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DEPOSITION OF BED LOAD AND SUSPENDED LOAD IN SAND-GRAVEL MIXTURE IN A STEEP SLOPE RESERVOIR

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The sediment deposition in a reservoir with sand-gravel mixture (of fine sand and coarse sediment) is studied in a steep channel with the formation of hydraulic jump, which divides a flow region into subcritical and a supercritical sections on building a small dam at the downstream end. Following the findings on experiments, the deposition profile consists of layers of fine particle and mixed particles and the concentration of sediment particles vary on the flow level. Both, bed and suspended load are analyzed and one-dimensional deposition configurations are simulated.

Key Words: *Sediment loads, modification factor, terminal fall velocity, sediment concentration, hydraulic jump, and delta*

1. INTRODUCTION

The phenomenon of sediment deposition in the mountain river depends on various factors, such as, topographical slope, sediment size and its mixture, flow, and other hydraulic parameters. The most probably sediment is transported in the form of sand-gravel mixture of fine and coarse sizes, rather than in the form of uniform sand. The process of sediment deposition with sand-gravel mixture experimentally in a steep channel building a small dam at the downstream end. The aim of the paper is to simulate the bed profile variation in steep channel reservoir by one-dimensional continuity equations of flow with hydraulic jump and sediment transport, considering the bed and suspended load.

In presence of dam, the hydraulic jump is formed, which divides the whole flow channel into two sections: the super-critical region of uniform flow depth and the sub-critical region of increasing flow depth. When the bed shear stress exceeds the critical value of initiation of motion (critical shear stress), the sediment particle moves, and it tends to deposit, when the bed shear stress becomes smaller with decreasing flow velocity.

Experimental study for the mixture(s) of sediment particles (0.1, 1.0, and 2.5mm) in a steep channel reservoir revealed that the two distinct layers of the deposition were formed[1)]. A thin layer of finer particles (F-layer) was formed on the initial bed, while another layer of mixed particles (M-layer-consists of more coarse grains) was formed on the top of F-layer. In view of sediment transport, as smaller particles can be transported for a longer distance before settling down; the deposition was progressed only in F-layer in the downstream side of the delta. Two-dimensional deposition of mixed particles and three-dimensional configurations of fine particles, and an increasing percentage of fine particles towards the dam (in M-layer) were observed.

In the one-dimensional simulation, the formation of hydraulic jump is considered. The sediment load for the sediment grain is calculated based on its individual composition in the mixture. The sediment transport occurs in the water column only[2)], below which there is an existence of a thin exchange layer[3)]. Previously, the average bed profile has been computed considering the average frequency of mixture and the sediment as bed load, where the bed load functions are estimated by the modification of tractive force for each grain size[4)]. In the sand-gravel mixture, bed shear stress depends on the sediment size for a given condition of flow. The states of bed and suspended load may depend on the sizes of the sediment particles of same density in the mixture of sand-gravel provided the same hydraulic conditions. Obviously, very fine particles are more in suspension and coarse materials are transported as bed load. In this study, the sediment load is considered as bed load and suspended load.

EXPERIMENTAL OBSERVATION

(1) Brief description

The sediment deposition for the sand-gravel mixture(s) was studied experimentally in a rectangular steep channel (0.15m wide, 0.30m deep, and 10.00m long) by building a small model dam at the downstream end. As shown in Table 1, the deposition process was observed in ten sets of experiments for the sediment particles (0.1, 1.0, and 2.5mm), dam height (0.07 and 0.10m), channel slope (1/50). The mixtures were made in an equal proportion of particles by dry volume. The flow discharge per unit width (q) and the unit sediment supply (q_b) were supplied at a constant rate from the upstream end of the channel.

The variations in bed levels due to the deposition and water depths were measured at appropriate time interval e. g., 30 minutes. It was observed that the sediment was deposited in the sub-critical region downstream of the hydraulic jump only. Moreover, the characteristic of hydraulic jump was observed as a normal and wavy or unstable surface during the deposition. Further, the locus of delta with hydraulic jump and distribution of sediment particles in M-layer were measured.

