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Reduction of the erosive effects of effluent jets from spillways by contractions in the flow

Redução dos efeitos erosivos de jatos efluentes de vertedouros através de contrações no escoamento

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ABSTRACT

Flaring Piers and Slit Buckets are structures that can improve the process of energy dissipation and have been implanted in Chinese spillways for at least four decades. These structures basically narrow the passages of the outflow through the spillway, promoting changes in the effluent jets, reducing their erosion potential. However, the literature available on the subject is very limited, and the benefits are disseminated only qualitatively. In order to learn more about how these structures perform, a test program on a hydraulic model was carried out, using a spillway originally designed with a conventional ski jump. The results indicate that there is a correlation between the angle of deflection of the walls that narrow the chute and the depth of the scour hole formed downstream. One of the alternative tests had scour depth 60% smaller than that generated by the spillway without the device, indicating that they can be promising solutions.

Keywords: Ski jump; Erosion; Flaring piers; Slit bucket.

RESUMO

Flaring Piers e Slit Buckets são estruturas que propiciam melhorar o processo de dissipação de energia e que vem sendo implantadas em vertedouros de barragens chinesas há pelo menos quatro décadas. Trata-se basicamente da implantação de estreitamentos na passagem do escoamento pelo vertedouro que promovem alterações no jato efluente, reduzindo seu potencial erosivo. No entanto, a bibliografia disponível sobre o assunto é bastante restrita e os benefícios são divulgados de forma apenas qualitativa. Visando aprofundar o conhecimento sobre o desempenho dessas estruturas, foi realizado um programa de ensaios em modelo reduzido utilizando um vertedouro projetado originalmente com salto de esqui convencional. Os resultados indicam existir uma correlação entre o ângulo de deflexão dos paramentos que estreitam a calha e a profundidade da fossa de erosão formada a jusante. Uma das alternativas ensaiadas teve profundidade máxima de erosão 60% menor do que aquela gerada pelo vertedouro sem o dispositivo, indicando que podem ser soluções promissoras.

Palavras-chave: Salto de esqui; Erosão; Pilares alargados; Defletores em fenda.

INTRODUCTION

Spillways are devices which ensure the safety of hydraulic works, appropriately discharging the surplus flow. It is essential to correctly size their discharge capacity and provide the dissipation of kinetic energy from the flow.

The classical forms used in the dissipation of energy from spillways consist in launching the jet downstream, which happens with ski jump spillways, or when a hydraulic jump is imposed, which happens with stilling basins spillways.

Often the excess energy resulting from the operation of these structures causes problems downstream, such as deep scour hole, formation of bars of eroded rock, return currents close to the dam, excessive fluctuation of the water level and damage to concrete in stilling basin slabs.

A classical case is that of the Jaguara Hydropower Plant, where the operation of the ski jump spillway created a deep scour hole, whose deepest point was situated 31 m below the rocky surface (PEREIRA; BRITO; GONÇALVES, 1991). This hole entrapped and caused fishes to die and it was necessary to open a channel for the fishes to get out from the hole. A similar case occurred at the Governor José Richa Hydropower Plant (Salto Caxias), on Iguaçu River, where fish were also entrapped. This was not due to the formation of a scour hole, but rather to the formation of a considerable bar, constituted by a eroded rock blocks. Problems involving damage to the stilling basin slab are also common, such as at the Hydropower Plants of Marimbondo and Porto Colombia (ABRH, 1997).

In the 1970s China began flourishing economic development, with the construction of many multiple use dams, including power generation. The construction of increasingly high dams, of more than 200 m, in narrow valleys often with rocks that had unfavorable characteristics for resistance to hydrodynamic effects, such as limestone, required the development of different solutions for the dissipation of energy of flow from their spillways. Noteworthy among the solutions implemented in China are the structures called Slit Buckets and Flaring Piers due to their vast application, as seen in the study presented by Lara (2011).

Basically, these structures are contraction of the released flow for the purpose of promoting changes in the flow to reduce their erosive potential, consequently reducing the occurrence and severity of damage downstream of the spillway (LARA, 2011).

In 2000, Gao, Liu and Guo published an extensive review of the state-of-the-art of Chinese dams, in which Slit Buckets and Flaring Piers are broadly analyzed. Table 1, elaborated based on the data from Gao, Liu and Guo (2000), presents some dams where these solutions were employed, as well as their type, height (Hb), difference between upstream water level and deflector elevation (Hd), design flow and type of spillway.

Seeking to gain a better understanding of how these devices function and to evaluate their performance, Companhia Paranaense de Energia (Copel) employed the Institutos Lactec (CEHPAR) in the Research and Development Program of Agência Nacional de Energia Elétrica (ANEEL) to develop a research project using a hydraulic model for this purpose. An extensive testing program was carried out using the hydraulic model of Mauá Hydropower Plant built on Tibagi River in Paraná State, to evaluate the hydraulic behavior and the efficiency of these structures in reducing erosion downstream of ski jump spillways. The present article is a summary of the main conclusions of this research.

Table 1. Chinese Dams with Flaring Piers and Slit Buckets.

Project	Type of Dam	Hb (m)	Hd (m)	Design Flow (m^3/s)	Type of dissipation
			Flaring Piers		
Geheyan	Gravity Concrete	151	-	17,060	Launching in plunge pool
Ankang	Gravity Concrete	128	-	37,000	Stilling basin
Dachaoshan	Roller Compacted Concrete	115	-	23,800	Stepped chute and stilling basin
Wuqiangxi	Gravity Concrete	84.5	-	55,962	Stilling basin
Yantan	Gravity Concrete	76	60.40	32,760	Stilling basin
Shuidong	Roller Compacted Concrete	57	-	8,232	Stepped chute and stilling basin
			Slit Buckets		
Shuibuya	Concrete Face Rockfill	234	171.00	15,243	Ski jump
Hongjiadu	-	182	-	6,996	Ski jump
Longyangxia	Gravity Concrete Arch	178	-	2,247*	Ski jump
Dongfeng	Concrete Arch	162	77.78	1,080*	Direct launching in plunge pool
Dongjiang	Concrete Arch	157	99.25	1,450*	Skijump
Lijiaxia	Concrete Arch	155	113	2,155*	Direct launching in plunge pool
Geheyan	Gravity Concrete Arch	151	77.1	1,013*	Launching in plunge pool
Xibeikou	-	95	78.89	2,233*	Ski jump
Nanyi	Gravity Concrete	-	-	-	Surface spillway

*Total flow through one gate. Source: Elaborated with data from Gao, Liu and Guo (2000).

SLIT BUCKETS AND FLARING PIERS

According to Huang, Zhang and Duan (2006), the first dam to use the device known as Slit Bucket was the Portuguese Dam of Cabril, built in 1950, where converging walls were implemented at the exit from a tunnel. There are records of experiences in other countries, but Slit Bucket began to be implanted systematically with the construction of several dams in China. Figure 1 shows a bottom outlet gate operating with Slit Bucket at the Chinese dam of Geheyan, when it was still being built.

This device consists of a relatively abrupt narrowing of the spillway chute wall in order to project vertically the effluent flow. In this kind of deflector, the effluent jet incorporates a lot of air and its area of impact on the river bed has a more favorable geometry than that produced by a conventional deflector (CEHPAR, 2009). The narrowing is located at the downstream extremity of the spillway chute, and it can be implanted simply by deflecting the walls or by broadening them, a decision that will depend on the analysis of the efforts provoked by flow. The Slit Bucket geometry is shown in Figure 2.

The main parameters that define the geometry of these structures are:

$$\eta = \frac{b}{B} \tag{1}$$

$$a = \frac{B-b}{2} \tag{2}$$

$$\theta = arctg\left(\frac{a}{L}\right) \tag{3}$$

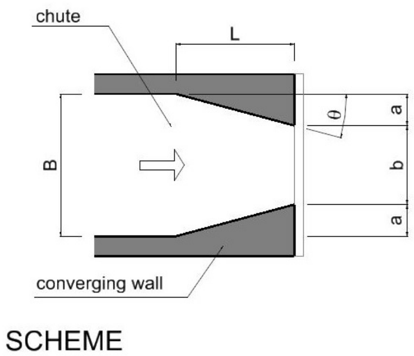
where:
B: Width of the chute upstream from the contraction (m);
b: Width of chute in the most contracted section of the contraction (m);
a: Distance between the pier ending edge and the beginning of the narrowing, perpendicular to the flow (m);
L: Length of contraction, parallel to the flow (m);
η: Contraction ratio (non-dimensional or percentage wise);
θ: Angle of deflection (degrees).

In their book on Chinese Dams, Gao, Liu and Guo (2000) recommend that the contraction ratio "η" vary between 1/3 and 1/6 and that the slope with the horizontal plane of the final stretch of the chute be situated between -10º and +45º. Figure 3 shows the intermediate outlet of the Dongfeng dam, where Slit Buckets were implanted in a stretch of chute with a negative slope.

The authors recommend also that the flow upstream of the deflector should have a Froude number greater than 4.0 to operate it. According to an experience performed by Ota and Tozzi (1994), aerator deflectors also do not operate adequately for flows with Froude number of less than 4.0. Gao, Liu and Guo (2000) warn however, that if the Froude number is too high, a strong shock wave may occur inside the deflector. They also cite that the implantation of the Slit Bucket may cause a reduction between 1/3 and 2/3 of the scour hole that would be provoked by a conventional spillway.

