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A simulation model for sedimentation process in gorge-type reservoirs

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Abstract A hydraulic simulation model for a one-dimensional sedimentation process in a gorge-type reservoir is developed. The model is a kind of uncoupled model consisting of parts for steady flow routing and sediment routing, and simulates not only the variation in the streamwise profile of reservoir beds, but also the alternation of strata in accumulated sediment layers. Considerable improvement is achieved, especially in the numerical technique to treat the sedimentation caused by those flows in which subcritical and supercritical flows coexist. In order to test the reliability of the model, it is applied to the numerical reproduction of the sedimentation process in an existing reservoir for 20 years after its construction. The simulation result shows sufficient agreement with the observations.

INTRODUCTION

In the design of reservoir projects, or in the planning of countermeasures to the various kinds of negative influence of sedimentation, it is necessary to predict the sedimentation process as accurately as possible. The application of the well-developed hydraulic theory of river bed transience may be most appropriate in the formation of the simulation model. When the sedimentation process under consideration is likely to be substantially affected by the re-erosion of previously deposited sediments, due to the large drawdown of the water surface level in a reservoir as well as the wide fluctuation of the inflowing water discharge, the alteration of the strata with different textures of particle size formed in the deposited sediment layer should be simulated at the same time as the deformation of the bed profile in order to precisely estimate the re-erosion rate. The information on the strata is also useful in the planning of the sediment control works.

In this paper, a hydraulic simulation model for the prediction of the one-dimensional sedimentation process in a gorge-type reservoir is described, and the reliability of the model is tested through its application to the numerical reproduction of sedimentation process in an existing reservoir.

BASIC EQUATIONS

The sedimentation process in Reservoirs is essentially common to the river bed transience in alluvial river reaches without reservoirs. Therefore, it can be simulated by an alternate sequence of the steady non-uniform flow routing based on the equations of mass and energy conservation and the sediment routing based on the equations of sediment transport and mass conservation.

Non-uniform flow

Assuming the flow to be gradually varied and ignoring the lateral inflow of other streams, the relationships of mass and energy conservation in the flow are written in the following forms:

(mass of water) $\partial(v\mathrm{A})/\partial x = 0$ (1)

(energy of flow) $\partial(v^2/2g + h + z)/\partial x = -S_F$ (2)

where x = streamwise coordinate; z = bed level; v = mean flow velocity; A = cross-sectional area of flow; h = flow depth; S_F = friction slope; g = gravitational acceleration; energy correction factor is assumed to be unity. Combination of equations (1) and (2) gives the basic equation for the non-uniform flow routing:

$$\partial\{Q^2/(2gA^2) + h + z\}/\partial x = -S_F \quad (3)$$

where Q = flow discharge. S_F may be evaluated by a mean velocity formula such as Manning's formula.

Sediment transport and bed level change

The mass conservation relationship for the calculation of bed level change is expressed, in a general form, as follows:

$$\partial A_s/\partial t + 1/(1-\lambda)\partial(Q_B + Q_S + Q_W)/\partial x = 0 \quad (4)$$

where t = time; A_S = cross-sectional area of movable sediment layer; Q_B and Q_S = transport rates of bed load and suspended load as bed material load, respectively; Q_W = transport rate of wash load; λ = porosity of bed. The term $\partial A_S/\partial t$ may be replaced by $B_B\partial z/\partial t$, in which B_B = width of movable bed; however, the former is more appropriate in treating reservoirs with arbitrary cross-sectional shapes, those that are other than rectangular.

From the practical point of view, the whole reach of sedimentation may be divided into the following three sub-regions (Fig. 1):

(a) River region: the bed load and the suspended load are in states of equilibrium at each cross-section and the wash load does not affect the bed level.

(b) Upstream-pond region: the suspended load is in a state of non-equilibrium, while the bed load keeps a state of equilibrium and the wash load does not affect the bed level.

