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A NUMERICAL SIMULATION OF TURBIDITY CURRENT AND SEDIMENTATION IN THE SHICHIKASHUKU RESERVOIR

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SYNOPSIS

A 3-D numerical model was developed to predict the behavior of fine solids carried by flood water into a reservoir. The model is based on the standard k-ε turbulence model using the Boussinesq approximation and combined with a diffusion equation in which the settlement of fine solids was taken into account by using their terminal velocity relative to the surroundings.

The model feasibility is tested for a flood caused by typhoon 9617 at Shichikashuku Reservoir where the authors have conducted detailed field measurements on turbidity currents and sedimentation: the travel of fine solids in the reservoir during the flood was simulated for the whole process from the inflow at the upstream end to the deposition at the bottom of the reservoir. The calculation results successfully reproduced the observed profiles of turbidity currents and the spatial distribution of deposited sediment.

INTRODUCTION

Most of the sediment carried by flood water in rivers of mountainous area is classified as "wash load", suspended solids much finer than bed materials passing through without deposition. However, once a large dam is constructed, the fine materials begin to deposit in the reservoir, decreasing its storage capacity and affecting water quality as they release attached nutrients into the surrounding water.

The degree of influence on decrease of the storage capacity depends on the depth where fine solids deposit: the effective storage capacity would be reduced if the deposition takes place in shallow areas, while little change occurs if deposition is in areas deeper than the lowest water level of operation. On the other hand, the nutrient release is usually active in deep areas where anaerobic condition tends to develop. Accordingly, it is important for reservoir management to understand and predict where and how the fine solids deposit in the reservoir.

Basic studies on the behavior of fine solids in reservoirs were actively conducted in 1970's(1)(2)(3) when continual discharge of highly turbid water from reservoirs attracted public concerns because of its effect on aquatic inhabitants

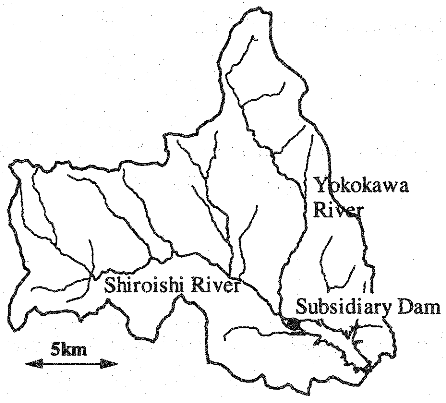

Fig. 1 The catchment area of Shichikashuku Reservoir

at downstream reach. Most of the researches at the time were based on laboratory experiments on reservoir models of idealized shapes; the most popular one was two-dimensional (2-D) triangle in a longitudinal plane. Their achievements contributed much to the basic understanding of the phenomenon and were referred to for planing and designing water intake facilities.

After a break, the study on fine solids behavior in reservoirs has been resumed in 1990's in a new fashion, as it has been further recognized by hydraulic researchers that fine solids not only cause problems of highly turbid water but also contribute to eutrophication of reservoirs by releasing nutrients, especially phosphorus. The need to solve this problem requires more detailed investigations on the behavior of fine solids as mentioned above.

On the other hand, the recent development of field measurement devices, which are less expensive and more sophisticated than before, enables hydraulic researchers to investigate real phenomena in the field(8)(9). In addition, it has also become possible to conduct realistic numerical simulation in three dimensional (3-D) with modern turbulence models with little cost and time, thanks to the great innovation of workstations and personal computers. These new measures would be useful for not only conducting the currently popular research subjects but also reworking of classical research subjects. Adding to this, these measures are expected to be used for practical works such as reservoir management.

In this study, extensive field measurements were carried out in Shichikashuku Reservoir in Miyagi prefecture on the whole process of the travel of fine solids in the reservoir, from the inflow at the upstream end to the deposition at the bottom, during a flood in 1996. The results were published in AJHE (in Japanese)(7) two years ago. This paper presents the subsequent achievements, a three dimensional numerical simulation model of fine solids behavior in a reservoir and its application to the flood in Shichikashuku Reservoir. In spite of the innovation of computers, 1 or 2 dimensional models are well used in cases of unsteady current or diffusion calculations in which the calculating area is large(5)(10). The model of this paper is based on the standard 3-D k-ε turbulence model including the effect of buoyancy by Boussinesq approximation and combined with a diffusion equation in which the settlement of fine solids is taken into account as falling with the terminal velocity relative to the surroundings. The calculation results are compared with the observed profiles of turbidity currents and the spatial distribution of deposited sediment.

