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EFFECTS OF SEDIMENT YIELD ON INUNDATION FLOW IN A HILLSIDE CITY

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SYNOPSIS

This study aims to develop an inundation flow model in hillside cities whose purpose is to estimate sediment yield. In this model, the hydrograph of flow discharge and sediment concentration calculated in the mountainous area are imposed as the boundary conditions of the urban area inundation analysis. In urban area, the horizontally two-dimensional inundation flow analysis based on the unstructured meshes is conducted. The above model is applied to Ikuta River basin in Kobe, Japan. The computed inundated area or water depth with consideration of the sediment effects is larger than that without it. Therefore, findings reveal that the concentration of sediment must be taken into account when an inundation flow analysis is made in the river basin with much sediment yield.

INTRODUCTION

Sediment disasters frequently occur in mountainous areas. Not only in mountainous areas but hillside cities are vulnerable to sediment disasters. In fact, severe flood disasters with much sediment yield occurred in Kobe in 1938 and 1967, and Nagasaki in 1982, in which 616, 91 and 299 people were killed, respectively. If heavy rainfall occurred in a big city again, not only many people would be killed or injured, but city facilities would be severely damaged.

Structural measures, such as the sabo dam, have been able to prevent sediment disasters, but they are not perfect ones. The residents awareness of the danger of their own community can help to reduce damage. The publication of hazard maps for sediment disaster is one effective measure, and in drawing these maps, a reliable prediction method is required to estimate how much sediment will be discharged and deposited. For example, Nakagawa et al. (1) developed such a model based on the Cartesian coordinate system and applied it to a village on the fan of a ravine. In urban areas, however, sediment or inundation water often behaves in a different way. In this study, an inundation flow model based on the unstructured meshes is developed. Using this model, the effects of sediment yield on inundation flow is examined.

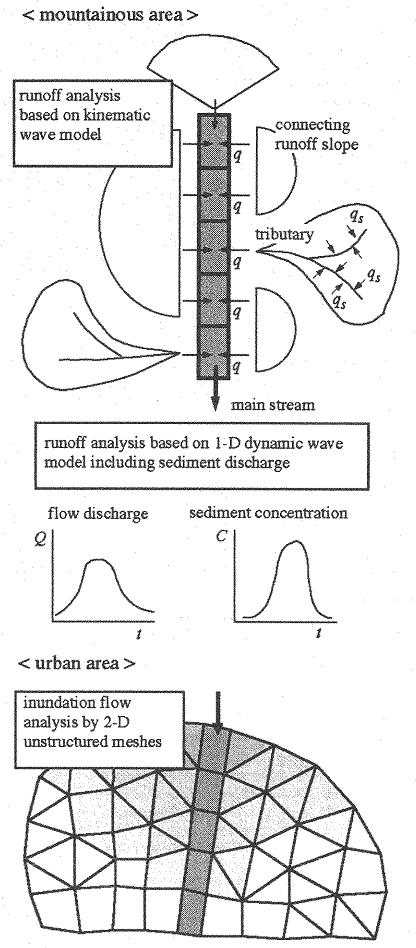


Fig.1 Framework of the model

METHOD OF ANALYSIS

A river basin studied is divided into upstream (mountainous area) and downstream (urban area) parts. In the mountainous area, the hydrograph of flow discharge and sediment concentration are calculated and imposed as the boundary conditions of the urban area inundation analysis. In the urban area, these hydrographs are given at the upstream boundary, and the two-dimensional inundation flow analysis based on the unstructured meshes is conducted. The framework of this model is shown in Fig.1.

Analysis in the Mountainous Area

The method of analysis in the mountainous area is modeled after that of Takahashi et al. (2). The river in the mountainous area is divided into 'tributaries' and 'main stream'. First, runoff discharge without sediment yield from tributaries and mountain slopes directly connected to the main stream is calculated using the kinematic wave model. Assuming that the bed slope and the friction slope of the St. Venant equation are dominant, the following equation is used:

$$q = \alpha h^m \tag{1}$$

where q = water discharge per unit width in the longitudinal direction of slopes or tributaries;

h = flow depth; and α and m = the coefficients. When using the Manning's formula, m is determined as $m = 5/3$, and $\alpha = \sqrt{\sin\theta_0}/n$, where θ_0 = bed slope; and n = roughness coefficient. The continuity equation can be expressed by the following ones:

Along the tributaries

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = \frac{q_s}{B} \tag{2}$$

Along the slopes

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r_e \tag{3}$$

where q_s = lateral inflow discharge per unit length from side slopes; B = river width; and r_e = effective rainfall intensity.

