Reduced hydraulic model of Forquilha IV tailings dam

Modelo hidráulico reduzido da barragem de rejeitos Forquilha IV

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Abstract

This paper presents the development of a reduced hydraulic model (RHM) for the outflow operating system at the Forquilha IV (scale 1:10) tailings dam, owned by Vale S.A. The studies were performed by Centro de Pesquisas Hidráulicas e Recursos Hídricos (CPH) of Universidade Federal de Minas Gerais (UFMG) and the company Vogbr Recursos Hídricos & Geotecnia Ltda. We present here a brief description of the model construction and the test battery set for the structure's hydraulic analysis. RHM involves the hillside culvert, the dissipation box and the exit to the restitution tunnel. The RHM project represents an essential step in the first analysis of the hydraulic behavior of the prototype, considering the designed flood station (ten thousand-year flood flow), as well as the analysis of its operation with more frequent flows.

Keywords: Reduced hydraulic model; tailing dam

Resumo

Esse trabalho apresenta o desenvolvimento de um modelo hidráulico reduzido (MHR) do sistema extravasor operacional da barragem de rejeitos Forquilha IV (escala 1:10), de propriedade da Vale S.A. Os estudos foram conduzidos pelo Centro de Pesquisas Hidráulicas e Recursos Hídricos (CPH) da Universidade Federal de Minas Gerais (UFMG) e pela empresa Vogbr Recursos Hídricos & Geotecnia Ltda. É apresentada, nesse trabalho, uma breve descrição da construção do modelo, bem como a bateria de ensaios prevista para análise hidráulica da estrutura. O MHR representa a galeria de encosta, a caixa de dissipação e a saída para o túnel de restituição. O projeto do MHR representa uma etapa vital na análise preliminar do comportamento hidráulico do protótipo frente à passagem da cheia de projeto (vazão decamilenar), assim como a análise de seu funcionamento para vazões mais frequentes.

Palavras-chave: modelo hidráulico reduzido; barragem de rejeitos

1. Introduction

According to Oliveira (2010), based on terms established by Brazilian Standard (NBR) 13028 (2006), a tailings dam is

"every structure that forms a wall to contain disposal" and that, considering the disposition of the materials, "stores the tailings inside the reservoir in a planned, designed and controlled way." Wrapping tailings reservoirs confined by dams are the most common form of disposal. These dams usually run from a starting dike, made of compact rockfill or embankment with successive raisings, which are performed using the tailings as construction material.

These dams in Brazil came from mining activities, which date back about 300 years ago (CBDB, 2012). However, in recent decades, especially with the progress of mining activities, increased operational scale and the development of new techniques for mining at even low mineral levels, the production of waste to be disposed of in the environment has increased significantly. Thus, the deployment of dams increasing both in relation to height and reservoir volume for tailings has become a reality. These large dams, besides the difficulties inherent to the construction of massif, also have challenges in the design of their components, such as operational and final outflow systems, and their hydraulic energy dissipation structures. There are several references showing criteria for hydraulic design of dam spillways and energy dissipators for multiple water uses, including Chow (1959), USBR (1987), Hager (1992), Sinniger and Hager (1989). However, there are no studies showing criteria for the hydraulic design of operational outflow systems of tailings dams with successive raisings.

2. The place in study

Forquilha IV tailings dam is being built in the area of Mina de Fábrica, in the city of Ouro Preto, Minas Gerais. The reservoir of the dam will be capable of storing a volume of approximately 35 Mm³ tailings. Its operation is scheduled to start in 2014 and will be performed in four major steps: a) starting dike (in compacted soil), height of about 20 m, b) initial dam (also in compacted landfill), height of about 45 m, c) implementation of outflow operating system (object of reduced hydraulic model presented in this work) and d) 7 raising dams of 10 m each, using tailings as construction material (the outflow operating system will serve this step, and the project is already in operation).

