The Safety of Bengawan Solo River Embankment at Dengkeng-Pusur Segment in The Return Periods of Discharge

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Abstract. This study aims to assess the safety of the Bengawan Solo River embankment at Dengkeng-Pusur segment in the return periods of discharge in terms of the freeboard's adequacy. The embankment was designed to control flood discharge of 1.240 m$^3$/sec with a freeboard of 1.1 meters. The hydraulic analysis using Hec-Ras software from point P.1 to P.14 with a Q2 return period of discharge of 811.9 m$^3$/sec to a Q100 return period of discharge of 1442.5 m$^3$/sec shows that the embankment is still able to pass the flood discharge. However, based on the freeboard's adequacy, at a Q10 return period of discharge of 1050.1 m$^3$/sec, the freeboard on the left embankment at P.8 less than 1 meter, namely 0.98 meters. Thus, it can be concluded that the Bengawan Solo River embankment at the Dengkeng-Pusur segment is not safe starting in a Q10 return period of discharge because, at any time, the capacity of flow discharge can be exceeded by wave phenomena and backwater effects so that can be endanger the embankment. This analysis also shows that the embankment is not safe at the design flood of discharge.

1. Introduction
Flood is one of the main issues in Bengawan Solo River’s management. Several efforts are made in order to control the flooding issue, such as embankments, reservoirs, river restoration, weir of motion, and floodway establishments. In the long-term scenario, the development of flood control infrastructure can reduce the inundation area from the original 5.6% of the total area into 2.1% [1].

The Bengawan Solo River embankment at Dengkeng-Pusur Segment, is part of the Upper Bengawan Solo River's flood control, and the construction takes time from 1988 to 1994. The embankment was built on the left and right side of the river and designed to increase flow discharge capacity from 400 m$^3$/sec to 1.240 m$^3$/sec [2].
The type of the Bengawan Solo River embankment at Dengkeng-Pusur segment is a soil embankment. Based on the as-built drawing, the average of embankment crest width is 4 m, and the embankment slope is 1: 2 on the two sides of the embankment. Meanwhile, the average of freeboard is 1.1 m, and an additional height of the embankment is an average of 1.1 m to anticipate land settlement so that the average elevation of the top of the embankment is 2.2 m from the highest flood water level or elevation of around 93.0 m [3].

All river structures, including embankments must be designed to be safe against a certain return period of discharge in accordance with applicable standards. If the standard of the return period of discharges for the river structure to be designed is not yet available, then the determination of the return periods for the river structures must consider safety, risks and consequences, as well as economic aspects, then it must be consulted with the competent authority responsible for the management of the river [4]. According to [5], the design flood return period for embankments in rural areas is 2 to 50 years while in urban areas, it is 50 to 200 years. In Indonesia, the design of the return period of discharge for urban drainage is determined based on city typology and water catchment area and varies from 2 to 25 years [6]. However, the flood discharge tends to increase so that the embankment crest elevation is increased. Several kinds of research show that climate change and the land use change influenced the enhancement of flood discharge, such as researches conducted by [7] and [8].

The embankment needs a high safety standard. The safety requirements for an embankment include: 1) safe against possible overflow at design flood of discharge; 2) the peak of the embankment must have adequacy freeboard at the design flood of discharge after the embankment is built; 3) in a longitudinal profile from upstream to downstream, the crest height of the embankment must be adjusted to the water level along the river; 4) design flood of discharge and the freeboard must be taken according to the applicable provisions; 5) the slopes of the embankments must be protected against damage due to local scouring by river currents at the design flood of discharge; 6) the embankment line to the river bank must be determined based on local conditions, taking into account both technical, economic and social factors. The distance between the embankment line and river bank is attempted to be far enough so that landslides or scouring on the riverbanks do not affect the stability of the embankment [4].