Next, adding these runoff discharges as lateral inflows, the water and the sediment discharges at the downstream end of the main stream are calculated by means of the one-dimensional dynamic wave model considering sediment yield from the riverbed of the main stream. The governing equations used here are as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} = \frac{q}{B} + i \tag{4}$$

$$\frac{\partial M}{\partial t} + \beta\frac{\partial (uM)}{\partial x} = -gh\frac{\partial H}{\partial x} - \frac{\tau_b}{\rho_T} \tag{5}$$

where M = x-component of discharge flux; u = x-component of flow velocity; i = erosion or deposition velocity ($i > 0$ erosion; $i < 0$ deposition); β = momentum correction coefficient; g = gravitational acceleration; H = flow surface elevation ($H = z_0 + z_b + h$); z_0 = original bed elevation; z_b = erosion or deposition thickness measured from the original bed elevation; τ_b = bottom shear stress; and ρ_T = density of the flow with water and sediment. The following equations are used for τ_b depending upon the volumetric concentration of sediment in the flow C:

For fully developed stony debris flow ($C \geq 0.4C_*$)

$$\frac{\tau_b}{\rho_T} = \frac{1}{8}\left(\frac{d_m}{h}\right)^2 \frac{u|u|}{\{C + (1-C)\rho_m/\sigma\}\left\{(C_*/C)^{1/3} - 1\right\}^2} \tag{6}$$

For immature debris flow ($0.02 \,\square\, C < 0.4C_*$)

$$\frac{\tau_b}{\rho_T} = \frac{1}{0.49}\left(\frac{d_m}{h}\right)^2 u|u| \tag{7}$$

For turbulent flow ($C < 0.02$)

$$\frac{\tau_b}{\rho_T} = \frac{gn^2 u|u|}{h^{1/3}} \tag{8}$$

where C_* = volumetric concentration of solids in the bed; ρ_m = density of the fluid including the fine particles; σ = density of the sediment particles; and d_m = mean diameter of the sediment particle. The erosion or deposition velocity is determined by following equations:

For erosion

$$i = \delta \frac{C_\infty - C}{C_* - C_\infty} |u| \tag{9}$$

For deposition

$$i = \delta' \frac{C_\infty - C}{C_*} |u| \tag{10}$$

where δ, δ' = coefficients equal to 0.0007, 0.001, respectively. The equilibrium concentration of sediment C_∞ is calculated using the following equations depending upon the energy gradient, $\tan\theta$:

For fully developed stony debris flow ($\tan\theta \geq 0.138$)

$$C_\infty = \frac{\rho_m \tan\theta}{(\sigma - \rho_m)(\tan\phi - \tan\theta)} \tag{11}$$

For immature debris flow ($0.03 < \tan\theta < 0.138$)

$$C_\infty = 6.7 \left\{ \frac{\rho_m \tan\theta}{(\sigma - \rho_m)(\tan\phi - \tan\theta)} \right\}^2 \tag{12}$$

For turbulent flow ($\tan\theta < 0.03$)

$$C_\infty = \frac{(1 + 5\tan\theta)\rho \tan\theta}{\sigma - \rho} \left(1 - \bar{\alpha}^2 \frac{\tau_{*c}}{\tau_*}\right) \left(1 - \bar{\alpha}\sqrt{\frac{\tau_{*c}}{\tau_*}}\right) \tag{13}$$

where ϕ = angle of internal friction of sediment particle on the bed; ρ = density of the clear water; and τ_*, τ_{*c} = non-dimensional shear stress and non-dimensional critical shear stress, respectively. They are calculated as follows:

$$\tau_* = \frac{u_*^2}{(\sigma/\rho - 1) g d_m} \tag{14}$$

$$\tau_{*c} = 0.04 \times 10^{1.72 \tan\theta} \tag{15}$$

where u_* = friction velocity ($u_*^2 = gh\tan\theta$), and $\bar{\alpha}$ is calculated as follows:

$$\bar{\alpha}^2 = \frac{2\left(0.425 - \frac{\sigma\tan\theta}{\sigma - \rho}\right)}{1 - \frac{\sigma\tan\theta}{\sigma - \rho}} \tag{16}$$

where energy gradient $\tan\theta$ is

$$\tan\theta = \frac{|\tau_b|}{\rho_T g h} \tag{17}$$

The continuity equation for the sediment component is

$$\frac{\partial(Ch)}{\partial t} + \frac{\partial(CM)}{\partial x} = iC_* \tag{18}$$

The equation for the variation of the bed surface elevation is

$$\frac{\partial z_b}{\partial t} + i = 0 \tag{19}$$

In this study, sediment yield from tributaries or side slopes is not taken into account.

