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STUDY ON EFFECTIVE INUNDATION ANALYSIS METHOD CONSIDERING CHARACTERISTICS OF GROUND ELEVATION IN CALCULATION GRID

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ABSTRACT

Inundation analysis methods are widely used and have presented effective information in examination of measures for water disaster. However, further improvements in precision and the effectiveness of analysis are desired. The detailed ground elevation data are recently obtained by development in the survey technology. In the usual analysis case, average ground elevation of 50m to 100m grids and average water depth in the grid are treated, and so the detailed ground elevation data is not used effectively. In this study, the new inundation analysis method (h-VA inundation analysis method) is developed. The new analysis model treats inundation water volume as unknown value. Inundation water depth is obtained from prepared relation between water depth and water volume. The momentum equation without advection term and viscosity term is analyzed for estimation of discharge by considering the characteristics of ground elevation within the grid. Though the results of h-VA inundation analysis with coarse gird size are similar to that of current inundation analysis with fine grid size, the calculation times of h-VA inundation analysis were reduced than that of current inundation analysis.

Keywords: inundation analysis method, ground level, numerical analysis

1. INTRODUCTION

Water disasters have occurred in a number of cities in recent years. While most of measures for water disaster have focused on inundations due to flood water in rivers, water disasters due to interior runoff have become more prominent recently. The importance of establishing measures for water disaster has been dominantly pointed out among a variety of water related events. Though inundation analysis methods are widely used and have presented effective information in examination of measures for water disaster, further improvements in precision and the effectiveness of analysis are desired. This study develops an effective and precise method for inundation analysis and verifies the usefulness of the developed method.

Modern measurement technology using highly advanced laser profilers allows for the collection of ground elevation data with a precision of 0.15 m per 2.5 m in each planar direction (Tachi, K. et al.(2002)). Though such ground elevation data is incorporated into inundation analysis, these data are used to determine average ground elevation of 50 to 100m grids in most cases, and such detailed ground elevation data is underutilized. On the other hand, direct use of the detailed data in analysis requires a long calculation time, because C.F.L. condition needs a very small time interval of calculation for a small grids size of a few meters. As actual work for establishment of measures for inundation problem requires numerous simulations of inundation phenomena under various conditions, so much computation time needs for such examinations. Therefore, inundation analysis methods with both high precision and appropriate grid size (for example, from 50 to 100 m) that can be applied over a wide area are desirable.

The current inundation analysis model developed by Iwasa, Inoue, and Mizutori (1980) is widely used based on shallow water equation. Recently, the descriptions of urban structures effecting on water behaviour, such as buildings roads and sewer system, has been treated in inundation analysis model (Takeda, M. et al. (2007)). Moreover, inundation analysis models for examination of the detailed water behaviour in urban area have been developed (Akiyama, J. et al.(2006)). It is necessary to use a small analysis grid to make precise descriptions of ground information. However, this treatment does not fit the engineering demands as described above. This study deals with the development and examination of an efficient inundation analysis method adopting the detailed ground elevation features in the grid. The proposed model retains the property of a pond model, and it is characterized by the relationship between the water depth and water volume reflected ground elevation features in the grid, as well as that between the water depth and the area of cross section at the each grid side.

2. INUNDATION ANALYSIS

2.1 The current inundation analysis method (the current model)

This section presents the current inundation analysis method, and discusses some of its problems. The following shallow water equations are usually used as governing equations of the inundation analysis method.

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y}=-gh\frac{\partial H}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right)-\frac{\tau_{bx}}{\rho} \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial uN}{\partial x}+\frac{\partial vN}{\partial y}=-gh\frac{\partial H}{\partial y}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial N}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial N}{\partial y}\right)-\frac{\tau_{by}}{\rho} \tag{3}$$

where, u and v are the flow velocities in the x and y directions, h is the water depth, M and N are the fluxes of the flow rate in the x and y directions, respectively $(M=uh,\ N=vh)$, H is the water level, τ_{bx},τ_{by} are the shear stresses of the bed in the x and y directions, respectively, ρ is the water density, g is gravity acceleration, $\varepsilon_x,\varepsilon_y$ are each coefficients of eddy viscosity in the x and y directions, x,y are planar axes, and t is time. The bed shear stresses are expressed by the Manning law, which are given by the following equations:

$$\tau_{bx}=\rho g n^2 M\sqrt{u^2+v^2}\Big/h^{4/3} \tag{4}$$

$$\tau_{by}=\rho g n^2 N\sqrt{u^2+v^2}\Big/h^{4/3} \tag{5}$$

As the water depth is used as an unknown value in Eq.1, the average water depth in the grid can be derived from the algebraic equations for numerical simulation. The average ground elevation in the grid is also used for this analysis. Moreover, discharge fluxes M and N (flow rate per unit width) are defined on grid sides. The momentum equation of Eq.(2) and Eq.(3) assumes similar flow on every point of grid side, but this assumption is not always appropriate in actual inundation phenomena.

2.2 The proposed inundation analysis method (the h-VA inundation analysis model)

In this study, the following assumptions are used.

A) Water flowing into a grid will instantaneously flows toward lower ground elevations, and not water depth but water volume is taken as an unknown variable in the continuity equation.

B) In the motion equations, advection terms and viscosity terms are assumed not to have significant effect, and they can be omitted. Flow rate is treated as an unknown variable.

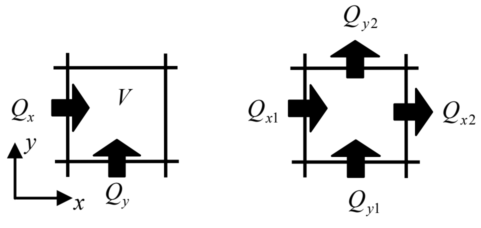


Figure 1 Locations of unknown variables

Assumption A is associated with taking the grid as a single pond. In order to simplify the calculation for inundation flow, advection terms and viscosity terms are ignored because they have usually much less effect on the inundation flow than that of pressure terms and bottom friction terms on the flow.

With regards to these two assumptions, the governing equations of the analysis model become two type equations, one taking original meaning “the net discharge is equal to the time variation rate of the inundation water volume”, and another one treating temporal change of the discharge on the plane for analysis. These equations are shown below.

$$\frac{\partial V}{\partial t} = (Q_{x1} - Q_{x2}) + (Q_{y1} - Q_{y2}) \tag{6}$$

$$\frac{\partial Q_x}{\partial t} = -gA_x \frac{\partial H}{\partial x} - \frac{gn^2 Q_x \sqrt{u^2 + v^2}}{h^{4/3}} \tag{7}$$

$$\frac{\partial Q_y}{\partial t} = -gA_y \frac{\partial H}{\partial y} - \frac{gn^2 Q_y \sqrt{u^2 + v^2}}{h^{4/3}} \tag{8}$$

where, V is the inundation water volume in a grid, and Q_x, Q_y are discharges ($Q_x = uA_x, Q_y = vA_y$) in the x, y directions, respectively. A_x, A_y are areas of cross sections in the x, y direction at the place of definition for Q_x, Q_y , respectively, and H is the water level. H is obtained by the following equation, where $z_{\min}$ is the lowest ground elevation in a grid, and h_m is the depth of the water at that location

$$H = h_m + z_{\min} \tag{9}$$

The unknown variable in Eq.6 is V, and it is set in each grid for analysis as shown in Figure 1. Q_x, Q_y are located at the sides of grid. The water level H is taken to be the same within the grid. The water level at the cross section where Q_x, Q_y are defined is determined from averaging the water levels located in the centre of adjoining grids.

Before the calculation, detailed ground elevation data is used to create $h-V$ curves (relationship between water depth h and inundation water volume V) on the basis of the lowest ground elevation in the grids, and $h-A$ curves (relationship between water depth h and area of cross section A) on the basis of the lowest ground elevation in the cross sections. The procedure of the calculation for Eq.(6)-(8) is as follows.

i) The water volume within a grid is numerically determined by explicit scheme with finite volume method according to continuity equation, and the water depth is calculated by using $h-V$ curve in the grid.

ii) The water level at the centre of the grid is calculated from water depth and lowest ground elevation. The water level at the defined positions of discharge is also calculated by averaging the water levels at the centre of the adjoining grids. The lowest ground elevation is subtracted from the water level to find the maximum water depth in the cross section. The $h-A$ curve is used to find the area of cross section with water depth.

iii) Discharge at the cross section is numerically calculated by explicit scheme with finite volume method from momentum equation. The results of the previous calculation are used in place of known values, and the calculation procedure above mentioned is repeated.