The operational outflow system has the following structural components: 1) hillside culvert, made of 13 towers for water intake and the gallery itself, 2) transition box, which has the purpose of hydraulic energy dissipation and restitution of the flow to the tunnel, 3) exit tunnel; 4) dissipation basin, which will aim to dissipate the stream energy before returning it to the thalweg adjacent to the reservoir of the Forquilha IV dam. Figure 1 shows the general arrangement of the Forquilha IV dam's outflow operating system, highlighting its structural components.
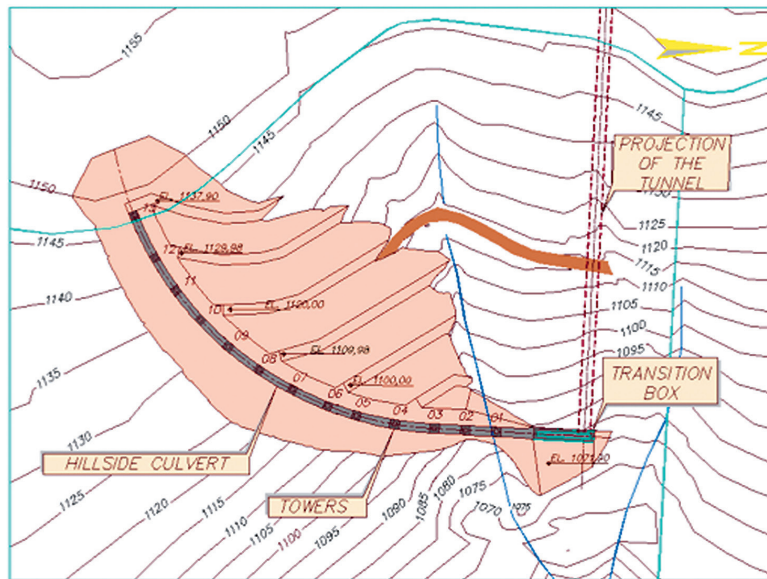

Figure 1
Overall arrangement of Forquilha IV dam outflow system operation

3. Materials and methods

The reduced hydraulic model for the outflow operating system of the tailings from the Forquilha IV dam was executed using a geometric scale of 1:10, considering the recommendations proposed by Lopardo (1986) and Teixeira (2008).

The scale for translating the results for the prototype obeyed Froude's Law (equality of Froude's Number with the prototype model), which is ruled by the following relationships:

$$\frac{L_p}{L_m} = \lambda \quad (1)$$

$$\frac{V_p}{V_m} = \sqrt{\lambda} \quad (2)$$

$$\frac{Q_p}{Q_m} = \sqrt[2]{\lambda^5} \quad (3)$$

$$\frac{q_p}{q_m} = \sqrt[2]{\lambda^3} \quad (4)$$

$$\frac{P_p}{P_m} = \lambda \quad (5)$$

Where: λ is the ratio of the geometric dimensions between the prototype (p) and the model (m) in meters;

L_p and L_m are the lengths (m);
V_p and V_m are the velocities (m/s);
Q_p and Q_m are the flows (m³/s);

q_p and q_m qm are the specific flow rates (m²/s);
P_p and P_m are the pressures (m.c.a.).

The reduced hydraulic model represents the hillside culvert, more precisely, the 6 towers located downstream (as shown in Figure 2), the transition box and the restitution of the flow to the exit tunnel.

The representation of these 6 towers more downstream is due to the fact that in a span of approximately 70 m of descending steps (prototype value), according to the methodology proposed by Matos (1999), the flow reaches maximum power dissipation and uniformity of aerated blade (air + water).
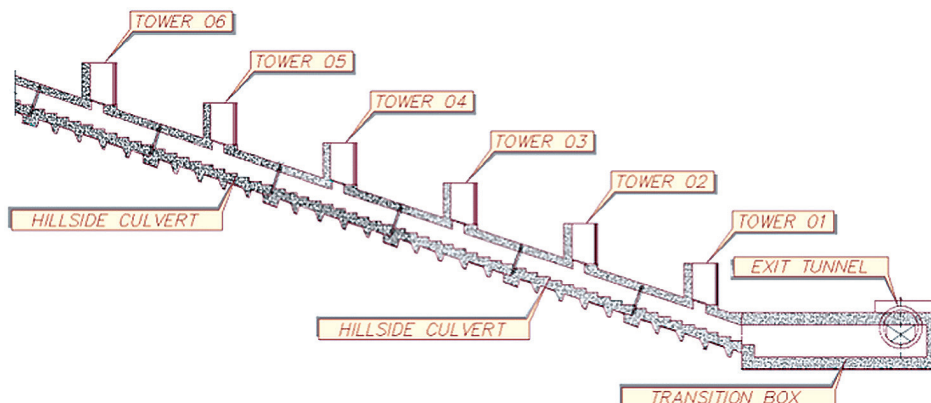

Figure 2
Hillside culvert represented in the reduced model.