Analysis in the Urban Area

The governing equations used here are the same as those of Nakagawa et al. (1) and they are as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = i + q_{rain} \tag{20}$$

$$\frac{\partial M}{\partial t} + \beta\frac{\partial (uM)}{\partial x} + \beta\frac{\partial (vM)}{\partial y} = -gh\frac{\partial H}{\partial x} - \frac{\tau_{bx}}{\rho_T} \tag{21}$$

$$\frac{\partial N}{\partial t} + \beta\frac{\partial (uN)}{\partial x} + \beta\frac{\partial (vN)}{\partial y} = -gh\frac{\partial H}{\partial y} - \frac{\tau_{by}}{\rho_T} \tag{22}$$

where τ_{bx}, τ_{by} = x, y components of the bottom shear stress; and q_{rain} = rainfall intensity per unit time. The following equations are used for τ_{bx} and τ_{by} depending upon the volumetric concentration of sediment in the flow C:

For fully developed stony debris flow ($C \geq 0.4C_*$)

$$\frac{(\tau_{bx},\ \tau_{by})}{\rho_T} = \frac{1}{8}\left(\frac{d_m}{h}\right)^2 \frac{(u,\ v)\sqrt{u^2+v^2}}{\{C+(1-C)\rho_m/\sigma\}\{(C_*/C)^{1/3}-1\}^2} \tag{23}$$

For immature debris flow ($0.02 < C < 0.4C_*$)

$$\frac{(\tau_{bx},\ \tau_{by})}{\rho_T} = \frac{1}{0.49}\left(\frac{d_m}{h}\right)^2 (u,\ v)\sqrt{u^2+v^2} \tag{24}$$

For turbulent flow ($C < 0.02$)

$$\frac{(\tau_{bx},\ \tau_{by})}{\rho_T} = \frac{gn^2(u,\ v)\sqrt{u^2+v^2}}{h^{1/3}} \tag{25}$$

As for the erosion or deposition velocity, the following equations are used.

For erosion

$$i = \delta\frac{C_\infty - C}{C_* - C_\infty}\sqrt{u^2+v^2} \tag{26}$$

For deposition

$$i = \delta'\frac{C_\infty - C}{C_*}\sqrt{u^2+v^2} \tag{27}$$

The equilibrium concentration of sediment C_∞ is defined by Eqs.11 $\sim$ 13, and the energy slope $\tan\theta$ is calculated by using Eq.17 and Eqs.23 ~ 25 as follows:

$$\tan\theta = \frac{\sqrt{\tau_{bx}^2 + \tau_{by}^2}}{\rho_T g h} \tag{28}$$

The continuity equation for the sediment component is

$$\frac{\partial(Ch)}{\partial t} + \frac{\partial(CM)}{\partial x} + \frac{\partial(CN)}{\partial y} = iC_* \tag{29}$$

For the variation of the bed surface elevation, Eq.19 is used.

Nakagawa et al.(1) developed a model based on the Cartesian coordinate system, while in this study the urban area is divided into arbitrary-shaped unstructured meshes, and the two-dimensional inundation flow analysis based on the Finite Volume Method is conducted (3). As for the location of unknown values, flow depth h, volumetric concentration of sediment in the flow C, erosion or deposition velocity i, and erosion or deposition thickness z_b are defined at the centroid of each polygon mesh and x, y components of discharge flux M, N and flow velocity u, v are defined at the middle point of each polygon side, as shown in Fig.2.

In the continuity equation, a polygon mesh is treated as a control volume, therefore, the following finite difference equation is used:

$$\frac{h_i^{n+3} - h_i^{n+1}}{2\Delta t} + \frac{1}{A_i}\sum_{l=1}^{m'}\left\{M_l^{n+2}(\Delta y)_l - N_l^{n+2}(\Delta x)_l\right\} = i_i^{n+1} + q_{rain} \tag{30}$$

where superscripts denote the time step, A_i = area of the control volume, i.e. area of mesh i; m' = number of sides which surround the control volume; and $(\Delta x)_l$, $(\Delta y)_l$ = the difference of the x and y coordinates at both ends of side l, respectively.

As for the momentum equations, in the computation on the border line L adjacent to mesh i and mesh j, the following finite difference equations are applied by means of the variables shown in Fig.3:

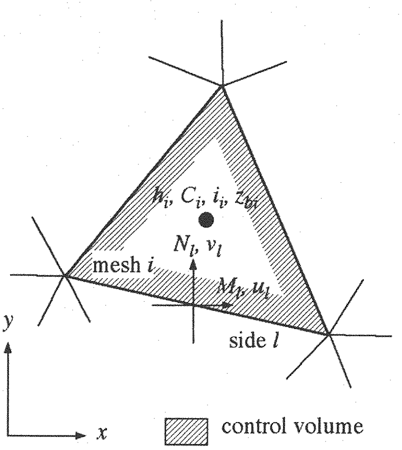


Fig.2 Definition position of variables

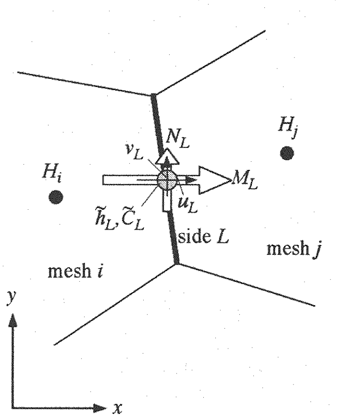


Fig.3 Calculation of momentum equation

$$\frac{M_L^{n+2}-M_L^n}{2\Delta t}+M1+M2=-g\tilde{h}_L^{n+1}(\nabla H)_x-T_x \tag{31}$$

$$\frac{N_L^{n+2}-N_L^n}{2\Delta t}+N1+N2=-g\tilde{h}_L^{n+1}(\nabla H)_y-T_y \tag{32}$$

where M_L, N_L and u_L, v_L = discharge fluxes and the velocity components on the border line L, respectively; $\tilde{h}_L$ = interpolated water depth on the line L; and $(\nabla H)_x$, $(\nabla H)_y$ = x and y components of water surface gradient between the mesh i and mesh j, respectively. The bottom shear stresses T_x, T_y are discretized depending on the interpolated sediment concentration $\tilde{C}_L$:

For fully developed stony debris flow ($\tilde{C}_L \geq 0.4C_*$)

$$T_x=\frac{1}{8}\left(\frac{d_m}{\tilde{h}_L^{n+1}}\right)^2\frac{\frac{M_L^{n+2}+M_L^n}{2\tilde{h}_L^{n+1}}\sqrt{(u_L^n)^2+(v_L^n)^2}}{\left\{\tilde{C}_L^{n+1}+(1-\tilde{C}_L^{n+1})\rho_m/\sigma\right\}\left\{\left(C_*/\tilde{C}_L^{n+1}\right)^{1/3}-1\right\}^2} \tag{33}$$

$$T_y=\frac{1}{8}\left(\frac{d_m}{\tilde{h}_L^{n+1}}\right)^2\frac{\frac{N_L^{n+2}+N_L^n}{2\tilde{h}_L^{n+1}}\sqrt{(u_L^n)^2+(v_L^n)^2}}{\left\{\tilde{C}_L^{n+1}+(1-\tilde{C}_L^{n+1})\rho_m/\sigma\right\}\left\{\left(C_*/\tilde{C}_L^{n+1}\right)^{1/3}-1\right\}^2} \tag{34}$$

For immature debris flow ($0.02 < \tilde{C}_L < 0.4C_*$)

$$T_x=\frac{1}{0.49}\left(\frac{d_m}{\tilde{h}_L^{n+1}}\right)^2\frac{M_L^{n+2}+M_L^n}{2\tilde{h}_L^{n+1}}\sqrt{(u_L^n)^2+(v_L^n)^2} \tag{35}$$

$$T_y=\frac{1}{0.49}\left(\frac{d_m}{\tilde{h}_L^{n+1}}\right)^2\frac{N_L^{n+2}+N_L^n}{2\tilde{h}_L^{n+1}}\sqrt{(u_L^n)^2+(v_L^n)^2} \tag{36}$$

For turbulent flow ($\tilde{C}_L < 0.02$)

$$T_x=\frac{gn^2\frac{M_L^{n+2}+M_L^n}{2}\sqrt{(u_L^n)^2+(v_L^n)^2}}{(\tilde{h}_L^{n+1})^{4/3}} \tag{37}$$

$$T_y=\frac{gn^2\frac{N_L^{n+2}+N_L^n}{2}\sqrt{(u_L^n)^2+(v_L^n)^2}}{(\tilde{h}_L^{n+1})^{4/3}} \tag{38}$$

$M1+M2$, $N1+N2$ = the convective terms, which are expressed by the following equations:

$$M1+M2=\frac{\beta}{A_{cv}}\sum_{l=1}^{m''}\left\{(u_l\hat{M}_l)(\Delta y)_l-(v_l\hat{M}_l)(\Delta x)_l\right\} \tag{39}$$