Several studies have been conducted to determine the embankment failure. The research conducted by [9] shows that overtopping causes slope erosion and erosion of the crest of the embankment. Scouring that is getting wider, causing embankment failure.[10] shows that overtopping caused an increase on erodibility,
which can lead the embankment failure. Based on the statistical data, the cause of large embankments/DAM failure occurs due to 48.4% overtopping, 46.1% piping, 5.5% landslide, and 1.6% earthquake and liquefaction [11].

This research will assess the embankment's safety in several return period of discharge in terms of the freeboard's adequacy. The freeboard is the hydraulic parameter to calculate the uncertainty of the water surface's height due to the uncertainty of the river cross-section geometry, the river's slope, and roughness of the flow calculations. The freeboard is used to ensure that the capacity of flow discharge did not exceed even in the occurrence of a wave caused by the flow, wood, or any object floating in the water surface and also the backwater effect on the local obstacle at the river caused by trees or an indented corner. The freeboard is calculated by considering the discharge (Q), sediment base (Sb), and floating wood (Fd) [12].

To find the freeboard on several return periods of discharge, a hydraulic analysis will be conducted using the Hec-Ras software. The return period of discharge is obtained from the result of the research conducted by [13] on the same location. In this research, the return period of discharge calculated based on The Gamma I Synthetic Hydrograph Method unit. Flood discharge calculation of Bengawan Solo River, Dengkeng-Pusur Segment, also calculates the maximum flood discharge that is let through from Gajah Mungkur Dam which is located in the upstream as big as 400 m³/sec [14]. As for the size, the catchment area of Bengawan Solo, Dengkeng-Pusur Segment is as big as 951.35 km². Whereas the data of river geometry, i.e., cross-section and long-section profile of the river are obtained from the terrestrial measurements conducted by BBWS Bengawan Solo based on terrestrial measurement [15].

Hydraulic analysis is conducted by using the Hec-Ras software. The Hec-Ras software (Hydrologic Engineering Center’s - River Analysis System) is developed by the United States Army Corps of Engineers [16]. This application allows us to study the issue of river flooding that could recommend a proper flood handling model, for example by enhancing the embankment's height, river normalization, retention pool establishment, such as shown in the studies conducted by [17] and [18].

The result of this research, hopefully can be used as input toward the planning, construction, maintenance, and rehabilitation of Bengawan Solo River's embankment.

2. Methods

This research requires data, i.e., the return period of discharge data, river cross-section, and long-section data. Furthermore, these data is used to analyze the flood water level using the Hec-Ras software version 5.0.3 to find the freeboard on several return periods of discharge.

2.1 Return Period

Return period is defined as the average elapsed time between the occurrences of an event with a certain magnitude or greater [19]. A return period could be linked to the probability of exceeding a rain percentage or particular discharge. The definition does not stand for the occurrence of rain or the discharge that will recur in every return period but rather the probability of occurrence in a specific time period [20].

2.2 The Embankment's Profil

The embankment is the main structure on the river whose purpose is to control the water flow, so it did not exceed the natural flow or the cushion and served as protection toward the surrounding location near the river flow from puddles and floods. An embankment consists of several parts, which are the crest, front and backside, berm, and the foot, such as shown in Figure 2.
The critical aspect in an embankment design is the freeboard, which is the additional height given to the embankment to accommodate the water leap from the surface of the flowing water. This leap could happen due to waves, tide, hydraulic leaps that happen along when a flood is occurring. The freeboard varied based on the river dimension itself. Table 1 shows an embankment’s freeboard however, the freeboard itself does not include the additional height caused by an embankment shrinkage.

| No. | Planned Flood Discharge (m$^3$/sec) | Freeboard (m) |
|-----|-----------------------------------|---------------|
| 1   | < 200                             | 0.6           |
| 2   | 200 - 500                         | 0.8           |
| 3   | 500 - 2,000                       | 1.0           |
| 4   | 2,000 - 5,000                     | 1.2           |
| 5   | 5,000 - 10,000                    | 1.5           |
| 6   | >10,000                           | 2.0           |

To understand the embankment’s profile, field measurement data is required. Field measurement process includes peg mounting, horizontal map framework measurement, vertical map framework measurement, situation measurement, river cross-section measurement, planimetric map coordination binding, map height binding, calculation data management and map drawing [21].