SITE DESCRIPTION

Shichikashuku Reservoir is a multi-purpose reservoir constructed in Shiroishi River, a tributary of Abukuma River flowing at the east side of Tohoku district. The reservoir has a capacity of about 1.0×10^8 m^3, a surface area of $4.1km^2$ and a maximum water depth of about 45m. Its catchment area is $237km^2$, 93% of which is covered by forest and the remainder is mainly used for farm land and residential area.

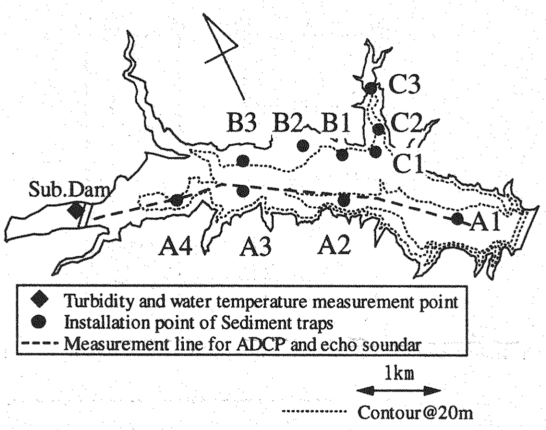

Fig. 2 Measurement points in the reservoir

Major inflowing rivers are Shiroishi River and Yokokawa River(Fig.1). The drainage area of the two rivers occupies 78% of the total catchment area of the reservoir. A subsidiary dam is installed at the upstream end of the reservoir to prevent rough sediments (bed material load) from entering the reservoir. The two rivers meet together just before the subsidiary dam. Because most of bed material load is trapped by the subsidiary dam, wash load is the major component of sediment carried into the reservoir. Under these circumstances, monitoring turbidity at the subsidiary dam is effective to estimate the time variation of fine sediment load into the reservoir.

FIELD MEASUREMENTS

In this section, the outline of field measurements in 1996 is described.

Methods

Field measurements were carried out for the flood caused by the typhoon 9617 which passed through Tohoku district on September 22, 1996. Fig.2 shows the locations of measurement stations in the reservoir. Three kinds of measurements were conducted during and after the flood:

1.Inflow conditions: Time series of turbidity and water temperature were measured with automatic recording turbidimeter(MTB-16k, Alec Electronic Co.Ltd.) and automatic recording water temperature meter(MDST, Alec Electronic Co.Ltd.) every hour at the subsidiary dam. Water was sampled at the same place and at two stations in Shiroishi River and Yokokawa River just upstream from the conjunction point every 1 or 2 hours. The water was analyzed for SS, T-P, PO4-P, ignition loss, and grain size distribution. The flow rate of each river was recorded by the dam management office, who also recorded the wind at the dam site.

2. Profiles of turbid current: Vertical profiles of horizontal velocity were obtained along the measurement line shown in Fig.2 by ADCP(Acoustic Doppler Current Profiler : RD-Instrument Ltd.) equipped to a boat with a vertical resolution of 50cm. An image of turbid water layer in a vertical longitudinal plane was also obtained by a high resolution echo sounder(Sembon Electronics Co.Ltd.). Vertical profiles of turbidity and water temperature were obtained by a water quality meter(ACL-1180, Alec Electronics Co.Ltd.) at four stations on the measurement line as shown in Fig.2.

3. Sedimentation of fine solids: Sediment trapping bottles were installed 2m above the bottom at ten points as shown in Fig.2 to capture falling sediments. The bottles were set one week before the flood and removed three weeks after the flood because it took about three weeks for the finest component of sediment to settle on the bottom of the deepest point. Bed materials were also sampled with a core sampler to estimate the total amount of sedimentation for 8 years after the dam was constructed.