The dimensions of the hillside culvert, for the transition box (prototype), and the physical model (including the towers for water intake) have the geometrical characteristics presented in Table 1.

The purpose of the transition box is to dissipate the energy from the flow of the hillside culvert and direct it to the exit tunnel.

	Characteristic	Model	Prototype
Hillside culvert	Internal section	Rectangular (15 cm x 18 cm)	Rectangular (1.5 m x 1.8 m)
	Extension	≅ 9 m	≅ 90 m
	Elevation	≅ 3.5 m	≅ 35 m
	Characteristic	Model	Prototype
Water intake towers	Quantity	06	06
	Internal section (throttle section)	Square (15 cm x 15 cm)	Square (1.5 m x 1.5 m)
	Altura	50 cm	5.0 m
	Characteristic	Model	Prototype
Transition box	Internal section	Rectangular (15 cm x 41 cm)	Rectangular (1.5 m x 4.1 m)
	Extension	2.15 m	21.5 m

Table 1
Geometric characteristics of hillside culvert

Importantly, the exit tunnel was not part of the system that makes up the reduced physical model.

Thus, only its mouth was patterned, positioned in the sidewall of the transition box.

It was then possible to verify the possible occurrence of drowning, even with the passage of flows from the outflow operating system design. The model consists of a passage in an opening 35 cm wide by 25 cm (model values), in an U-shaped section. Figure 3 shows a detail of the water intake tower to be installed in this outflow system.
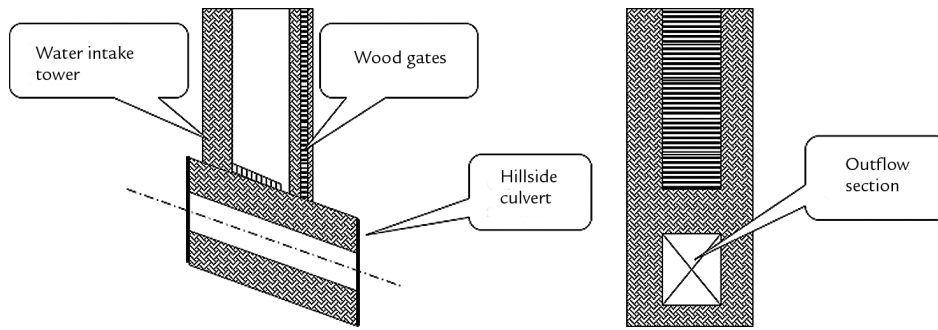
Figure 3
Detail of the water intake tower
(built into the hillside culvert).

For the hydraulic dimensioning of the outflow system, in the design phase, we considered the assumptions that control would be made by the towers and water intake and that the structure would work in a free-flow situation.

Thus, for determining the discharge curve, both for the passage of the flow from only the sides of a tower as in the situation of restitution through two towers (flow input plus the side input from the upstream tower).

$$Q = C_d \cdot L \cdot H^{1,5} \tag{6}$$

Where: Q is the flow spilled (m³ / s), C_d is the discharge coefficient (m^{0,5}/s) = 1.7 (adopted value presented by Azevedo Netto and Alvarez, 1988, and, Porto, 1998), H is the hydraulic head (m), L is the sill width (m).

The model was constructed of wood, supported by a metal frame.

The connection of the model to the water supply system was made using flexible hoses connected to centrifugal pumps, controlled by frequency inverters.

The wood waterproofing was made with SikaTop (consisting of a coating, semi-flexible, impermeable, protective, and based on cement, sand and selected acrylic resin). Figures 4 to 7 show stages of construction of the reduced model of the outflow system of Forquilha IV dam.

Figure 4
Hillside culvert surrounded by metal framework that will support the structure for the reduced model

Figure 5
Water reservoir and towers already waterproofed with SikaTop.

Figure 6
Hillside culvert
connected to the outlet pipe

Figure 7
Front view of hillside culvert and reservoir

4. Tests

The outflow operating system for the Forquilha IV dam has been designed for the passage of a ten thousand-year flood (flow rate 25 l/s, corresponding to the model value).

