Hydrodynamic simulation of a dam breach of Cipanas Dam using HEC-RAS 5.0.5

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Hydrodynamic simulation of a dam breach of Cipanas Dam using HEC-RAS 5.0.5

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Abstract. Dams have many benefits for living creatures. On the other hand, dam breaks may also become disasters that cause potential losses of life and property. The Cipanas Dam has been planned for construction in Sumedang, West Java, and will have a storage capacity of up to 210 million m³. The area downstream of the Cipanas Dam contains many major infrastructures such as the Cikopo-Palimanan Toll Road and Kertajati International Airport that can be impacted by dam breach floods. This study analysed Cipanas Dam breach flow using HEC-RAS 5.0.5. The simulation assumed that a dam breach occurred through piping with 5 scenarios of breach time formation. The simulation resulted in flood hydrographs and flood inundation maps of the area downstream of the dam. The findings revealed that a breach formation time of 1 hour had the greatest flood effect. The maximum flood discharge was 38,823.3 m³s⁻¹ with a released water volume from the reservoir of 178,814,590 m³. The arrival time of the flood at the Cikopo-Palimanan Toll Road Bridge was 3 hours 45 minutes after the breach occurred, and the maximum flood depth was 15.78 m. Kertajati International Airport was not affected by the flood discharge.

Keywords: Dam Breach, Cipanas Dam, HEC-RAS, hydrodynamic simulation

1. Introduction

Dams have important roles for human life, such as for hydropower, agricultural water source, drinking water source, flood control, and so on. In contrast, dams may also present a huge threat to the area downstream of the dams, especially if they collapse. Dam breaches can cause an overwhelming flood discharge flowing in a relatively short time.

Occurrences of dam breaches must be avoided by the dam administrator agency. Hence, the Ministry of Public Works and Public Housing of Indonesia issued Regulation Number 27/PRT/M/2015 regarding Dam Structure. The regulation presupposes that the structural design of a dam must include an emergency contingency plan document simulating dam breach occurrences.

The Ministry of Public Works and Public Housing is building several dams to fulfil national food, energy, and water sustainability. The Cipanas Dam will be built in Cibuluh, Ujungjaya, Sumedang, West Java. The dam has been designed to store 210 million m³ of water, with a dam height of 65 m. On the other hand, huge amounts of stored water possesses a big disaster risk. The area downstream of dam contains several settlements, the Cikopo-Palimanan Toll Road, and Kertajati International Airport. A dam breach occurrence can inundate the settlements and disturb operations of the airport and toll road. Thus, a dam breach simulation was conducted to design an emergency contingency plan.

Dam breach occurrences of earthfill dams may be caused by one of the following cases [1].
1. Overtopping
   Overtopping is caused by water overflowing the dam crest, generating erosion and landslide on
   the dam body. Furthermore, the overflowing water can erode the dam foundation.

2. Piping
   Piping is caused by water flowing through the dam body. A high piping velocity induces slow
   erosion in the area upstream of the dam. Over time, the erosion can reach the area downstream
   of the dam body.

Several previous studies regarding dam breaches had been conducted in Indonesia. A breach on
Kadumalik Dam caused by overtopping and piping had been modelled in 2017 [2]. Flood routing
revealed that there were four inundated villages: Lebaksiu, Jatiwang, Putridalem, and Ujung Garis. The
distance between the dam location and the inundated villages are 17.72 km, 30.89 km, 62.64 km, and
104.93 km respectively. Furthermore, the flood discharge would reach the affected village within 1.17
hours to 15.20 hours. A breach of the Pacal Dam was hydrodynamically simulated by employing a DTM
(Digital Terrain Model) and a Q_{PMF} of 2,047.71 m$^3$s$^{-1}$ in 2013 [3]. The simulation showed that the flood
wave reached a distance of 39,578 km in 9 minutes, whereas the flood peak of 1,033.81 m$^3$s$^{-1}$ occurred
in 4.37 hours (262 minutes). In 2016, a different scenario of a breach of the Cipanas Dam was
hydrodynamically simulated [4]. The research assumed that a dam breach occurred by overtopping and
piping. A dam breach caused by overtopping was not simulated because the dam spillway could convey
PMF discharge. The dam breach was analysed by simulating two scenarios. These scenarios involved
the collapse and non-collapse of the Cikopo-Palimanan Toll Road Bridge. The breach formation time
was assumed to be 1 hour based on the Froehlich equation. Research findings showed that the peak
discharge from the dam body occurred in 7 hours 53 minutes, and the discharge amount was 39,503 m$^3$s$^{-1}$
Scenario 2 revealed that Cikopo-Palimanan Toll Road became inundated for 4 hours and a backwater
effect occurred downstream of the dam for 6 hours.

