Model of discharge coefficient of crest gate rubber weir at fully closed condition

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Abstract. Crest Gate Rubber Weir is a modification of rubber weir with adding a metal plate or crest gate on the upstream side. The rubber in this weir functioning as a support while the crest gate serves on elevating water. Although many have been implemented, this weir's discharge coefficient needs be researched considering its unique shape. This study looks for discharge coefficient to determine the discharge that passes through weirs at fully closed conditions. The research was conducted with a hydraulic model resembling part of Tirtonadi Weir in Surakarta with a hydraulic model. The model is made in an angle 53°, which represents the prototype at fully closed condition. Laboratory experiment shows that the discharge coefficient of this weir is greater than the Ogee Weir and Sluice Gate for the same height because of less flow resistance from this weir structural form.

Keywords: crest gate weir, discharge coefficient, hydraulic model, rubber weir, sloped upstream weir

1. Introduction.

The crest gate rubber weir is the modification of rubber weir being produced by Obermeyer Hydro Inc. under the name Spillway Crest Gate System and Inflatable Bladder. This kind of weir was patented in 1998 at the United States Patent and Trademark Office. This weir is unique because it has a curved metal plate at the upstream face of rubber called the crest gate, as shown in figure 1. This crest gate acts as a water barrier and is supported by a smaller rubber weir. The crest gate also has protection fins to improve the protection of the rubber weir behind it from debris which usually scratches or slits the rubber weir. This weir also has a hinge or support at its bottom, which requires no upper structure to lift its metal crest gate.

With these advantages, this weir has been installed in several countries such as Portugal, France, the United States, Malaysia, and others. This kind of weir has various heights, from 2.0 m in Oberhofer Germany, 3.0 m in Surakarta Indonesia, as shown in figure 2, to 4.2 m in Roman Romania. The dimension of rubbers as a supporting structure is only around 30%-50% of the weir height from those installed weirs. For example, the Tirtonadi Weir in Surakarta Indonesia has a total height of 3 m but is only supported by rubber with a dimension of about 1.4 m.
Although this kind of weir has been applied in several countries, water flowing over this weir still needs to be studied further. This research focuses on finding the discharge coefficient (Cd) for Crest Gate Rubber Weir at its maximum height or the fully closed condition. In analysing the Cd value, the character of the crest gate as sharp-crested weir and sloped upstream weir face must be understood.

Figure 1. Components of Spillway Crest Gate and Inflatable Bladder.  
Figure 2. Tirtonadi Weir in the City of Surakarta, Indonesia.

2. Material and Methods
The discharge equation for the sharp-crested weir, according to Chow (1959) and Subramanya (1986), is obtained from integrating flow that crosses the finite thickness (dh) above the weir into the following equation:

\[ Q = \frac{2}{3} C_d \sqrt{2gBH^{1.5}} \]  

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Where  
- \( B \) = length of the weir, \([L]\)  
- \( C_d \) = discharge coefficient, [-]  
- \( g \) = gravitational acceleration, \([L/T^2]\)  
- \( H \) = depth of water over the crest without \( v^2/2g \), \([L]\)

The equation shows that the discharge flowing through the sharp-crested weir is affected by the water height above the weir. The discharge coefficient \( C_d \) is obtained by comparing the observed and theoretical discharge and is a dimensionless variable. The value of \( C_d \) has been the object of several studies. Rehbock (1929) revealed that \( C_d \) is influenced by the water head over weir and weir height (\( H/P \)). Kinsvater and Carter (1957), as cited by Bos (1989), introduced weir width over the channel width (b/B) as the addition of \( H/P \) as a variable in the \( C_d \) equation. Swamee (1988) suggested a comprehensive \( C_d \) equation for sharp-crested weir, narrow crested weir, broad crested weir, and long-crested weir concerning weir geometric. Bagheri and Heidampour (2010), as cited by Naderi et al. (2014), develop a \( C_d \) equation from analysis on velocity on nappe. Those previous equations are listed in table 1.

| Researcher                        | Equation                                      |
|-----------------------------------|-----------------------------------------------|
| Rehbock (1929)                    | \( C_d = 0.611 + 0.08 \frac{H}{P} \)         |
| Kinsvater and Carter (1957)       | \( C_d = 0.602 + 0.075 \frac{H}{P} \)        |
| Swamee (1988)                     | \( C_d = 0.611 + 0.075 \frac{H}{P} \)        |
| Bagheri and Heidampour (2010)     | \( C_d = 0.829 \ln\left(1 + \frac{0.73 \frac{H}{P} + 3.64}{6.11}\right) \) |
For weirs that have sloped upstream, Shaker and Sarhan (2017) find an influence of weir slope on the discharge coefficient. Weirs with an angle will give a greater \( C_d \) value than a vertical weir with the same height. It is due to the flow transition, which reduces energy loss when flow collide with the weir.

