Effectivity of underwater dam for reducing reservoir sedimentation, case study: Cipanundaan reservoir, West Java, Indonesia

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Abstract. As one of dam priority in Indonesia, Cipanundaan dam faced severe problem related to the sedimentation. The sedimentation in Cipanundaan derived from both soil erosion and landslide (earth slide and earth flow) along the river. Based on analysis, total potential sediment reached until 137,819 m³, which is shortened the dam lifespan only for 10 years. This research is conducted the effectivity of application of underwater dam in order to maintain intake system. Three underwater dams are constructed for controlling 8 mm/year of sedimentation from both erosion and translational landslide. The numerical modelling used ANSEDIM program to develop surface sediment elevation in reservoir. The result showed the infrastructure is successfully suspending sediment enter the system, thus, the dam has a longer lifetime. The research revealed that application of three underwater dams will reduce 2.5 times of sediment volume, increase up to 6 times of effective volume and extend the dam’s lifetime until 250% from existing condition. This outcome will be helpful to planner, engineers and managers for better managing of reservoir sedimentation and water resources.

Keyword: effectivity, underwater dam, sedimentation, reservoir

1. Introduction
Nowadays, the world faces a tremendous water demand in line with climate change, population development and the recent process of modernization[1] [2][3][4]. Indonesia, as a pre-developed country, also faces problem related to the availability of existing freshwater which is no longer sufficient in order to meet the escalation in demand so that additional provision of freshwater becomes necessary. Therefore, in order to solve the problem, the government has constructed dams in several areas which have water supply problems or are being projected to develop water scarcity.
One alternative location of dam is Cipanundaan dam, in Cirebon, West Java, Indonesia. However, development of a dam always leads to a series of operation and maintenance problems, especially after the impounding stages. The processes of water and sediment retention in large reservoirs always have major implications. Furthermore, the sedimentation also affects the lifetime of a dam. Once the accumulated sedimentation meets its storage capacity, the lifetime of dam will be ended[5]. Therefore, the potential effects of the sedimentation in a dam should be investigated and managed properly[6][7][8]. In Cipanundaan, the problem becomes more complex because of the intensively of land erosion. This erosion comes from both translational landslide (earth slide) and earth flow. The classification system based on the kind of material involved and the mode of movement. The translational slide is a bedrock slide moved by debris slide and earth flow is a rock flow (deep creep) moved by debris flow[9].

Generally, application of regular check dams becomes ultimate alternative solution for reducing both runoff and sediment yield [10][11][12]. On the other hand, check dams have numerous application such as: to stop land degradation, to decrease the lag times and peak discharges of the rivers, to accumulate sediments, to improve water quality, and to restore shape and structure of the river channel [13][14][15]. This infrastructure also could be able for altering the sedimentation properties of a channel and aids in maintaining a more stable morphology of stream networks.

This research approached a new type of check dam to manage sedimentation in the reservoir called the underwater dam. Three series of underwater dams are applied for the purposes of maintaining the intake of Cipanundaan dam. They are constructed to suspend the sediment enter the intake system, thus, the dam will have a longer lifespan. The research objectives is to simulate the changing of sedimentation pattern after the underwater dam has applied.

2. Location and Methods

2.1. Site Location
Cipanundaan dam (6° 54’ 01” - 6° 54’ 01” S and 108°39’ 11” - 108°39’ 24” E) is located in Cirebon, West Java, Indonesia. The catchment has 10.98 km² area with 5.07 km main river length. Cipanundaan dam is zonal earthfill dam which consist of main and saddle dam. These dams have homogenous earthen which consist of: clay, filter, toe drain and rip-rap. The location of Cipanundaan dam is shown in Figure 1.

![Figure 1](image_url)  
(a) Location of Cipanundaan dam; and (b) Geological mapping of Cipanundaan dam

Cipanundaan dam has two parts of crest length. The main dam has 516.17 m and saddle dam has 193.32 m. This dam has 27.80 m height with crest elevation + 46.80 m. The dam has normal elevation.
+ 44.00 m, with minimum water level + 28.00 m, and flood elevation + 46.02 m. Furthermore, this dam has high risk classification (22 from 30 ICOLD standard).

2.2. Field Mapping of Landslide from Scarps

The location faces geological problems related to fault, joint, type of soil. The joint shows in the location of dam and reservoir. Generally, it combines between crushed joint and tensile joint with space between close to rare. In the field, joint used to analysis geological features, which are believed to have formed before or on the fault development. In addition, there are fold with west north – southeast pattern, with anticline structure. Based on desk study, there is also an increasing fault of Bumiayu with 1.4 km distance from main dam. The geological mapping of Cipanundaan dam and reservoir is shown in Figure 2.

