# DISCHARGE RATING CURVE AND SCALE EFFECTS CORRECTION IN MORNING GLORY SPILLWAYS①

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**Abstract** Dam spillways are the structures that lead rightly and safely the outflow downstream, so that the dam integrity can be guaranteed. Many accidents with dams have been caused by an inadequate spillway design or insufficient capacity. This situation is particularly important in embankment or rockfill dams, because the possibility of overtopping failure of the dam. The morning glory spillway may be used when there is not available space for a conventional spillway. Engineers use physical modeling to design this kind of structures, and therefore scale effects can cause a difference between model and prototype discharge rating curve. This paper has the objective of analyze the discharge flow rating curve in a vertical shaft with morning glory inlet and to correct scale effects for low heads. An experimental study has been carried out, using the spillway model of Paraitinga Dam in 1:51,02 scale. As a result equations are proposed in order to correct the discharge coefficient in the discharge rating curve for low heads.

**Key words** morning glory spillway; shaft bend; discharge flow rating

## 1 INTRODUCTION

Vertical drop shafts have been built since antiquity (Chanson, 2004) and they are being used in metropolitan areas, with the purpose of draining pluvial waters from superficial area to underground galleries (Zhao et al, 2006).

Vertical shafts with morning glory entrance can be used as spillways in earth or embankment dams, or where there is not enough space for a conventional spillway in the dam. One may use the same shaft to transport the flow to turbines and also to discharge flooding, if the water intakes are set in different levels. Another advantage of the morning glory spillway is that the tunnel used for the river deviation, in the phase of dam construction, can be used as the spillway tunnel, since it has been appropriately designed for this.

Several researchers have studied vertical shafts with morning glory inlet and defined their own characteristics. One may find a revision of each part of the morning glory spillway design in Genovez (1997) and Fais (2007). Mussali (1969), Ribeiro and Tomás (1976) and USBR (1987) described the discharge characteristics in morning glory spillways. The flow characteristics of a morning glory spillway depend on the dimension of its different elements. So, the crest diameter, the geometry of the transition and the diameter of the vertical shaft can be designed so the spillway may discharge more or less flow.

Discharge rating curve varies with the water level over the crest. For low heads, flow increases considerably with small head increments, the water tends to concentrate in the lateral shaft walls, and so one has a core with air entrainment. As the head

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over the crest increases, the flow thickens and it can fill out all the cross section. If head keeps increasing, the crest will be submerged, causing the spillway submergence and changing the discharge rating curve control. In these conditions, there is a great increment of the head for a small increase of the flow discharge. With the progressive increase of the flow, the vertical shaft becomes pressure flow and then, the flow will fill out the tunnel.

According to the presented information, the morning glory spillway can also be a good option to limit the flow downward, since, from the submergence, there are no great flow increments, even with the increase of the water head on spillway crest. Besides, due to its revolution type form, the wall thickness is small when compared with other types of spillway, becoming an inexpensive spillway construction. In case of physical modeling of a vertical shaft with morning glory entrance, it needs to determine the prototype discharge rating curve. This paper has the objective of define a criterion to correct the discharge rating curve in circular spillways, for low heads.

## 2 SCALE EFFECT IN DISCHARGE RATING CURVE

Studies with physical modeling are carried out with the purpose of flow simulation in these structures, so as hydraulic structures can be rightly designed. One of the problems in using physical models is the scale effect, caused by the impossibility of reduction of viscosity forces and surface tension; therefore, their effects are increased in the model.

Spillway models are built according to Froude laws of similitude and they will be valid if the effects of surface tension and viscosity can be neglected, avoiding the scale effect. In case of spillway channels, Reynolds number should be larger than $10^5$ (Kobus, 1982), coincident result with the one of Genovez (1991) for vertical shafts. Also, Weber number should be larger than 500 (Pinto, 1982).

Free flow in a morning glory spillway can be calculated through the expression:

$$Q = C \cdot 2\pi R \cdot H^{3/2} \qquad (1)$$

where

C = discharge coefficient;

R = morning glory crest radium;

g = gravity acceleration;

H = water level over the crest.