2.3 Hydraulic Analysis
Natural river flow could be classified as a steady flow and unsteady flow. To determine the water surface level, hydraulic analysis theory is used with the presumption of a steady flow. The water surface profile is calculated by dividing the channel into sections of the shorter channel (segment), calculated gradually from one end to another. This method is usually called as Direct Stage Method. The calculation scheme of water surface’s height in a segment could be seen in Figure 3 below [22]:

![Figure 2. Embankment parts [23]](image-url)
Figure 3. Calculation scheme of water surface’s height on a segment throughout $\Delta x$ [22]

The height of the total energy on both ends of the cross-section 1 and 2 is calculated using the equation below:

$$S_o \Delta x + y_1 + \alpha_1 \frac{y^2}{2g} = y_2 + \frac{V^2}{2g} S \Delta x$$

$$\Delta x = \frac{E_2 - E_1}{S_o - S_f}$$

Where:
- $E$ = specific energy,
- $\alpha_1 = \alpha_2 = \alpha_3$,
- $y$ = the depth of the flow (m),
- $V$ = average velocity (m/second),
- $\alpha$ = energy coefficient,
- $S_o$ = base slope,
- $S_f$ = sliding slope,
- $g$ = gravity’s velocity ($m^2$/second),
- $\Delta x$ = distance between cross-section 1 and 2 (m).

This hydraulic calculation is conducted with HEC-RAS which integrated and designed to be able to be used in an interactive way with varied command conditions. There are five stages to create an HEC-RAS model to calculate the water surface profile on a consistent flow (Steady flow): (1). Start a new project; (2). Input the geometry data; (3). Input the flow data and limit condition; (4). Command the hydraulic calculation, and (5). shows and prints the result.

3. Result and Discussion

3.1 Return Periods of Discharge

The maximum amount of flood discharge on Bengawan Solo River at Dengkeng-Pusur Segment using the Gamma I Synthetic Hydrograph Analysis can be seen on Table 2.
Table 2. Maximum flood discharge Gama-I synthetic hydrograph method [13]

| Recurring Period (Year) | River Discharge from Gajah Mungkur Dam (m³/sec) | Bengawan Solo River Discharge - Dengkeng River Discharge Upstream (m³/sec) | Dengkeng River Discharge (m³/sec) | Accumulation of Bengawan Solo River Discharge (m³/sec) |
|-------------------------|-----------------------------------------------|--------------------------------------------------------------------------|-----------------------------------|-----------------------------------------------------|
| 1.01                    | 400.0                                         | 115.8                                                                    | 120.4                             | 636.1                                               |
| 2                       | 400.0                                         | 186.2                                                                    | 225.6                             | 811.9                                               |
| 5                       | 400.0                                         | 256.9                                                                    | 291.5                             | 948.5                                               |
| 10                      | 400.0                                         | 315.6                                                                    | 334.5                             | 1050.1                                              |
| 25                      | 400.0                                         | 404.9                                                                    | 388.3                             | 1193.2                                              |
| 50                      | 400.0                                         | 483.9                                                                    | 428.1                             | 1311.9                                              |
| 100                     | 400.0                                         | 574.6                                                                    | 467.9                             | 1442.5                                              |

3.2 River Cross-Section Profile

Based on terrestrial measurements of the Bengawan Solo River at Dengkeng-Pusur segment along the 1.3 km conducted by [15], there are 14 river cross-sections from P.1 to P.14 with the 100 meters distance between each peg. Figure 4 shows the location of the river cross-section measurement.

![Figure 4. Location of cross-section measurement](image)

The cross-sections and long-section river profile data shows that the lowest river bed elevation at point P.6 of 83.47 meter and highest at P.2 of 85.32 meter. The elevation on the right embankment tends to be more stable than the left side. On the left embankment, there is a decrease of the embankment at several points, and generally, the elevation of the left embankment is lower than the right embankment. The elevation of the lowest embankment is on the left embankment at P.14 of 91.78 m and the highest on the right embankment at P.12 of 93.99 m. Table 3 shows the cross-sectional profile data of P.1 to P.14.