The Flaring Piers consist in the narrowing of the chute immediately downstream from the spillway crest, so that the changes provoked in the flow begin already in the chute. In this solution, the concentrated flow of adjacent gates, after passing through the contraction, spread through the chute colliding with each other and generating flow patterns in the shape of very marked and aerated "rooster tails". Besides the efficiency in reducing the potential for erosion, this type of structure presents the advantage

Figure 1. Slit Bucket at Geheyan Dam in China. Source: China Gezhouba Group International Engineering Co. Ltd (2010).



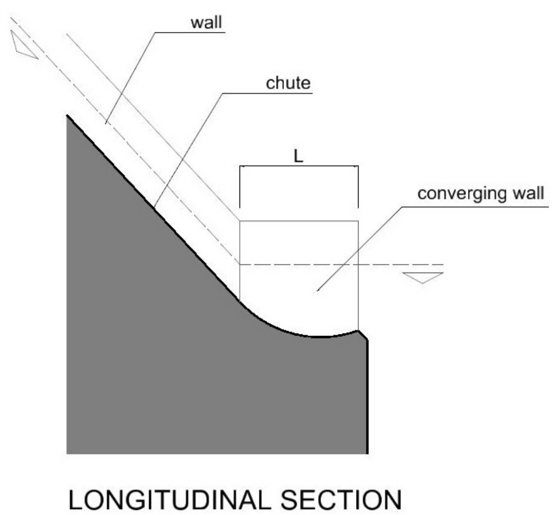


Figure 2. Sketch and typical section of Slit Bucket.

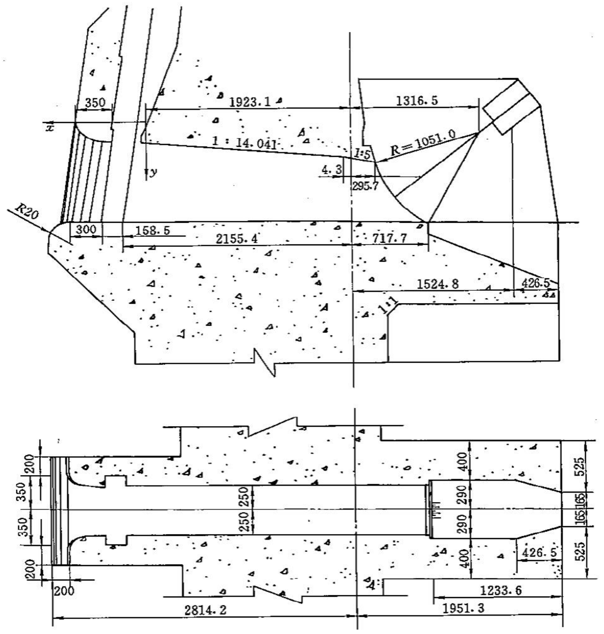


Figure 3. Outlet of the Dong Feng dam. Source: Gao, Liu and Guo (2000).

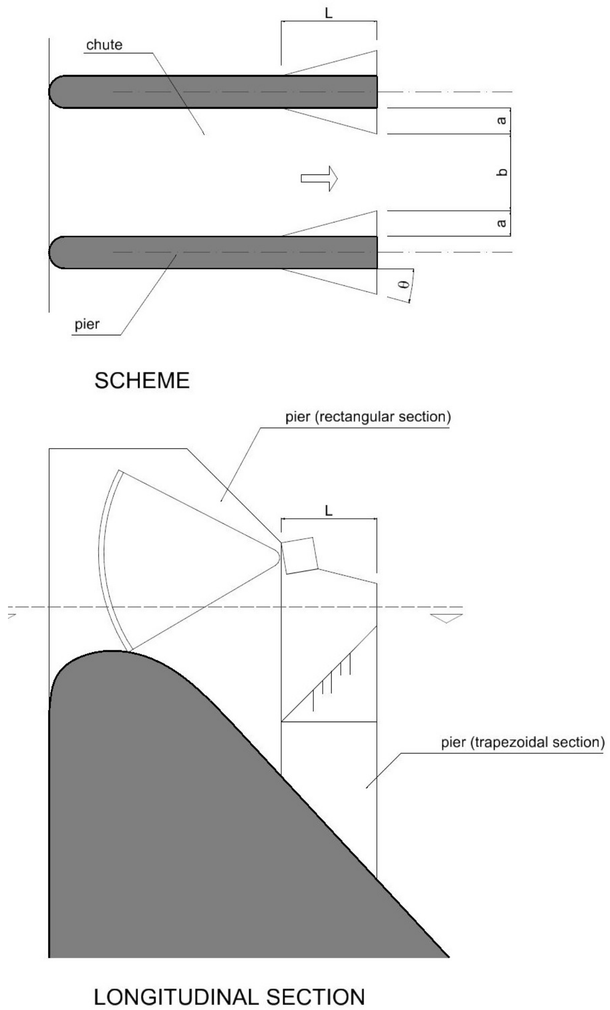


Figure 4. Scheme and typical sections of Flaring Pier.

Figure 5. Dachaoshan spillway. Source: MD&A (2018).

of being more versatile than the Slit Buckets, because it enables a combination not only with ski jumps, but also with a stilling basin, stepped chute and others.

The parameters that define their geometry are the same that define the Slit Bucket geometry, as shown in Figure 4.

The contraction ratio usually adopted in these devices is larger than one suggested for the Slit Buckets, with a value between 0.7 and 0.3. According to Gao, Liu and Guo (2000), this structure enabled the implantation of dams in narrow valleys with a geology of soft rocks, ie., the Flaring Piers provided the Chinese with a solution for less favorable local conditions of these constructions (Figure 5).

It should be emphasized that these devices are not really energy dissipators, but they change the effluent jet so as to diminish the energy concentration in the area where jet impact the riverbed, reducing the erosion potential.

HYDRAULIC MODEL TESTS

In order to study the Slit Buckets and Flaring Piers the hydraulic model of Maua Hydropower Plant spillway was used. It had been constructed and calibrated in the laboratory of the Institutos Lactec (CEHPAR), and had to be adapted especially for the tests. This plant has a roller compacted concrete dam (RCC), with a maximum height of 85 m, which includes a controlled spillway with four gates measuring 11.40 m wide and with 16.00 of water head for the maximum normal level. It has a single chute with a total width of 57.60 m and a ski jump with slope of bucket lip at 20º (VLB ENGENHARIA, 2009), as shown in Figure 6.

The dam lies over a layer of diabase and the region that receives the impact of the jet is formed by sedimentary rock. Despite the contribution of the present research, the spillway design of UHE Mauá was defined previously and did not benefit from this study.

The model was conceived according to the Froude similarity criterion, and its geometric scale is 1:100. In order to perform scour tests with movable bed, a box was constructed downstream from the spillway, under the riverbed level. The box was filled with gravel (relative density δs= 2.65), representing rock blocks 1.1 m in diameter on prototype scale (CEHPAR, 2006). The configuration of this box was for the purpose of simulating scour that was reasonable from the practical point of view, since, considering the type of rock in the region, steep embankments are expected for the scour hole in the prototype.

Table 2 shows the alternatives tested, which can be divided into three groups: conventional ski jump, ski jump with Slit Buckets and ski jump with Flaring Piers.

Alternative 1 simulates the original project of the spillway of Mauá Hydropower Plant. In Alternative 2 the piers were lengthened so as to constitute four independent chutes. These two alternatives, without any contraction in the chute were studied for comparison with those where the Slit Buckets and Flaring Piers were implanted. In Alternatives 3 to 5, Slit Bucket deflectors with different wall geometries were tested in an exploratory form. The geometry of Alternatives 6 and 7 was adjusted due to the performance problems found in the exploratory tests. In alternatives 8 and 9 the Flaring Piers were analyzed.

Thus, it was considered useful for the analyses to separate the tests into two groups: Alternatives 1, 8 and 9 to study Flaring Piers (consisting of a single chute), and Alternatives 2 to 7 to study the Slit Bucket (consisting of four independent chutes).

Figure 6. Pilot hydraulic model used in tests – original configuration.

Five discharges were tested for each alternative: 2,070 m^3/s; 3,371 m^3/s, 4,491 m^3/s, 5,792 m^3/s and 7,173 m^3/s, which correspond, respectively, to the times of recurrence [Tr] of 5, 25, 100, 500 and 10,000 years at the dam site. Each flow was tested for 2 hours, which corresponds to 20 h of operation in the prototype.

For the test with a flow corresponding to a 5-year recurrence, the movable bed was set to the original level of the river bed. The other tests were performed in ascending order of flow, and the scour in the previous test was maintained, in order to simulate what really happens during a flood. In order to verify this criterion, the last flow was imposed for over 2.5 hours, and no changes were detected in the measures of scour, which shows that stabilization of the erosive process occurs within the 2 h interval.

Various observations and records were performed of the flow patterns during the tests. The longitudinal profiles of the jet, as well as their horizontal throw distance were measured. After each test the scour hole formed was emptied and measured according to five profiles parallel to the direction of flow, so as to cover the entire hole and the bar of rock blocks formed downstream.