2. Materials and Methods

2.1. Flood routing
   Flood discharge routing flowing through a river valley will experience flow characteristic changes such
   as reduction in flood peak, reduction of flood peak time, and change in flood hydrograph [5]. Flow
   characteristic changes are caused by storage effect in the floodplain, shear stress in the riverbed,
   discharge loss, expansion and contraction of river area, and transverse river structure. Hydraulic routing
   for dam breach simulation is influenced by the variables of space and time [5]. This research employed
   the HEC-RAS software to conduct dam breach flood routing.

2.2. Dam breach
   Previous studies concluded that 34% of dam breach occurrences (of all dam types) were caused by
   overtopping, while foundation failure amounted to 30%, and the rest was caused by other factors [6].
   For earthfill dams, dam breaches generated by overtopping amounted to 35%, piping amounted to 38%,
   foundation failure amounted to 21%, and the rest was induced by other factors. Table 1 shows several
   factors that account for occurrences of dam breaches.

   In simulating dam breach hydrodynamics, several researchers suggested a simplified dam breach
   model in a trapezoidal shape [6]. Moreover, dam breach parameters were described as average breach
   width, breach side slope, and breach time formation. The simplification of breach model parameters is
depicted in Figure 1. Table 2 shows breach formation parameter ranges applied to simulate dam breach
occurrences.

   Equations (1) and (2) were suggested as a result of investigations of 74 earthfill, zoned earthen,
   earthen with core wall, and rockfill dams to develop equations for predicting average breach width,
breach side slope, and breach formation time.
Table 1. Factors that generate dam breach based on dam body type

| No. | Failure Mode        | Earthen/Embankment | Concrete Gravity | Concrete Arch | Concrete Buttress | Concrete Multi-Arch |
|-----|---------------------|--------------------|------------------|---------------|------------------|---------------------|
| 1.  | Overtopping         | ✓                  | ✓                | ✓             | ✓                | ✓                   |
| 2.  | Piping/Seepage      | ✓                  | ✓                | ✓             | ✓                | ✓                   |
| 3.  | Foundation Defects  | ✓                  | ✓                | ✓             | ✓                | ✓                   |
| 4.  | Sliding             | ✓                  | ✓                | ✓             | ✓                | ✓                   |
| 5.  | Overturning         |                    |                  |               |                  |                     |
| 6.  | Cracking            | ✓                  | ✓                | ✓             | ✓                | ✓                   |
| 7.  | Equipment Failure   | ✓                  | ✓                | ✓             | ✓                | ✓                   |

Source: Brunner (2014)

