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# Process of reservoir sedimentation in steep channel

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## ABSTRACT

The process of sedimentation has been studied in a small, steep laboratory flume with a dam, which causes the hydraulic jump in the reservoir. The two-dimensional and three-dimensional bed profiles were observed in experiments with coarse and fine sediment, respectively. The profiles of water surface and sediment deposition are simulated numerically with the application of one-dimensional continuity flow equation and sediment transport. The simulated results coincide well with the observed ones except undulation bed profiles.

## INTRODUCTION

Future development of Nepal is dependent on capturing the hydropower potential. In this context, the construction of reservoir is a major dilemma (Sthapit 1995). The bed profile of a reservoir in mountain rivers with steep slope, like in Nepal, is characterised by the water level profile with the hydraulic jump. The deposition of sediment in reservoir is always a principal problem, which affects useful life of reservoir in the water use projects reducing its storage capacity. A popular example of sediment deposition in the middle mountains of Nepal is the Kulekhani Reservoir (Galay et al. 1995). The study of sediment deposition in reservoirs has become an important issue in the development of the water resource.

The sediment deposition pattern in a reservoir, as a delta form, can reflect transport process in the reservoir and its delivery and distribution process (Morris and Fan 1997). The sediment fed to the reservoir is from the watershed (derived from the land slides and erosion) and the bed load of river system itself.

A schematic diagram of sediment deposition is shown in Fig. 1, where Q and $Q_s$ are the water discharge and sediment from the upstream end, respectively. From the section of the hydraulic jump, the sediment deposition starts in a steep channel due to the reduction of flow velocity, and the sediment progressively moves towards the dam and upstream. Temporal variations in bed level are shown in Plate 1, which shows the two-dimensional variations in coarse sediment (Run C) and three-dimensional variations in fine sand (Run G).

The process of sediment deposition has been studied experimentally in a small and steep laboratory flume with a model dam, which causes the hydraulic jump in the reservoir. Then the one-dimensional sediment deposition profiles were numerically simulated for the same parameters as of the experiment, taking the shift of the location of hydraulic jump into consideration.

## EXPERIMENTAL STUDY FOR SEDIMENT DEPOSITION PROCESS

### Summary of the experiment

The flume (Fig. 2) consisted of a rectangular glass channel (7 m long, 0.15 m wide, and 0.30 m high) with

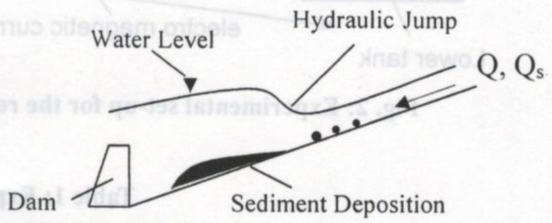



**Fig. 1: Concept of reservoir sedimentation**

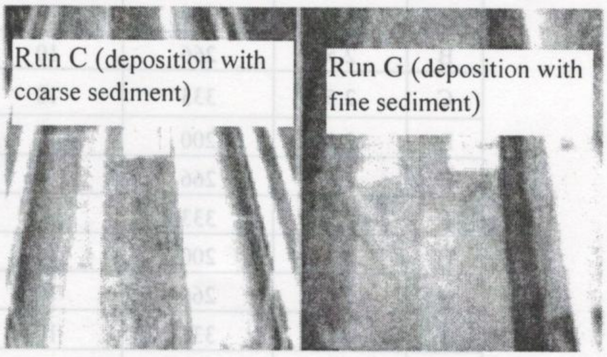



**Plate 1: Plan views of Run C and Run G (after 5 hours)**

adjustable slope. An electronic profile indicator (EPI) with the depth-recording gauge was connected to a data recorder, which was possible to move throughout the top of the flume. A hopper of wood was built to feed the sediment and a dam was built at the downstream end of the flume. Measurements of bed and water levels with respect to distance were made carefully. The discharge of water was controlled by means of a computer.