Except for the test performed for the 10,000-year flood, the tests were performed maintaining the reservoir level at the elevation of 635.00 m. For the discharge of the 10,000-year flow the project of Mauá foresees the additional elevation of 1.5 m in the reservoir level, and as in the prototype this condition was imposed on the model.

The downstream level was set by an uncontrolled spillway of a small old hydro plant located about 500 m downstream from the pilot spillway. The total head of flow, H [m], measured between the reservoir level and the water level downstream, varied from 61.45 m to 66.43 m.

RESULTS AND DISCUSSION

Hydraulic behavior of the slit buckets

The observations made in the Slit Bucket tests confirmed the descriptions of Gao, Liu and Guo (2000) about the aspects of the effluent jet, especially regarding its longitudinal dispersion. Part of these aspects is shown in Figure 7, drawn from observations during the tests.

Table 2. Structures Tested.

Name of alternative	Type of structure	Contraction Ratio "η"	Angle of deflection "θ"	Chute	Shape of cross-section
Alternative 1	Conventional Ski Jump	0	0	Single	rectangular
Alternative 2		0	0	Divided	rectangular
Alternative 3*	Ski Jump with Slit Bucket	0.50	14.3	Divided	rectangular
Alternative 4*		0.33	18.9	Divided	rectangular
Alternative 5*		0.16	23.2	Divided	rectangular
Alternative 6		0.33	10.1	Divided	rectangular
Alternative 7		0.25	11.2	Divided	in "Y"
Alternative 8	Ski Jump with Flaring Piers	0.70	15.0	Single	rectangular
Alternative 9		0.50	19.0	Single	rectangular

(*) Exploratory tests

These observations allow distinguishing what happens with the flow in three stretches:

- the first stretch lies between the beginning of the chute contraction and the section where the standing waves collide. These waves are generated at the time when the flow is affected by deflections of the walls and advance with the streamflow in the direction of the chute axis;
- the second stretch begins in the section where the collision of the standing waves occurs (vertex), which is well defined and stable. At this point a vertical superior "rooster tail" (unstable) is generated and another inferior one (stable), and a great air adduction via the vertex can be observed. The stretch ends at the section where the streamflow reaches maximum contraction according to its horizontal projection shown in Figure 7;
- the third stretch begins after the maximum contraction section and ends in the region of jet impact downstream. In this stretch the "rooster tails" expand up to the top of their parabolic trajectory, which confers the aspect of great longitudinal dispersion cited by the bibliography. In several tests it was observed that in this region the flows from adjacent gates touch or even unite.

It should be emphasized that a series of effects considered inadequate from the point of view of the hydraulic operation of the spillway were observed during the Slit Buckets tests, with contraction ratios of 50%, 33% and 16%, showing that these structures (Alternatives 3, 4 and 5) were not well sized. Among these effects can be cited the fact that the jet overtops the deflector walls and the inclination of the "rooster tails", which at one point was vertical, with streamflow returning to the chute in one of the tests, showing an indication that the flow did not have the energy to pass the deflector without being controlled by it. These effects culminated in drowning the flow inside the deflector, which happened to the structure with a contraction ratio of 16%. These observations are discriminated for each flow in Table 3.

Except for the flow with a recurrence time of 500 years, the flows were imposed with equal openings for the four gates. For the flow with a 500-year recurrence time, the two central gates operated with partial opening, while the lateral gates operated completely open. Therefore, the results, both of hydraulic behavior and of scour, where distinct from other alternatives and were ignored in order to not distort the analysis.

The explanation for this inadequate behavior was found in the studies performed by Yarnell (1934a,b), which deal with the behavior of supercritical flows in channel contractions. According to these studies, based on the contraction ratio "η" and the Froude number of flow upstream from the contraction, it is possible to distinguish the flow with "unlikely" drowning from flow with "inevitable drowning" based on Equations 4 and 5.

$$\eta^2 = \frac{27 \cdot Fr_1^2}{\left(2 + Fr_1^2\right)^3} \quad (4)$$

$$\eta = \frac{\left(2 + 1/\eta\right)^3 Fr_3^4}{\left(1 + 2Fr_3^2\right)^3} \quad (5)$$

Plotting the Froude numbers calculated for the tests as a function of the contraction ratio of each alternative, it was found that the drowning of the flow based on the discharge with a 100-year recurrence (Fr=4.99) is inevitable for Alternative 5 (Figure 8). At the other extreme, Alternative 3 has an "unlikely"

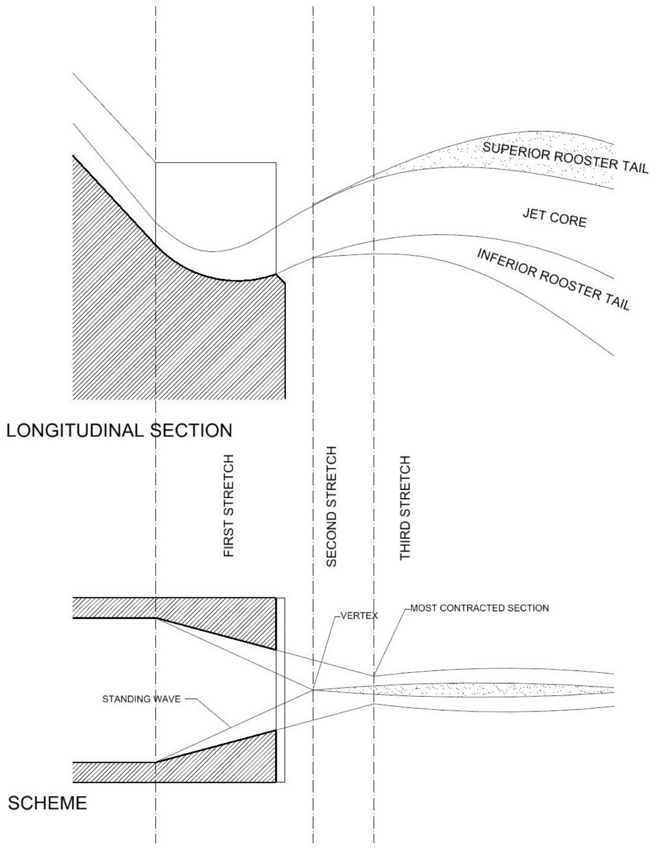


Figure 7. Aspect of effluent jet from Slit Buckets.

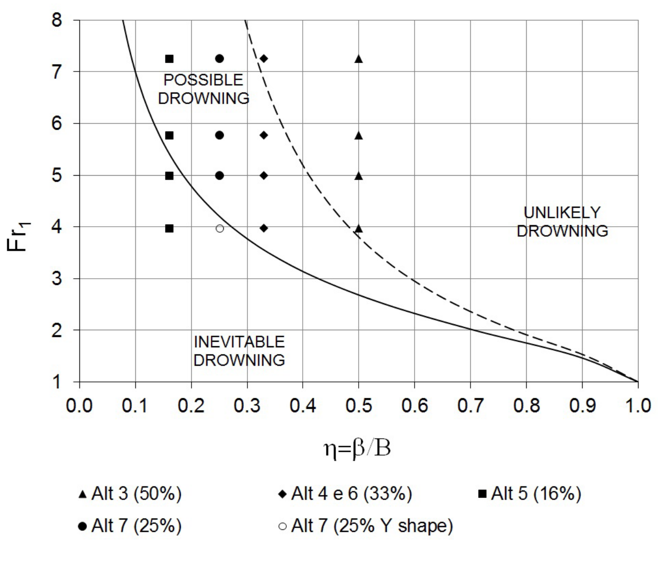


Figure 8. Data of the Slit Bucket tests plotted with the Yarnell equations.

drowning condition for all flows, which was evidenced in the observation of the tests.

However, the studies by Yarnell were performed for horizontal channels, in order to evaluate the effect provoked by bridge piers, and do not take into account friction and minor head losses. In this study there are losses along the chute and walls of the spillway. Thus, for more precise results, it is necessary to perform analytic changes in the equations.

In order to verify the influence of angle of deflection "θ" on the hydraulic behavior of the deflectors, alternatives with smaller angles were tested (Alternatives 6 and 7). The inadequate characteristics of the hydraulic behavior of the Slit Buckets of these alternatives can be considered less important compared to those of Alternatives, 3, 4 and 5, and, in brief, were the intersection of the standing waves within the structure and to incidence of the "rooster tails" against the wall for intense flows.

Alternative 7, besides the smaller angle was conceived with a "Y" shaped cross section, as in Figure 9, so as to have additional area to not control streamflows with discharges greater than the 100-year (4,491 m^3/s), an artifice that had a positive effect. Flaring Piers with a "Y" shaped cross section are found in many Chinese dam spillways.

Hydraulic Behaviors of the Flaring Piers

The observations of the tests with Flaring Piers (Alternatives 8 and 9) showed that despite the similarity with the Slit Buckets regarding the mechanism to generate flow disturbances, the effects of these disturbances are propagated along the chute, taking on distinct characteristics as can be seen in Figure 10.