Figure 1. Description of breach parameters

Table 2. Range of possible values of breach parameters

| Dam Type              | Average Breach Width | Horizontal component of Breach Side Slope (H/H:V) | Failure Time, $t_f$ (hours) | Agency       |
|-----------------------|----------------------|---------------------------------------------------|----------------------------|--------------|
| Earthen/Rockfill      | (0.5 – 3.0) HD       | 0 – 1.0                                           | 0.5 – 4.0                   | USACE 1990   |
|                       | (1.0 – 5.0) HD       | 0 – 1.0                                           | 0.1 – 1.0                   | FERC         |
|                       | (2.0 – 5.0) HD       | 0 – 1.0                                           | 0.1 – 1.0                   | NWS          |
|                       | (0.5 – 5.0) HD*      | 0 – 1.0                                           | 0.1 – 4.0*                  | USACE 2007   |
| Concrete Gravity      |                      |                                                  |                            |              |
|                       | Multiple Monoliths   | Vertical                                         | 0.1 – 0.5                   | USACE 1980   |
|                       | Usually ≤ 0.5 L      | Vertical                                         | 0.1 – 0.3                   | FERC         |
|                       | Usually ≤ 0.5 L      | Vertical                                         | 0.1 – 0.2                   | NWS          |
|                       | Multiple Monoliths   | Vertical                                         | 0.1 – 0.5                   | USACE 2007   |
| Concrete Arch         | Entire Dam           | Valley wall slope                                 | ≤ 0.1                      | USACE 1998   |
|                       | Entire Dam           | 0 – valley walls                                  | ≤ 0.1                      | FERC         |
|                       | (0.8 L) - L          | 0 - valley walls                                  | ≤ 0.1                      | NWS          |
|                       | (0.8 L) - L          | 0 - valley walls                                  | ≤ 0.1                      | USACE 2007   |
| Slag/Refuse           | (0.8 L) – L          | 1.0 – 2.0                                         | 0.1 – 0.3                   | FERC         |
|                       | (0.8 L) – L          |                                                  | ≤ 0.1                      | NWS          |
\[ B_{ave} = 0.27 K_0 V_w^{0.32} h_b^{0.04} \]  
\[ t_f = 63.2 \frac{V_w}{gh_b^2} \]

Here, \( B_{ave} \) is the average breach width (m), \( K_0 \) is a constant (1.3 for overtopping and 1.0 for piping), \( V_w \) is the storage volume when the dam failure occurs (m\(^3\)), \( h_b \) is the final breach height (m), \( g \) is the gravitational acceleration (9.81 ms\(^{-2}\)), and \( t_f \) is the breach formation time (hours).

The aim of this research is to compare Cipanas Dam hydrodynamic characteristics caused by different breach formation times. One breach formation time employed in this research was calculated using Equation (2).

2.3. HEC-RAS
HEC-RAS is a hydraulic simulation software developed by the US Army Corps. HEC-RAS employs the continuity and momentum equations as basic equations to perform hydraulic simulations [7].

1. Continuity equation
\[ \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_t = 0 \]  

2. Momentum equation
\[ \frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA \left( \frac{\partial z}{\partial x} + S_f \right) = 0 \]

Here, \( x \) is the cross section distance (m), \( t \) is time (hour), \( Q \) is discharge (m\(^3\)s\(^{-1}\)), \( A \) is the cross section flow area (m\(^2\)), \( q_t \) is lateral inflow (m\(^3\)s\(^{-1}\)), \( S_f \) is the energy line slope, and \( V \) is the flow velocity (ms\(^{-1}\)).

2.4. Data
The secondary data used in this research are described below.

1. Dam data and probable maximum flood discharge data.
   Data for dam dimension, location, and discharge were obtained from DED and the Test Model of the Cipanas Dam in Sumedang Regency document by the Cimanuk Cisanggarung River Authority (BBWS) [8]. The probable maximum flood discharge hydrograph can be seen in Figure 2. The peak discharge of the hydrograph is 2,074.06 m\(^3\)s\(^{-1}\). The hydrograph was applied as the upstream boundary condition, while the downstream boundary condition was the normal depth condition.

2. Topography data
   The DEMNAS (seamless digital elevation model) provided by Geospatial Information Agency of the Government of Indonesia was applied in this research as topographic data. The simulation area is limited up to Kertajati International Airport. The limitation was established because the topographic slope condition downstream of the Cipanas dam is very small; hence, the inundation area can be very large.
3. Results and Discussion
Breach formation parameters were calculated by employing the empirical Equation (2). The resulting breach parameter was correlated with the dam breach characteristic values issued by the USACE. Dam breaches were simulated by employing 5 different time variables. Table 3 shows the results of breach formation parameter calculations.

