ANALYSIS OF SEDIMENT MOVEMENT IN A RIVER DIVERSION SYSTEM

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ABSTRACT

Sediment-related disaster especially debris flow occurs frequently in various places in Indonesia. It has been well known in general that debris flow contents big size of materials which huge power to destroy the river and surrounding area. Comprehensive measures and rising awareness to prevent the loss of human lives against sediment disaster is necessary. River diversion system aimed to lessen sediment load by considering its capacities and sediment prevention facilities becomes an alternative counter measure of sediment flood disaster. Information about river diversion capacity and associated phenomena due to sediment gravity flow is useful for establishing reasonable sediment control plans. Physical model compared to simple mathematical model are conducted to estimate river diversion capacity to convey sediment. The experiment used a channel made of masonry with 80 cm wide in average and 400 cm length, and 10 % gradient. The proposed sabodam as sediment control facilities comprises two types, there are open type sabodam with 33 cm wide, 16cm high (at +1.245m elevation of crest) and four slits in main stream river, and close type sabodam with 41 cm wide, 15 cm high (at +1.255m elevation of spillway) for side-channel. The distance of these facilities is 110 cm. The result of this study is expected to be able to explain the sediment gravity flow behavior in the field. It shows that the performance of side-channel and open type sabodam control volume depend on quantity and mechanism of sediment flow from upstream, and also elevation of crest of the open type sabodam. The largest amount of sediment gravity flow entering diversion channel is about 7 % of sediment inflow for +1245 m open sabodam crest elevation and +1255 m side-channel spillway elevation.

Keywords: Natural disaster, sediment gravity flow.

1 INTRODUCTION

Indonesia lies among three tectonic plates, i.e. Eurasia, Indo-Australia, Pacific and Philippine. This condition leads geological characteristic in Indonesia to be complicated. Having mostly areas traversed by fractured zone, Indonesia frequently encounters natural hazard as the cause of sediment gravity flow. Sediment gravity flow disaster is a kind of floods carrying several materials including loose sediments which contains sand, and mud with gravel, or grains in diverse shapes and sizes (Takahashi, 1979). High sediment concentrations called debris flow has caused massive destruction. Debris flow hazard is one of the most devastating hazards that can cause loss of properties and many people killed. Disaster management against high concentration of sediment flow (debris flow) needs getting full of attention and being carried out in comprehensive way.

A mean of disaster management has been developed through intensive discussions, namely sediment gravity flow load sharing conveyed high inflow discharge. Deep study and research are required to be conducted in order to ensure the implementation of this idea will be going well. It should be bore in mind that disaster management towards high concentration of sediment flow (debris flow) should be associated with comprehensive knowledge about debris flow behavior (Takahashi, 1979). Impact force can be estimated by assessing flow behavior and transport sediment volume. Hence, information about sediment gravity flow behavior in river diversion turns out to be imperative in an attempt to lessen sediment load of the river when severe flood occurs. This research can be a recommendation for relevant stakeholders or everyone who concerned in disaster management against sediment gravity flow. It can be an effort in losses alleviating caused by sediment gravity flow.

Sediment gravity flow behavior in river diversion associated with its mechanism is important to be analyzed for establishing reasonable sediment control plans. Estimation of the capacity of sand bypass which is used for diverting debris flow is also required. It can be a practical guide for diverting sediment gravity flow to the safe area where losses and damages towards human lives and traversed river due to sediment-related disaster can be avoided.

This study is aimed to analyze the capacity of flood control structures in river diversion system through physical and simple mathematical model. The proposed flood control structures are open type sabodam in main stream river and conventional type dam as side-channel. Mathematical model was conducted using software in Basic language of computer program. The main objectives of this research are summarized as follows:

a) To analyze sand by pass capacity in sediment diverting, particularly high sediment concentration incurred by severe flood.
b) To obtain the basic design of sediment control structures that can be a consideration in decision making.

2 RESEARCH METHODOLOGY

Location of the research is at Boyong River, about 1240 m above sea level. It belongs to Pakem sub district, Sleman District, Yogyakarta Special Province. This location was selected by considering a mean of flow and sediment diversion from Boyong River to Kuning River when flood occurs. The proposed flood control structures were sediment control structure in slit type dam (sabodam) and sand bypass building or side-channel as shown in Figure 1.