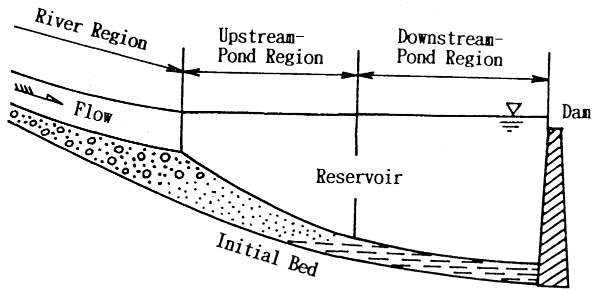

Fig. 1 Schematic diagram of the three sub-regions for sediment routing.

(c) Downstream-pond region: only the transport and the deposition of the wash load take place. Based on this restriction of phenomena, equation (4) may be modified by each sub-region as:

(River region) $\partial A_S/\partial t + 1/(1-\lambda)\partial(Q_{BE} + Q_{SE})/\partial x = 0$ (5-a)

(Upstream-pond region) $\partial A_S/\partial t + 1/(1-\lambda)\partial(Q_{BE} + Q_{SN})/\partial x = 0$ (5-b)

(Downstream-pond region) $\partial A_S/\partial t + 1/(1-\lambda)\partial Q_W/\partial x = 0$ (5-c)

where Q_{BE} and Q_{SE} = equilibrium transport rate of bed load and suspended load, respectively, to be evaluated by the formulas of bed material load; Q_{SN} = non-equilibrium transport rate of suspended load.

By the vertical integration of the diffusion-convection equation of suspended load, the term $\partial Q_{SN}/\partial x$ in equation (5-b) can be equated as:

$$\partial Q_{SN}/\partial x = \Sigma V_F(C_{BE}-C_B)B_B \tag{6}$$

where V_F = fall velocity of suspended load; C_{BE} and C_B = bottom concentration of suspended load in states of equilibrium and non-equilibrium, respectively; the symbol Σ means summation with respect to particles of different sizes. For the calculation of C_B, a practical basic equation has been proposed by Okabe (1983), namely,

$$\frac{\mathrm{d}C}{\mathrm{d}x} = \frac{(V_F/q)(1-C)(E-1)^2}{2(C/V)(E-1)^2+(1-E)+[-V+\{V+\exp(-V)-1\}/C]E/C} \tag{7}$$

where $C = C_B/C_{BE}$; $V = V_F h/\epsilon$; ϵ = cross-sectional mean diffusion coefficient; $E = \exp(V/C)$; q = flow discharge in unit width.

The streamwise variation in the transport rate of wash load may be approximately expressed as:

$$\partial Q_W/\partial x = -K_W V_{FW} B_S(Q_W/Q) \tag{8}$$

where V_{FW} = representative fall velocity of wash load; B_S = water surface width; K_W = empirical constant. It should be noted that equation (8) has been deduced on the assumption of homogeneous flow.

Grain size composition in bed surface

The grain size composition in the bed surface layer (exchange layer) considerably affects the sediment transport rate and, consequently, the process of bed profile variation. Especially in the simulation of a reservoir sedimentation process where the rapid streamwise variation in sediment transport capacity of the flow causes typical grain sorting, it is necessary to take the change in grain size composition into account as strictly as possible. At the same time, the data about grain size composition in the whole region of the accumulated sediment layer should be preserved to cope with the phenomena of deep erosion of the layer.

In this simulation model, the calculation of the variation in the grain size composition due to bed material load is carried out based on the one-layer exchange model proposed by Hirano (1971), namely,

$$\partial P_j/\partial t = -1/\{\delta B_B(1-\lambda)\}\partial(Q_{Bj} + Q_{Sj})/\partial x - (P_{0j}/\delta)\partial z/\partial t \tag{9}$$

where P_j, Q_{Bj} and Q_{Sj} respectively equal size fraction, transport rate as bed load and transport rate as suspended load of grains with j-th class size; δ = thickness of exchange layer; $P_{0j} = P_j$ when $\partial z/\partial t > 0$, otherwise ($\partial z/\partial t < 0$), P_{0j} = size fraction of grains with j-th class size in sediment layer just below exchange layer.

NUMERICAL CALCULATION METHOD

The numerical solution of the basic equations described above is achieved with the aid of a finite difference method. In this paragraph, some major points concerning the discretization of the basic equations as well as the computational technique are described.