(2) Results from the Observation

The deposition configuration of sand-gravel mixture (M and F-layers) the distribution of grains on the mixed layer was observed as shown in Photo 1: two-dimensional bed profile of M-layer and a three-dimensional configuration of F-layer in front of the delta. Fig.1 shows typical average bed profiles with M-layer and F-layer (z_a and z_s) and the water surface (h) profiles are shown for Run K for a time suffix in minute. The layer of fine particles (F-layer) consists of only fine particles on the initial bed. Yu et al. (2000) stated that the concentration of deposition layer becomes uniform[5]), vertically below the front of delta. However, M-layer consists of mixed particles of all sizes with the inconsistency in composition of fine and coarse particles. Typical distribution curves in M-layer(s) for Run K (bimodal) and Run R (trimodal) sand-gravel mixture for the fine and coarse particles (d_1=0.1mm, d_2=1.0mm, and d_3=2.5mm) are shown in Fig. 2. The percentage of coarse particle decreases towards the dam in the M-layer, because coarser grains tend to deposit faster at a short time compared with fine particles. On the other hand, fine grains are

Table 1 Sets of experiments for sand-gravel-mixture in steep channel reservoir

Sets (Runs)	Sediment Sizes (d_i) in mm	Dam Heights (W) in m	Water Discharge (q) in $m^3/s/m$
K	0.1, 2.5	0.10	2.00×10^{-2}
L	-Do-	0.10	2.66×10^{-2}
M	-Do-	0.10	3.33×10^{-2}
N	-Do-	0.07	2.0×10^{-2}
O	-Do-	0.07	2.66×10^{-2}
P	-Do-	0.07	3.33×10^{-2}
Q	0.1, 1.0, 2.5	0.07	2.66×10^{-2}
R	-Do-	0.10	2.66×10^{-2}

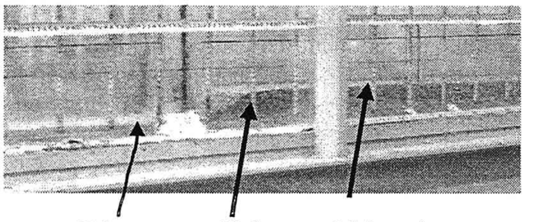

Photo 1 Deposition layers with delta in Run R (3 hours)

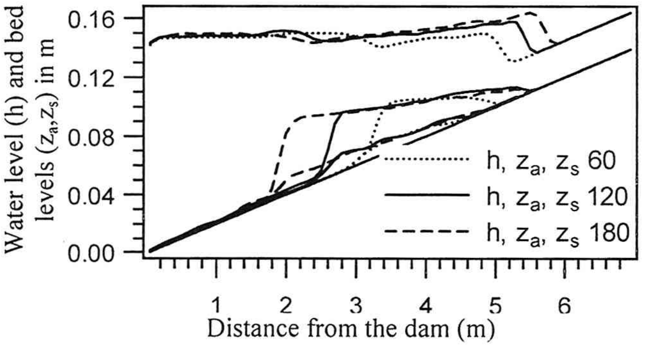

Fig.1 Total bed profiles with the layers of mixed and fine particles (M and F-layer) in Run K

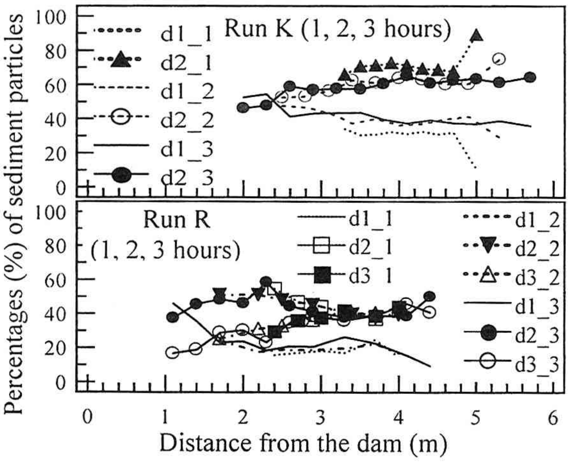

Fig. 2 Typical composition of fine and coarse particles (d_1, d_2, d_3) in M-layer (Run K and R)

transported for a longer time in suspension along the channel and the composition of fine sediment increases towards the dam.