Figure 2. Claystone type around the reservoir

Cipanundaan river has 10-meter width with average water level 50 cm. The river has a northward direction and has “U” shaped river valley. The landscape around the site is a bumpy hilly landscape. Based on field mapping activity, the translational landslide occurred in clay soil, claystone soil and joint section. Shallow landslide occurred along the reservoir area with maximum 1-meter depth. Furthermore, some locations have potential translational landslide (earth slide) and earth flow. These erosions come from weathered volcanic limestone of Gintung formation. This landslide has maximum area about 1-meter depth. The most potential landslide problem comes from claystone soil. This soil has air slake type that will be break and eroded when they face some changes in water level. When they happened, it will demand to severe landslide that will be fulfilling the reservoir and disturbing intake system. Total potential sedimentation from this landslide is 137,819 m³ from 154,918 m² area.

2.3. Sediment Sampling

The process of sedimentation will always occur in every transversal infrastructure on the rivers. Therefore, in the dam design, total sediment calculation that will be entered becomes necessary. These processes should be limited in order to maintain the dam and to achieve lifetime goal regard to economic reasons. In Cipanundaan design, sediment yield is calculated using National Standard of Indonesia No. 03-3414-1994 about “Method of Suspended Sediment Sample Extraction from River based on Depth Integration of Discharge”.

The observation of discharge and sediment carried on rainy season, especially from 13 October 2017 with 4 (four) samplings as shown in Table 2 below.
Table 1. Number of Discharge and Sediment Sampling

| Experiment | Sediment Concentration (mg/l) | Discharge (m³/sec) |
|------------|-------------------------------|-------------------|
| 1          | 2000                          | 11.195            |
| 2          | 1265                          | 4.080             |
| 3          | 1240                          | 3.480             |
| 4          | 1501                          | 6.360             |

2.4. The Underwater dam design

Underwater dam is a laid transversal structure in the upstream of reservoir. They are constructed in front of the intake system as they help to trap sedimentation and to maintain intake, so it will have a longer lifetime. Once it constructed, this structure will be inundated by water.

First underwater dam has 2,445.15 meters length from main dam. Second underwater dam has 862.75 meters length, and third underwater dam has 312.50 meters from main dam. The location of these underwater dams is shown in Figure 3.

Figure 3. Location of Underwater dam; and (b) Typical of Underwater dam

The underwater dam core structure made from cyclops concrete, which is covered by a reinforced concrete with 25 cm thick. It consists of main dam (apron), spillway and sub dam. Firstly, sediment will be detained by the spillway and settled in the main dam. Next, using the spillway function to reduce the velocity, the sediment also will be settling in the sub dam. So, both of dam will provide a larger volume for catching the sediment.
2.5. Sedimentation modelling

Based on Sedimentation Control of Reservoirs Guidelines, Bulletin 67, ICOLD 1989, total sediment concentration is correlated with river discharge, water temperature and sediment concentration on mg/liter, as follows:

$$Q_s = 0.0864 \times C \times Q_w$$  \hspace{1cm} (1)

Where $Q_s$ is sediment concentration (ton/day), $C$ is sediment concentration (mg/liter) and $Q_w$ is water discharge (m³/sec). Next, the amount of total sediment that will be settling in dam area was calculated using Grunnar Brune diagram (Figure 4).

![Figure 4. Diagram of Grunnar Brune Trap Efficiency](image)

Sedimentation modelling used an “ANSEDIM” software for estimating dam lifetime (United States Department of the Interior Bureau of Reclamation 1988 standard). Input data set for developing model are average inflow (m³/sec), catchment area (km²), normal capacity of reservoir (m³), normal water level (m), return period (year), sediment transport (ton/day), sediment density (ton/m³), clay concentration (%), silt concentration (%), sand concentration (%) and number of reservoir elevation data (set).

Equations are used to calculate total sediment per year as follow:

$$Y = T \times 365 \times X_s$$  \hspace{1cm} (2)

Where $Y$ is total sediment per year (mm/year), $T$ is return period (year), and $X_s$ is total sediment transport (ton/day). Total sediment for $T$ year, was calculated as follow:

$$Q_A = 365 \times 3600 \times 24 \times Q_a$$  \hspace{1cm} (3)

Where $Q_A$ is total sediment (mm/year) and $Q_a$ is total sediment per second (mm/sec). Another calculation used ratio between normal capacity of reservoir and total sediment in order to calculate trap efficiency, based on Grunnar Brune diagram.

$$RAT = \frac{Q_p}{Q_A}$$  \hspace{1cm} (4)