Non-uniform flow routing

With respect to the range between i-th and $(i + 1)$-th set cross-sections, equation (3) is approximated by the following discrete form:

$$\{Q^2/(2gA_i^2) + h_i + z_i\} - \{Q^2/(2A_{i+1}^2) + h_{i+1} + z_{i+1} = -S_{FV}\Delta x \tag{10}$$

where i = streamwise number of set cross-section; S_{FV} = virtual friction slope; Δx = streamwise distance between i-th and $(i + 1)$-th cross-sections. A step-by-step calculation with equation (10) gives the hydraulic quantities necessary for the calculation of sediment transport rate.

The important problems in the simulation of gorge-type reservoirs in deep mountain areas, where subcritical flow and supercritical flow are apt to coexist, are how to search for the control sections and how to evaluate S_{FV} using only the hydraulic quantities at discretely set cross-sections. In this model, the control sections are searched according to the method proposed by Ishikawa & Hayashi (1983). On the other hand, S_{FV} is calculated with a weighted method empirically deduced by Okabe *et al.* (1992), that is,

$$S_{FV} = w_i S_{F,i} + w_{i+1} S_{F,i+1} \tag{11}$$

where $S_{F,i}$ and $S_{F,i+1}$ = friction slopes at i-th and $(i + 1)$-th cross-sections, respectively; w_j and w_{j+1} = weight parameters defined as:

$$w_j = R_{U,i+1}R_{c,i+1}/(R_{U,i}R_{C,i} + R_{U,i+1}R_{C,i+1}) \tag{12-a}$$

$$w_{j+1} = R_{U,i}R_{C,i}/(R_{U,i}R_{C,i} + R_{U,i+1}R_{C,i+1}) \tag{12-b}$$

where $R_U = |S_F/S_B - 1|$ when $S_B > 0$, otherwise $R_U = 1$; $R_C = h_C/h$; S_B = bed slope; h_C = critical depth.

Sediment routing

The spatial derivative term of sediment transport rate in the mass conservation equation has been usually discretized by backward- or forward- difference scheme depending on whether the flow is subcritical or supercritical, respectively. This method is based on the kinematic theory of bed-disturbance propagation. In the event of a coexistence of subcritical and supercritical flows the above mentioned method yields a serious error, as has been pointed out by Michiue *et al.* (1990), in the total mass balance between the inflowing sediments and the deposited sediments. In order to avoid this type of error, equations (5-a) and (5-b) were discretized according to the model proposed by Okabe (1992) on the basis of a hyperbolic theory of bed-disturbance propagation; on the other hand, Equation (5-c) was discretized by a backward-difference scheme.

In Okabe's model, the residual of sediment transport rate in a division between i-th and $(i + 1)$-th cross-sections is assumed to be distributed to each cross-section proportionally to the reciprocal of the propagation velocities concerned (Fig. 2). As the result, the change in the cross-sectional area of sediment layer at i-th section in a small time interval, $\Delta A_{S,i}$, which is affected by the residuals in the two division just upstream and downstream of this cross-section, is equated as:

$$\Delta A_{S,i}\Delta x_{S,i} = \{\Delta T_{S,(i-1)}c_{U,(i-1)}/(c_{U,(i-1)} + c_{D,(i-1)} + \Delta T_{S,(i)}c_{D,(i)}/(C_{U,(i)} + C_{D,(i)})\}\Delta t/(1-\lambda) \tag{13}$$

where Δt = time interval; $\Delta x_{S,i} = (x_{i+1} - x_{i-1})/2$ in which x_{i+1} and x_{i-1} denote x-values at $(i - 1)$-th and $(i + 1)$-th sections, respectively; ΔT_S = residual of sediment

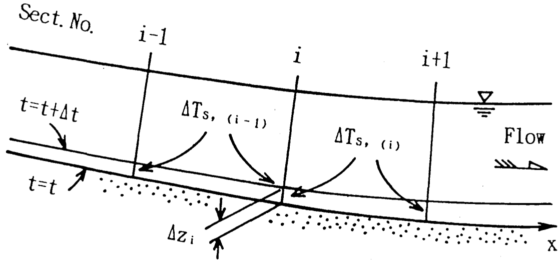

Fig. 2 Definition sketch of Okabe's model.