According to Sarginson (1972), in flows with a circular surface, the influence of surface tension increases with the decrease of the free surface radium of curvature. In sharp crested spillway, the discharge coefficient increases with head, until a point that the influence of the surface tension can be neglected. For circular crested spillway, a crest with small radium has a small discharge coefficient than a crest with large radium, under the same head. Several authors determined equations for the calculation of discharge in sharp crested spillway. Rebock, mentioned by Sarginson, proposed equation (2) for the calculation of discharge coefficient C in circular crested but he did not take into account the effect of surface tension.

$$C = 0.92 + 0.295\sqrt{30 - \left(5 - \frac{H}{R_c}\right)^2} \qquad (2)$$

where

H = water level over the crest;

$R_c$ = crest radium.

Because of Rebock's equation is an empirical one, it would only be valid if similitude conditions were satisfied.

Hay and Markland, mentioned by Sarginson (1972), proposed an equation for sharp crested spillway, also considering the influence of the approach velocity. The expression is:

$$Q = L \cdot H^{1.5}\left(1.81 + \frac{4.22}{We} + 0.22\frac{H}{P}\right) \qquad (3)$$

where

$We = \rho g H^2/\sigma$ = Weber number;

$\rho$ = water density;

$\sigma$ = surface tension of water;

P = height of spillway.

Sarginson (1972) increased to Jaeger's equation a second term, so that it could consider the surface tension effect. So, Jaeger's equation modified by Sarginson was equal to:

$$C = 3.2\frac{H}{R_c}a - \frac{5}{We}b \tag{4}$$

where:

$$a = \left[1 + 1.2\frac{H}{R_c} - \left(1 + 1.2\frac{H}{R_c}\right)^{5/9}\right]$$

$$b = 1 - \left(1 + 1.2\frac{H}{R_c}\right)^{-4/9}$$

At Sarginson's paper time there was not available any analytical treatment of viscosity and surface tension effects in circular crested spillways. From Jaeger's and Rebock's equations, Sarginson (1972) proposed a new one to calculate the discharge coefficient in circular crested spillways, taking into account the effects of surface tension, viscosity and the approach velocity. Results obtained experimentally showed a good agreement with the theoretical ones. Therefore, the discharge coefficient can be calculated as:

$$C = 1.17 + 0.242c - b + 0.266H/P \tag{5}$$

where

P = the spillway height;

$$c = \sqrt{33 - \left(5.5 - \frac{H}{R_c}\right)^2}$$

Kolkman (1984) also refers to the influence of flow velocity when the height of the crest is small, being able to cause scale effect. For physical modeling studies, the water level over the crest should be at least from 0.010m to 0.012m so as prototype values can be reduced appropriately.

According to Sarginson (1984) one of the factors that contribute to the scale effects in spillway models is the presence of a boundary layer in the crest of the spillway, which is proportional to its radium. In two models geometrically similar, the boundary layer thickness is proportionally larger in the small model. Therefore, in order to avoid scale effect, it is necessary that boundary layer thickness is neglected when compared to water level in the spillway crest.

Among other recent works, it can be mentioned the experimental study of Heidarpour and Chamani (2006), that also defined an equation to determine the discharge coefficient for circular crested spillway. The expression, as a function of $H/R_c$ relation is equal to:

$$C = 1.1757\,(H/R_c)^{0.1469} \tag{6}$$

One may note that several works were carried out in order to analyze the influence of surface tension in the spillway flow. Therefore, allowing it to be properly reproduced through the physical models in circular and sharp crested weirs, but circular spillways as the morning glory one.

# 3 EXPERIMENTAL STUDY

An experimental study was done in the Hydraulic and Fluid Mechanics Laboratory of the Civil Engineering, Architecture and Urbanism College, University of Campinas, using the Paraitinga Spillway model in 1:51.02 scale, Fais (2007). The experimental setup was assembled according to Genovez (1997).

The water level in the reservoir was measure through two point gauges (0.80 m, 0.1mm precise), diametrically opposed. Flow was measured with an ultrasonic flow meter set in the entrance pipe (system 990 Uniflow, working in the range of diameter from 0.0635m to 9.144m, 0.1L/S precision). More details from the experimental setup and methodology may be seen in Fais (2007).