3. ANALYSIS CONDITIONS

This study used ground elevation data at 5m intervals, and three analysis cases are examined. In Case 1, the current 2-dimensional inundation analysis method (the current method) is applied with 10m grid (average ground elevations set in the grid). In Case 2, the current method is applied with 50m grid (average ground elevations set in the grid). In Case 3, the h-VA inundation analysis method is applied with 50m grid (lowest ground elevations set in the grid).

Furthermore, in order to examine the influence of ground elevation positioning in the control volume ("CV") used in the calculation, the following three cases are taken into consideration in the use of the h-A curve at the cross section. In Case 3a, the h-A curve is calculated by using ground elevation data at the cross section where the discharge was defined. In the Case 3b, the calculation uses the maximum ground elevation along the flow direction in the CV. In Case 3c, calculation uses average ground elevation along the flow direction in the CV.

In this study two locations within the Nagoya city are used, where ground gradients are both gentle case (grids of 357 × 550 for Case 1, and 71 × 100 for Cases 2 and 3) and steep case (grids of 227 × 490 for Case 1, and 45 × 98 for Cases 2 and 3). The subjects of analysis are inundation phenomena caused by dike break due to

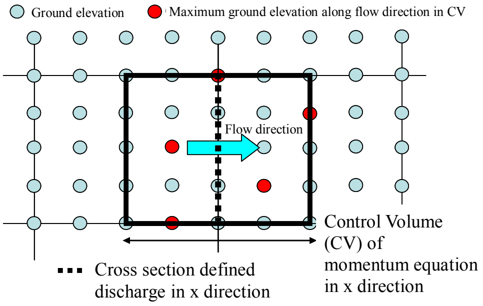
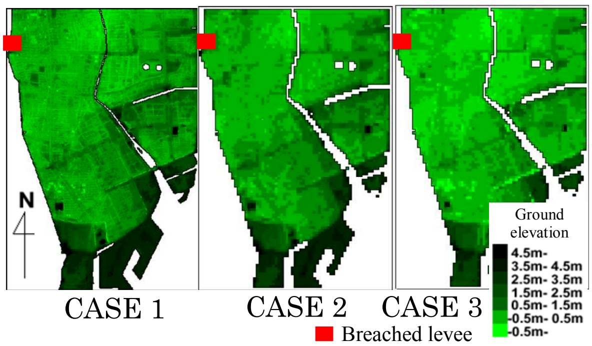
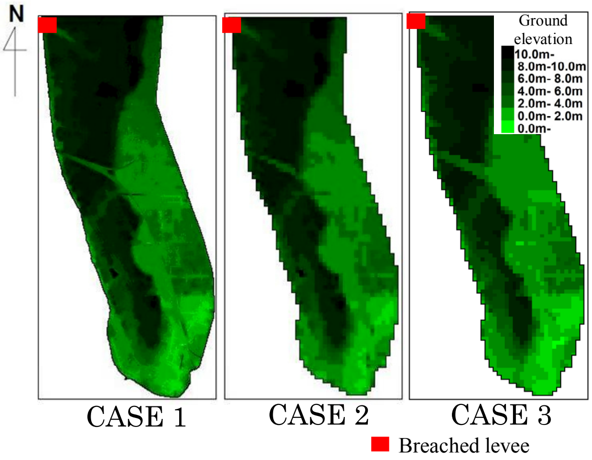