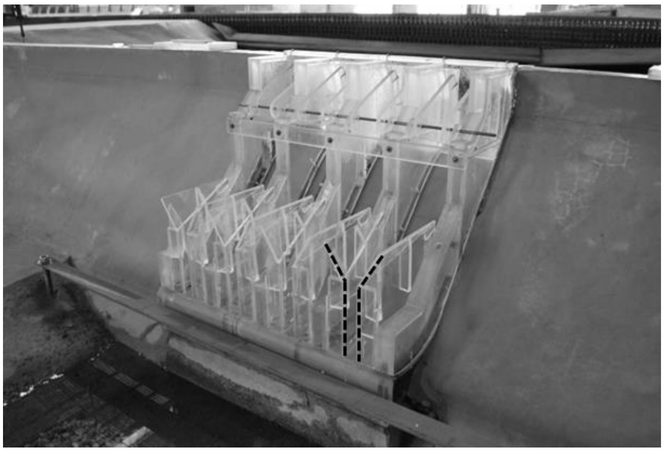


Figure 9. "Y" shaped Slit Bucket structure (Alternative 7).

Table 3. Summary of the hydraulic behavior of the Slit Bucket tests.

Structure	Tr (years) Q (m^3/s)	5 2,070	25 3,371	100 4,491	10,000 7,713
Conventional	Alternative 2 η=1.00 θ=0 Individual chutes	Adequate	Adequate	Adequate	Adequate
Slit Buckets	Alternative 3 η=0.50 θ=14.3º	Adequate	Adequate	Shock of standing waves at the limit of the structure	Flow overtops the deflectors
	Alternative 4 η=0.33 θ=18.9º	Shock of standing waves within the structure Vertical "rooster tails"	Shock of standing waves within the structure Vertical "rooster tails"	Shock of standing waves within the structure Vertical "rooster tails" Flow overtops the deflectors	Flows overtop the deflectors Jets unite
	Alternative 5 η=0.16 θ=23.2º	Occurrence of drowning Flow overtops the deflectors	Occurrence of drowning Flow overtops the deflectors	Occurrence of drowning Flow overtops the deflectors Jets with a vertical tendency	Flow overtops the deflectors Jets unite
	Alternative 6 η=0.33 θ=10.1º	Shock of standing waves within the structure	Shock of standing waves within the structure	Shock of standing waves within the structure	Shock of standing waves within the structure "Rooster tails" hit the structure
	Alternative 7 η=0.25 θ=11.2º "Y"	Shock of standing waves within the structure Slender jets	Shock of standing waves within the structure Slender jets Clash of the "rooster tails" with the structure	Very slender water jets Intense shock of "rooster tails" against the structure	Very slender water jets Intense shock of the "rooster tails" against the structure Water overflow "glues" to the superior part of the slit

The “rooster tails” that came from the contractions formed with the shock of the standing waves (chute axis), are launched downwards and present more discreetly than those from the Slit Buckets. On spreading immediately downstream from the pier ending edge, the main part of the flow of each gate, with large specific discharge, collide against the streamflow of the adjacent gates forming very marked “rooster tails” compared to those formed in a spillway with conventional geometry.

A marked characteristic of the effluent jet of this type of spillway are a strong lateral nappe with great dispersion of the jet.

As shown in Table 4, the tests with Flaring Piers presented adequate behavior for the first flows, but there was a certain amount of instability for the larger discharges, which led to spraying, close to the region of jet impact, a problem also reported by Gao, Liu and Guo (2000).

The structure that presented the best behavior was Alternative 9, with a contraction ratio of 50%. The tests confirmed the information of Caihuan, Guobing and Yuanming (2002) about the three-dimensional aspect of the flow, as seen in Figure 11.

In the same way as for the alternatives with Slit Buckets, the Froude numbers of the test with Flaring Piers were calculated and plotted against the contraction ratios to compare them with the Yarnell equations (Figure 12).

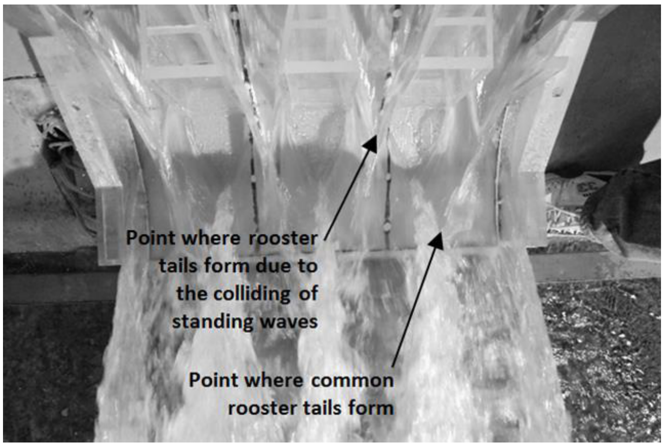


Figure 10. Flaring Piers used in the tests.

In the case of the Flaring Piers, the analysis of this graph allows concluding that it is not very likely that the flow will be controlled by the contraction of these alternatives. However, by

Figure 11. Test performed with Flaring Piers (Alternative 9) for flow with a 100-year recurrence.

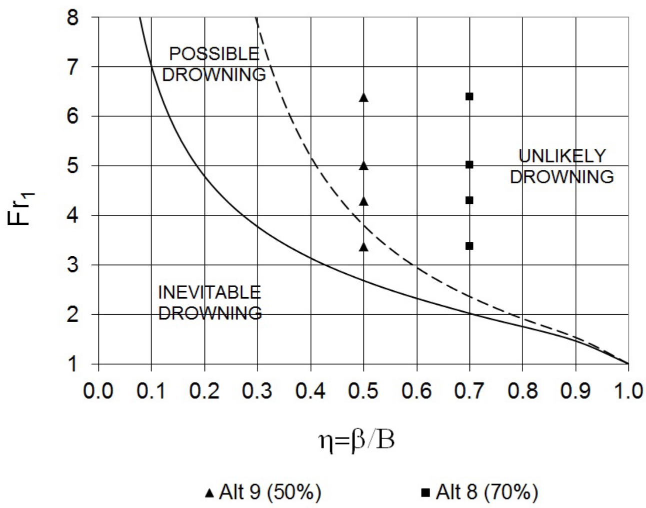


Figure 12. Data of the Alternatives tested with Flaring Piers in relation to the Yarnell equations.

Table 4. Summary of the hydraulic behavior of the Flaring Pier tests.

Structure	Tr (years)	5	25	100	10.000
	Q (m^3/s)	2,070	3,371	4,491	7,713
Conventional	Alt. 1 η=1.00 θ=0 Single chute	Adequate	Adequate	Adequate	Unstable “Rooster tails”
Flaring Piers	Alt. 8 η=0.70 θ=15.0º	Adequate lateral nappe	Steep jets Lateral nappe	Steep “Rooster tails” Flow overtopping the walls Lateral nappe	Extremely steep “Rooster tails” Flow overtopping the walls Very large lateral nappe Extreme instability
	Alt. 9 η=0.50 θ=19.0º	Adequate lateral nappe	Adequate lateral nappe	Flow overtopping the walls	Flow overtopping the walls Very unstable “Rooster tails” Spray/Instability Overtopping the walls

itself this fact does not guarantee that no other undesirable effects will occur, or even indicate the best alternative, since Alternative 9 presented the best performance, even being close to the region of "possible drowning"

Scour formed in the alternatives with Slit Buckets

The tests with the alternatives using Slit Buckets did not present major differences compared to those performed with the conventional spillway with independent chutes (Alternative 2).

Figure 13 shows the longitudinal profile of the scour hole formed in the Slit Bucket tests (Alternatives 3 and 4), compared to that formed with the conventional spillway (Alternative 2) for flow with a 5-year recurrence (2,070 m^3/s). Figure 14, in turn, presents this same comparison for the tests performed with 10,000-year flow (7,713 m^3/s).

The tests of the alternatives with Slit Buckets showed a small reduction (<10 m) of the depth compared to the test with the conventional spillway. However, for the test with 10,000-year flow it can be seen that the scour hole with the conventional spillway (Alternative 2), reached the upstream limit of the movable bed box, which did not occur for the tests with Slit Buckets (Alternatives 3 and 4). It is emphasized that scour happened very close to the spillway structure and may, in practice, compromise the overall stability of the structure.

It is interesting to note that the scour hole of these alternatives presented a wave format, with the formation of valleys with axes that coincide with the axis of the spillway gates, as seen in Figure 15, an effect provoked by the formation of submerged rolls parallel to the flow. This characteristic disappeared with the evolution of the scour hole caused by the tests with larger flows than those with a 25-year recurrence.