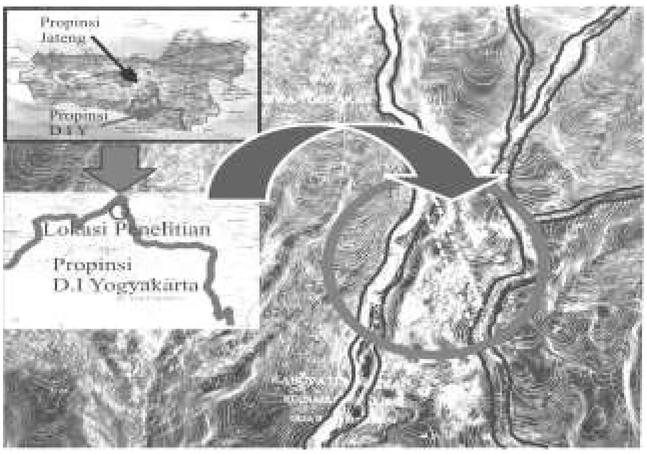

Figure 1. Research Location.

Sediment size fraction was analyzed in Hydraulic Laboratory of PSIT UGM(Research Center for Engineering Student UGM). Rainfall analysis was based on nearby rainfall station that affects to referenced catchment area (Plawangan station). Physical modeling was conducted in Hydraulic Laboratory of Civil and Engineering Department UGM.

Physical model compared to simple mathematical model are conducted to estimate side-channel capacity to convey sediment. The experiment used a channel made of masonry with 80 cm wide in average and 400 cm length, and 10 % gradient. Prototype of sabodam as sediment control facilities which were proposed in the research comprises two types, there are open type sabodam with 33 cm wide, 16cm high (at +1.245m elevation of crest) and four slits in main stream river and close type sabodam 41 cm wide, 15 cm high (at +1.255m elevation of spillway) for side-channel. The distance of these facilities is 110 cm.

Boyong River facilitated with open type sabodam, Kuning River, and side-channel were modeled using undistorted model approach in a scale of 1:100. Total river length was approximately 3.8 m, river width was 0.7 m, and water elevation was 0.4 m. Fix bed model was applied in side-channel channel. Side-channel model was 15 cm in height, 5 cm in wing section height, and 41 cm in spillway width. Open type sabodam model was 16 cm in height, 5 cm in wing section height, 2 cm in slit width, and 3 cm in slit height. Height of open type sabodam spillway model was 33 cm.

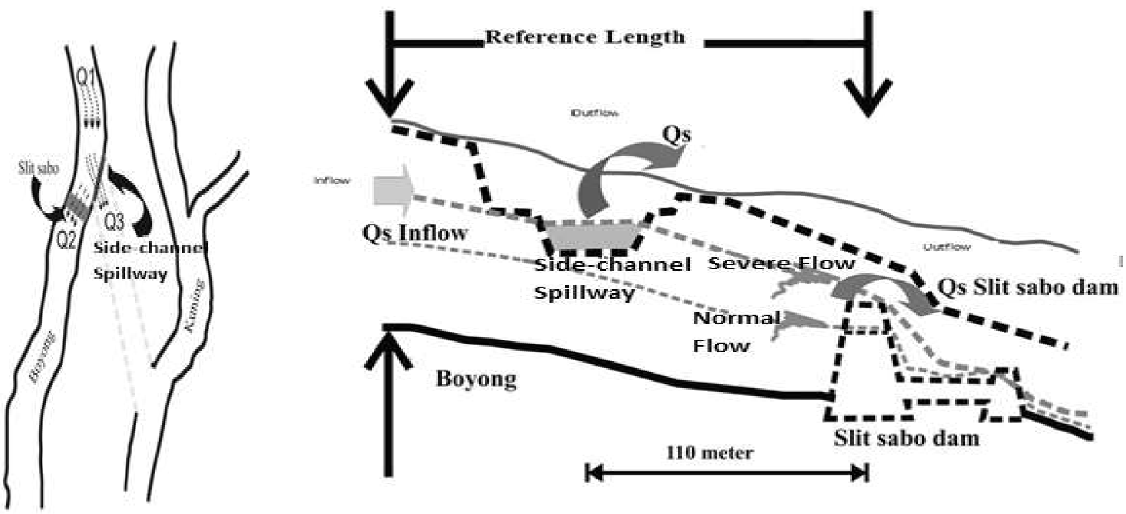

Figure 2. River flow routing.