Figure 2 Treatment of $h-A$ curve



Gentle slope cases



Steep slope cases

Figure 3 Analysis regions

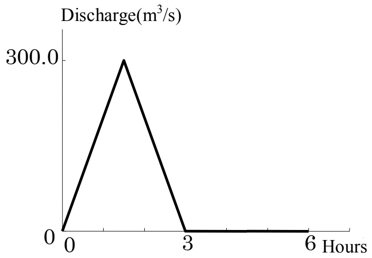


Figure 4 Inflow discharge at breached levee

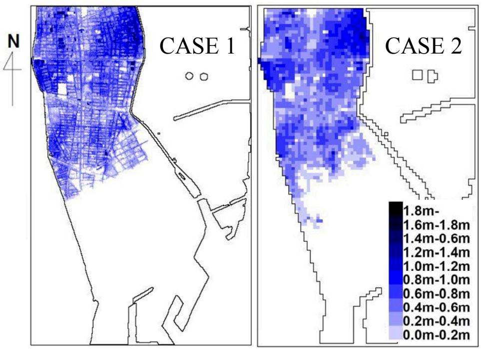


Figure 5 Maximum inundation water depth for Cases 1 and 2

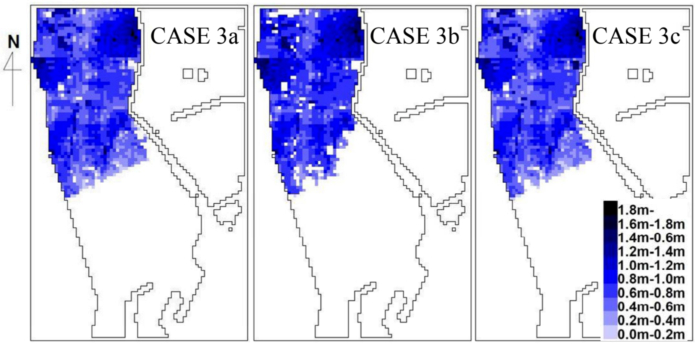


Figure 6 Maximum inundation water depth for Case 3

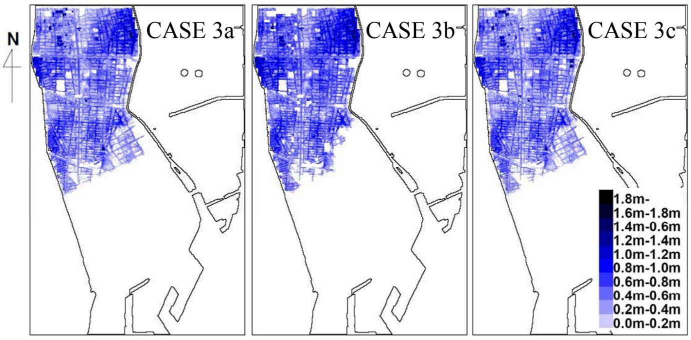


Figure 7 Maximum inundation water depth for Case 3 (considering ground elevations in Case 1)

river flood and interior runoff due to heavy rain. Figure 3 shows the analysis region and distribution of ground elevation. Figure 4 shows the discharge condition in the analysis case of breached levee. The rainfall condition is assumed that precipitation of 10 mm/hour continues from the start of calculations for a period of 3 hours. In both cases, the period of calculations is 6 hours. The roughness coefficient used was 0.067.

In this study, the calculation results of Case 1 were taken as the most precise values because of its small grid size, and then we examined the results of other cases through the comparison between the calculated values in the larger grid cases and that in case 1.

4. Results in gentle slope cases

4.1 Flood cases with breached levee

Figure 5 shows the distribution of maximum inundation water depth for Case 1 and Case 2. The results of Case 1 indicate inundation along roadways. Though the results of Case 2 show a similar inundation pattern to that in Case 1, the inundation along roadways is not appeared because the grid scale is large. Furthermore, the result of Case 2 shows wider spread of inundation than that of Case 1.