In order to perform a quantitative evaluation of the benefit provided by the Slit Buckets to reduce the erosive process, the classical formula of Veronese (1937) was used. It is presented in Equation 6, which was obtained by means of hydraulic model tests with fine and non-cohesive granular material. This equation allows forecasting the maximum depth of erosion D [m], measured from the downstream level, based on the specific discharge q [$m^2.s^{-1}$], on the water head H [m] and on the coefficient "c" which varies according to the characteristics of the riverbed.

$$D = c \cdot q^{0,54} \cdot H^{0,225} \quad (6)$$

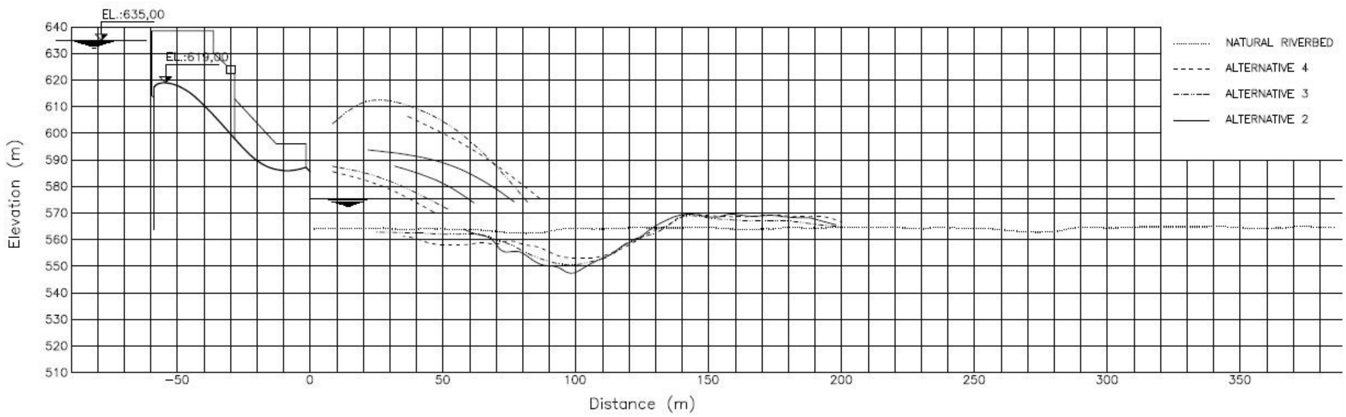


Figure 13. Results with Slit Buckets (Alternatives 3 and 4) and with conventional spillway (Alternative 2) for Tr=5.

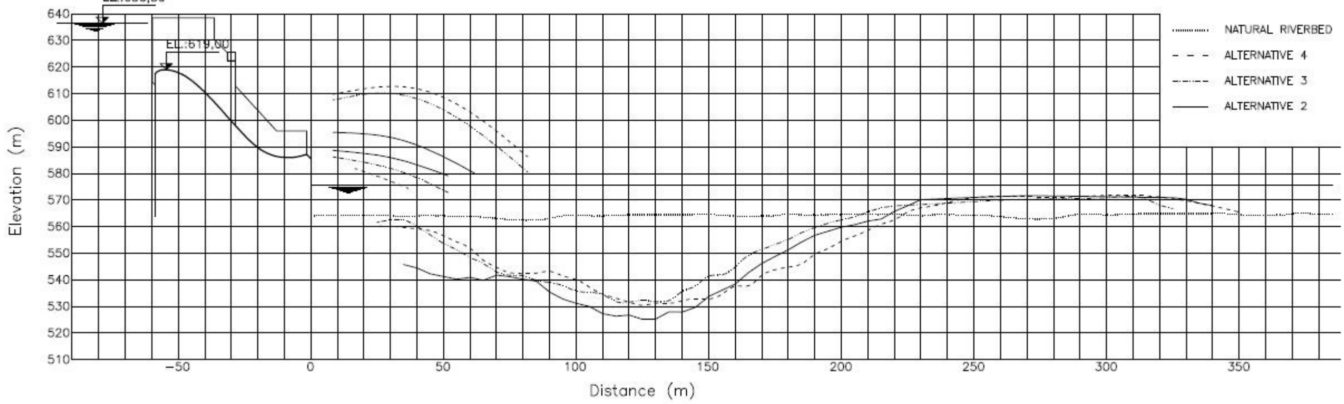


Figure 14. Results with Slit Buckets (Alternatives 3 and 4) and with conventional spillway (Alternative 2) for Tr=10,000.

This equation presupposes that the influence of other factors such as characteristics of aeration and jet turbulence are considered in the coefficient "c", whose value found in the Veronese tests was 1.9. For practical cases this coefficient may be smaller. According to the Brazilian Committee of Large Dams (Comitê Brasileiro de Grandes Barragens – CBDB, 1994), the confrontation with measurements in prototypes leads to values of c = 0.7 for resistant rocks, c = 1.2 for rocks with medium resistance and c = 1.5 for less resistant rocks. These values are suggested for conventional ski jump spillways.

The measurements performed in the tests in this study enabled calculating the "c" coefficients for each test, based on specific discharge "q", water head "H" and maximum depth "D", and also confronting these depths with those calculated using the values of 1.9 and 1.2, recommended by Veronese and by the CBDB, respectively. These parameters are presented in Table 5. For each flow the Froude number was also calculated based on the flow characteristics immediately upstream from the deflectors.

Among the alternatives with Slit Buckets, Alternative 5 was the one that presented the lowest value of coefficient "c" (0.77 to 1.30). It should be pointed out that, despite the inadequate behavior observed in the tests of Alternatives 3, 4 and 5, the measurements of maximum depth of the scour hole were not excluded from the analyses due to the low dispersion of the values found for coefficient "c" –maximum standard deviation 0.246 and coefficient of variation 25.2%, obtained for the most unstable structure.

It should be noted that there was a considerable reduction of coefficient "c" for Alternative 2, compared to Alternative 1, presented in Table 6 due to the fact that the flow resistance along the chute is higher in the configuration with four independent chutes, because it has a larger perimeter of contact between the flow and structure in relation to the configuration in a single chute.

The analysis of the values of coefficient "c" obtained for the different alternatives tested presupposes that the effects promoted by the Slit Buckets and Flaring Piers are considered intrinsically in this coefficient, just as other factors already cited, such as jet aeration, degree of rock fracture and riverbed topography.

Based on this hypothesis, it was attempted to correlate the coefficient "c" with the contraction ratio "η", which for the Slit Buckets is shown in Figure 16.

As shown in Figure 16 there is no clear correlation between coefficient "c" and the contraction ratio "η" for the alternatives with Slit Buckets (Alt 2, 3, 4, 5, 6 and 7). A complicating factor was the different results of scour obtained for the Alternatives 4 and 6, which have the same contraction ratio.

However, the analysis resulted in an interesting conclusion: there was no reduction of the maximum depth of scour with the reduction of the contraction ratio in the Slit Buckets as expected at the beginning of the study. It is shown that the erosion found in Alternative 6 was even greater than that produced in the test with the conventional spillway (Alternative 2). The same analysis was repeated, this time seeking to correlate coefficient "c" with the angle of deflection "θ", which is shown in Figure 17.

This graph shows that there is a correlation between coefficient "c" and the angle of deflection "θ" in the tests performed with Slit Buckets, a correlation which is not found in the comparison with

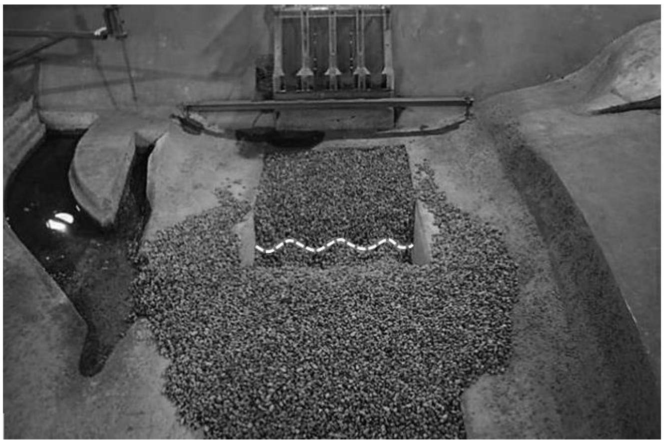


Figure 15. Scour hole formed in the test of Alternative 3 for a flow with a 5-year recurrence.

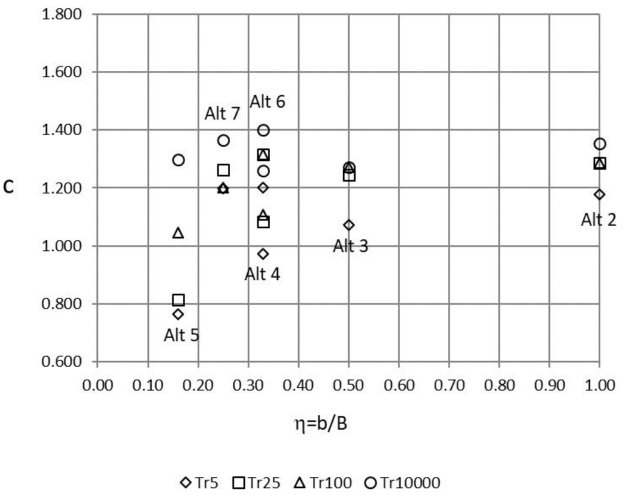


Figure 16. Coefficient "c" and the contraction ratio "η" for the Alternatives with Slit Buckets.

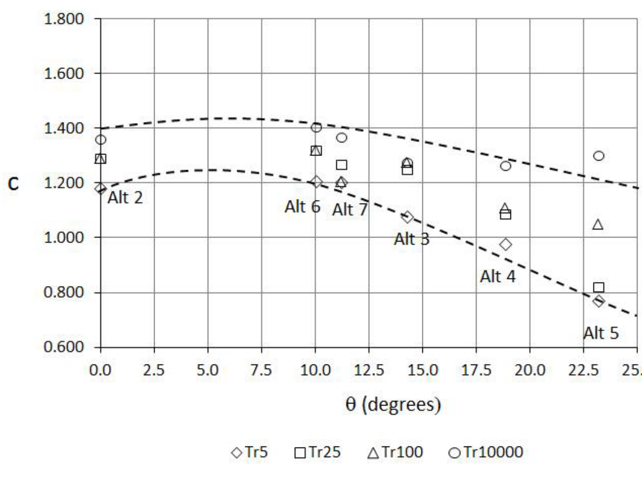


Figure 17. Coefficient "c" and the angle of deflection "θ" for alternatives with Slit Buckets.