The existing condition of the embankment could be seen in Figure 5. From the figure, it can be seen that the top of the embankment has decreased and is getting sloping.
Table 3. The cross-sections profile [15]

| Peg | Distance (m) | Cumulative Distance (m) | River Bed Elevation (m) | Embankment Elevation (m) |
|-----|--------------|-------------------------|-------------------------|-------------------------|
|     |              |                         |                         | Left                    | Right                   |
| P1  | 0            | 0                       | 84.31                   | 93.64                   | 93.55                   |
| P2  | 100          | 100                     | 85.32                   | 93.44                   | 93.73                   |
| P3  | 100          | 200                     | 85.28                   | 93.27                   | 93.78                   |
| P4  | 100          | 300                     | 84.7                    | 93.35                   | 93.73                   |
| P5  | 100          | 400                     | 84.58                   | 93.11                   | 93.64                   |
| P6  | 100          | 500                     | 83.47                   | 93.09                   | 93.81                   |
| P7  | 100          | 600                     | 83.63                   | 93.4                    | 93.71                   |
| P8  | 100          | 700                     | 83.7                    | 92.21                   | 93.71                   |
| P9  | 100          | 800                     | 84.03                   | 93.17                   | 93.59                   |
| P10 | 100          | 900                     | 84.82                   | 92.92                   | 93.32                   |
| P11 | 100          | 1000                    | 84.49                   | 92.8                    | 93.28                   |
| P12 | 100          | 1100                    | 84.94                   | 93.62                   | 93.99                   |
| P13 | 100          | 1200                    | 85.02                   | 92.66                   | 93.05                   |
| P14 | 100          | 1300                    | 85.48                   | 91.78                   | 92.07                   |

3.3 The Embankment’s Freeboard

The result of Hec-Ras modeling from point P.1 to P.14 with a Q5 return period of discharge of 948.5 m³/sec, the embankment is able to pass the flood discharge and the freeboard more than 1 meter. On a Q10 return period flood discharge of 1050.1 m³/sec, the embankment is able to pass the flood discharge, but on the left embankment at P.8, the freeboard is 0.98 m. On a Q25 return period of discharge of 1193.22 m³/sec, the embankment is still able to pass the flood discharge, but on the left embankment at P.8, the freeboard is 0.64 m. Until a Q100 return period of discharges of 1442.48 m³/sec, the embankment is still able to pass the flood discharge; however, the freeboard on the left embankment at P.8 is only 0.12 m or almost overtopping the embankment while the freeboard on the right embankment at P.1 is 0.66 m. Based on the adequacy freeboard, it could be concluded that the Bengawan Solo River embankment at Dengkeng-Pusur, especially on the left side, is not safe for the Q10 return period of discharge of 1050.1 m³/sec, while on the right side, the embankment is not safe on a Q50 return period of discharges of 1311.96 m³/sec. Table 4 shows the water surface level and the freeboard for a Q50 return period of discharges at point P.1 to P.14. From the Tables, it can be seen that the lowest freeboard is on the left embankment at P.8 with a water surface level at 91.82 m. Meanwhile, the long-section profile of P.1 to P.14 on a Q50 return periods of discharges can be seen in Figure 6.
The recapitulation of the freeboard on several return period of discharge can be seen in Table 5.