Figure 6 shows the distribution of maximum inundation water depth for Case 3. In this figure, expanded inundation states are indicated because the water depth at the lowest ground elevation in the grid is displayed. Figure 7 shows the maximum inundation depth for case 3 at the ground elevation corresponding to those in Case 1. This figure shows that the results of Case 3a and Case 3c represent very similar inundation patterns to that of Case 1 and also they

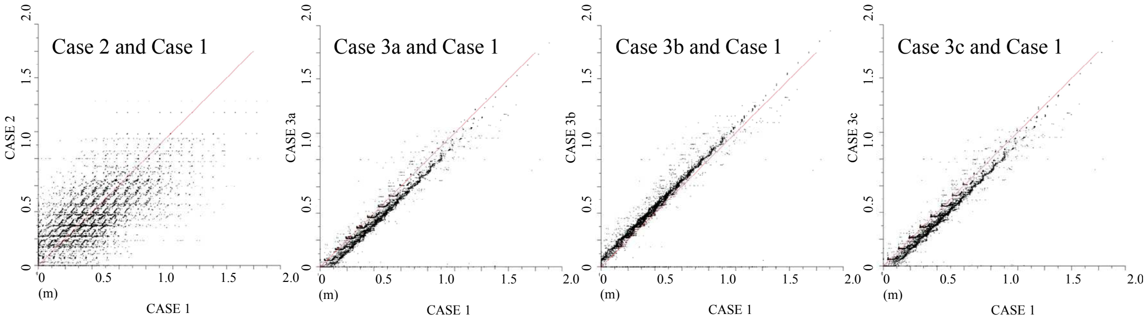
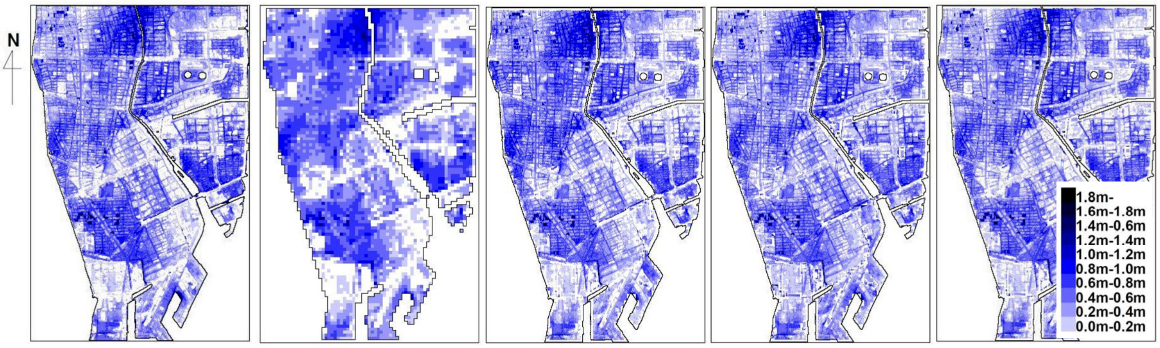