The experimental conditions are shown in Table 1. Two types of sand were used: fine ( 0.1 mm in size) and coarse (2.5 mm in size). Runs A to F were carried out with comparatively large amount of sediment supply of large grain size with compared to fine sediment, whereas runs G to J were with a small amount of fine sand. The channel slope was exactly 1/50. Manning's roughness coefficients were calculated to be 0.013 for the supercritical flow region of upstream side, where there is no sediment deposition, and 0.03 for the subcritical flow region of sediment deposition.

The water levels and deposition profiles of sediment were measured for each experimental run at an interval of 30 minutes and in every 10 cm along the channel starting from the dam. Firstly, the rectangular channel was fixed to a required slope (Fig. 2). The discharge of water (controlled by a computer) and the sediment supply (by means of a hopper) were ensured carefully at a constant rate from the upstream end of the flume. The water level along the channel was measured manually with mesh scale drawn on the transparent sidewall of the flume. The variations of bed levels

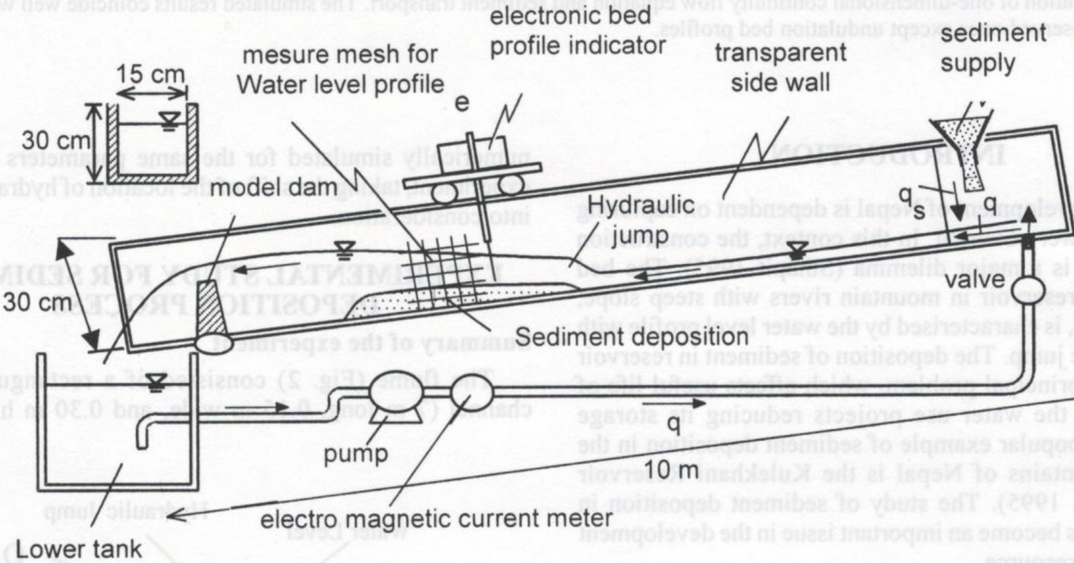



**Fig. 2: Experimental set-up for the reservoir sediment deposition in a steep channel**

**Table 1: Experimental conditions**

| Run | Sediment size (mm) | Water discharge, q ($cm^2/s$) | Dam height, W (cm) | Channel slope, $I_e$ | Normal depth, $h_0$ (cm) | Froude number, $F_{r1}$ | Sediment supply, $q_b$ ($cm^2/s$) |
|---|---|---|---|---|---|---|---|
| A | 2.5 | 200 | 10 | 0.02 | 2.7 | 1.44 | 0.111 |
| B | 2.5 | 266 | 10 | 0.02 | 2.8 | 1.81 | 0.089 |
| C | 2.5 | 333 | 10 | 0.02 | 3.2 | 1.86 | 0.105 |
| D | 2.5 | 200 | 7 | 0.02 | 2.5 | 1.62 | 0113 |
| E | 2.5 | 266 | 7 | 0.02 | 2.7 | 1.91 | 0.111 |
| F | 2.5 | 333 | 7 | 0.02 | 3 | 2.05 | 0.111 |
| G | 0.1 | 200 | 10 | 0.02 | 2.2 | 1.96 | 0.036 |
| H | 0.1 | 266 | 10 | 0.02 | 3 | 1.63 | 0.031 |
| I | 0.1 | 333 | 10 | 0.02 | 3.7 | 1.49 | 0.033 |
| J | 0.1 | 333 | 7 | 0.02 | 3.7 | 1.49 | 0.038 |

were recorded with the EPI in terms of voltage, which was calibrated later in proper unit. The trends of longitudinal deposition pattern were measured in three locations (i.e., along the left sidewall, the right sidewall, and the centre of the channel). However, the deposition profiles were observed almost uniform laterally for coarser sand on the contrary to the three dimensional profiles for finer sediment.