As a result, the sediment was only transported and no deposition was observed in supercritical region. Although the percentages of coarse and fine particles vary in M-layer, it is found that the composition tends to be close to the average value. The temporal variations of bed and the water levels in a given time were found with the upward advance of the hydraulic jump.

2. ONE-DIMENSIONAL SIMULATION OF BED VARIATION

In one-dimensional approach, water surface profile and the bed profile of deposition are calculated by the transport equations of bed load and suspended load with the continuity of flow.

(1) Hydraulic jump and shear stress velocity

When a supercritical flow changes into subcritical flow approaching to a greater depth, the hydraulic jump is formed and satisfies the Eq. (1).

$$h_2 = \frac{\sqrt{1+8F_{r1}^2}-1}{2}h_1 \qquad (1)$$

where h_1 is the approaching flow depth, h_2 is the flow depth after the jump, $F_{r1}\left(= v_1/\sqrt{gh_1}\right)$ is the Froude number, v_1 is the flow velocity in upstream before the formation of the jump.

In the transport of sediment load, the relationship between the mean flow velocity (v) and local shear velocity (u_*) can be stated as below:

$$\frac{v}{u_*} = 6.0 + 5.75\log\left(\frac{h}{k_s}\right) \qquad (2)$$

where k_s ($\approx \alpha_1 d$, α_1: constant) is the equivalent roughness. The bed load and the suspended load are transported with shear velocity (u_*).

(2) Bed load in sand-gravel mixture

The sediment particles move, when the dimensionless value of normal shear stress τ_{*i} ($=u_*^2/sgd_i$) exceeds the critical shear stress τ_{*c} (=0.047). Parker et al. (2000)[2] and Kuhnle and Southard (1988)[6] revealed the possibility of equal mobility of particles in the mixture of sediment. Equal frequencies (i_b) of the grains can be considered to estimate the bed load. The total bed load (q_B) of each grains for the equilibrium sediment discharge as given by Suzuki et al. (1995)[4]:

$$q_B = \sum_{i=1}^{n} q_{Bi};\; q_{Bi} = i_b\sqrt{sgd_i^3}\,K\left(\varepsilon_1\tau_{*i} - \varepsilon_2\tau_{*c}\right)^m \qquad (3)$$

where i_b is the frequency of the sediment particle

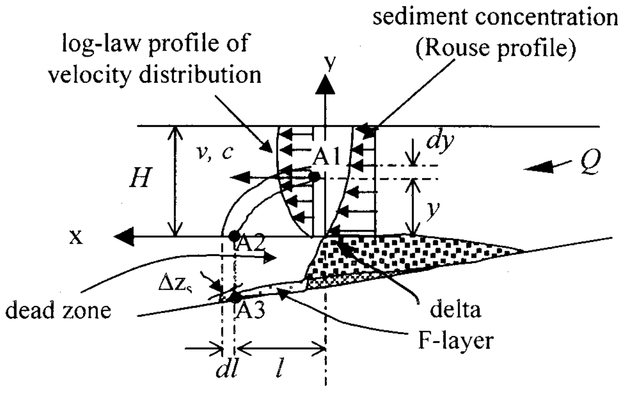

Fig. 3 Movement and deposition of suspended particle at the downstream of the delta (after Sugio, 1974)

(d_i) on the surface of the mixture, q_{bi} is the bed load for the individual grain, s is the submerged relative density of the sediment, ε_1 and ε_2 are the modification factors for the shear stresses τ_{*i} and τ_{*c}, respectively, K(=8) and m(=3/2) are the constant coefficients.

