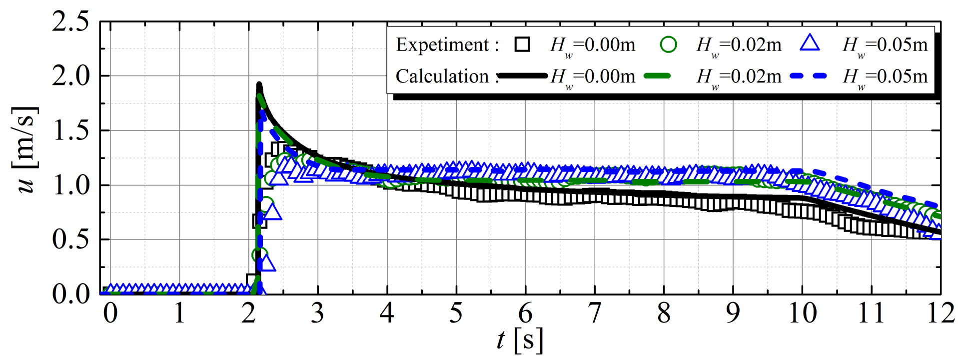


(b) Horizontal velocity

Figure 11. Comparison between numerical and experimental results at *x* = 1.0 m.



(a) Inundation depth



(b) Horizontal velocity

Figure 12. Comparison between numerical and experimental results at *x* = -1.0 m.

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