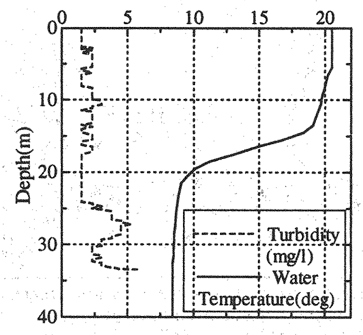

Fig3. The Profile of water temperature and turbidity at A1-st. the day before the flood

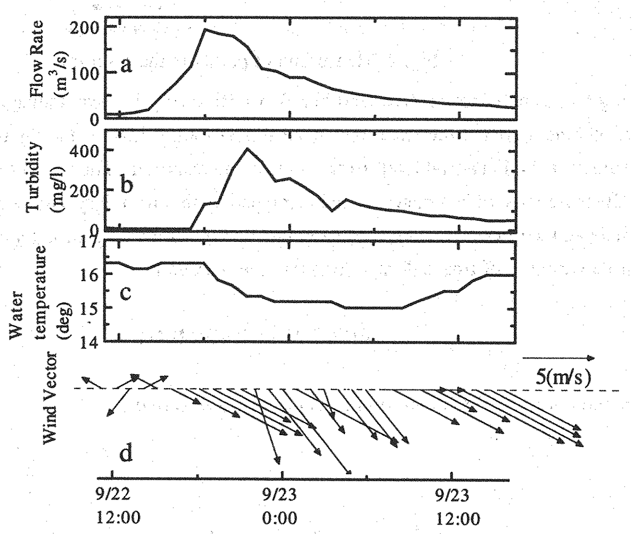

Fig4. Time series of inflow conditions

General Conditions during Measurements

Fig. 3 shows the vertical profiles of water temperature and turbidity measured at A1-st. the day before the flood. It is noted there existed a persistent seasonal thermocline with the temperature difference of about 12 °C around 15m below the water surface, and the turbidity was around 5 ppm or less over the whole column of water. These are used for initial state conditions in the simulation.

Fig. 4-a shows the time history of flow rate at the subsidiary dam obtained by the addition of flow rates of the two rivers, while Fig. 4-b shows the record of turbidity at the subsidiary dam. It should be noted that the peak of turbidity is behind that of flow rate, because of the retardation of mass transport from the transmission of flood wave in the subsidiary reservoir, in other words, the effect of storage. This retardation is observed in temperature as shown in Fig. 4-c; the water temperature started to drop after the peak of flow rate. The turbidity is expressed with the unit of mg/l like SS(Suspended Solid) because the turbidity meters used in this study were standardized by SS of 50μm kaolin. The correlations of the turbidity of definition with SS in the two rivers flowing into the reservoir is shown in Fig.5, in which the latter is 90 % of the former. Therefore, turbidity is treated as a conservative quantity as SS in this study. Fig.4-d shows the wind record at dam site. These data are used as boundary conditions in the numerical simulation described in the next section.

The results of measurements in the reservoir will be displayed with the results of calculation in the results and discussion section.

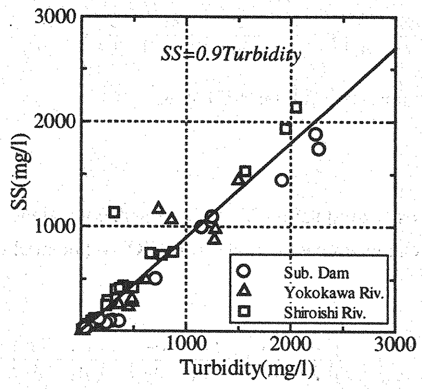

Fig. 5 Correlation between turbidity and SS

NUMERICAL MODEL DESCRIPTION

The standard three dimensional (3-D) k-ε turbulence model including the effect of buoyancy by using the Boussinesq approximation is combined with a diffusion equation in which the settlement of fine solids is taken into account by using their terminal velocity relative to the surrounding water.

Governing Equations

Momentum equations are

$$\frac{Du}{Dt}-\frac{\partial}{\partial x}\left(\nu_L\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_L\frac{\partial u}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_T\frac{\partial u}{\partial z}\right)=fv-\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{1}$$

$$\frac{Dv}{Dt}-\frac{\partial}{\partial x}\left(\nu_L\frac{\partial v}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_L\frac{\partial v}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_T\frac{\partial v}{\partial z}\right)=-fu-\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{2}$$

$$\frac{Dw}{Dt}-\frac{\partial}{\partial x}\left(\nu_L\frac{\partial w}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_L\frac{\partial w}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_T\frac{\partial w}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\delta g \tag{3}$$

where x and y = horizontal coordinates; z = vertical coordinate in upward; u, v and w = velocity components in x, y and z direction, respectively; p = residual pressure (real pressure minus static pressure for reference density); f = Coriollis coefficient($8.6\times10^{-5}s^{-1}$ for the latitude of the reservoir), ν_L = kinetic eddy viscosity in horizontal; ν_T = effective kinetic eddy viscosity.