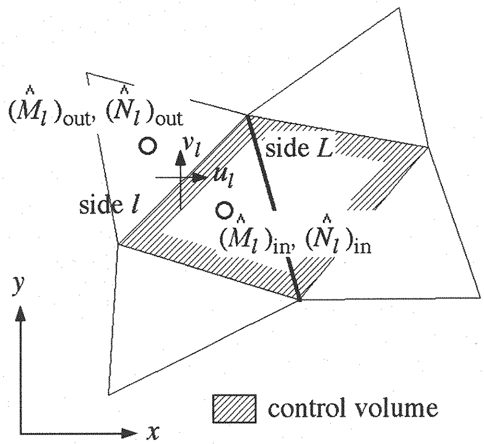


Fig.4 Calculation of convective terms

$$N1 + N2 = \frac{\beta}{A_{cv}} \sum_{l=1}^{m''} \left\{ (u_l \hat{N}_l)(\Delta y)_l - (v_l \hat{N}_l)(\Delta x)_l \right\} \tag{40}$$

where A_{cv} = area of the control volume which denotes the two meshes adjacent to the line L (see Fig.4); m'' = number of sides which surround the control volume; and $\hat{M}_l$, $\hat{N}_l$ = interpolated discharge fluxes on the centroid of the mesh. The upstream side of $\hat{M}$ and $\hat{N}$ are adopted depending on the direction of u_l and v_l.

As for the erosion or deposition velocity:

For erosion

$$i_i^{n+3} = \delta \frac{C_\infty - C_i^{n+3}}{C_* - C_\infty} \sqrt{(\hat{u}_i^{n+2})^2 + (\hat{v}_i^{n+2})^2} \tag{41}$$

For deposition

$$i_i^{n+3} = \delta' \frac{C_\infty - C_i^{n+3}}{C_*} \sqrt{(\hat{u}_i^{n+2})^2 + (\hat{v}_i^{n+2})^2} \tag{42}$$

where $\hat{u}$, $\hat{v}$ = interpolated flow velocity on the centroid of the mesh.

As for the continuity equation for sediment component:

$$\frac{C_i^{n+3} h_i^{n+3} - C_i^{n+1} h_i^{n+1}}{2\Delta t} + \frac{1}{A_i} \sum_{l=1}^{m'} \left\{ \bar{C}_l^{n+1} M_l^{n+2} (\Delta y)_l - \bar{C}_l^{n+1} N_l^{n+2} (\Delta x)_l \right\} = i_i^{n+1} C_* \tag{43}$$

where $\bar{C}_l$ = sediment concentration on the centroid of polygon, and the upstream side of them is adopted depending on the direction of discharge flux M, N.

As for the variation of the bed surface elevation:

$$\frac{{z_b}_i^{n+3} - {z_b}_i^{n+1}}{2\Delta t} + i_i^{n+3} = 0 \tag{44}$$

APPLICATION TO KOBE CITY

Studied Area

The area studied is shown in Fig.5. The Sanno-miya district which is the central part of Kobe City is located in the center of Fig.5. The reason why Ikuta River, whose width is about 20m, is adopted in this study was that there was a disaster in this river basin in 1938. The river runs through this Sanno-miya district and the overflow may cause much damage to its river basin.

The above mentioned models in the mountainous area and the urban area are applied to the respective area shown in Fig.5. Between them there is some small area called 'hilly area', which is not included in the Ikuta River basin, but has runoff discharge flowing directly into the urban area. For the sake of simplicity, only runoff discharge without sediment is considered from this hilly area. The area studied of the mountainous area, the hilly area and the urban area are 10.8km^2, 1.5km^2 and 9.6km^2, respectively.

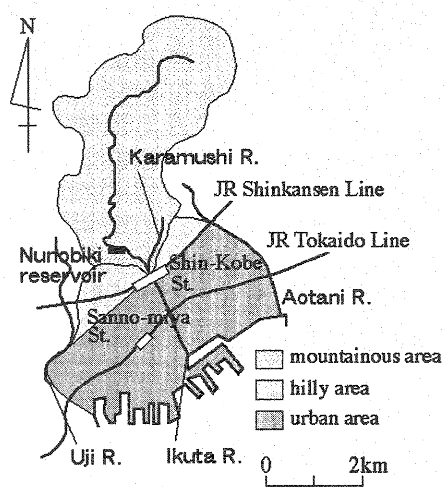


Fig.5 Studied area

Results in the Mountainous Area

In this study, the rainfall record in 1938 at Kobe meteorological station is used. The total computation time is 108 hours (4.5 days). The computational grid size is Δx=20m and Δt=0.1s.