| Peg | Q2 (811.85 m³/sec) | Q5 (948.49 m³/sec) | Q10 (1050.06 m³/sec) | Q25 (1193.22 m³/sec) | Q50 (1311.96 m³/sec) | Q100 (1442.48 m³/sec) |
|-----|-----------------|---------------------|----------------------|----------------------|----------------------|----------------------|
|     | Left Embankment | Right Embankment    | Left Embankment       | Right Embankment      | Left Embankment       | Right Embankment      |
| P1  | 2.46            | 2.37                | 1.95                 | 1.75                 | 1.66                 | 1.36                 |
| P2  | 2.27            | 2.56                | 1.84                 | 1.54                 | 1.83                 | 1.15                 |
| P3  | 2.17            | 2.68                | 1.75                 | 1.46                 | 1.97                 | 1.08                 |
| P4  | 2.35            | 2.73                | 1.93                 | 1.65                 | 2.03                 | 1.28                 |
| P5  | 2.13            | 2.66                | 1.71                 | 1.43                 | 1.96                 | 1.05                 |
| P6  | 2.33            | 3.05                | 2.65                 | 1.66                 | 2.38                 | 1.32                 |
| P7  | 2.75            | 3.06                | 2.68                 | 2.11                 | 2.42                 | 1.77                 |
| P8  | 1.61            | 3.11                | 1.24                 | 0.98                 | 2.48                 | 0.64                 |
| P9  | 2.67            | 3.09                | 2.30                 | 2.04                 | 2.46                 | 1.71                 |
| P10 | 2.54            | 2.94                | 2.17                 | 1.92                 | 2.32                 | 1.60                 |
| P11 | 2.59            | 3.07                | 2.23                 | 1.99                 | 2.47                 | 1.68                 |
| P12 | 3.73            | 4.10                | 3.41                 | 3.19                 | 3.56                 | 2.91                 |
| P13 | 2.94            | 3.33                | 2.62                 | 2.40                 | 2.79                 | 2.13                 |
| P14 | 2.27            | 2.56                | 1.94                 | 1.71                 | 2.00                 | 1.43                 |

The recapture of the freeboard on several return period of discharge can be seen in Table 5.
Table 5. shows that based on the freeboard's adequacy, the Bengawan Solo River embankment at Dengkeng-Pusur is safe at Q5 return period of discharge of 948.5 m$^3$/sec, and the embankment is unsafe start from on a Q10 return period of discharge of 1050.1 m$^3$/sec or unsafe for the flood discharge design as well.

Figure 7 shows the flood water level at several return periods discharges at the left embankment at P.8 which is the most crucial embankment point and the right embankment at P.12, which is the safest embankment point.

![Figure 7. (a) (b) . The water surface level on return periods discharges](image)

The distance between P8 and P12 is relatively close, which is 400 meters only, but the changes in the water surface level and the freeboard between the 2 (two) points appear in contrast. Therefore, further studies are needed to assess the embankment condition and the river flow capacity that affect changes in the water surface level and the freeboard.

4. Conclusion

The result of the hydraulic analysis using Hec-Ras software from point P.1 to P.14 shows that with a Q5 return period of discharge of 948.5 m$^3$/sec, the Bengawan Solo River embankment at Dengkeng-Pusur is able to pass the flood discharge and the freeboard more than 1 meter.

On a Q10 return period of discharges of 1050.1 m$^3$/sec until a Q100 return period of discharges of 1442.48 m$^3$/sec, the embankment is still able to pass the flood discharge, but the freeboard is less than 1 meter. On a Q10 return period of discharges, the freeboard on the left embankment at P.8 is 0.98 meter. Meanwhile on a Q100 return period of discharges, the freeboard on the left embankment at P.8 is 0.12 meter or close to being overtopping, while the right embankment at P.1 is 0.66 meter.

Based on the freeboard's adequacy, the Bengawan Solo River embankment at Dengkeng-Pusur is safe on a Q5 return period of discharge of 948.5 m$^3$/sec but starting from a Q10 return period of discharge of 1050.1 m$^3$/sec, the embankment is not safe because at any time the capacity of flow discharge can be exceeded by wave phenomena and backwater effects that can endanger the embankment.

The embankment design flood of discharge of 1240 m$^3$/sec is between the return period of discharge Q25 and Q50. So, based on the results of the modeling, the Bengawan Solo river embankment of the Dengkeng-Pusur segment is not safe at the design flood of discharge.

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