Table 5. Characteristics of the tests with Slit Buckets compared to the conventional spillway with distinct chutes.

Tr (years)	Q (m^3/s)	q ($m^3/s/m$)	N.A.R. (m)	N.A.J. (m)	Minimum scour elevation (m)	H (m)	Froude Nº	$q^{0.54}xH^{0.225}$	D (m)			c
									Measured	Veronese	CBDB	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Alternative 2												
5	2,070	35.9	635.00	568.67	547	66.33	7.3	17.78	21.67	33.78	21.33	1.177
25	3,371	58.5	635.00	569.34	539	65.66	5.8	23.08	30.34	43.85	27.70	1.287
100	4,491	78.0	635.00	570.28	534	64.72	5.0	26.86	36.28	51.04	32.23	1.287
10,000	7,173	124.5	636.50	572.03	524	64.48	4.0	34.56	48.03	65.66	41.47	1.355
Alternative 3												
5	2,070	35.9	635.00	568.67	550	66.33	7.3	17.78	18.67	33.78	21.33	1.073
25	3,371	58.5	635.00	569.34	541	65.66	5.8	23.08	28.34	43.85	27.70	1.245
100	4,491	78.0	635.00	570.28	536	64.72	5.0	26.86	34.28	51.04	32.23	1.271
10,000	7,173	124.5	636.50	571.51	526	64.99	4.0	34.62	45.51	65.78	41.55	1.271
Alternative 4												
5	2,070	35.9	635.00	568.62	551	66.38	7.3	17.78	17.62	33.78	21.34	0.972
25	3,371	58.5	635.00	569.80	545	65.20	5.8	23.04	24.80	43.78	27.65	1.085
100	4,491	78.0	635.00	570.32	541	64.68	5.0	26.86	29.32	51.03	32.23	1.107
10,000	7,173	124.5	636.50	572.33	529	64.17	4.0	34.52	43.33	65.59	41.43	1.261
Alternative 5												
5	2,070	35.9	635.00	568.57	555	66.43	7.3	17.78	13.57	33.79	21.34	0.766
25	3,371	58.5	635.00	569.70	551	65.30	5.8	23.05	18.70	43.80	27.66	0.816
100	4,491	78.0	635.00	570.73	543	64.28	5.0	26.82	27.73	50.96	32.18	1.045
10,000	7,173	124.5	636.50	572.00	527	64.51	4.0	34.56	45.00	65.67	41.48	1.299
Alternative 6												
5	2,070	35.9	635.00	568.57	547	66.43	7.3	17.78	21.57	33.79	21.34	1.201
25	3,371	58.5	635.00	569.55	540	65.45	5.8	23.06	29.55	43.82	27.68	1.316
100	4,491	78.0	635.00	569.73	535	65.28	5.0	26.91	34.73	51.13	32.30	1.316
10,000	7,173	124.5	636.50	572.94	526	63.57	4.0	34.45	46.93	65.45	41.34	1.400
Alternative 7												
5	2,070	35.9	635.00	568.69	548	66.31	7.3	17.78	20.69	33.78	21.33	1.198
25	3,371	58.5	635.00	570.34	541	64.66	5.8	23.00	29.34	43.70	27.60	1.263
100	4,491	78.0	635.00	569.73	537	65.27	5.0	26.91	32.73	51.13	32.29	1.201
10.000	7,173	124.5	636.50	571.99	525	64.52	4.0	34.56	46.99	65.67	41.48	1.365

the contraction ratio "η" for the same alternatives. It can also be noted that there was a greater range of the results of coefficient "c" for greater angles of deflection.

It is observed that the influence of the angle of deflection "θ" in the Slit Buckets is practically negligible for alternatives with angles of deflection smaller than 15º. This is explained by the fact that small deflections do not manage to impose sensitive changes to the flows with great inertia. For the flow with a 10,000-year recurrence time, the scour did not have significant alterations among the alternatives tested. For Alternative 6 the effect was even worst, as cited previously, due to the fact that the contractions served only used to concentrate flow.

On the other hand, in tests with less than 10,000-year recurrence flows, it was clear that the angle of deflection influenced the reduction of scour, and it is precisely for these situations of more frequent occurrence that one should have a solution that will reduce the erosive potential of flow.

It should be noted that the alternatives with greater angles of deflection and inadequate hydraulic behavior showed a greater range of results of coefficient "c" which varied from 0.77 to 1.30 in Alternative 5 against 1.20 to 1.40 in Alternative 6.

Scour formed in the alternatives with Flaring Piers

The scour holes formed in tests with Flaring Piers were smaller than both in tests with conventional spillways (Alternatives 1 and 2) and in those using Slit Buckets (Alternatives 3 to 7).

Figure 18 presents the longitudinal profiles of the scour hole formed for tests with Flaring Piers (Alternatives 8 and 9), compared to that formed in the test with a conventional spillway (Alternative 1) for flow with a 5-year recurrence time (2,070 m^3/s). Figure 19 presents longitudinal profiles formed for these alternatives in tests with a 10,000-year recurrence flow (7,173 m^3/s).

The analysis of Figure 18 shows that there was no significant reduction of the scour hole in tests with Flaring Piers compared to the test with the conventional spillway for the tests with 5-year recurrence flow. On the other hand, for tests with 10,000-year

Table 6. Characteristics of the tests with Flaring Piers compared to the conventional single chute spillway.

Tr (years)	Q (m^3/s)	q ($m^3/s/m$)	N.A.R. (m)	N.A.J. (m)	Minimum scour elevation (m)	H (m)	Froude Nº	$q^{0.54}xH^{0.225}$	D (m) Measured	D (m) Veronese	D (m) CBDB	c
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Alternative 1												
5	2,070	35.9	635.00	570.06	547	64.95	6.4	17.69	23.05	33.62	21.23	1.303
25	3,371	58.5	635.00	572.92	537	62.09	5.0	22.79	35.92	43.30	27.35	1.519
100	4,491	78.0	635.00	574.72	532	60.28	4.3	26.43	42.72	50.23	31.72	1.605
10,000	7,173	124.5	636.50	575.29	518	61.21	3.4	34.16	57.29	64.90	40.99	1.677
Alternative 8												
5	2,070	35.9	635.00	570.49	550	64.84	6.4	17.69	20.49	33.61	21.22	1.181
25	3,371	58.5	635.00	571.68	547	63.26	5.0	22.89	24.68	43.49	27.47	1.065
100	4,491	78.0	635.00	572.92	544	62.09	4.3	26.61	28.92	50.56	31.93	1.091
10,000	7,173	124.5	636.50	574.48	537	61.45	3.4	34.19	37.48	64.96	41.03	1.102
Alternative 9												
5	2,070	35.9	635.00	570.16	552	64.84	6.4	17.69	18.16	33.61	21.22	1.027
25	3,371	58.5	635.00	571.74	548	63.26	5.0	22.89	23.74	43.49	27.47	1.033
100	4,491	78.0	635.00	572.91	545	62.09	4.3	26.61	27.91	50.56	31.93	1.045
10,000	7,173	124.5	636.50	575.05	541	61.45	3.4	34.19	34.05	64.96	41.03	1.005

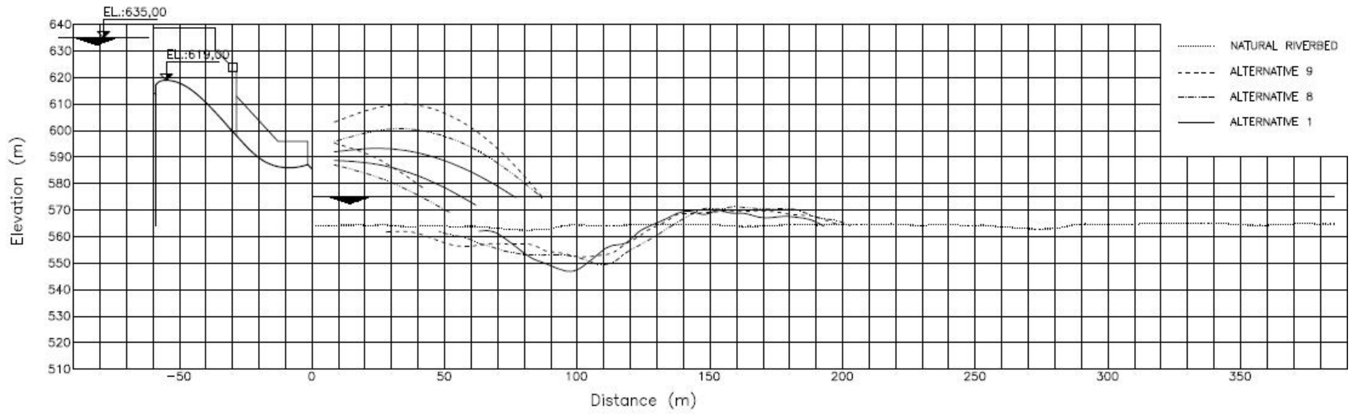


Figure 18. Results with Flaring Piers (Alternatives 8 and 9) and with conventional spillway (Alternative 1) for Tr=5.