transport rate including that both of bed load suspended load; c_U and c_D = representative propagation velocities of bed-disturbance towards upstream and downstream directions, respectively; the subscript put in a couple of parentheses indicates the number of a division defined as equal to the number of the upstream cross-section bounding the division. The values of c_U and c_D are the smaller two of the three roots of the following characteristic curve equation:

$$\omega^3 - 2\omega^2 + \omega = (\xi/6)\omega^2 + (1/F_r^2 - \xi/6)\omega - (7/6)\xi/F_r^2 \tag{14}$$

where $\omega = c/v$ = relative propagation velocity, Fr = Froude number, ξ = non-dimensional parameter representing the sensitivity of sediment transport rate to the change of flow condition as defined $[1/(1 - \lambda)](\partial q_S/\partial v)/h$, in which q_S = sediment transport rate in unit width. The bed level change at i-th cross-section in Δt, indicated by Δz_i, can be evaluated accurately by the following relation of 2nd-order accuracy:

$$\Delta A_{S,i} = B_{B,i}\Delta z_1 + (1/2)(dB_{R,i}/dz_i)\Delta z_i^2 \tag{15}$$

where $B_{R,i}$ = width of reservoir at elevation of z_i in i-th cross-section.

The derivative term of sediment transport rate of the individual grain size in equation (9) is discretized also in the same manner as described above concerning equations (5-a)-(5-b).

APPLICATION TO THE KOMINONO RESERVOIR

The simulation model described above was applied to the numerical reproduction of the sedimentation process in the Kominono Reservoir for 20 years after its construction.

Brief description of the Kominono Reservoir

The Kominono Reservoir, planned only for water power generation and completed in 1968, is located on the most upstream reach of the Naka River south of Tokushima Prefecture, Japan. The drainage area above the dam is 266.8 km^2 and the original gross storage capacity is 16.75 Mm^3.

The annual rainfall in the basin ranges from 2200 mm to 4500 mm. Because of the heavy rainfall as well as the weak geological structure consisting mainly of sandstone, mudstone and slate, a large amount of sediment yield occurs in the basin. According to the reservoir survey data, the annual specific rate of sediment runoff from the basin is about 1000 m^3 km^{-2} $year^{-1}$. In Fig. 3 the observed variation in the streamwise bed profile of the reservoir is briefly shown with the geological columns surveyed in 1977.

Simulation and result

The simulation model was run with the following input information: the original shape of the reservoir and the upstream river reach surveyed with an interval of 200 m; the grain size composition of original bed surface estimated from the existing data; observed data of inflowing discharge and water surface elevation as hourly-averaged

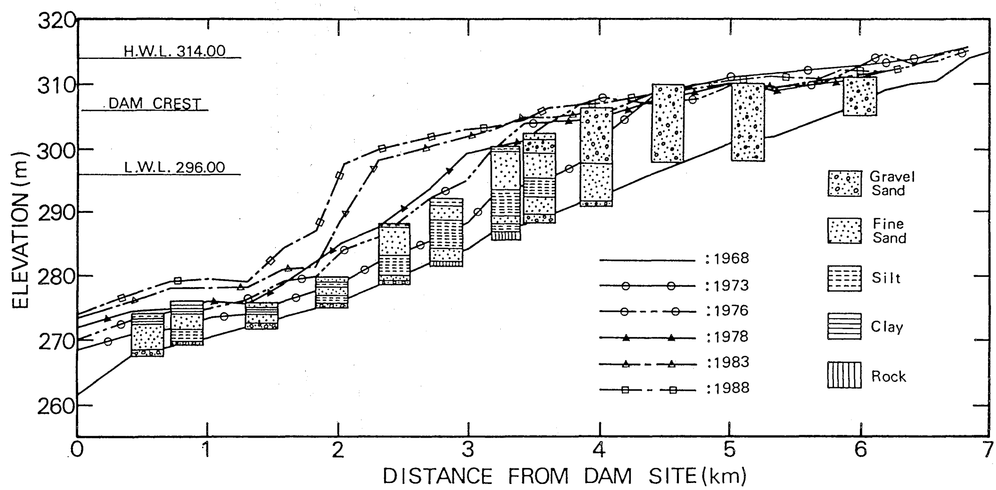

Fig. 3 Variation in streamwise bed-profile and geologic columns observed in the Kominono Reservoir.

data in major flood periods (several floods in a year) and daily-averaged data in other periods; Manning's roughness coefficient estimated as $n = 0.039$ by referring to the surface marks of floods; the thickness of exchange layer set at O.4 m for the river and upstream-pond regions, at 0.05 m for downstream-pond regions; an empirical relationship between the bed porosity and the mean size of deposited sediment.