3 THEORITICAL APPROACH

Sediment flood may occur in a condition comprising sediment, water, and river slope that allows sediment to move. Sediments in volcanoes area are proceed from volcano slopes, river bed, and the eruption. There are four cases which can cause high sediment concentration flow occur:

a) Enormous landslide with large upstream area. High rainfall may induce rapid stream flow conveying ruined materials downstream.
b) Natural damming due to landslide on steeply slope (for instance, steeply slope of riverbank). It can collapse at the time when natural damming cannot restrain the increase of water pressure/volume behind. The incurred flood may bring several materials with.
c) A severe flood (abnormal) that erodes riverbed and causes landslide on riverbank (right and left of the river channel.
d) Volcano eruption. Magma produced from volcano crater and ruined materials can be accumulated along the upstream river. High rainfall can induce soil movement, fall, sliding, surface erosion, and debris flow/mud flow/lahar flow.

3.1 Flow Routing

The capacity of side-channel is analyzed using flow routing. A flow routing is conducted to a river where the proposed flood control structures including sediment control will be placed in conformity with field observation result. Sabodam is expected to be able to control the desired flow (Legono and Istiarto, 1993). Given dam geometry takes important part in sediment transport mechanism.

Flow routing was derived using Muskingum method of continuity equation as shown in the followings equation:

$$\Delta S_i = \Sigma I_i . \Delta t - \Sigma O_i . \Delta t \quad (1)$$

$$or \quad \left(\frac{I_1+I_2}{2}\right)\Delta t - \left(\frac{O_1+O_2}{2}\right)\Delta t = S_2 - S_1 \quad (2)$$

where I is inflow (m^3/hour), Δt is time discrete (hour), O is outflow (m^3/hour), S is storage volume (m^3).River outflow should be equal to the inflow after being adjusted to all changes in storage volume.

Hydraulic approach was used for estimating outflow capacity. Outflow volume was dependent with the overflow height above side-channel spillway. Sabodam was located in Boyong River, and a conventional type in side-channel as the tributary of Boyong River was implemented. In case of high inflow, drip hole on sabodam is assumed being covered by ruined materials. The following equation represents the outflow through sabodam and side-channel by assuming that it uses Ogee type spillway:

$$Q_{sabodam} = C.B.h^{\frac{3}{2}} \quad (3)$$

where Q is design discharge (m^3/s), C is discharge coefficient ranges from 0.8 to 2.2 depending upon the overflow characteristic, B is width of the crest of sabo dam (m), h is flow depth at near upstream of the crest of sabo dam (m).

A flow routing equation is summarized below (see sketch in Figure 3):

Calculation formula from the first routing (*j-1*) to the second one (*j*) can be explained as follows:

a) Inflow: $I_j = Q_{in-j}$ (4)

b) Outflow: $O_j = Q_{out-j}$ (5)

$$Q_{sabodam} = C_{sd}.B_{sd}.\left(Elevation_j - CrestElevation_{sd}\right) \quad (6)$$

$$Q_{side\text{-}channel\ spillway} = C_{ss}.B_{ss}.\left(Elevation_j - CrestElevation_{ss}\right) \quad (7)$$

$$Q_{out\text{-}j} = \left(Q_{sabodam} + Q_{side\text{-}channel spillway)}\right) \quad (8)$$

c) Muskingum equation:

$$S_j - S_{j-1} = \left(\frac{I_{j-1}+I_j}{2}\right)\Delta t - \left(\frac{O_{j-1}+O_j}{2}\right)\Delta t \quad (9)$$

where C_{sd} is discharge coefficient of sabodam, B_{sd} is crest width of sabodam (m), C_{ss} is discharge coefficient of side-channel spillway, and B_{ss} is crest width of side-channel spillway (m).

3.2 Capacity of Sabodam

Height of dam crest highly affects the capacity of sabodam (Ikeya, 1976). Static and dynamic slope approach was used for determining location of side-channel. Figure 3 illustrates how to determine the location of side-channel. If height of sabodam is 16 meter, river slope is 0.1, crest elevation is +1245 m and side-channel is approximately 110 m from crest of sabodam.