Weber and Reynolds numbers were calculated in order to verify models similitude, besides Mach number, to verify incompressible flow. From the results, one could check that for small heads Weber number was lower than the minimum required, showing that scale effects will appear; Mach number was always lower than 0.2, being incompressible flow. Reynolds number was larger than $10^5$, so viscosity effect could be neglected.

In Figure 1 one shows the 1:51.02 model discharge rating curve, with the prototype one (in

Froude scale). It were also represented the ones obtained by Genovez (1997) for the some spillway in model scales of 1:63.17 and 1:83.29.

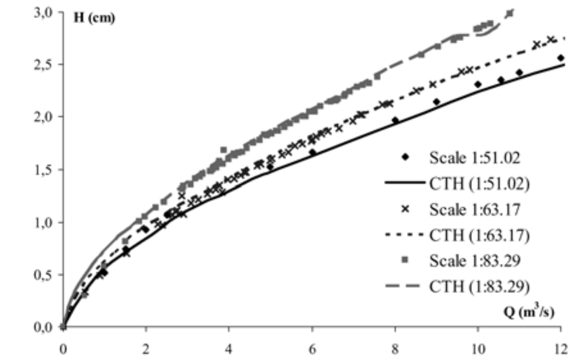


**Fig. 1** Model discharge rating curve in scales 1:51.02; 1:63.17 e 1:83.29

One may note that, for flows up to 0,002m$^3$/s (scale 1:83.29), 0,004m$^3$/s (scale 1:63.17) and 0,007m$^3$/s (scale 1:51.02), there is no good agreement between model and prototype (in Froude scale) discharge rating curve. These flows correspond to approximately 20% the prototype submergence flow, which is equal to 677m$^3$/s (according to CTH, 1971). The disagreement occurs for water levels ranking from 0.010m a 0.015m, approximately, confirming Kolkman's (1984) results.

Because there are no specific equations to correct the discharge coefficient in circular weirs, which is the case of the morning glory spillway, it were used Sarginson's (1972) and also Heidarpour and Chamani's (2006) equations to correct the experimental results showed in Figure 1. Therefore, a comparison with the discharge rating curve corrected with equations (2) to (6) was made, and the results are showed in Figure 2. In Table 1 the maximum percent difference among the prototype discharge flows and the experimental corrected ones (in 1:51.02 scale) is showed.

Observing the graph of Figure 2 and the values showed in Table 1, one may note that the equations did not correct the curves appropriately. This is due to the fact that the equations were proposed for sharp crested spillways or circular crested ones, and not for circular weirs as the morning glory spillway.

**Table 1** **Maximum difference in prototype flows and experimental corrected curves**

| Author equation | Difference (%) |
|---|---|
| Sarginson (1972) | 4～30 |
| Heidarpour e Chamani (2006) | 22～28 |
| Rebock (n. a.) | 24～34 |
| Jaeger (n. a.) | 9～31 |
| Hay and Markland (n. a.) | 17～50 |

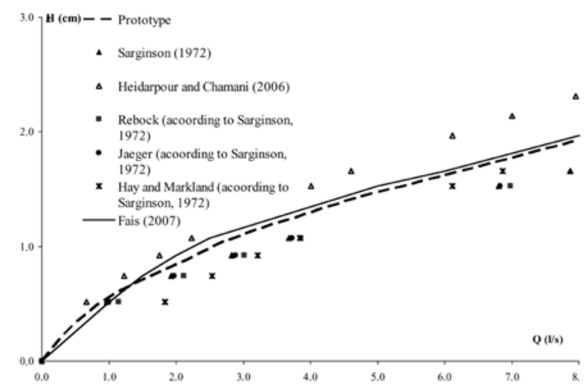


**Fig. 2** Corrected discharge rating curve

The morning glory is a circular weir, therefore, the crest diameter is one of the parameters that is usually taken into account in the spillway discharge. Taking into account the tested equations, it is proposed a new one considering the morning glory crest radium R. Ordinarily, there is no approach velocity influence for great P/H relations. Therefore, the discharge coefficient in the morning glory can be calculated through the equation:

$$C = 1.17 + 0.242d - e \tag{7}$$

where:

$$d = \sqrt{33 - \left(5.5 - \frac{H}{R}\right)^2 2}$$

$$e = 1 - \left(1 + 1.2\frac{H}{R}\right)^{-4/9}$$

It was also proposed a change in Heidarpour and Chamani's (2006) equation, replacing $H/R_c$ for H/R and adjusting its coefficients. Then, the discharge coefficient will be expressed by:

$$C = 2.967\ (H/R)^{0.178} \tag{8}$$

Figures 3, 4 and 5 show the correction in the discharge rating curve with the proposed equations (7) and (8), using the experimental data from the models in 1:51.02; 1:63.17 and 1:83.29 scales. One may observe that the proposed equations correct appropriately the flow values in the models.

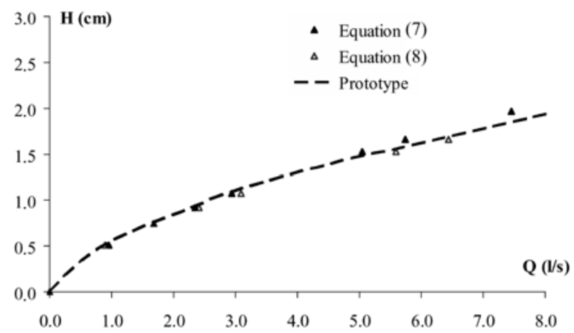


**Fig. 3** Corrected discharge rating curve, model scale 1: 51.02

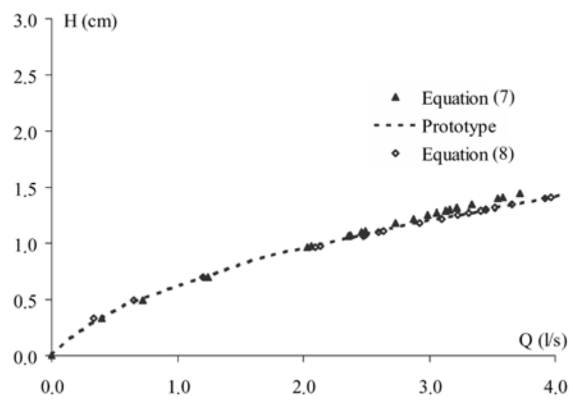


**Fig. 4** Corrected discharge rating curve, model scale 1: 63.17

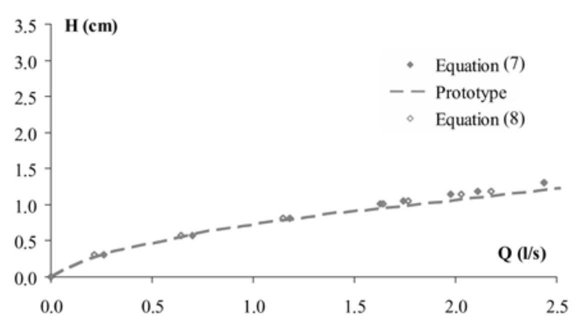


**Fig. 5** Corrected discharge rating curve, model scale 1: 83.29

The suggested correction equations (7) and (8) allow a good agreement in the discharge rating curve, with maximum percent differences of 1,5% and 2.5%, respectively. Equation (8) is easily applicable because it is just a function of H/R.

## 4 CONCLUSIONS

Vertical spillways with a morning glory entrance are a good option when there is no space available in the dam or in embankment and rockfill dams. Besides, vertical shafts have been used in drainage, to convey water flow from a high level to a low one.

This kind of structure is usually designed with physical model studies, that allow reproducing spillway performance in the laboratory, contributing to a good design.

One of the problems of model study is the occurrence of scale effects, because it is impossible to reduce viscosity and surface tension effects. There is a difference in the model discharge-rating curve, related to the prototype one, for small heads over spillway crest.

From experimental results using different scales models, equations were proposed to correct the discharge coefficient of morning glory spillway.

The proposed equations allowed a good agreement between model and prototype data within 2.5% maximum percent difference.

At last, one hopes that this paper can help the design of vertical shaft with morning glory entrance.

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