The conservation equations of turbulent kinetic energy (TKE) k, dissipation rate ε and buoyancy δ and fine solids concentration C are written as,

$$\frac{Dk}{Dt}-\frac{\partial}{\partial x}\left(\nu_{Lk}\frac{\partial k}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_{Lk}\frac{\partial k}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_{Tk}\frac{\partial k}{\partial z}\right)=P_r+G-\varepsilon \tag{4}$$

$$\frac{D\varepsilon}{Dt}-\frac{\partial}{\partial x}\left(\nu_{L\varepsilon}\frac{\partial \varepsilon}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_{L\varepsilon}\frac{\partial \varepsilon}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_{T\varepsilon}\frac{\partial \varepsilon}{\partial z}\right)=C_1\frac{\varepsilon}{k}P_r+C_1(1-C_3)\frac{\varepsilon}{k}G-C_2\frac{\varepsilon^2}{k} \tag{5}$$

$$\frac{D\delta}{Dt}-\frac{\partial}{\partial x}\left(\nu_{L\delta}\frac{\partial \delta}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_{L\delta}\frac{\partial \delta}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_{T\delta}\frac{\partial \delta}{\partial z}\right)=S\Rightarrow 0 \tag{6}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+(w-w_0)\frac{\partial C}{\partial z}-\frac{\partial}{\partial x}\left(\nu_{LC}\frac{\partial C}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu_{LC}\frac{\partial C}{\partial y}\right)-\frac{\partial}{\partial z}\left(\nu_{TC}\frac{\partial C}{\partial z}\right)=0 \quad (7)$$

and continuity equation for incompressive fluid is written as,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (8)$$

where ν_{Li} = horizontal eddy viscosity for quantity "i"; ν_{Ti} = vertical equivalent; S = the rate of buoyancy production; P = production rate of TKE ; G = energy conversion rate from TKE to potential energy by vertical mixing. P and G are written as follows:

$$P_r=\nu_t\left[2\left\{\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right\}+\left\{\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2+\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)^2\right\}\right] \quad (9)$$

$$G=-g\nu_{T\delta}\frac{\partial \delta}{\partial z} \quad (10)$$

The horizontal kinetic eddy viscosity is estimated with Richardson's -4/3 power law,

$$\nu_L=0.01L^{4/3} \quad (11)$$

where L = the horizontal grid scale. The vertical kinetic eddy viscosity is estimated from the assumption of standard k-ε model,

$$\nu_T=\nu+\nu_t=\nu+C_\mu\frac{k^2}{\varepsilon} \quad (12)$$

where ν is eddy viscosity of water of reference density. Diffusion coefficients are related to eddy viscosity as follows.

$$\nu_{Lk}=\nu_L;\ \nu_{Tk}=\nu_T;\ \nu_{L\varepsilon}=0.77\nu_L;\ \nu_{T\varepsilon}=0.77\nu_T$$

$$\nu_{L\delta}=1.2\nu_L;\ \nu_{T\delta}=1.2\nu_T;\ \nu_{LC}=\nu_L;\ \nu_{TC}=\nu_T \quad (13)$$

The standard values of C_1, C_2 and C_μ are recommended as follows:

$$C_1=1.44;\quad C_2=1.92;\quad C_\mu=0.09 \quad (14)$$

The best value for C_3 has not been proposed yet. In this paper, C_3 is assumed to be 1.0, following Michioku(6) and Yoon et al.(11)

Buoyancy δ depends on both water temperature and turbidity. In the conditions of Shichikashuku Reservoir, the difference of water temperature is about 12°C(Fig.3), while that of turbidity is about 70mg/l(Fig.7). When these differences are converted into density difference, the effect of turbidity on density is about 2.5% of that of temperature. Therefore, buoyancy is assumed to be determined by water temperature only in this study. δ is treated as a conservative quantity, i.e., S is assumed to be zero, because the duration of calculation (30 hours) is so short that heat transfer through the water surface changes the temperature structure less than the intruding flood water does.

Calculation Conditions

The above equations are discreterized with finite volume method for staggered grids in Cartesian coordinate, the grid size in longitudinal (Δx) is 100m, that in lateral (Δy) is 50m and that in vertical (Δz) is 1m, considering the aspect ratio of general dimensions. In the region near the upstream end, Δx and Δy are 50m and 25m, respectively, because rate of flow variation must be larger. The time increment Δt is taken as 60 second.