The tests for the reduced physical model of Forquilha IV's outflow system are described below.

1. Tests to verify the discharge curve given the floodwater being restored only by the sides of a tower's outlet water. Situations in which flooding occurs from towers 01, 02 and 05 are demonstrated in Table 2.

2. Tests to verify the discharge curve (7 flows, including full project) of the outflow operating system, whereby at first the floodwater was restituted by tower 01 (entrance by the sill) and 02 (side entrance), afterwards by towers 02 and 03 and, in sequence, by towers 05 and 06, the latter being located further upstream. Table 3 presents a summary of the testing for this situation.

Test	Flow (prototype values – m³/s)	Flow (model values – l/s)	Total of tests
	0.95	3	3
	1.58	5	3
	3.16	10	3
Towers 01; 02; 05	4.74	15	3
	6.32	20	3
	7.91*	25*	3
	9.49	30	3
Total of tests			21

Table 2
Test battery for incoming
flow from the sides of the towers

* Flow rate corresponding to a ten thousandyear flood.

Tests	Flow (prototype values – m³/s)	Flow (model values – l/s)	Total of tests
Towers 01 and 02; 02 and 03; 05 and 06	0.95	3	3
	1.58	5	3
	3.16	10	3
	4.74	15	3
	6.32	20	3
	7.91*	25*	3
	9.49	30	3
Total of tests			21

Table 3
Test battery for incoming flow through the downstream tower sill and the side of the upstream tower (subsequent).

* Flow rate corresponding to a ten thousand year floodwater.

Figures 8 to 10 show passage of the ten thousand-year floodwater, considering outflow through the sill of tower 02 and side of tower 03, simultaneously.

In Tables 2 and 3, the hydraulic flow discharge values on the tower sill and sides are estimated from the flow depth measurements performed using a ruler installed in the reduced model structure.

Figure 8
Passage of ten thousand-year floodwater (flow rate of 25 l/s, corresponding to the model value), simultaneously through the sill of tower 02 and side of tower 03- view from the transition box.
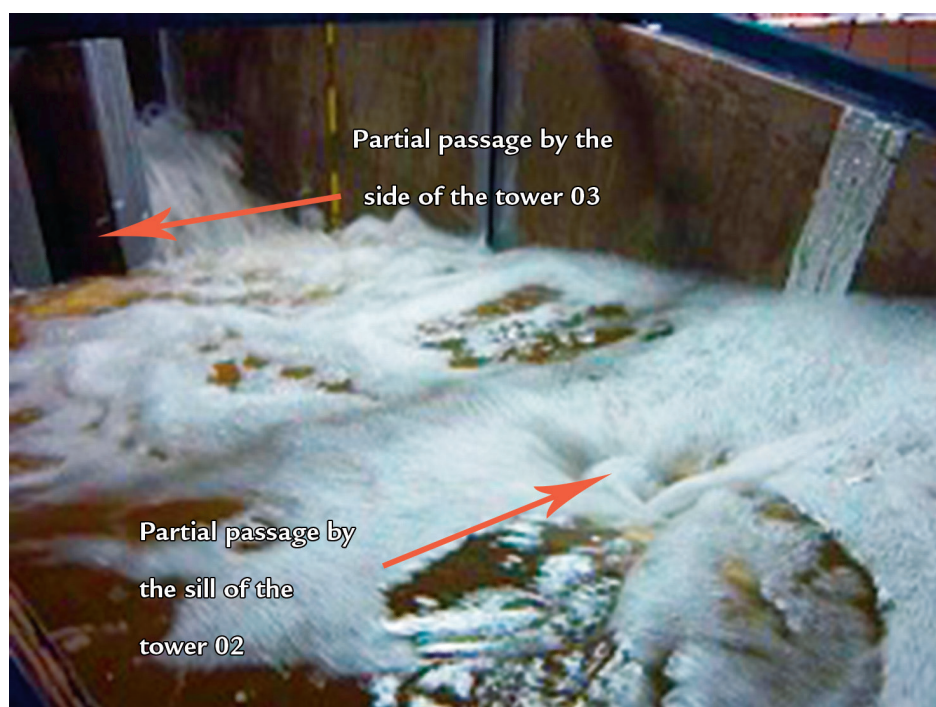