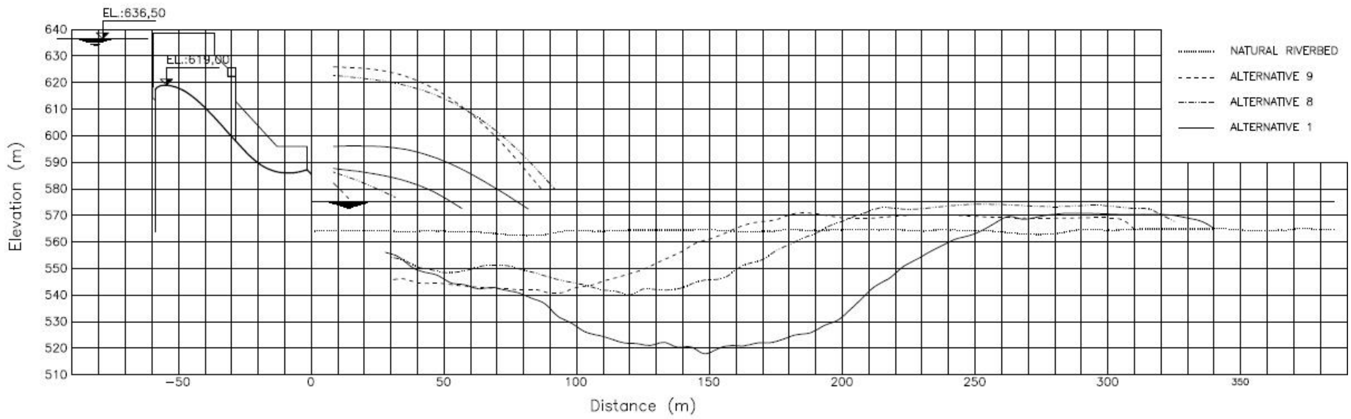


Figure 19. Results with Flaring Piers (Alternatives 8 and 9) and with conventional spillway (Alternative 1) for Tr=10,000.

flow (Figure 19) there was a major reduction of scour hole, both in depth and in length. For the first parameter there was a reduction of about 20 m from the Flaring Piers tests to the conventional spillway. It should, however, be emphasized that for Alternative 9, the scour reached the upstream limit from the movable bed box, which is an undesirable characteristic, as mentioned previously.

The analysis of the benefit provided by the Flaring Piers followed the methodology used for the Slit Buckets, shown in the previous item, i.e., calculating the coefficients "c" of the Veronese equation based on the specific discharge "q", water head "H" and maximum depth "D" recorded in each test, as shown in Table 6.

For Alternative 1, the value of "c" ranged from 1.30 to 1.68, with a mean of 1.53. It is thus inferred that the movable material used in the tests represents rock which is neither as resistant as the mean considered by the CBDB, nor materials which is as erodible as that used in the Veronese tests.

Among the structures of Flaring Pier type, Alternative 9 presented the smallest value of "c", around 1.0 for all flows analyzed, and with a satisfactory hydraulic behavior except for the 10,000-year flow. It is thus considered that for a spillway with characteristics similar to those of the Mauá Powerplant, which needs to reduce its erosive potential, a structure with these configurations may be promising.

Figure 20 shows the correlation between coefficient "c" and the contraction ratio "η" obtained for tests with Flaring Piers.

The analysis of this graph allows concluding that in the case of the tests with Flaring Piers, differently from those with Slit Buckets, there is a tendency to diminish coefficient "c" diminishing the contraction ratio "η". There was a significant reduction of this parameter between the tests for alternatives with the deflectors (Alt 8 and 9) and those for the conventional spillway (Alternative 1).

It should be noted that in the alternatives using deflectors, coefficient "c" was greater for flow with 5-year recurrence time than for the other flows. This can be attributed to the fact that for lower discharges the effect of the jet dispersion applied by the deflectors is smaller.

Figure 21 presents the correlation between coefficient "c" and the angle of deflection "θ" for the alternatives using Flaring Piers.

Analysis of the graph allows concluding that there is tendency for the reduction of coefficient "c" with the increase of the deflection angle "θ" just like that found for the correlation of this coefficient with the reduction of contraction ratio "η".

The alternatives using Flaring Piers promoted considerable benefits in relation to the others (Figure 21), confirming the results of the surveys of the total volumes of eroded material, which will be presented ahead. These alternatives also showed a correlation between the reduction of the coefficient "c" and the increase of the angle of deflection "θ". It is noteworthy that Alternative 9, whose hydraulic behavior found during the tests was reasonably adequate, had coefficient "c" values that were practically the same for the different flows tested.

Since it was the first Brazilian study of this kind of deflectors, it was exploratory, mainly for the purpose of understanding and evaluating advantages and disadvantages of using these devices. Given the previous lack of knowledge on the subject, and the scarcity of information in the literature, some alternatives were conceived during the testing program, adapted to solve hydraulic behavior problems, and for this reason, tests were not performed for each alternative in a quantity that would favor statistical treatment and the search for an equation correlating the angle of deflection "θ" with coefficient "c".

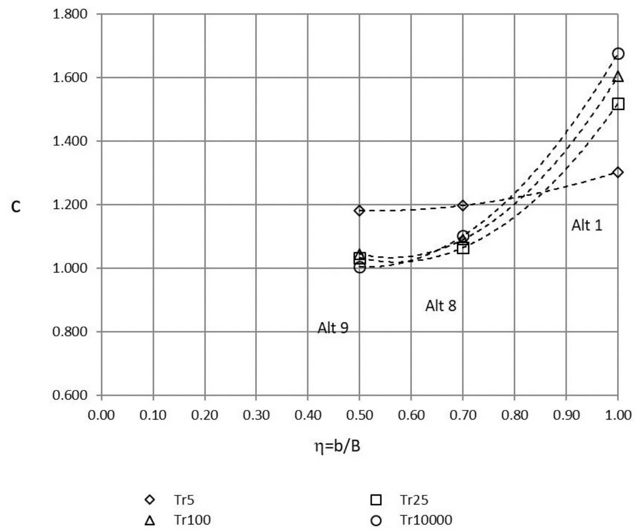


Figure 20. Coefficient "c" and the contraction ratio "η" for the Alternatives with Flaring Piers.

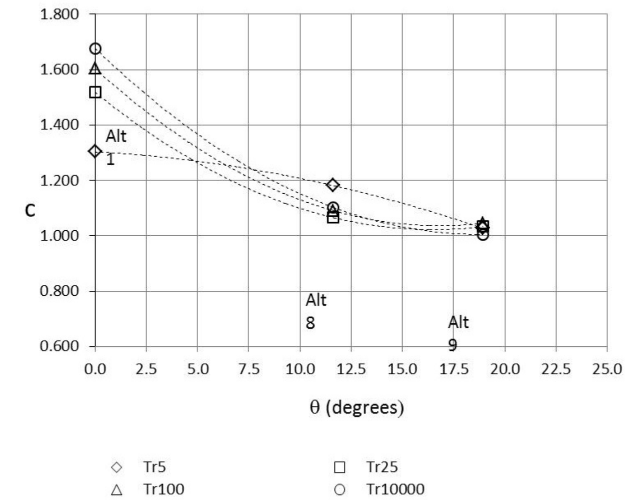


Figure 21. Coefficient "c" and the angle of deflection "θ" for Alternatives with Flaring Piers.

Total volume of eroded material

In general, both the Slit Buckets and the Flaring Piers reduced the volume of the scour hole (LARA, 2011). This may be verified by comparing the total volume of eroded material among the alternatives using these devices and those with the conventional ski jump (Figure 22).

The eroded material was deposited, constituting bars of blocks downstream or laterally to the scour hole (Figure 23). The volumes of both the eroded material and that deposited in the bars of blocks downstream were calculated based on the surveys performed after each test. Part of the blocks was transported beyond the limits of the model, and it was not possible to measure their volume. In this case the volume was obtained by the difference between the volumes of eroded material and that deposited in the bar downstream.

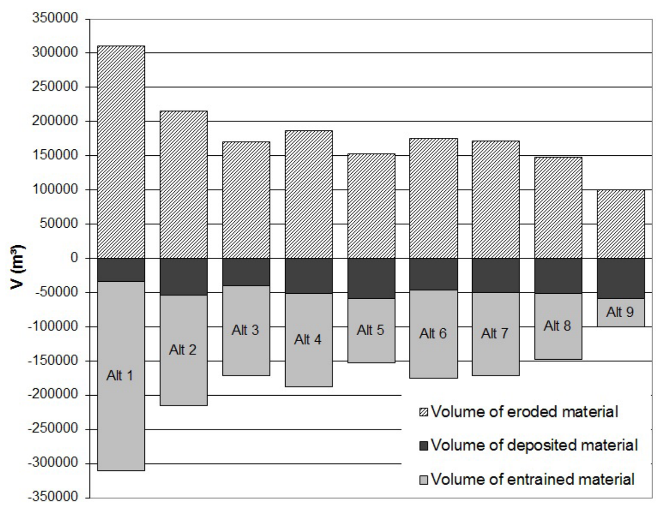


Figure 22. Comparison of the total volume of eroded material after test with 10,000 year flow.