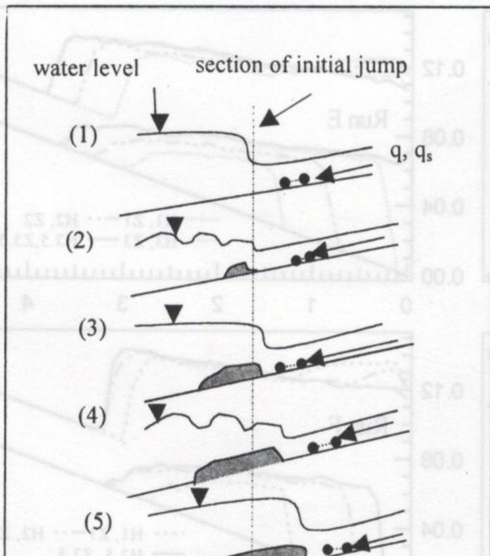
**Process of sediment deposition with a hydraulic jump**

To observe the phenomenon of sedimentation in a reservoir with a steep slope, formation of a hydraulic jump was considered. The jump characterised the profiles of deposition. A constant rate of sediment was fed from the upstream end and there was no deposition in the supercritical region upstream of the hydraulic jump. Because of the greater water depth in subcritical region downstream of the jump, flow velocity is reduced and the deposition of sediment starts. The bed and water surface profiles are in phase, while the flow is moving in the downstream, and both sand and water surface waves are actually moving in the upstream in case of fine sediment.

The process of sedimentation can be schematically illustrated as in Fig. 3. Initially there occurs a fully developed hydraulic jump. As it starts to deposit the sediment, it advances rapidly to downstream side of the section of the hydraulic jump, but also in a small rate to upstream side; then the flow over the jump takes the form of surface waves. This wavy jump becomes full hydraulic jump again with some more deposition of sediment. The location of jump is shifted also upwards from the initial position with the sediment deposition in the subcritical section, which was also reported by Matsushita (1976). This phenomenon repeatedly occurs in the steep channel reservoir. The sediment deposition is found only in the subcritical region.

**Configuration of sediment deposition and bed profiles**

The bed forms of the sediment deposition in Runs A to F with larger sediment were found to be two-dimensional; i.e., the depth of deposition varies only along the longitudinal direction, and is almost uniform in the transverse direction. In the case of fine sand (Runs G to J), bed forms of sediment deposition were found three-dimensional with sand waves, where the deposition configuration was also found varied along the transverse direction at any section of the channel. For example, typical observations of two-dimensional bed profiles in Run B of coarse sediment and three-dimensional bed profiles for the three longitudinal lines in Run G of fine sediment and their average are shown in Fig. 4. In it, Zs represents the longitudinal bed profiles to the left and right sides of the section, which are the same in both sides in the case of coarse sediment (Run B). Zl and Zr represent the longitudinal bed profiles to the left and right of the section, respectively in Run G. Zc and Za represent the longitudinal bed profiles in the centre of the section and the average of those three values, respectively. Fig. 5a and 5b show the temporal variations of water surface (*H*) and bed profiles (*Z*) averaged over three longitudinal lines for the both larger and smaller sizes of sediment where sub suffixes are times in hours.




In figure, q,q$_s$ are the water and sediment discharge per unit width. After feeding sediment with water discharge from upstream end, the sediment starts to deposit; then hydraulic jump (1) becomes wavy jump (2). This wavy jump again becomes full hydraulic jump (3) with the progress of deposition to upward direction also, but the position of this hydraulic jump is shifted to upstream side of initial one (1). Regarding the continuous sediment deposition, the full jump (3) again starts to be a wavy jump (4), which later exists as a full jump (5) with the upward advancement from previous position.