The modification factors (ε_1 and ε_2) for the sediment particles of larger size (Egiazaroff, 1965)[7] can be calculated as follows:

$$\frac{d_i}{d_m} \ge 1; \qquad \varepsilon_1 = \left\{\frac{\log_{10}19(d_i/d_m)}{\log_{10}19}\right\}^2$$
$$\varepsilon_2 = \frac{\sqrt{3}}{\sqrt{(d_i/d_m+1)^2-1}} \qquad (4)$$

Similarly, for the sediment particles of smaller size ε_1 and ε_2 are as given below:

$$\frac{d_i}{d_m} < 1;\; \varepsilon_1 = 1,\; \varepsilon_2 = \left\{\frac{\log(30.2)}{\log(30.2d_i/d_m)}\right\}^2 \qquad (5)$$

where d_m is the mean diameter in the mixture.

The bed variation due to the bed load with respect to time can be estimated by the continuity equation of sediment at a given section as below:

$$\frac{\partial z_b}{\partial t} + \frac{1}{(1-\lambda)B}\frac{\partial(q_B B)}{\partial x} = 0 \qquad (6)$$

where t is time, λ is the porosity of the sediment, B is the width of the channel or riverbed, q_B is the sediment discharge per unit width of the channel.

(3) Suspended load

The finer particle can be transported for a longer distance and it can be in suspension for a longer period. The sediment transport as suspended load in the Layer of fine particles (F-layer), particularly downstream of the delta, is in high probability as explained by Sugio (1974) below[8].

Suspended particles move downstream of the delta as shown in Fig.3. Let the particle starts to move at a level y (A1) with a flow velocity (v) and

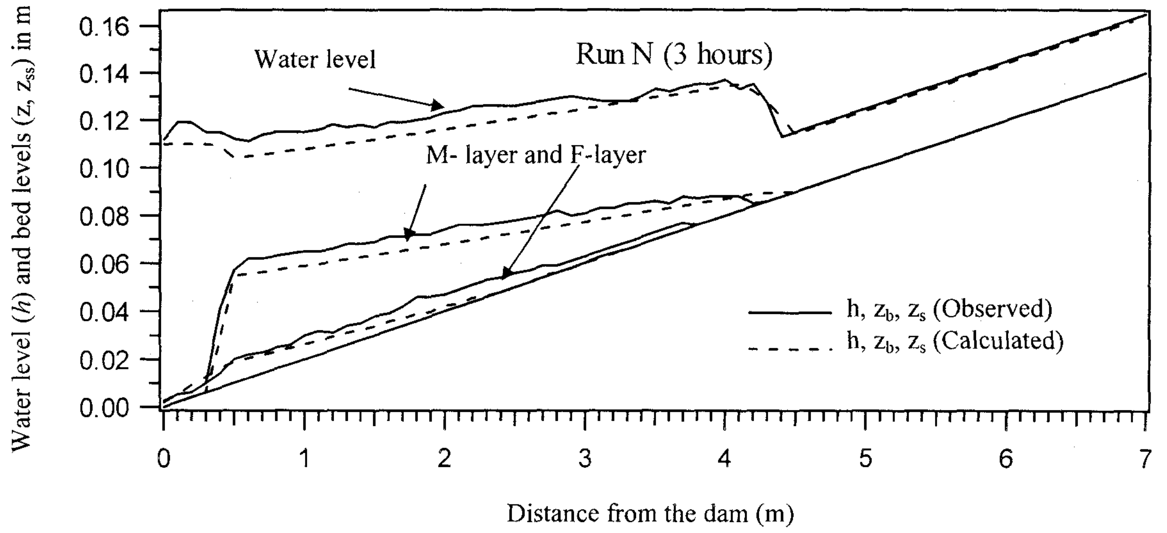

Fig.4 Typical comparison of observed and simulated profiles water level (h) and bed levels (z, and z_{ss}) for Run N (3 hours)