Other paragraphs are indented (BodytextIndented style), where RAT is the ratio between $Q_p$ (normal capacity of reservoir) and $Q_A$. Next, trap efficiency calculated for getting the Y1 (percentage
of trap efficiency). Formula to calculate sediment condition type is derivated from the percentage of three variables i.e: clay, silt and sand, as follow:

\[ W = (W_c P_c) + (W_s P_s) + (W_m P_m) \]

(5)

\[ R_k = (R_c P_c) + (R_s P_s) + (R_m P_m) \]

(6)

Where \( W \) is settling velocity, which is consist of clay, silt and sand and. And sediment volume is calculated as follow:

\[ W_t = W + \left( 0.434 R_k \frac{t \log t}{(t-1)-1.0} \right) \]

(7)

\[ V_t = \frac{Y_t}{W_t} \]

(8)

\[ E = S_t + \left( \frac{(V_t - V_i)(S_i + S_t)}{V_{i+1} - V_t} \right) \]

(9)

Where \( R_k \) is ratio between clay, silt and sand, \( t \) is timespan (year), \( V \) is sediment volume (m\(^3\)), \( Y_i \) is trap efficiency (%) \( W_t \) is settling velocity per time, \( E \) is sediment volume (m\(^3\)), \( S \) is storage (m\(^3\)).

Next, effective volume of dam is calculated as follow:

\[ V_e = Q_p - V_t \]

(10)

where \( V_e \) is effective volume (m\(^3\)) and \( V_t \) is sediment surface volume (m\(^3\)). Furthermore, bedload calculation is following equation below:

\[ Q_{s(i)} = 0.084 C_i Q_{w(i)} \]

(11)

\[ Q_{sr} = \frac{Q_{st}}{n} \]

(12)

\[ Q_t = Q_{sr} + Q_b \]

(13)

\[ W = 365 Q_t \]

(14)

\[ H_t = \frac{W}{(C_A G_m \cdot 10^6)} \]

(15)

where \( Q_{s(i)} \) is number of concentration sediment data \( i \), \( C \) is suspended sediment concentration (mg/liter), and \( Q_{st} \) is suspended load data (ton/day), \( Q_{sr} \) is suspended load total (ton/day), \( Q_b \) is bedload total (ton/day), \( Q_t \) is total sediment transport (ton/day), \( C_A \) is catchment area (km\(^2\)) \( G_m \) is total sediment density (t/m\(^3\)) and \( H_t \) is sediment transport per year (mm/year).

3. Results and Discussion

The inundation area of reservoir has 76.07 Ha in the normal condition, with 6,119,928.99 m\(^3\) reservoir volume. Intake is placed on the left of dam on + 25.50 m of elevation. The results are shown in Figures 5-7. Using data set of average inflow 1.20 m\(^3\)/sec, reservoir capacity in normal condition with cumulative volume 6,119,928.99 m\(^3\). Sediment density is 1.45 t/m\(^3\), and particle distribution consist of clay 23%, silt 40% and sand 37%. Model resulted a vary results performance between with and without underwater dam (UD). Sediment yield total becomes 2,174.17 ton/day for without UD and 348.67 ton/day with UD. For sediment volume shows 5,449,578 m\(^3\) for 10 years without UD and 2,115,208 m\(^3\) for 25 years with UD. Trap efficiency is 82.11% without UD and 80.70% with UD. And for effective volume is 670,351 m\(^3\) without UD and 4,004,721 m\(^3\) with UD. Furthermore, model results 25 year of life when three underwater dams have been applied. On the other hand, it is only 10 years of life span without underwater dam.
Figure 5. Reservoir performance result: (a) Sediment Transport; and (b) Sediment Volume

Figure 6. Reservoir performance result: (a) Trap efficiency; and (b) Effective Volume

Figure 7. Reservoir performance result of lifetime

The result of this study shows that application of three underwater dam in the reservoir led to super effective management of sediment deposition. A change point of application the underwater dam is these infrastructures able reduce 2.5 times of sediment volume, increase up to 6 times of effective volume and extend the dam’s lifetime until 250% from existing condition. It is suggested to combine underwater dam with adaptive vegetation strategies. The vetiver grass will have short-time effect to restrain small erosion. This outstanding result is impossible to achieve with application of regular check dam in the upstream or drainage system all around the reservoir.
4. Conclusions
Application of underwater dam provides a longer lifetime in order to maintain intake system in a dam. The long-term simulations of sedimentation are successfully calculated reservoir’s lifetime and provided a sediment surface elevation in front of the intake system. However, this program only covered bed load calculation along the reservoir. For this reason, further studies are required to develop a better performance of underwater dam, including the calculation of suspended load which might be settled in the intake system.

Furthermore, this study contributes to a new sight of application infrastructure in the reservoir area. Underwater dam also can be applied for many dam reservoir in order to achieve a longer lifetime of reservoir. However, physical modelling is required in order to gain an accurate result in the future.

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