Figure 9
Passage of ten thousand-year floodwater, simultaneously through the sill of tower 02 and side of tower 03.
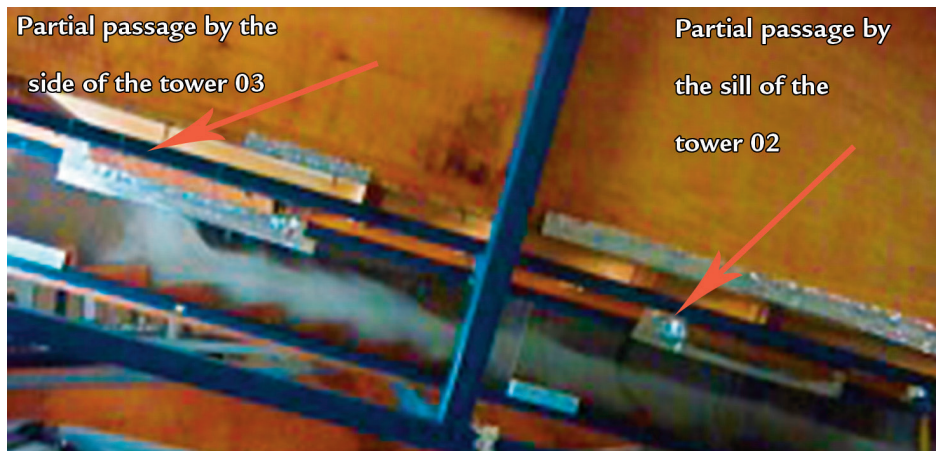
Figure 10
Passage of ten
thousand-year floodwater, simultaneously
by the sill of the tower 02 and the side of
the tower 03 - view from the culvert.

5. Discussion

A comparison of analytical and experimental values of discharge flow on the tower sill and sides is performed using the results presented in Tables 2 and 3. The analytical flow estimates are based on the equation proposed by Azevedo Netto and Alvarez (1988) and Porto (1998).

Figure 11 presents the comparison of discharge curves resulting from tests in which the flow occurs only from the side of one tower, as shown in Table 2. It can be noted that the curves are parallel to each other and have good adherence to the theoretical discharge curve

determined in the design, according to Equation 6. The charge differences are about 0.10 m. The analysis of Figure 12 also shows that tower 5 presented a slight lag result ($\cong 0,30$ m). We can explain this because of the proximity of the tower to the model's pipe flow supply. This proximity made the spill occur in a turbulent way, hindering the accurate reading of the water level inside the reservoir model.

Figure 12 shows a comparison of discharge curves resulting from tests in which the flow occurs through the tower sill and simultaneously through the side

of the upstream tower (tests according to Table 3).

The results for towers 1 and 2 (as well as for towers 2 and 3 - which showed identical results) are slightly higher ($\cong 0.05$ m) than the predicted design values (Eq. 6). Again, there is an exception presented by the outflow from towers 5 and 6, where the discharge curve became distanced from predicted values ($\cong 0.15$ m) in design (Eq. 6). Also this fact can be explained by the proximity of the towers to the flow supply pipe of the model, as aforesaid.