concentration (c). At a time t, the particle can travel a horizontal distance (l), when it reaches a point A2. The flow velocity is almost zero value below the location A2, which is called dead zone. As a result, suspended particle tends to settle vertically at A3 with a settling fall velocity (ω). The distance (l) transported in suspension by flow velocity and then settles down to deposit is given by[8]:

$$l = \frac{u_*}{\omega} y \left(6.0 + 5.75 \log \frac{y}{k_s} \right) \tag{8}$$

The terminal fall velocity can be calculated by Rubey's (1931) simplified formula[9]:

$$\omega = \frac{\left\{ 1636(\rho_s - \rho) d_i^{\,3} + 9\mu^2 \right\}^{0.5} - 3\mu}{500 d_i} \tag{9}$$

where μ is the dynamic viscosity of the fluid. Initiation of suspension for a given particle may be defined by the Rouse parameter[10]. The concentration of sediment particles (c) at y is given by the Rouse (1937) equation as follows:

$$\frac{c}{c_a} = \left(\frac{H-y}{y} \frac{a}{H-a} \right)^Z \tag{10}$$

where H is the total depth of flow, $Z=\omega/\beta k u_*$, β (Lane and Kalinske (1941) assumed the value of β equals unity) is the a factor of proportionality and function of coefficients of momentum diffusion (ε_s) and the kinematic eddy viscosity for fluid (ε_m), k is universal Prandtl-von Kármán constant (=0.4 for clear water), c_a is the concentration of sediment at a depth a, and a is the distance above the bed ($\approx 0.05h$).

The concentration of sediment particle at the depth a in Eq. (10) is calculated (Ashida, 1970)[11] as given below:

$$c_a = 5.55 * \Delta F(w) \left[\frac{1}{2} \frac{u_*}{\omega} \exp\left(-\frac{\omega}{u_*} \right)^2 \right]^{1.61} \tag{11}$$

where, $\Delta F(w)$ is the average percentage of the sediment particle in ppm unit.

The part of deposition of suspended particles in □t second is calculated by the continuity equation of concentration of the suspended sediment as below:

$$\Delta z_s = \frac{c\omega}{(1-\lambda)} \Delta t \tag{12}$$

where, Δz_s is the bed variation due to the suspended load. The flow velocity is zero in the dead zone; the further transport of particle is assumed negligible.

(4) Simulation

The flow depth at I section h(I) and flow velocity v $(=q/h)$ in both sub- and super-critical sections are calculated using the equation of continuity of flow. Using the local shear velocity (u_*) in the Eq. (2), the bed load (q_{Bi}) can be estimated from the Eq. (3) with the modification factors (ε_1 and ε_2) given in the Eqs. (4) and (5). On the other hand, concentrations of suspended particle (c_a and c) can be calculated by Eqs. (11) and (10), respectively.

The variation in bed level due to the bed load (Δz_b) and suspended load (Δz_s) for a small distance (Δx=10 cm) and a time interval (Δt=1 sec) can be conveniently calculated from the Eq. (6) and (12), respectively. The summation of this variation to the previous bed level (z_{t-1}) gives the new bed level ($z_t=\Delta z_b+\Delta z_s+ z_{t-1}$) for the time t.