**Fig. 3: Schematic diagram showing upward advance of hydraulic jump with deposition**

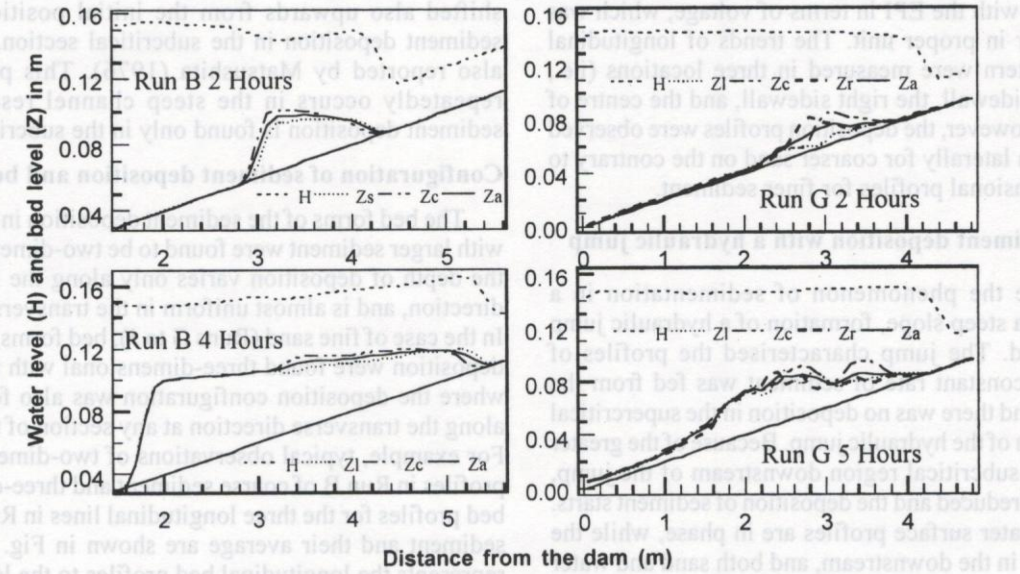



**Fig. 4: Longitudinal bed profiles in three lines in Run B and Run G**

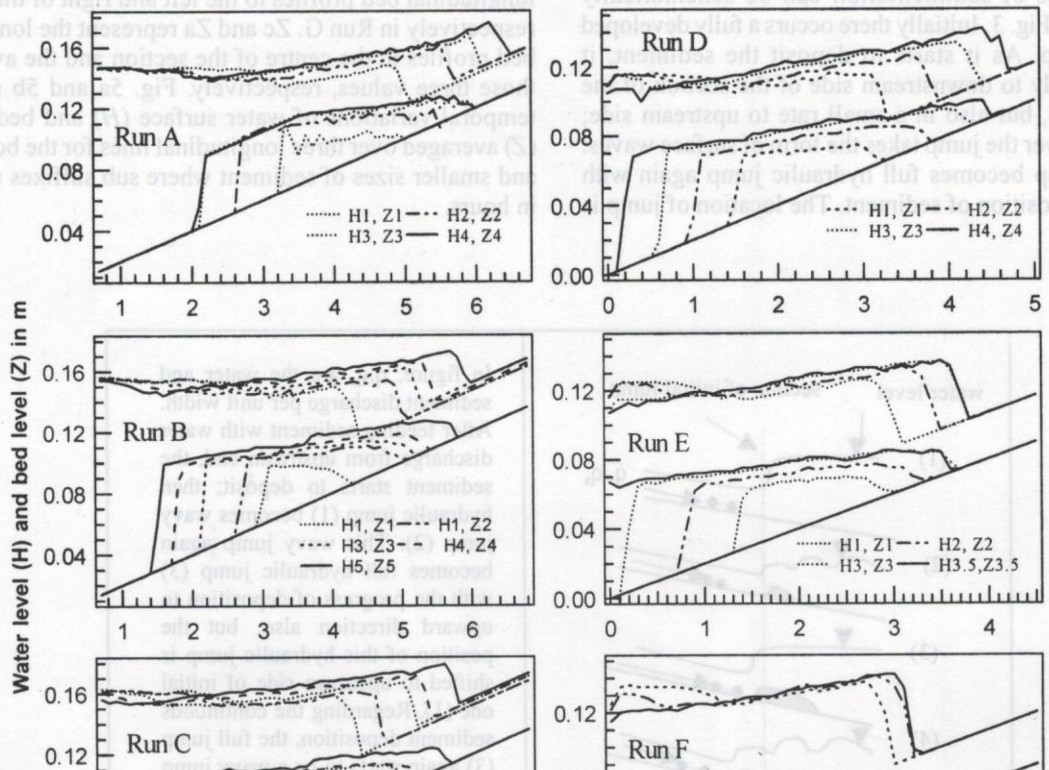



**Fig. 5a: Observed temporal variation of bed profile and water surface in coarse sediments (Runs A, B, C, D, E, and F)**

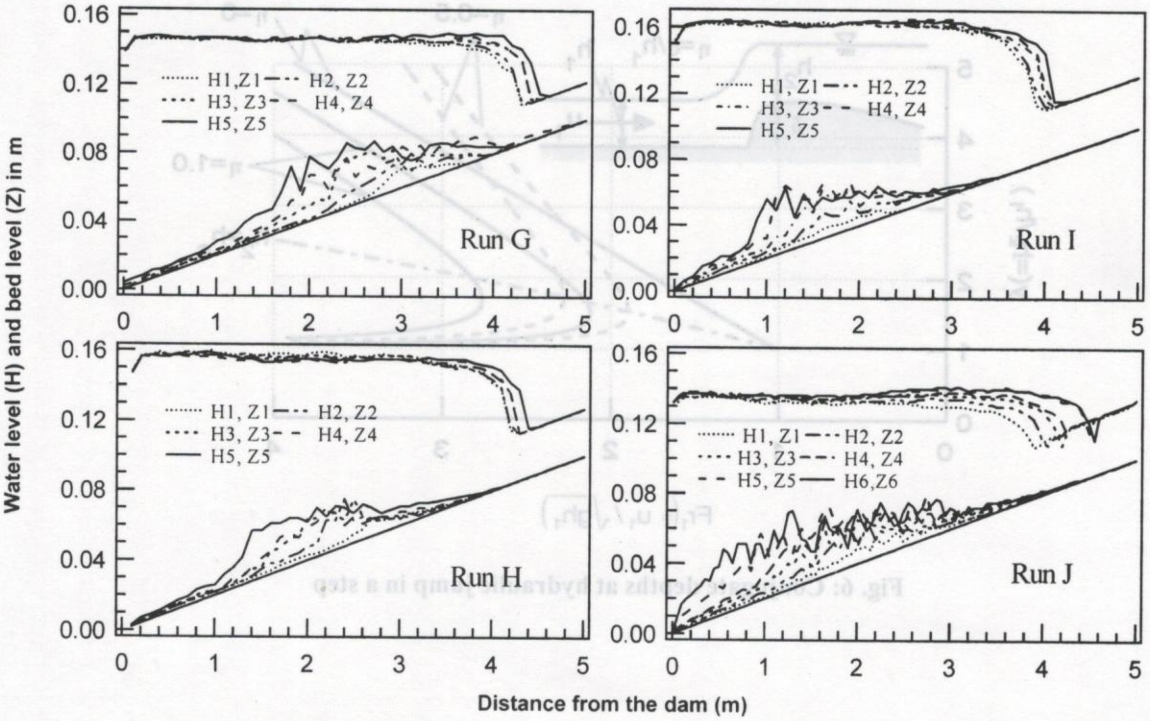



**Fig. 5b: Observed temporal variation of bed profile and water surface in fine sediment (Run G, H, I, and J)**

The deposition of sediment starts from just downstream of the hydraulic jump section, and progresses rapidly both towards the dam and upwards. With the development of deposition, the location of the hydraulic jump is shifted to upstream side from its previous position. In case of larger size of sediment (i.e., Runs A to F), it is observed that the upward speed of advancement of deposition is comparatively more than in case of smaller size of sediment (i.e., Runs G to J).