This phenomenon was also found by USBR (1987) in the \( C_d \) graph of the Ogee Weir, which was made by observing the flow behavior through sharp-crested weirs. USBR produces a graph showing the difference in \( C_d \) values for Ogee weirs with upstream slopes of 1:3, 2:3, and 3:3.

This study will examine the \( C_d \) model of the Crest Gate Rubber Weir at a fully closed condition at an angle of \( 53^\circ \). Because at a fully closed condition, the weir will greatly affect the water level upstream of the weir.

Analysis of \( C_d \) value for this type of weir, a physical hydraulic model was inspired by the Tirtonadi weir prototype in Surakarta City. The model is made by taking the simple form of the prototype by removing the pillars, bases, and slopes of the downstream apron, as shown in Figure 3.

Research on the model is conducted in the River Engineering Laboratory of Universitas Brawijaya. The weir model is made from acrylic with the height of weir (\( P \)) is 30.35 cm and the length of weir (\( L \)) is 22.87. Following the prototype's shape, the weir model has a curvature with a radius of curvature of \( r=109.83 \) cm with a chord length of 38 cm and sagitta = 1.6 cm. The model's width is 0.4 m or as wide as a flume. The weir model is made with a position of \( 53^\circ \) from the horizontal, which is the maximum closing position of the weir prototype.

The model is placed on a rectangular flume with the dimension of 0.55 m high, 0.4 m wide, and 9 m long, where the weir model is mounted 5 m downstream of the flume entrance. Water enters the flume through the stilling system, then passes over the weir and ends up in the settling basin of the flume. There is a rechbook weir in the upstream, which has been calibrated to measure the flow rate in the flume, as shown in figure 4.

The discharge varies from 2, 5, 8, 11, 14, 17, until the maximum flume capacity at 20 L/s. Various discharges are analysed to determine water levels at different discharges. Measurement of water elevation is carried out with a point gauge, and velocity measurements are conducted with a pitot after stable flow.

Measurements are conducted by measuring water elevation and flow velocity upstream of the model and above the model. Measurements on the upstream model were carried out at 110 cm, 60 cm, 40 cm, and 20 cm from the weir model. The elevation and velocity measurements above the model are carried out at the beginning of the model, at a distance of 7.6 cm or 1/3 of the horizontal length of the model, at a distance of 15.3 cm or 2/3 of the model length, and at the end of the model as the Brink point. Measurements upstream of the weir model are carried out to determine the head over the weir (\( H \)), while the measurements above the model aim to determine the brink head and hydraulic behavior of the flow above the weir model.

**Figure 3.** Cross of Weir Prototype (Left) and Isometric of Hydraulic Weir Model (Right)
3. Result and Discussion
After being drained, the weir model is measured and documented from the side of the flume, topside, upstream, and downstream of the weir model. Side view photos are in figure 5 to figure 11.

![Figure 4. Flume and Weir Hydraulic Model (unscaled)](image)

**Figure 5.** Flow at Discharge 2 L/s

**Figure 6.** Flow at Discharge 5 L/s

**Figure 7.** Flow at Discharge 8 L/s

**Figure 8.** Flow at Discharge 11 L/s
From the experiment, it can be seen that the increase in Head (Ho) and Head over the weir (H) is not linearly related to the increase in flow rate. The relationship between Ho and Q has a curvature that resembles a rating curve. The increase in Ho gives a milder slope for larger discharges. Because the weir height P is constant, the graph for H also has the same graph as Ho, which resembles a rating curve as shown in figure 12.
Substituting the values of \( H \) and \( Q \) into equation (1) will get the value of \( Cd \) for each discharge, as shown in table 2. The largest discharge coefficient value is 0.764 at discharge 2 L/s. Value of \( Cd \) will gradually decrease for larger discharges, giving \( Cd = 0.689 \) at discharge = 20 L/s.