3. COMPARISON AND DISCUSSIONS

The simulated bed profiles (both total bed profile

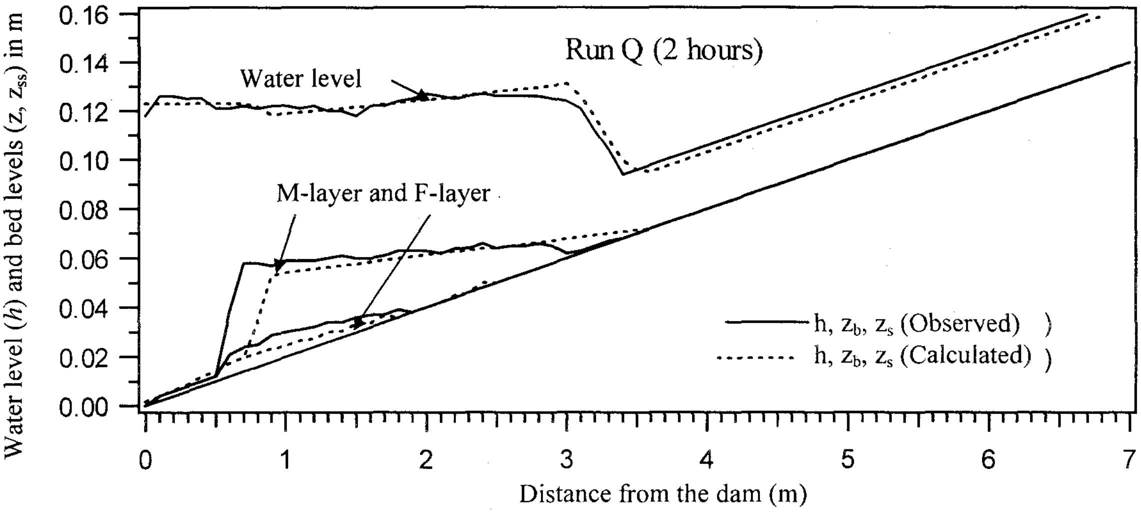

Fig. 5 Typical comparison of observed and simulated profiles water level (h) and bed levels (z, and z_{ss}) for Run Q (2 hours)

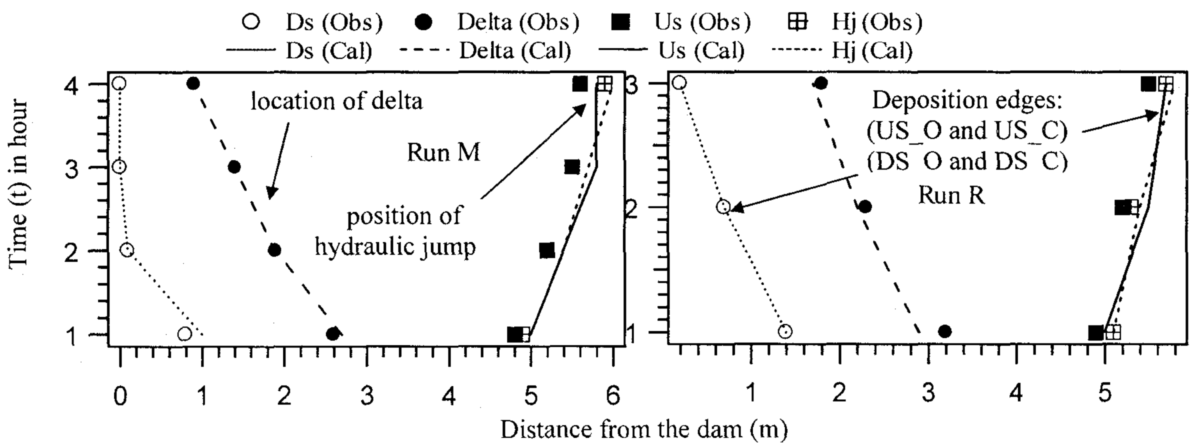

Fig. 6 Typical observed and calculated positions of temporal variations of the hydraulic jump and the edges of sediment depositions in experiments with the coarse and fine sediment (in Run M and Run R)

with M-layer and F-layer) and water depths are compared with the observed ones. For example, typical simulated bed profiles (z_b, z_s) and the water surface (h) with the observed ones in Run N (bimodal mixture for 3 hours) are shown in Fig. 4 and in Run Q (trimodal mixture for 2 hours) in Fig. 5. The bed level of M-layer is calculated by modifying the bed load functions, where the bed variations corresponding to the flow depths calculated by the application of the hydraulic jump. Similarly, the bed profiles (z_s) variation in F-layer, particularly found more distinctly visible below the delta, are due to the suspended particles. Results show that the progress of deposition was found with the movement of delta and the hydraulic jump as observed in the experiments.