The observed bed profiles show that sediment depositions are in the form of delta deposition in the case of coarse sand and tapering deposition in the case of fine sand as shown in Fig. 5a and Fig. 5b, respectively. The position of the hydraulic jump is observed to be shifted upwards rapidly in the experiment with the coarse sediment, where the sediment pattern is two-dimensional in the form of delta. But, the position of hydraulic jump is found to be shifted upwards from its initial position very slowly in the case of fine sand, where a tapering form of sediment deposition is observed.

## NUMERICAL SIMULATION

The simulation procedure of one-dimensional bed profile includes the calculation of water levels and bed variations throughout the channel using the equations of energy and continuity of water, and equations of sediment transport and continuity.

**Numerical calculations**

The water depth is calculated numerically for given bed profile and flow discharge by differentiating the following Bernoulli's energy equation, with the distance increment $\Delta x$(=10 cm) as follows:

$$(\partial / \partial x)(z + h\cos\theta + \alpha v^2 / 2g) = -I_e \qquad (1)$$

where $x$ = coordinates of flow direction, $z$ = bed level, $h$ = water depth, $v$ = average velocity over cross-section, $g$ = acceleration due to gravity, $\theta$ = bed slope angle, $I_e$ = energy slope given by Mannig's law ($= n^2 v^2 / R^{4/3}$), and $R$ = hydraulic radius.

Hydraulic jump occurs at the section of the slopped channel (Rang Raju 1988), where the following condition of Equation (2) is satisfied:

$$h_2 / h_1 = (\sqrt{1+8G_1^2} - 1)/2, \quad G_1^2 = F_{r1}^2 / (\cos\theta - KL\sin\theta / (h_2 - h_1)) \qquad (2)$$

where $h_1$ = flow depth before the jump, $h_2$ = flow depth after the jump, L=length of the jump=6($h_2$-$h_1$), and $K$=modified coefficient ($\approx$ 1.0).

The position of hydraulic jump can be determined by considering an influence of bed variation due to the sediment deposition (d) as step as shown in Fig. 6. The two conjugate depths can be calculated by the relation (3) (Hasegawa 1988), where ratio of two conjugate depths $h_2 / h_1$ is represented by $y$.