| Discharge Q (L/s) | Water Head \( Ho \) (cm) | Head Over Weir \( H \) (cm) | Discharge Coefficient \( Cd \) |
|------------------|--------------------------|---------------------------|-----------------------------|
| 2                | 32.1                     | 1.8                       | 0.731                       |
| 5                | 33.6                     | 3.3                       | 0.722                       |
| 8                | 34.8                     | 4.5                       | 0.721                       |
| 11               | 35.9                     | 5.6                       | 0.712                       |
| 14               | 36.9                     | 6.6                       | 0.707                       |
| 17               | 37.9                     | 7.6                       | 0.694                       |
| 20               | 38.8                     | 8.5                       | 0.689                       |

Plotting the discharge coefficient with the flowing discharge, it can be seen that the \( Cd \) value will have a downward trendline curve, as shown in Figure 13.

\[
Cd = 0.7502(Q)^{0.025} \\
R^2 = 0.8274
\]

\[
Cd = 0.665(H/P)^{0.036} \\
R^2 = 0.8355
\]
If the observed Cd is plotted with H/P as shown in Figure 14, it will be seen that the curve will resemble the curve of Cd-Q. It is because the increase in H will be in line with the increase in discharge. From Figure 14, it can be seen that a larger H/P ratio will give a smaller Cd value. In this experiment, the value of Cd varies from 0.731 at H/P = 0.056 and will tend to decrease to Cd = 0.689 at H/P = 0.277.

The graph on Cd-Q will be more sloping than Cd-H/P because the change in Q from 2 L/s to 20 L/s is nine times while the change in H/P is only 3.8 times. It is consistent with the common rating curve that the y-axis (H) increase will be continuously smaller for an increase in the x-axis (Q).

Suppose this H/P value is substituted into the Cd equation from Rehbock for sharp-crested weir. In that case, it will be found that the Cd value for this Crest Gate rubber weir has a higher Cd value. Comparison of Crest Gate Weir's Cd to common vertical sharp-crested weir can be shown in figure 15. It can be seen that the Cd for Crest Gate Rubber Weir is higher than others. It shows a positive relationship from the sloped upstream in Crest Gate Weir to water flow.
Finding the relationship between the slope on the weir face and discharge coefficient, the obtained Cd was compared with the research of Shaker and Sarhan in 2017. Shaker and Sarhan's research tried to find the effect of slope on Discharge Coefficient by comparing several weirs with heights of 6 cm, 8 cm, 10 cm, and 12 cm with varying angles of 45°, 36.9°, 26.6°, and 21.8°.

This study found in line with Shaker and Sarhan; there is a positive relationship between the slope upstream of the weir and the magnitude of the Discharge Coefficient. The milder sloped upstream, the greater the value of Cd will be.

Figure 16 shows that the Cd values of Crest Gate rubber weir in blue dots are on the left of the curves from Shaker and Sarhan's research. Suppose the trendline of the Crest Gate rubber weir is extended. In that case, it can be expected for the same H/P value that the Crest Gate rubber weir will have a lower Cd value than Cd of other weirs. It is because flow transition at the Crest Gate rubber weir has a greater resistance than the flow resistance from other milder slope weirs. Figure 16 confirms the positive relationship between the face angle of the weir into the magnitude of the Discharge Coefficient.

4. Conclusion
Model discharge coefficient on Crest Gate Rubber Weir investigated experimentally in the open channel by modelling weirs, and flow can be concluded:

1. Performance of crest gate rubber weir is influenced by geometric weir, sloped upstream face and a curvature. There is an increase of discharge coefficient up to 24% compared to the vertical sharp-crested weir.

2. The discharge coefficient value will change according to the flow discharge, where Cd will be high at a small discharge and gradually decrease for a large discharge. Understanding the decreasing value of Cd at large discharges is important considering the main reason for using Crest Gate.

3. Rubber Weir is for flood control, which considers large discharges.

4. The discharge coefficient model for this weir in fully closed condition (angle of 53°) is $Cd = 0.6649 (H/P)^{0.036}$

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