The inflowing rate of bed load and suspended load was given for individual grain sizes by the calculation with respect to an assumed control section of bed material load.

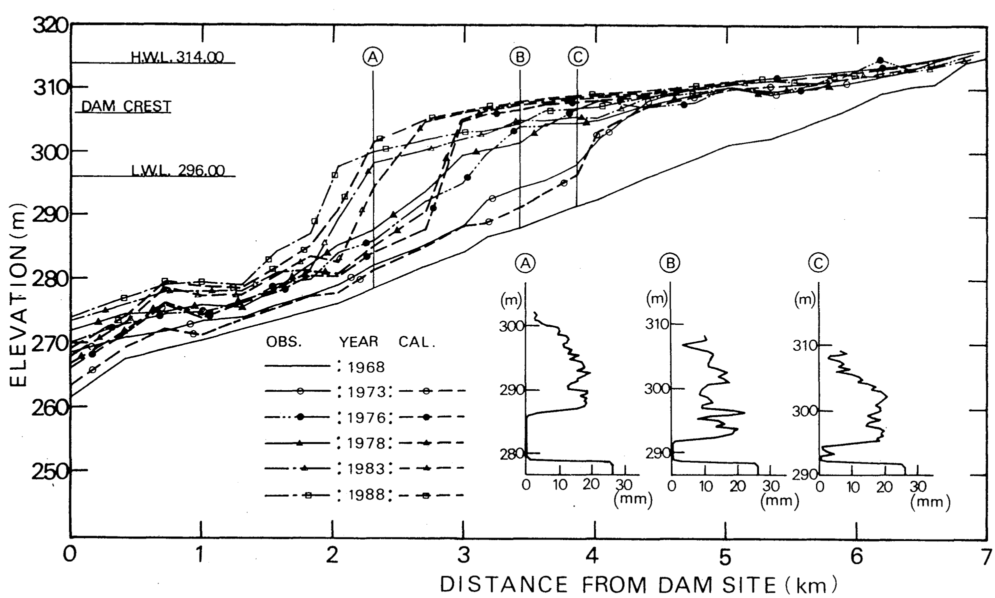

Fig. 4 Simulation results of variation in streamwise bed-profile, compared with observations, and of vertical distribution of mean grain size in sediment layer.

The particle size of bed material load was classified into 10 grades of between 0.1 mm to 200 mm. For the calculation of the bed material transport, the formulae proposed by Ashida & Michiue were employed, after making a slight modification to adjust the calculated total volume of inflowing sediments to the observations, along with the expression for the critical tractive force of individual grain sizes in sediment mixture proposed by Michiue & Suzuki (1988). However, a Brown-type formula was used in the evaluation of the propagation velocity of bed disturbance. The inflowing rate of wash load was also calculated with a relationship, namely $Q_w = 0.51 \times 10^{-6} Q^2$ (in $m^3 s^{-1}$ unit), as obtained from field observations. K_w and V_{Fw} in equation (8) were set at 1.0 and 0.0013 m s^{-1}, respectively.

The simulation was performed without the generation of serious instability in the computation. The simulation result is shown in Fig. 4 in which the simulated variation of streamwise profile of the reservoir bed is drawn and compared with the observations, furthermore, the simulated vertical distribution of the mean sediment size in the final sediment layer is presented for the representative cross-sections. The simulation results are in sufficient agreement with the observations, although the alteration of strata in the sediment layer is not so clear as the observations.

PERSPECTIVE

The grain sorting process seems to be simulated more exactly by introducing a kind of multi-layer model for the change in the grain size composition in bed surface layers. On the other hand, the variation in the streamwise bed profile will be simulated more accurately if the influence of the stream constriction on the re-erosion of deposited sediments is taken into account. The clarification of the transport rate of the sediment mixture of wash load and bed material load is also an important problem.

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