The period of calculation is from 11 a.m. on September 23rd, three hours before the flood water started to flow in, to 5 p.m. on September 24th, several hours after the flood is almost settled. As shown later, the nose of turbid current had reached to the dam at the end of calculation and stably stratified condition was established.

Initial Conditions and Inflow Conditions

At the beginning of calculation, the velocity field is assumed to be quiescent, while the profiles of water temperature and turbidity are assumed to be as observed at St-A1, one day before the flood as shown in Fig.3. Sufficiently small values of k and ε are given for initial values: k and ε at quiescent condition are zero theoretically, but this setting causes overflows in calculation because of the singularity of k-ε equations.

The flow rate, the water temperature and the turbidity at the upstream end are given by the measurements shown in Fig. 4(a-c). The distribution of inflow for grids are described in the next section. Only the inflow through the subsidiary dam is considered in this simulation although there are some small streams that flow directly into the reservoir. The inflow conditions for such small streams were unknown but because the runoff water from 78 % of the total catchment area flows through the subsidiary dam, they can be ignored.

Boundary Conditions at Water Surface, Bottom and Side Walls

For the simulation the water surface was considered as a "rigid wall" , so that the outflow rate is always kept equal to the inflow rate. In reality the dam gate was operated in a way that the water in surface mixed layer was extracted from the reservoir so that the water surface level was kept close to the normal water level. As a result, the rise of the water surface was less than 2 m, which is much smaller than the vertical dimension of the reservoir. So, the assumption of rigid wall for the water surface had little effect on the behavior of the density currents.

The momentum flux at the surface rigid wall is given by wind stress through the following equations:

$$\nu_T \frac{\partial u}{\partial z} = (U_*^2)_x ; \quad \nu_T \frac{\partial v}{\partial z} = (U_*^2)_y \tag{15}$$

where $(U_*^2)_x$ and $(U_*^2)_y$ are the wind stress components in x and y-directions, respectively. The absolute values of wind stress are estimated with the following formula(4).

$$\rho_w U_*^2 = 0.5 \times 10^{-3} \rho_a U_{10}^{2.5} \tag{16}$$

where ρ_w = density of water; ρ_a = density of air; U_{10} = wind velocity at 10m height, which is shown in Fig. 4-d. Fluxes of quantities at the water surface other than momentum are set to zero in this study.

At the bottom and side walls, all components of velocity are set to be zero as well as fluxes of other quantities, k, ε and δ. As for C, sedimentation onto the reservoir bed is considered under the condition of (5)

$$\nu_{TC} \frac{\partial C}{\partial z} + w_0(1-A)C = 0 \tag{17}$$

Assuming static sedimentation, in this study A=1. In this study, resuspension of sediment is treated as negligible

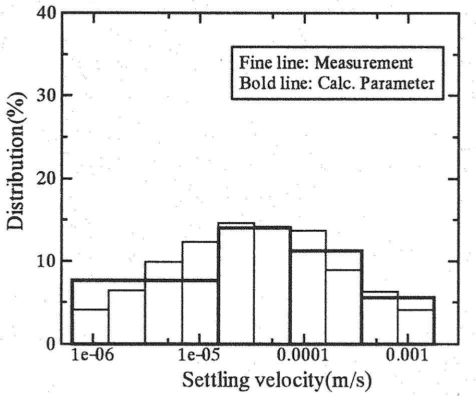

Fig. 6 Distributions of settling velocity of fine solids

Table 1 Diameters, settling velocitis and their proportions for the parameter of the calculation

Diameter(μm)	Settling Velocity(m/s)	Proportion(%)
31.232	8.00×10^{-4}	12
14.142	1.63×10^{-4}	24
6.404	3.35×10^{-5}	30
1.951	3.11×10^{-6}	34

because the current is not so fast (about 0.1m/s at the fastest) enough to erode the bottom deposit and the calculation duration is short.

Settling velocity of the suspended sediment w_0 is estimated from the grain size distribution of the sediment collected in the reservoir. The particle size was deduced from the settling velocity assuming Stokes law. Fine line of Fig.6 shows the distribution of settling velocity which was calculated from the observed particle size. Table 1 and the bold line on Fig.6 are the sediment velocity and their proportions for the calculation.