Figure 8 Comparison of maximum inundation water depth



CASE 1 CASE 2 CASE 3a CASE 3b CASE 3c

Figure 9 Maximum inundation water depth for rainfall

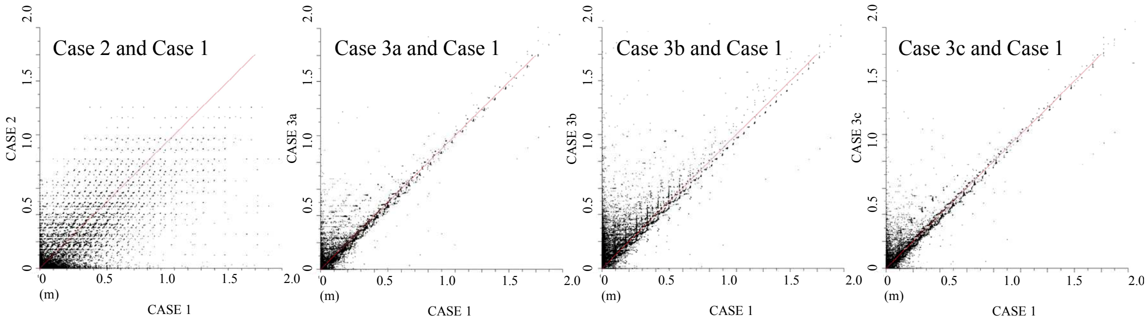
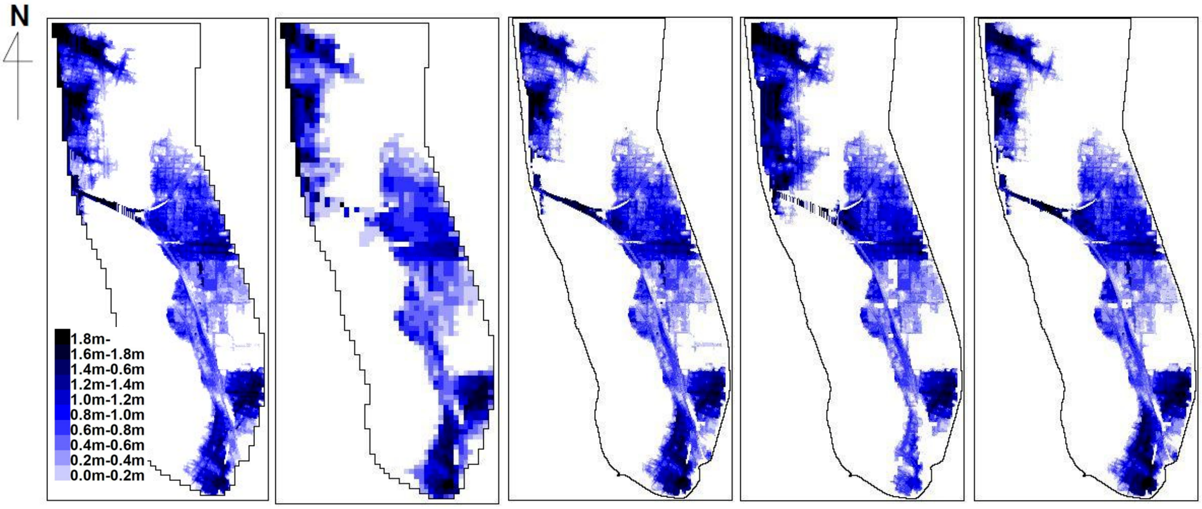


Figure 10 Comparison of maximum inundation water depth

give sufficient precision such as inundation depths along roads. However, the results of Case 3b shows a narrower spread pattern of inundation than that of Case 1 because of with less area of flow section. In order to compare the value of inundation depth for above cases, Figure 8 shows a plot of the maximum inundation water depths for Case 1 on the horizontal axis and the inundation depths at corresponding points of other Cases on the vertical axis. This Figure shows a very close correspondence between Case 3a,3c and Case 1.

4.2 Interior runoff cases due to rainfall

Figure 9 shows distribution of maximum inundation water depth in various cases. Result of Case 1 shows inundation along roads similar to the flood case mentioned in 4.1. The result of Case 2 shows similar inundation to that of Case 1, but detail of inundation states along roads are not represented due to coarse grid size. The results of Case 3a and Case 3c show inundation along roads similar to that of Case 1. However, the result of Case 3b shows increasing of inundation depths due to inhibition of flow. Moreover, the result of Case 3 appears wider distribution of deep inundation water depths than that of Case 1, because the



CASE 1 CASE 2 CASE 3a CASE 3b CASE 3c

Figure 11 Maximum inundation water depth in the breached levee case

rain water and inundation water are assumed to flow into lower elevation parts in the grid instantaneously. This result is the feature of the h-VA inundation analysis method. Figure 10 shows a plot of the maximum inundation depths of Case 1 on the horizontal axis and the inundation depths at corresponding points of other Cases on the vertical axis. This figure shows that Case 3 gives a more precise correspondence to Case 1 than that of Case 2. However, differences of both appear in parts of low inundation depth because of the assumption for the water flow in h-VA analysis method. In view of precision on analysis results, the results of h-VA inundation analysis method are consequently far better than that of the current method with a large grid scale.