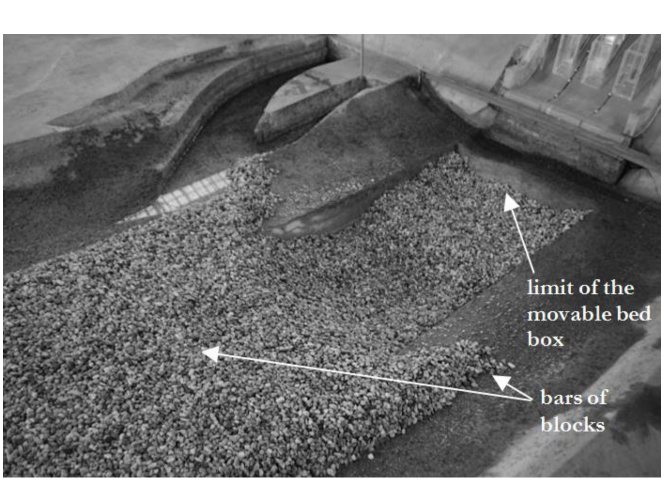


Figure 23. General aspect of erosion in Alternative 9, after test with 100-year flow.

It was observed that the tests with conventional spillways (Alternatives 1 and 2) produced the largest volumes of eroded material. The difference between the two alternatives is due to flow resistance along the chute, because, as already mentioned in Alternative 2, the spillway was separated into four separate chutes, increasing the perimeter of contact of flow with the solid surface, thus causing head loss.

Among the Slit Buckets, Alternative 5, with a wider angle of deflection from the walls (θ=23.2°) presented the smallest volume of erosion. Also among the Flaring Piers, Alternative 9, with the largest angle of deflection (θ=19.0°), presented the smallest volume of erosion.

The maximum volume of eroded material in Alternative 9 was the smallest among all alternatives tested and corresponds to one third of that found for the conventional spillway (Alternative 1). Besides, the maximum scour depth of this alternative was only 35 m, which corresponds to 60% of the scour depth obtained in the test with the conventional spillway. However, the scour reached the upstream limit of the movable bed box.

CONCLUSIONS

Seven alternatives of flow contraction were evaluated according to the questions regarding erosive potential and hydraulic behavior. Since these structures are as yet little known outside China, more laborious analyses were performed in the evaluation of the reduction of erosive potential compared to conventional ski jump structures. There was a clear possibility of obtaining benefits from applying them. Thus, it is suggested that further studies be performed attempting to gain an even better understanding of their hydraulic operation.

Two types of contraction were looked at: the Slit Buckets (extremity deflectors) and Flaring Piers (deflectors by pier widening). Among the alternatives tested, the best performance was for the Flaring Pier with a contraction ratio of 50%, which promoted a 60% reduction in the maximum depth of erosion caused by the direct impact of the jet, in comparison to the conventional spillway. However, the extension of erosion upstream reached the limit of the movable material box, and it is recommended to verify in future studies what safety distance should be guaranteed in relation to the spillway foundation.

As to the volume of eroded material, this alternative had only one-third the erosion that was found in the conventional spillway, proving that the device is effective.

It is however highlighted that the effects resulting from flow aeration expected in prototype could not be verified in the model used due to the lack of a Weber similarity, since the surface tension are the same in the model and in the prototype. For the geometrical scale of the model used in tests, the Weber number is 100 times smaller than in the prototype and, therefore, the effect of surface tension on the model is 100 times greater, impairing bubble formation.

Pinto, Neidert and Ota (1981) cite that the effects related to the influence of surface tension may be ignored for Weber numbers above 1,000, but for the tests in this study, this parameter was below 60. Thus, the effects of the deflectors studied must provoke even greater alterations in the prototype as regards the emulsifying of air in the effluent jet, which should contribute even further to reduce scour.

The study concludes that the Flaring Pier reduces the erosion provoked by ski jump spillways and could be adopted with a contraction ratio close to 50%, in a spillway with characteristics similar to the one tested and that needs mitigation of the erosive effects on the riverbed. However, it would be necessary to invest in studies to solve the problems related to effluent jet instability through changes in the geometry and location of the contraction along the chute.

REFERENCES

ABRH – ASSOCIAÇÃO BRASILEIRA DE RECURSOS HÍDRICOS; FURNAS CENTRAIS ELÉTRICAS S.A. *Relato do trabalho da subcomissão desenvolvimento de pesquisa – estudo de flutuação de pressão em bacia de dissipação – Caso da Usina de Porto Colômbia*. Rio de Janeiro, 1997.

CAIHUAN, W.; GUOBING, H.; YUANMING, C. Development and practice of a new type dissipator. In: YANGTZE RIVER SCIENTIFIC RESEARCH INSTITUTE. *Geheyan project*. Wuhan: Yangtze River Scientific Research Institute, 2002

CBDB – COMITÊ BRASILEIRO DE GRANDES BARRAGENS. *Erosão em Bacias de Lançamento – Aspectos Hidráulicos e Geotécnicos*. Rio de Janeiro: Comissão de Hidráulica, 1994. Publicação 3/96.

CEHPAR – CENTRO DE HIDRÁULICA E HIDROLOGIA PROF. PARIGOT DE SOUZA. *Projeto HL 156 – Estudos Hidráulicos em Modelo Reduzido da Usina Hidrelétrica Mauá*. Curitiba, 2006.

CEHPAR – CENTRO DE HIDRÁULICA E HIDROLOGIA PROF. PARIGOT DE SOUZA. *Projeto HL 168 – Estudo da Eficiência Hidráulica de Dissipadores de Energia Tipo Flaring Piers*. Curitiba, 2009.

CHINA GEZHOUBA GROUP INTERNATIONAL ENGINEERING CO. LTD. *Slit Bucket at Geheyan Dam in China*. China, 2010. Available from: <HTTP://www.gzbgj.com/english/article.asp?id=471>. Access on: 22 June 2010.

GAO, J.; LIU, Z.; GUO, J. *Energy dissipation for high dams: large dams in China – a fifty year review*. Beijing: Chinese National Committee on Large Dams, 2000.

HUANG, G.; ZHANG, Q.; DUAN, W. Study of narrow opening energy dissipator in spillway of high fall head and large discharge per unit width. In: CONVEGNO DI IDRAULICA E CONSTRUZIONI IDRAULICHE – IDRA, 30., 2006, Roma. *Proceedings*… Roma: Università La Sapienza, 2006. Available from: <https://www.tib.eu/en/search/id/TIBKAT%3A574678212/Atti-XXX-Convegno-di-Idraulica-e-Costruzioni-Idrauliche/#documentinfo>. Access on: 20 Mar. 2018.

LARA, R. *Utilização de defletores em fenda e pilares alargados para redução da erosão provocada por vertedouros com salto de esqui*. 2011. 158 f. Dissertação (Mestrado em Engenharia de Recursos Hídricos e Ambiental)-Setor de Tecnologia, Programa de Pós-graduação em Engenharia de Recursos Hídricos e Ambiental, Universidade Federal do Paraná, Curitiba, 2011.

MD&A – MALCOLM DUNSTAN & ASSOCIATES. Devon, 2018. Available from: <http://www.rccdams.co.uk/dams/dachaoshan/>. Access on: 20 Mar. 2018.

OTA, J. J.; TOZZI, M. J. Estudo sobre ranhura de aeração em túneis de descarga com baixa declividade. In: CONGRESSO LATINO AMERICANO DE HIDRÁULICA, 16., 1994, Santiago. *Proceedings*… Santiago: International Association for Hydro-Environment Engineering and Research, 1994. p. 369-378.

PEREIRA, G. M.; BRITO, S. N. A.; GONÇALVES, E. S. Considerações sobre a utilização de dissipador de energia em salto de esqui em maciços rochosos sãos muito fraturados – o caso da UHE Jaguara. In: SEMINÁRIO NACIONAL DE GRANDES BARRAGENS, 19., 1991, Aracaju. *Proceedings*… Aracaju: Comitê Brasileiro de Barragens, 1991. p. 165-186.

PINTO, N. L.; NEIDERT, S. H.; OTA, J. J. *Prototype and laboratory experiments on aeration at high velocity flows - water power and dam construction*. Curitiba: Universidade Federal do Parana, Companhia Paranaense de Energia - Copel, 1981. n. 36.

VERONESE, A. Erosioni di fondo a valle di uno scarico. *Annali dei Lavori Pubblici*, v. 75, n. 9, p. 717-726, 1937.

VLB ENGENHARIA. *UHE Mauá – consolidação dos dimensionamentos hidráulicos*. Curitiba, 2009.

YARNELL, D. L. *Pile trestles as channel obstructions*. Washington: U. S. Department of Agriculture, 1934a. (Technical Bulletin, n. 429).

YARNELL, D. L. *Bridge piers as channels obstructions*. Washington: U. S. Department of Agriculture, 1934b. (Technical Bulletin, n. 429).

Authors contributions

Rafael de Lara: data collection, data analysis, article elaboration.

André Luiz Fabiani: coordination of physical model tests, data analysis, article revision.

José Junji Ota: main analysis and conclusions of the research, article elaboration and revision.