The progress of deposition was found in the sub-critical region only. The sediment particles were only transported in the upstream region of the hydraulic jump as shown in the figure without deposition due to the higher value of shear velocity. As a result, the sediment grains were found deposited in the subcritical region, where the flow depth tends to increase towards the dam. The downward movement of the delta in every period of time(s) is obvious as shown in Fig.6, where Delta(Obs) and Delta(Cal) are observed and calculated locations, respectively. Moreover, the downstream movement of the delta was found greater than upstream movement.

Similarly, in the process of sedimentation, the hydraulic jump was moved upwards from its initial position with reference to the time. For example, As shown in Fig. 6, the location of the hydraulic jump (Hj) for the first 1 hour shifts upwards in the next (2, 3, and 4 hours in Run M and 2 and 3 hours in Run R) period of time. The location of the downstream edges (Ds) and the upstream edges (Us) of deposition show the progress of deposition. The simulated locations of the hydraulic jump and deposition profiles were coincided with the experimentally observed positions.

In the calculation of bed profile in M-layer, the equal or average frequency of the grains in the exchange layer is considered and the tractive forces modified for the grains. Guo et al. (1999) considered the averaged depth to calculate the bed variation by knowing the average concentration of sediment[12]. The movement of finer particles below the delta can be considered for a longer distance as stated by Sugio (1974). The deposition due to the suspended load (F-layer) is calculated using average concentration of sediment along vertical direction. The results show the coincidence of simulated and observed profiles of bed levels (in M-layer and F-layer) and the water surfaces for the sand-gravel (of bimodal as well as of tri-modal) mixtures.

4. CONCLUDING REMARKS

The research consists of the experimental study and the one-dimensional numerical simulation of reservoir bed profile for bimodal and trimodal sediment mixture. The one-dimensional bed profile in view of bed load and suspended load for the sand-gravel mixture is simulated.

The deposition occurs in the downstream side and sediment is transported from the upstream side of the hydraulic jump. The reason is the tractive force tends to be smaller in the subcritical regions as the shear velocity decreases. On the other hand, the flow velocity and tractive force are of higher values at the upstream side of the hydraulic jump.

One-dimensional analyses with the continuity equations of flow and energy with the momentum equation of formation of a hydraulic jump are applied to calculate the water surface profiles. The profile of deposition of sediment mixture is calculated by means of sediment transport equation for the bed load and the sediment in suspension. In the estimation of bed level (z_s) in mixed layer, the equal frequency of sediment particles in the flow level and the modification of bed load functions (for the tarctive force (ε_1) and for the critical shear stress (ε_2) of initiation of motion) are considered. In calculation of bed variations (z_{ss}) due to the sediment in suspension (for the finer particles in the F-layer of deposition), the concentration of sediment grains with settling flow velocity is considered.

The front of the delta moves downwards and the hydraulic jump is shifted upward in the deposition, while the locus of the sediment deposition is at the downstream and the upstream side. The simulated locus of the deposition and the hydraulic jump were found closed to the observed results. Further, The simulated bed profiles are found well coincided with average observed bed profiles (total bed profiles including F-layer and M-layer). In comparison of the simulated and the observed profiles of bed and water level, results show the good agreement.

Finally, the results show that the deposition of sediment mixture in a steep channel reservoir can be calculated by the one-dimensional equations of flow and sediment transport. The deposition layers of mixed particles (M-layer) is well estimated by modifying the bed load functions and considering the equal frequency of sediment particles in the flow level. The bed profile of fine particles (F-layer), deposited under the M-Layer, is simulated with the concentration and the settling velocity of sediment particles. Obviously, the model seems to be applicable to calculate the average bed profile (including M-layer and F-layer) of deposition for the sand-gravel mixture in a steep channel reservoir.

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