Boundary Conditions at Upstream and Downstream End

Water flowing from the subsidiary dam will plunge under the reservoir water at some distance and form a density underflow. The distance of the plunging point from the subsidiary dam is about 100 m according to visual measurement. This fact means that horizontal grids of 10m or finer are required to reproduce the "rapidly varied flow" at the upstream reach, but such fine grids are not feasible for the whole area of reservoir. Accordingly, in this study, a virtual boundary condition is adopted based on the following considerations: After the plunging point, a density under flow is developed. This flow, an inclined plume, has a tendency to reach a "steady state".

To obtain the current field at the inflow, it is assumed that the influent water enters through the lower half of the cross section, and the flow velocity is obtained by dividing flow rate by the influent cross section.

At the downstream end, the way of discharge at Shichikashuku Reservoir is to let the water out from the surface. The current around the spillway is rapidly varied as if the water in the surface mixed layer was extracted. Considering the location of the spillway, current velocity at downstream edge boundary condition is given to every mesh on the northern half of the dam and depths from 0(water surface) to 15m.

RESULTS AND DISCUSSION

Velocity Profiles

Calculated profiles of velocity and turbidity are compared with measurements at the stations(A1-A4) in Fig.7. The time of the calculation results of this fugure corresponds to that of the observation. Calculation results of turbidity agree well with the observation of turbidity although the results of velocity do not so well. In spite of this, the following characteristics of current pattern can be read from the figure. Wind induced current has been developed near the surface. Turbid water intrudes along the thermocline around the depth of 15m, and reaches the downstream end. Between these currents, an upstream current occurs for compensation.

Sediment Distribution

Calculation for sediment process is simplified as follows in order to shorten calculation time, because the model is three-dimensional and the duration for the finest particle to reach the bottom is about three weeks. At the end time of calculation(T=30hr), the turbidity current has already reached the dam site, and an almost level stratification has been formed. It is considered, therefore, that large advection will not be generated after this time. Most of the suspended

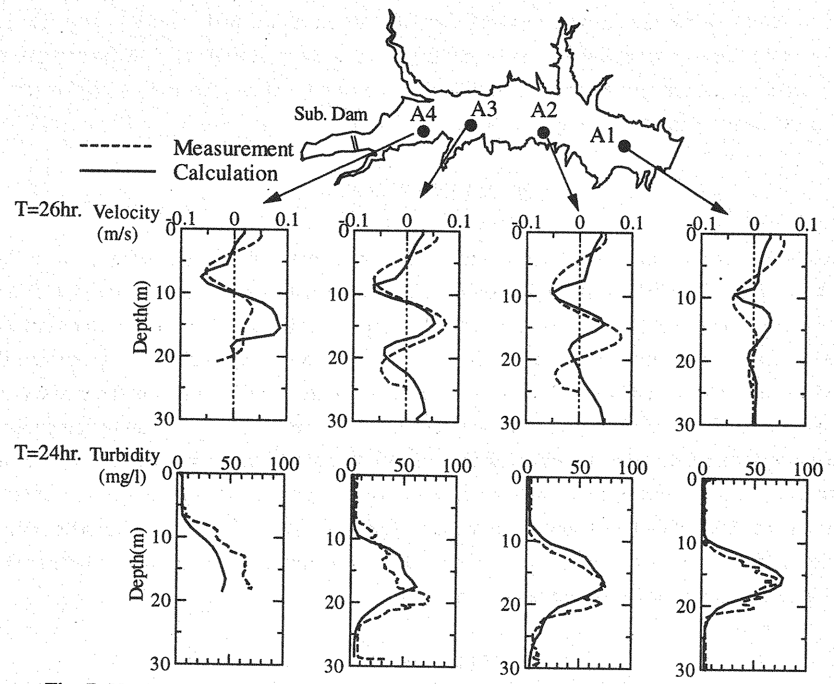

Fig. 7 Vertical profiles of velocity and turbidity, comparing measurement and simulation