Fig.6 shows the hydrograph of flow discharge without sediment, and Fig.7 shows the hydrograph of flow discharge including sediment and the temporal change of sediment concentration. In the case of consideration of only rainfall discharge, the peak flow discharge is 148m^3/s,

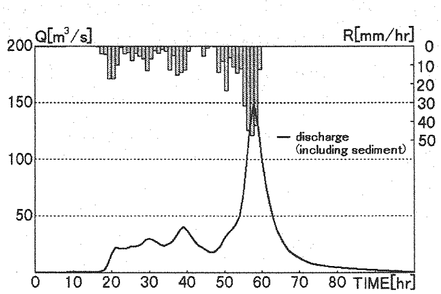


Fig.6 Discharge hydrograph without sediment

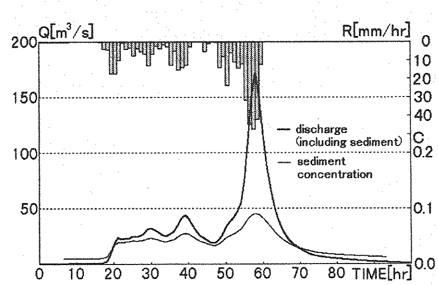


Fig.7 Discharge hydrograph with sediment and sediment concentration

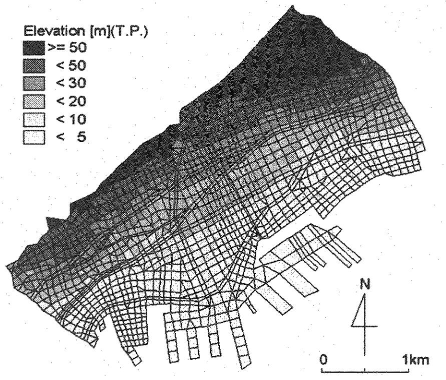


Fig.8 Meshes for computation and original bed elevation

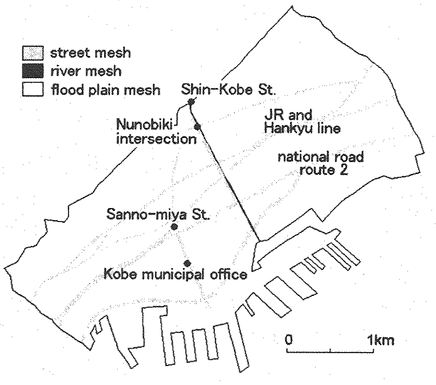


Fig.9 River, street and flood plain meshes

while in the case of consideration of rainfall and sediment, the peak flow discharge is $170\text{m}^3/\text{s}$. The difference between these discharge hydrographs is due to the sediment volume. According to the survey of the Disaster Science Institute in 1938 (4), the peak flow discharge of Ikuta River was $138\text{m}^3/\text{s}$, which is not so different from the computational results obtained in our study.

Results in the Urban Area

The computational meshes and the original bed elevation used in this study are shown in Fig.8. These meshes are grouped into three types of categories: river, street and flood plain. Fig.9 shows the distribution of these mesh categories. The total number of the meshes for computation is 1844, and the number of the river and the street meshes are 27 and 319, respectively.

As the boundary condition, the above mentioned hydrographs are imposed at the upstream end of Ikuta River. At the meshes adjacent to the hilly area, the runoff discharge (without sediment) obtained by the kinematic wave model is imposed. At the other boundaries of rivers, sea and river mouth, the discharge flux is calculated by using drop formula.

The area studied is highly urbanized, so factors such as streets and buildings should be taken into consideration. Here, according to Inoue et al. (5), the occupying ratio (the ratio of the buildings area to the mesh area) and the invasion ratio (the ratio of the side length, through which inundation water can go into or out, to the total side length) are introduced. In this study, the occupying ratio λ=0.64 and the invasion ratio $\hat{\beta}$=0.35, which are determined from the detailed geographical map of the studied area, are used in the whole studied area. Using these values, discharge fluxes are corrected as follows.

$$M^* = \hat{\beta} M; \qquad N^* = \hat{\beta} N \tag{45}$$

As for the continuity equation, the following equation including the above corrected discharge fluxes is used instead of Eq.20.

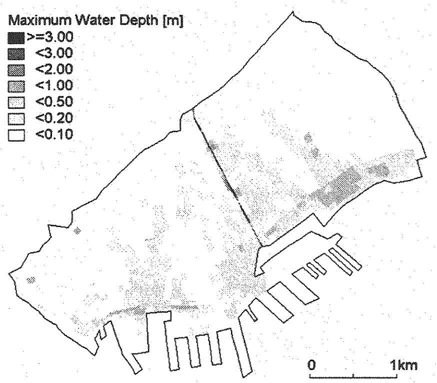


Fig.10 Maximum water depth (without sediment)

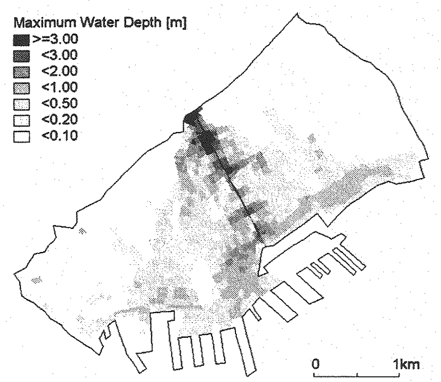


Fig.11 Maximum water depth (considering rainfall and sediment yield)

$$(1-\lambda)\frac{\partial h}{\partial t}+\frac{\partial M^*}{\partial x}+\frac{\partial N^*}{\partial y}=i+q_{rain} \tag{46}$$