5. Results in steep slope cases

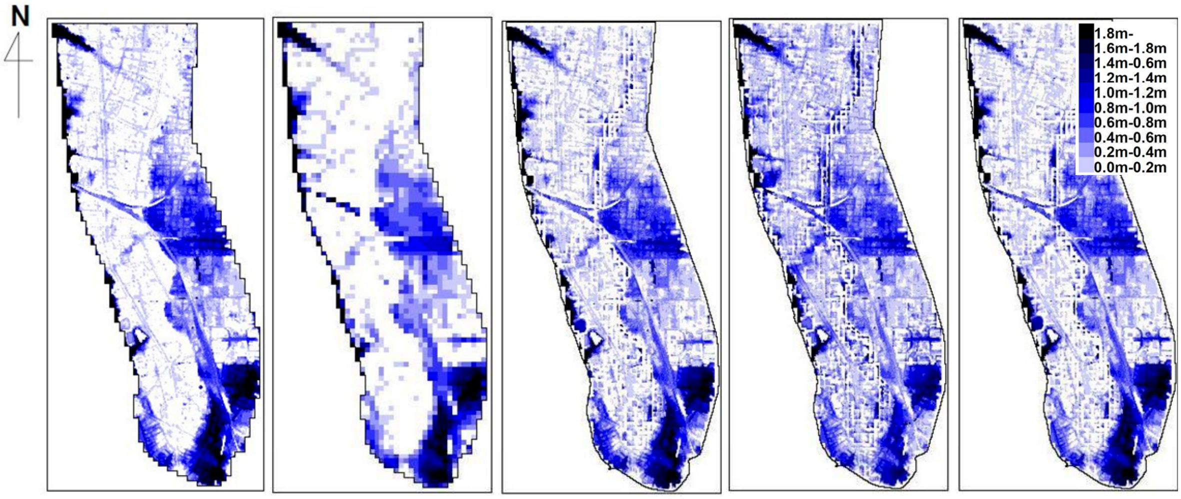
5.1 Flood cases with breached levee

Figure 11 shows the distributions of maximum inundation water depths analyzed in various cases. This figure shows that the results of Case 2 is roughly similar to that of Case 1, but detail of inundation phenomena is not represented due to coarse grid size. On the other hand, the maximum inundation water depth in Case 3a and Case 3c show very similar to that of Case 1. Especially, the results of Case 3a are good agreement with the results of Case 1.

5.2 Interior runoff cases due to rainfall

Figure 12 shows the analysis results of maximum inundation water depth. In this figure, the results of Case 3 show the enlargement of inundation area due to a characteristic of the h-VA inundation analysis method mentioned before. However, the results of this method are far better than that of the current method with a large grid scale.

Based on these results, the effectiveness of the h-VA inundation analysis method in the analysis of inundation phenomena is indicated. Moreover, the best result is obtained by using h-A curve determined from ground elevation data at cross section.



CASE 1 CASE 2 CASE 3a CASE 3b CASE 3c

Figure 12 Maximum inundation water depth in the rainfall case

Table 1 Calculation time

	Gentle sloped ground		Steep sloped ground	
	Levee	Rain	Levee	Rain
Case 1	144 min	384 min	84 min	137 min
Case 2	7 min	8 min	3 min	3 min
Case 3	12 min	13 min	4 min	7 min

6. Utility of the h-VA inundation analysis method in view of calculation times

Table 1 shows the time required for each calculation. The computer used in this study was a commercially available PC (NEC Express 5800 Pentium 4 at 3.80GHz). Case 3 (h-VA inundation analysis method with large size grid) has approximately the same precision to Case 1. However, Case 3 does not require the long calculation time as shown in Table 1. This efficiency of calculation indicates the usefulness of the h-VA inundation analysis method from aspect of utility.

7. Conclusion

This study discusses the practical problems of the current inundation analysis method, and presents a new method of inundation analysis that can improve the efficiency and precision of calculation. The presented inundation analysis model (h-VA inundation analysis model) treats each grid as a single pond. This model consists of continuity equation related water volume and momentum equation related flow rate, and also advection terms and viscosity terms are ignored in momentum equations. Inundation calculations were performed by current inundation analysis model and h-VA inundation analysis model in the both conditions as to the ground gradient which is gentle and steep.

Though the comparison of these calculation results, h-VA inundation analysis model with rough grid size is sufficiently verified in view of the precision on calculation values. Moreover, the calculation times of h-VA inundation analysis method were extremely short compared with current inundation analysis method. The usefulness of the h-VA inundation analysis method is shown from these results.

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