Figure 11
Discharge curves for situation of flow
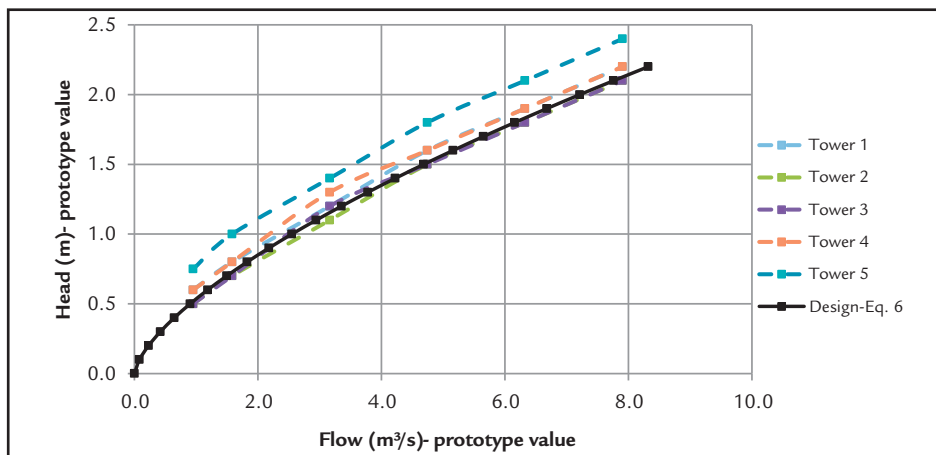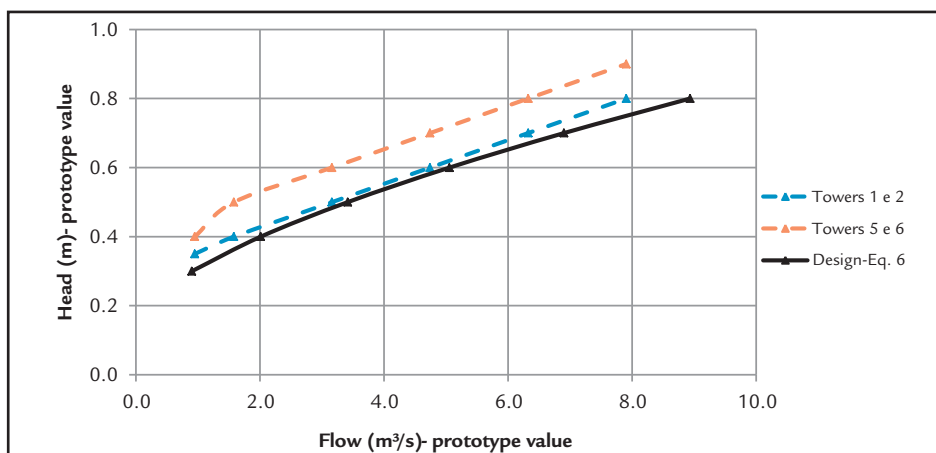through the lateral of water intake towers.

Figure 12
Discharge curves for the situation
of the outflow through the sill of the downstream tower and through the side of
the upstream tower (subsequent).

The average relative deviation of the values depicted by the discharge curves obtained from the hydraulic reduced model for the outflow operating system of Forquilha IV tailings dam in comparison with the values predicted by Eq. 6 for the prototype are within the range from 5% until 15% for both test experimental conditions, flow through the tower side (Figure 11) and flow through the sill of the tower (Figure 12).

The small values of relative deviation between the modeled experimental test results and the predictions from the classical equation (Eq. 6) indicate that this equation can be employed to render the basic dimensions of the outflow operating system of Forquilha IV tailings dam. However, in the preliminary design stages, it is highly recommended to perform studies using reduced models in order to estimate the discharge curves for different flow and operating conditions.

Due to the fact that the dam crest (considering each proposed raising) is always higher than 5.0 m from the tower sill, we can state that the outflow operating system is capable of draining the design flow (ten thousand-year floodwater).

6. Conclusions and recommendations

According to the tests obtained from the reduced model of the outflow operating system in the Forquilha IV dam, we can state that it is able to drain the designed flow (Ten thousand-year floodwater recurrence), for situations anticipated operational (inlet flow only from the side of the towers or entry, concomitantly, the sill and side tower amount), ensuring building integrity.

Observation of the phenomena of water entrance in the structure, both through the sill and through the side of the tower, allows proposing changes to the design of the structure in order to reduce its dimensions, while maintaining its discharge capacity. This indicates the possibility of optimizing the structure by reducing installation costs. The results of this physical model allows for the preliminary hydraulic evaluation of similar structures, such as future operations of the Forquilha V (Mina de Fábrica, Ouro Preto/MG) and Fazenda Velha (Mining Complex Vargem Grand, Rio Acima/MG) dams.

However, we recommend that the physical models be implemented in the early stages of design, because such studies are able to stimulate improvements for structures, such as decreasing insurance costs for project implementation.

In future investigations, pressure measurements on the hillside culvert and on the dissipation box as well as flow speed measurements can be performed in the model. With the measured pressure and velocity fields, it would be possible to obtain a reliable estimate for the hydraulic forces, which could be very useful for the structural design of the prototype.

7. Acknowledgements

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