As for the continuity equations for the sediment component and for the variation of the bed surface elevation, the following equations are used instead of Eqs.29 and 19, respectively.

$$(1-\lambda)\frac{\partial (Ch)}{\partial t}+\frac{\partial (CM^*)}{\partial x}+\frac{\partial (CN^*)}{\partial y}=iC_* \tag{47}$$

$$(1-\lambda)\frac{\partial z_b}{\partial t}+i=0 \tag{48}$$

Also, different values are given to the roughness coefficient n depending on the mesh categories. For the street meshes n=0.043 (6), and for the river and flood plain meshes n=0.020 and 0.067 (7) are given, respectively.

As for the other parameters, σ=2650kg/m^3, ρ_m=1150kg/m^3, C_*=0.65, $\tan\phi$=0.7, and mean diameter of sediment particle is d_m=1.14mm, which is obtained from the sediment sampled at the middle point of the main stream. According to Nakagawa et al. (1), the momentum correction coefficient β is assumed to be 1.25 in the case of the stony debris flow, and 1.0 in the case of immature debris flow and turbulent flow. The computational time step is Δt=0.5s.

The maximum inundation water depth without sediment is shown in Fig.10. The inundated area where the maximum water depth is more than 0.5m is very limited. Fig.11 shows the maximum inundation water depth considering both runoff discharge and sediment yield, and Fig.12 shows the thickness of sediment deposition at t=108hr. The computed sediment volume deposited in the urban area (400,000m^3) has a good agreement with the estimated volume by the Disaster Science Institute in 1938 (480,000m^3) (4). Fig.12 shows that the sediment deposition area is widely extended on both sides of Ikuta River. Around the reach from Shin-Kobe station to 1km downstream of it, thickness of deposition amounts to more than 1m. Especially around the Nunobiki intersection, more than 3m of sediment deposition can be found. This may be due to the fact that the river bed slope becomes abruptly mild around this location.

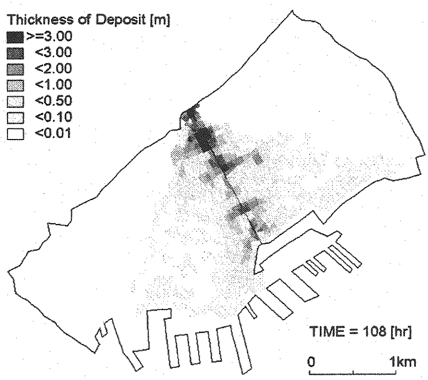


Fig.12 Thickness of sediment deposition

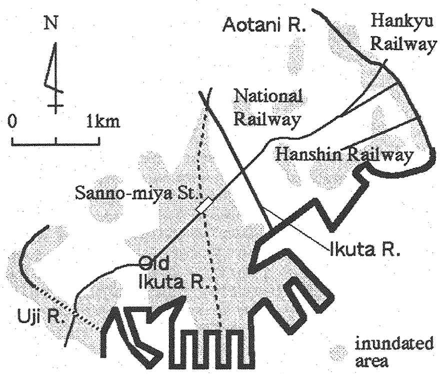


Fig.13 Inundated area in 1938

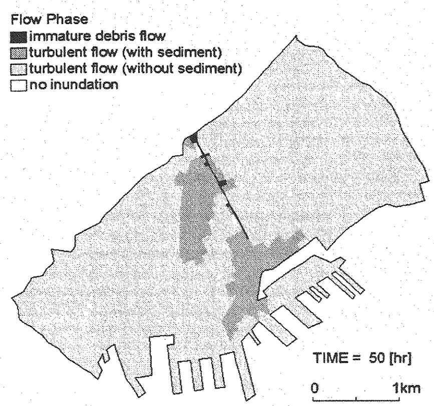
The inundated area observed in 1938 is shown in Fig.13, where the inundated area is found only on the right bank side of Ikuta River. From this figure, inundation water and sediment seemed to flow down along the old Ikuta River, while Fig.11 shows the inundated area on both sides of Ikuta River. Under the present topographical conditions of Ikuta River basin, it is hard to imagine that inundation water flows along the old Ikuta River. Therefore, for some reason, inundation water and sediment occurred severely only on the right bank side of Ikuta River in 1938. For example, Ikuta River was a closed conduit at that time, and driftwood blocked its upstream mouth, which might induce the heavy overflow to the right bank side flood plain.