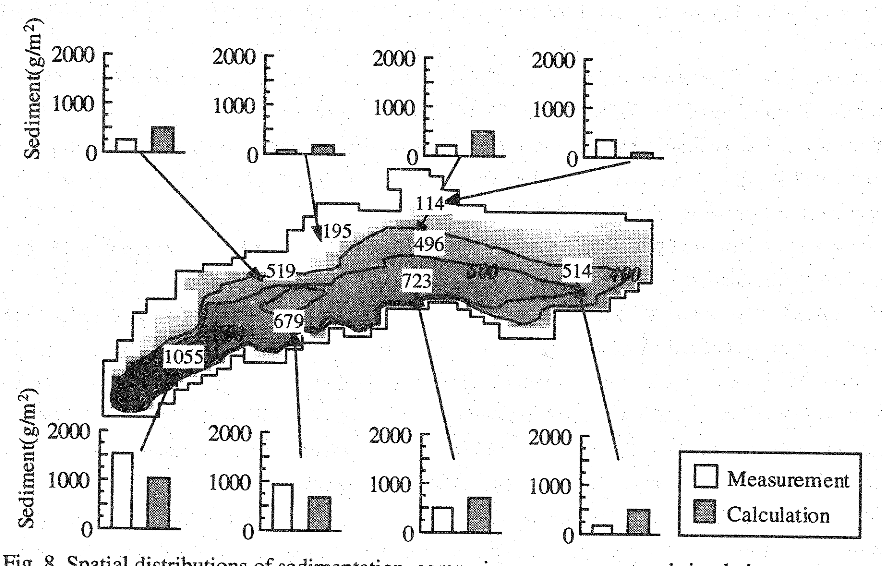

Fig. 8 Spatial distributions of sedimentation, comparing measurement and simulation

matter seems to settle down in the reservoir, since the reservoir carries out surface layer discharge and the turbidity near the surface at the dam is almost zero. Consequently, particles which are suspended at T=30hr are settled vertically onto the bed, and the whole amount of sediment distribution was estimated as the sum of this settling and the sediment during the 30hr. calculation.

The result is shown in Fig.8. The planar distribution figure shows the calculation result, and observation results are shown by the bar-graph. Calculated amounts of sediment at the observation points are marked with the tip of the arrow. The distribution of the calculated sediment deposition agrees with the observed distribution but there is a tendency for the model to overestimate in the downstream area and underestimate in the upstream area. The proportions of sedimentation velocities(as seen in Table1.) influence the distribution of sediments. The proportions were to be varied then this would cause changes on the sedimentation distribution. Therefore, the settling velocity has to be estimated with good accuracy in order to improve the calculation accuracy.

CONCLUDING REMARKS

In this study, a 3-D numerical model was developed to simulate the turbid water current and the process of suspended solids sedimentation for a flood in Shichikashuku Reservoir. The calculations of current velocity, turbidity and the distribution of sedimentation agreed with the observation. We think that the numerical simulation model presented in this study makes an effective tool for reservoir management. However, there are several points to improve this model. First, the boundary conditions around the inflow and the outlet are a little expedient because the model is not precise enough to express the rapidly varied flow around these boundaries. Second, settling velocities of suspended material also need to be more accurate for more accurate calculation. Third, inflows from tributaries, which occupies about 20% of the total catchment area, is not considered in this study. In this reservoir, the creeks are expected to work like the subsidiary dam, the effect of the tributaries on the amount of sediment is not so large in the middle of the reservoir. When this model is adopted to some reservoir with complicated shape, the effect of tributaries may have to be taken into account. These points have to be argued more afterwards.

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APPENDIX NOTATION

The following symbols are used in this paper:

A = bed absorbency coefficient;
C = fine solids concentration;
C_1, C_2, C_3, C_μ = k-ε model coefficients;
f = Coriollis coefficient ($8.6\times10^{-5}s^{-1}$);
G = energy conversion rate form TKE to potential energy;
g = gravitational acceleration;
k = turbulent kinetic energy;
L = horizontal grid scale;
p = residual pressure;
P = production rate of turbulent kinetic energy;
S = the rate of buoyancy production;
U_{10} = wind velocity at 10m height;
U_* = friction velocity of wind;
u, v, w = velocity components in x, y, z-direction, respectively;
w_0 = settling velocity of suspended solid;
x, y = horizontal coordinates;
z = vertical coordinate in upward;
δ = buoyancy;
ε = dissipation rate;
ν = eddy viscosity of water of reference density;
ν_t = kinematic eddy viscosity of vertical direction;
ν_T = effective kinetic eddy viscosity;
ν_L = kinetic eddy viscosity in horizontal;
ν_{Li} = horizontal eddy viscosity for quantity "i";
ν_{Ti} = vertical eddy viscosity for quantity "i";
ρ_A = density of air; and
ρ_w = density of water.

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