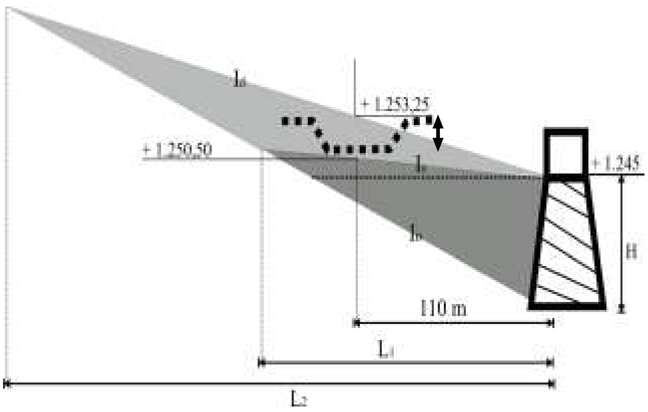

Figure 3. Static and dynamic slope of sabodam.

There are two type of sabodam namely close and open type sabodam. Open type sabodam capacity can be estimated using the following equations:

$$L_1 = \frac{H}{(I_0 - I_s)} \quad (10)$$

$$L_2 = \frac{H}{(I_0 - I_d)} \quad (11)$$

Dead storage:

$$V_s = ½. H . B . L_1 \quad (12)$$

Total volume:

$$V\ total = ½.H.B.L_2 \quad (13)$$

where H is height of open type sabodam (m), I_o is river slope, I_s is static slope (= ½ I_o), I_d is dynamic slope (= 2/3 I_o – ¾ I_o), L_1 is the horizontal distance measured from crest of sabodam to meet static slope (m), L_2 is the horizontal distance measured from crest of sabodam to meet dynamic slope (m), V_s is dead storage (m^3).

If the available data is as follows:

$I_o = 0.1$ $H = 16$ m $I_s = 0.05$
$B = 70$ m $I_d =$ 0.075
$L_1 = H/(I_o\text{-}I_s) = 320$ m
$L_2 = H/(I_o\text{-}I_d) =$ 640 m

Dead storage volume of open type sabodam:
$V_s = ½. H . B . L_1 = 179{,}200$ m^3

Total volume:
$T_{otal} = ½. H . B . L_2 = 358{,}400$ m^3

Thus, control volume of open type sabodam (V_c) becomes:
V_c = total volume– dead storage volume = 179,200 m^3

4 RESULTS AND DISCUSSIONS

The model showed ragged trend line between the overflowing sediment and sediment load from upstream (not linier). When open type sabodam crest was +1,245 m, side-channel spillway was +1,255 m, the overflowing sediment reached 2.9% for 750,000 m^3 upstream sediment, and 6.9% (562,000 m^3). It is evident that debris flow problem is very complex. Decrease in sediment discharge affects the downstream river flow due to the increasing total mass through the flow. When low sediment gravity flow occurs, sediment will be deposited in the downstream of open type sabodam and incurs change in flow direction. The flow directed to side-channel may cause the overflowing sediment becomes higher.

A mathematical approach for estimating the overflowed high sediment concentration volume is extremely difficult. It is indicated by the result of the experiment which tends to be vague. As seen from the presented results (see Figure 4 to Figure 7), physical model incorporating with mathematical model resulted different runoff coefficients.

Change in either dam crest, or side-channel spillway elevation gives significant effect towards the overflowing sediment. When open sabodam crest was +1,245 m and side-channel spillway was +1,255 m, high concentration sediment overflowed side-channel in the range of 0.5% and 7%. This value can be predicted using mathematical model with a discharge coefficient, C_{ss} of 1.6 as shown in Figure 4. Sediment conveyed to side-channel or open type sabodam was estimated by adjusting height difference between those structures. If dam crest elevation was +1256 m, overflowing sediment volume was between 0.2% and 1.5% (see Figure 5).