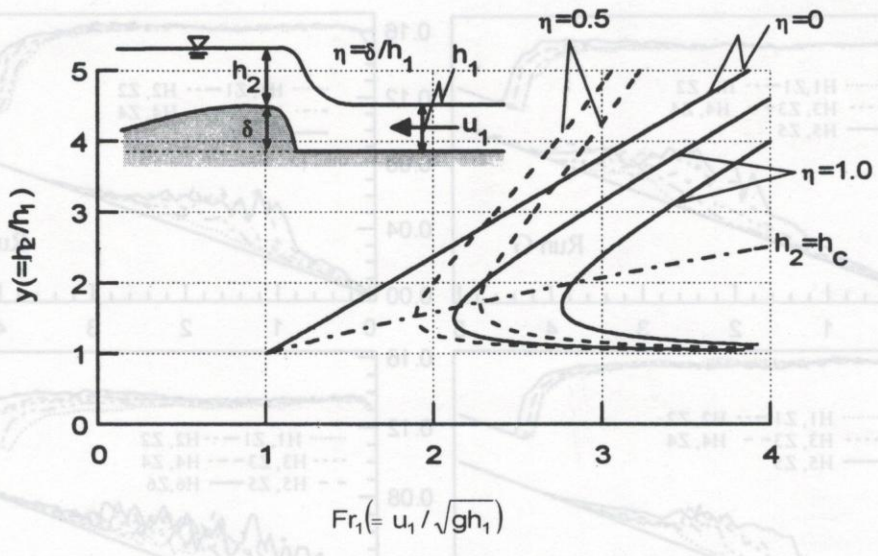



**Fig. 6: Conjugate depths at hydraulic jump in a step**

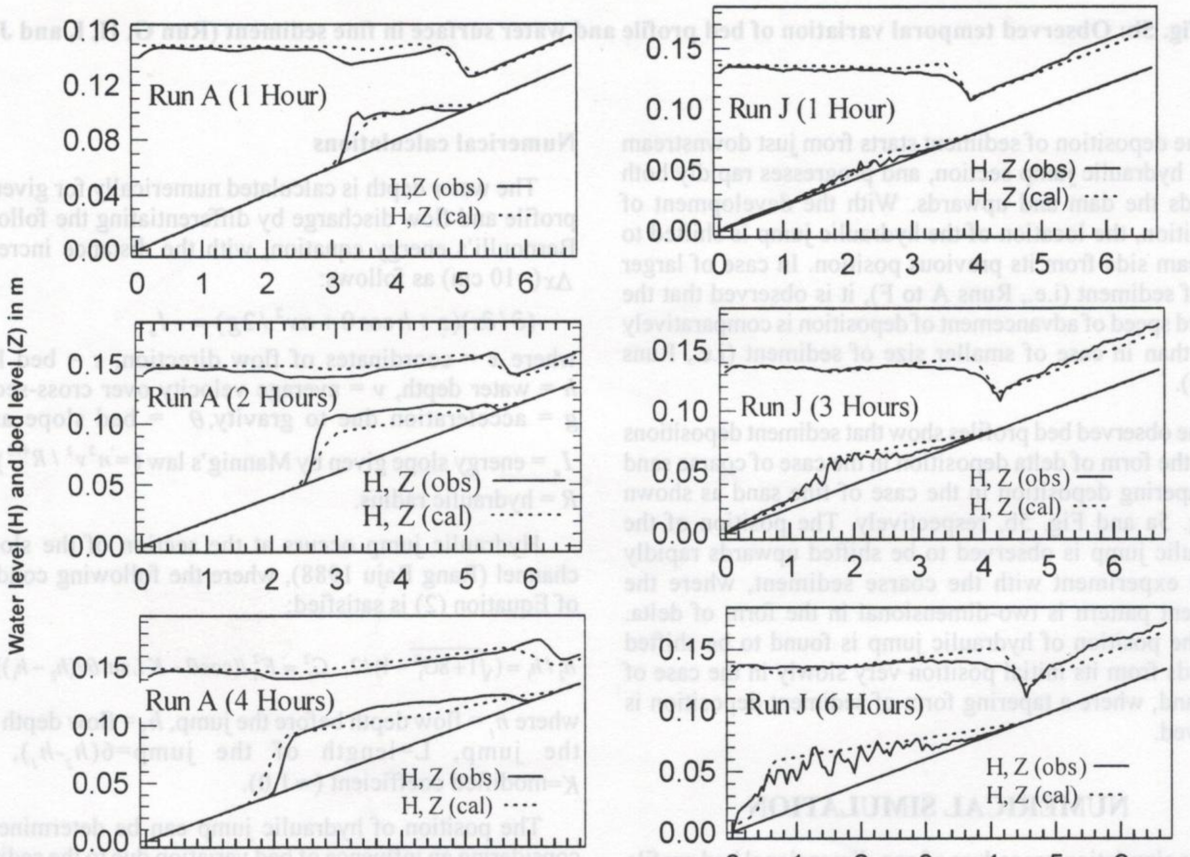



**Fig. 7: Observed and calculated temporal variations of water surface and averaged bed profiles in Run A and Run J**

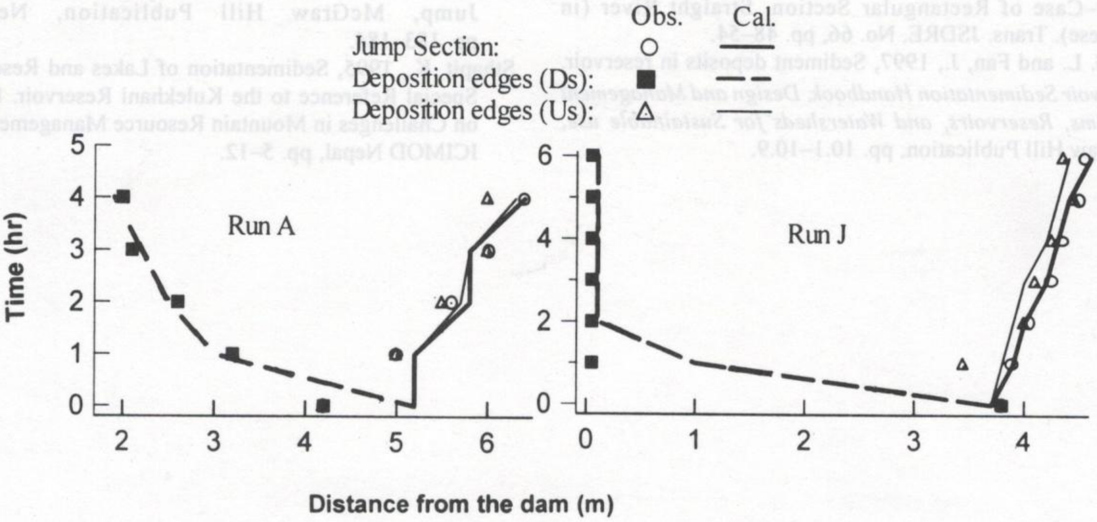



**Fig. 8: Observed and calculated temporal variations of the hydraulic jump and the edges of sediment depositions in Run A and Run J**

$$y^3 + 2\eta y^2 - (2F_{r1}^2 + 1 - \eta^2)y + 2F_{r1}^2 = 0 \qquad (3)$$

where $y = h_2 / h_p$, $\eta = d/h_1$, and $F_{r1} (= u_1 / \sqrt{gh_1})$ = Froude number in supercritical section.

The bed variation $\Delta z$ is calculated by differentiating the equation of continuity of sediment in the discrete time interval of $\Delta t$ (=5 sec.) in a small time $\partial t$, during which the flow given by Equation (1) is assumed to be steady as follows:

$$(\partial z / \partial t) + (\partial Q_B / \partial x) / B(1 - \lambda) = 0 \qquad (4)$$

where $t$ = time, $Q_B$ = sediment discharge (which is calculated by Meyer-Peter and Müller type equation of sediment transport), B = channel width, and $\lambda$ = sediment porosity.

### Comparison of simulated bed profiles with observed ones

The observed bed profiles averaged over three longitudinal lines and water levels were compared with the simulated ones for each run. A typical comparison of these profiles for the coarse sediment size (Run A) and the fine sand (Run J) are shown in Fig. 7, where $H$ and $Z$ represent the water level and bed level, respectively. Similarly, the upward advancements of hydraulic jump with the progress of sediment deposition are observed in both runs, which are compared with simulated positions of the hydraulic jumps as shown in Fig. 8. The symbols Ds and Us represent the edges of sediment deposition in the downstream end and upstream end, respectively. The simulated results, both for the water surface and bed profiles, coincide well with the observed ones.

## CONCLUSIONS

The bed profile of deposition for fine sediment is observed to be three-dimensional with sand waves, whereas longitudinal bed profiles of two edges and centre of the channel are found irregular. However, the bed profiles of coarse sediment is two-dimensional. The profiles of sediment deposition in both cases of fine sediment (average profiles of three longitudinal lines) and coarse sediment, can be simulated well by one-dimensional analysis with the application of the hydraulic jump. The deposition of sediment is found to be started at the section, just below the downstream of the hydraulic jump and progressively moving towards the dam, and slowly upwards as a tapering form in the case of fine sediment. However, it progressed rapidly upwards and slowly towards the dam as a delta form in the case of coarse sediment. Due to these patterns of sediment deposition, the upward shift of the location of the hydraulic jump from its previous position is rapid in the case of coarse sediment and very slow in the case of fine sand. Because a mountain riverbed consists of a mixture of sand and gravel, the deposition pattern of sediment of each grain size should be taken into consideration in the further research.

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