Table 3. Values of breach parameters

| No. | Parameters                        | Scenario | 1 | 2     | 3     | 4     | 5     |
|-----|-----------------------------------|----------|---|-------|-------|-------|-------|
| 1   | Breach formation time (hours)     | 1        | 1 | 1.78  | 2     | 3     | 4     |
| 2   | Breach width (m)                  | 113.5    | 113.5 | 113.5 | 113.5 | 113.5 |
| 3   | Breach bed elevation (m)          | +90      | +90  | +90   | +90   | +90   |
| 4   | Breach side slope (m)             | 1H:0.7V  | 1H:0.7V | 1H:0.7V | 1H:0.7V | 1H:0.7V |

Research findings revealed that the simulation employing a breach formation time of 1 hour yielded the highest flood peak, $40,305.61 \text{ m}^3\text{s}^{-1}$. This finding showed a higher flood peak discharge than the results obtained in the previous research [4]. The different result might be caused by a difference in the topography data utilized in the previous research, wherein the previous research utilized LIDAR data. Figure 3 shows the comparison hydrograph of several scenarios as the result of dam breach simulations. Simulation results showed that longer dam breach formation times yielded longer flood durations. The flood duration was taken from the beginning of the rise to the end of the fall. The peak times and flood times obtained from the simulations can be seen in Table 4.

This research also found that breach formation times influenced flood depths in every cross section. Flood depth differences for cross sections located just downstream of dam were significant. For the 1-hour dam breach formation time, the flood depth was +99.75 m, whereas for 4 hours, the dam breach formation time yielded a flood depth of +93.92 m. Figure 4 illustrates the flood surface water level for all scenarios. The findings showed that the surface elevation differences were not significant for downstream reach because the discharge flow spilled into the right side of the river. At Station 0, Scenario 1 caused a flood depth of +65.01 m, whereas Scenario 5 generated a flood depth of +63.59 m. Figure 5 depicts the comparison of flood depths for all scenarios.
Figure 3. Flood hydrograph as the result of simulations

Figure 4. Water surface elevation hydrograph as the result of simulations

The inundation map was generated using Scenario 1 because it had the biggest flood effects. Inundation map generation was limited by the Cikopo-Palimanan Toll Road and Kertajati Airport. Flood discharge reached the Cikopo-Palimanan Toll Road Bridge in 3 hours 45 minutes and receded in 11 hours 15 minutes, and the highest flood surface elevation was 15.78 m. Fortunately, the flood would not reach Kertajati Airport. Figure 6 shows the inundation area map as would be caused by a Cipanas Dam breach.

Figure 5. Water surface elevations as result of dam breach simulations
To minimize casualties and property losses, an early warning system is needed to be developed by considering evacuation times for each village and other important assets. Evacuation times were derived based on time needed by the discharge flow to reach the villages after a dam breach occurrence. Table 4 presents the evacuation times for planning an early warning system.

Table 4. Evacuation time for several areas induced by a Cipanas Dam breach

| No. | Inundated Area   | Regency       | Evacuation Time (hours) |
|-----|-----------------|---------------|-------------------------|
| 1   | Cikawung        | Indramayu     | 3:30                    |
| 2   | Cibuluh         | Sumedang      | 3:25                    |
| 3   | Mekarjaya       | Majalengka    | 4:45                    |
| 4   | Mekarmulya      | Majalengka    | 4:50                    |
| 5   | Sukarjaya       | Sumedang      | 4:45                    |
| 6   | Kertasari       | Majalengka    | 5:15                    |
| 7   | Sukamulya       | Majalengka    | 7:00                    |
| 8   | Sukakerta       | Majalengka    | -                       |
| 9   | Bantarjatilor   | Majalengka    | -                       |
| 10  | Babakan         | Majalengka    | 5:15                    |
| 11  | Palasah         | Majalengka    | 6:10                    |
| 12  | Kertawinangun   | Majalengka    | 6:55                    |
| 13  | Palasari        | Sumedang      | 5:25                    |
| 14  | Sukamulya       | Sumedang      | 6:05                    |
| 15  | Pakubereum      | Majalengka    | 6:45                    |

4. Conclusion
There are several conclusions generated from the Cipanas dam breach simulation. First, a shorter breach time formation would generate the highest flood peak. The flood discharge would reach the Cikopo-
Palimanan Toll Road in 3 hours and 45 minutes and recede in 11 hours, and the highest flood depth would be 15.78 m. Fortunately, Kertajati International Airport would not be inundated by floods.

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