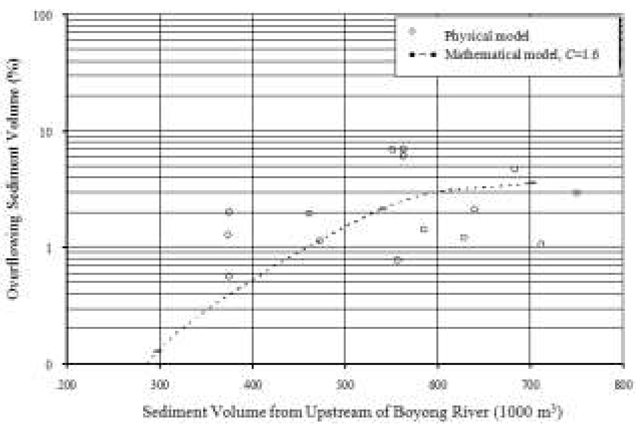

Figure 4. Percentage of sediment volume that overflowed side-channel spillway for +1,245 open type sabodam crest elevation and +1,255 side-channel spillway elevation.

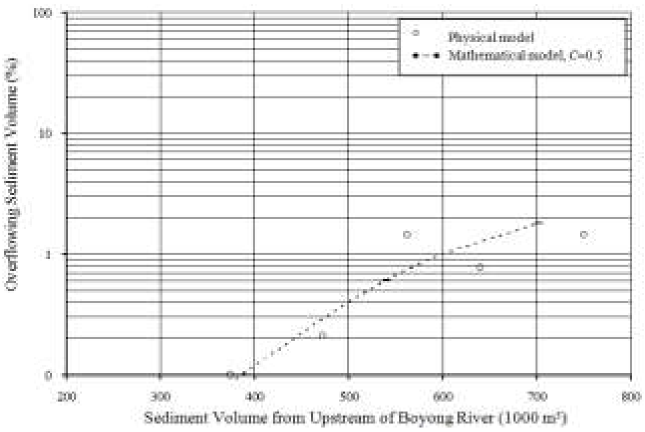

Figure 5. Percentage of sediment volume that overflowed side-channel spillway for +1,245 open type sabodam crest elevation and +1,256 side-channel spillway elevation.

Decrease in sediment volume was also resulted when dam crest was +1246m and side-channel spillway was +1255m. Volume of sediment which overflowed side-channel spillway was in the range of 1% and 5% as presented in Figure 6.

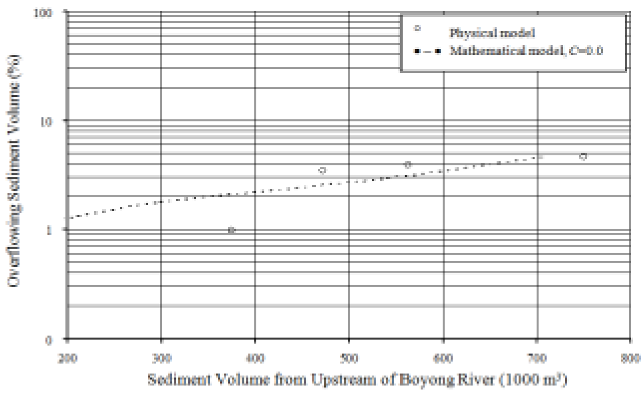

Figure 6. Percentage of sediment volume that overflowed side-channel spillway for +1,246 open type sabodam crest elevation and +1,255 side-channel spillway elevation.

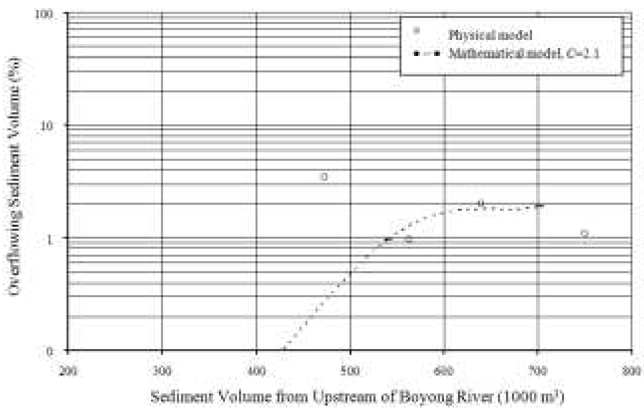

Figure 7. Percentage of sediment volume that overflowed side-channel spillway for +1,246 open type sabodam crest elevation and +1,256 side-channel spillway elevation.

Runoff coefficient was varied to obtain the conformity between physical model and mathematical model, so that correlation between two models could be determined.