Fig.14 shows the temporal change of flow phase distribution. At t = 50hr, inundation water with sediment flows down to the right bank around the Nunobiki intersection and to both sides around the Ikuta River mouth. At t = 60hr, more sediment spreads with the increase of runoff discharge and sediment concentration from the mountainous area. Compared with Fig.9, the area of immature debris flow is found out to haveexpanded along the street meshes from Ikuta River. Therefore, it can be assumed that sediment is conveyed and deposited along the streets. More than 2m sediment deposition can also be found along the street meshes in Fig.12. At t = 70hr, runoff discharge and sediment concentration are decreasing.

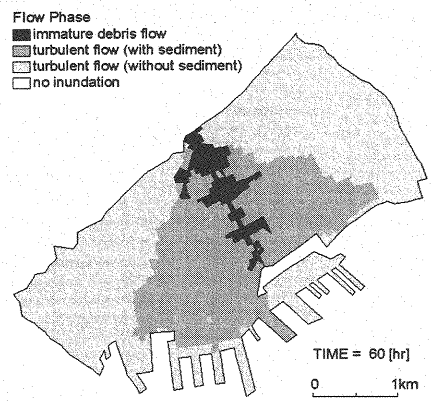
From the comparison between Fig.10 and Fig.11, the computed inundated area in consideration of the sediment effects is larger than that without it, because the Ikuta River bed is aggradated due to the sediment deposition, which causes much overflow discharge from the river. Especially in the upstream part of the urban area along Ikuta River, maximum inundation water depth increases by 1-2m. Therefore, in the inundation flow analysis in hillside cities with a mountainous area on their back such as Kobe, it is very important to take into account the sediment yield effects. These figures also indicate that the damage due to inundation can reduce greatly by controlling the sediment yield from the mountainous area.

CONCLUSIONS

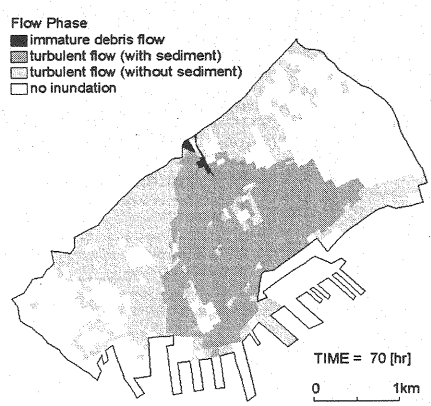
The conclusions obtained from this study can be summarized as follows.



(a) 50 hours after computation start



(b) 60 hours after computation start



(c) 70 hours after computation start

Fig.14 Temporal change of flow phase distribution

1) An inundation flow model considering sediment yield has been developed based on the unstructured meshes, which can be applicable to a hillside city.

2) From the comparison of the computational results between the case with and without sediment yield, the inundation behavior in a hillside city is much influenced by the sediment yield in their river basin.

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APPENDIX - NOTATION

The following symbols are used in this paper:

A = area of the control volume;

A_{cv} = area of the control volume used for computation of the convective terms;

B = river width;

C = volumetric concentration of sediment in the flow;

C_* = volumetric concentration of solids in the bed;

C_∞ = equilibrium concentration of sediment;

d_m = mean diameter of the sediment particle;

g = gravitational acceleration;

h = flow depth;

H = flow surface elevation;

i = erosion or deposition velocity;

m = numerical constant of the kinematic wave model;

M, N = respective discharge flux in x and y directions;

M^*, N^* = respective corrected discharge flux in x and y directions;

n = Manning's roughness coefficient;

q = water discharge per unit width in the longitudinal direction of slopes or tributaries;

q_{rain} = rainfall intensity per unit time;

q_s = lateral inflow discharge per unit length from side slopes;

r_e = effective rainfall intensity;

t = time;

u, v = respective flow velocity in the x and y directions;

u_* = friction velocity;

x, y = coordinates of the flow;

z_0 = original bed elevation;

z_b = erosion or deposition thickness measured from the original bed elevation;

α = numerical constant of the kinematic wave model given by $\alpha = \sqrt{\sin\theta_0}/n$;

$\bar{\alpha}$ = numerical constant;

β = momentum correction coefficient;

$\hat{\beta}$ = invasion ratio;

δ = numerical constant of the equation of erosion;

δ' = numerical constant of the equation of deposition;

Δt = computational time step;

θ = energy gradient;

θ_0 = bed slope;

λ	=	occupying ratio;
ρ	=	density of clear water;
ρ_m	=	density of fluid including fine particles;
ρ_T	=	density of flow with water and sediment;
σ	=	density of sediment particle;
τ_{bx}, τ_{by}	=	respective bottom shear stress in x and y directions;
τ_*	=	non – dimensional shear stress;
τ_{*c}	=	non – dimensional critical shear stress; and
ϕ	=	angle of internal friction of sediment particle on the bed.

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