As higher density of sediment gravity flow occurs, sedimentation begins due to lower flow velocity. However, sediment deposit will be eroded by continuing flow from the upstream river. Erosion and sedimentation occurring in turn repeatedly induces rough bed and changeable flow stream. This condition gives impact to the runoff volume over those tributaries.

Figure 8 shows the rough and wave bed as the impact of sedimentation and erosion. Flow course changes in time and distribution runoff volume fluctuates.

Figure 8. Material deposits due to sedimentation and erosion (non-scaled).

Figure 9 below illustrates changes in water course during experiment run.

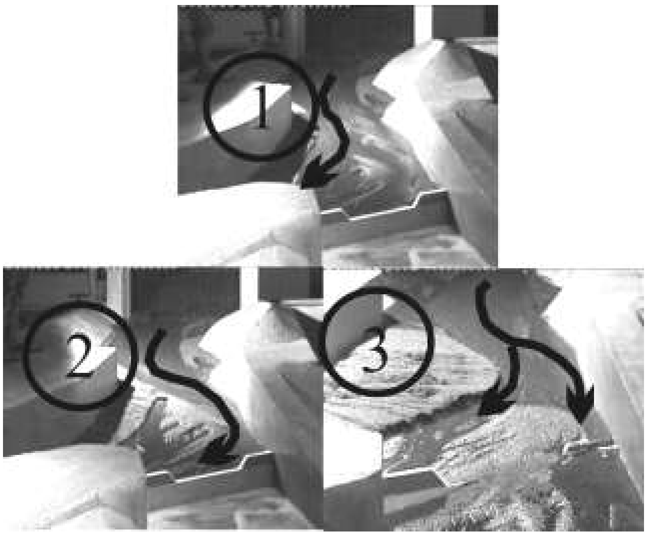

Figure 9. Alteration of flow course affecting distribution runoff volume over side-channel (scaled 1:100, undistorted).

In order to attain optimal design of open type sabodam aimed for flow diversion, further analysis towards appropriate structures elevation is highly necessary. It can help estimating construction cost since structures dimension is determined by elevation difference. The smaller its difference, the shorter distance between two control structures, so that dimension of open type sabodam structure will be smaller. Conversely, larger elevation difference will cause higher cost to construct higher crest of open type sabodam due to larger dimension design. A length between two controls structures should be designed such that it is not too short or too long since too short distance can cause all sediments is conveyed to side-channel. Crest width is determined by considering the calculation result of design flood and river capacity according to allowed design flood. Percentage of runoff volume can be controlled from elevation of open type sabodam side-channel spillway.

Some information obtained from physical and mathematical model simulation results are summarized below:

a) Based on the several simulation scenarios, just a very small percentage of sediment volume overflows side-channel spillway. The largest volume is presented by +1,245 m of dam crest elevation and +1,255 m of side-channel spillway elevation.
b) The results show a close correlation between upstream runoff volume and side-channel overflow.
c) Mathematical model approach results varying runoff coefficients against four simulation scenarios to satisfy trend line of physical model results.
d) It is difficult to get the exact distribution sediment volume due to indistinct trend line.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Concerning to the results which are explained at the prior section, some conclusions can be summarized as follows:

a) River diversion capacity depends on quantity and mechanism of sediment flow from upstream and the height difference of two control structures (open type sabodam and side-channel spillway).
b) Overflowing sediment volume is between 0.5% - 7% with 110 m length of open type sabodam to side-channel, +1,245 m dam crest elevation, and +1,255 m side-channel spillway.
c) Sedimentation and erosion process that occur in the upstream river give effect to overflowing sediment since it affects flow course and velocity.
d) High concentration sediment flow is hard to estimate by mathematical approach as proved at varying runoff coefficients.

5.2 Recommendations

For research development, there are several things which are necessary to concern:

a) Due to the complexity problem, a deeper study about high concentration sediment is highly required.
b) It is necessary to scale up the physical model.
c) A study about variation of structures positions and angles is necessary to conduct.
d) The experiment may use sediment supply with varied distribution of grain size, and concentration so that mathematical equation can be developed to predict volume of sediment run off.
e) More laboratory research should be carried out incorporating with field data comparison in order to develop an interpretation or empirical equation which can be used for subsequent research for predicting desired overflowed sediment volume.

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