SKIMMING FLOWS DESIGN IN A STEPPED STRUCTURE. DISCHARGE IN A RESTORED RIVER

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ABSTRACT

The environmental management of an open pit-mining project in Colombia requires considering actions in order to keep and preserve the environmental natural conditions. Drummond Ltd Company performs mining actions in the south of the department of Cesar, as it also implements an environmental management plan, building different structures that assure the basin´s restoration, mainly in the intervened area.

Part of the works are the design and construction of the main channel realignment and management of the tributaries, using the best environmental and hydraulic practices to deal with the changes in the delivery level due to the river’s modification. These works assure a proper functioning of the basin’s drainage system, allowing free development and movement of the local aquatic fauna.

INTRODUCTION

The technical and conceptual design considerations of an energy dissipation structure for the influent discharge to a river are presented in this work. The structure allows managing in a safe manner the discharge of the natural stream called “Caño Piedras”, to the realigned main channel of the San Antonio River, located in the Colombian department of Cesar. In this location, the San Antonio River’s main channel is an artificial section that has the purpose of changing the natural stream´s alignment, allowing the Drummond's pit-mining project.

The aim of the structure is to reduce most of the remaining energy due to the delivery of the Caño Piedras stream to the San Antonio realigned channel, caused by the topographic level difference between both of them. Thereby, taking into account the geomorphological characteristics of the delivery, a stepped structure with skimming flow and its corresponding adjunct works was designed.

To define the structure's dimensions, it was necessary to take into account several hydrological variables such as surface runoff and precipitation in the considered area, order to calculate the estimate values for maximum instantaneous flows, which are the ones defining the structure's size, kind and features. The geographic information-processing tool, ArcGis, served to make a simplified terrain model of the last section of the stream, bases on a previous topographical survey.

In order to establish the structure's definitive dimensions, it was necessary to consider land limitations, geomorphological characteristics of the zone, stream features such as cross section, fluvial dynamic of the current, the budget and available materials. Finally, the chosen structure was the one with a geometry that is able to control the greatest amount of energy for the particular conditions on extreme hydrological events.

PROJECT BACKGROUND

Currently, Drummond Ltd is making an open-pit mining exploitation in an area named Pribbenow, which is located in the south of Cesar department in Colombia close to the population of La Jagua de Ibirico. To carry out the works, it was necessary to modify some of the natural streams; this means to design and build, along a 10 Km long reach, the temporary realignment of the Arroyo San Antonio, to lead the basin's runoff to the delivery point on the main stream.

Figure 1. View of the Realignment No. 4 of the San Antonio River

The mentioned work is taking into account the detailed previous studies that were made on this realignment, which include both the hydrological information processing and the hydrological transit using the HEC-HMS model. It also uses as a the primary reference the conditions, parameters and models that were brought up in the previous study *Consultancy for the evaluation of hydrological and hydraulic studies in the natural-state basins that make up the mining area of the center area of Cesar. Maximum and minimum flows*, which was made by the Escuela Colombiana de Ingeniería Julio Garavito (Colombian Engineering School Julio Garavito).

A stepped structure for skimming flows was selected as the energy dissipation structure to manage the inflow of the Caño Piedras stream to the realignment channel. This kind of structure was chosen after considering different dissipation structures, taking into account the topography and the manner in which the kinetic energy dissipation occurs, the construction easiness and the riverbed particular topography.

This work encloses ta thorough analysis of the plant and profile design of the structure and the corresponding cross section dimensioning. It has then been possible to suggest a transition between the natural riverbed and the structure to assure an adequate inflow condition along the way.

SIMPLIFIED TERRAIN MODEL

After refining and analyzing the topographical data, a terrain model for the surrounding area of the stream inflow was generated, with its corresponding contour lines. With that information, it was possible to establish a preliminary main axis for the structure, using as a reference the lower points of the riverbed (thalweg). It was also possible to establish the dominant condition in order to analyze the stream's hydraulic characteristics and to define the structure's dimensions.

The Caño Piedras stream is an ephemeral river whose alignment changes depending on the basin's hydrological condition. In this case, establishing the dominant stream's cross section generates uncertainty about the dynamic processes and makes more difficult to define the delivery structure's configuration.

Once established the main channel and taking into account the geomorphological variables of the area, it was possible to define the dissipation structure's axis, cross sections and longitudinal profile based on the terrain model. It allowed to obtain the topographical characteristics that are required to dimension the delivery structure from Caño Piedras to the definitive realignment.

DESIGN FLOW

To determine the design flow, a previous study was taken into account. The study was carried out by the Escuela Colombiana de Ingeniería Julio Garavito (Colombian Engineering School Julio Garavito), entitled as *Hydrological and hydraulic study and design for the Arroyo San Antonio No. 4*, in which the maximum instantaneous flows for different return periods were determined.

To define the return period for the design flow of the structure, it was necessary to analyze thoroughly the structure's location, the collapse risk and the project's lifetime. Finally, the selected return period was 50 years. From the previously mentioned study and hydrological model, he design flow obtained was 55 m^3/s, for the return period of 50 years.

HYDRAULIC DESIGN OF THE STEPPED STUCTURE. SKIMMING FLOW

Once defined the design flows and topographical characteristics, different dissipation structures were considered, finally establishing that a skimming-flow stepped structure would be the most suitable, taking into account the structural constructive process characteristics and the previously established features of the flow in the delivery zone of the stream.

In the first place, the design of a flexible structure was posed. This structure would be built using elements such as "*Bolsacreto"* (geotextile bag filled with concrete) or rubble, because these elements are able to adapt to the current's dynamic and the foundation material. However, as it was difficult to find the proper materials in the region, a rigid concrete structure was chosen. The junction between the natural streambed and the dissipation structure was planned to be made using rock material properly set.

Figure 2. Stepped structure with skimming flow for the Caño Piedras-La Loma, Cesar

The stepped structure design was made by defining, in the first place, the most suitable tread and riser dimensions, according to the terrain profile and the methodology posed by Ohtsu, I; Yasuda, Y; Takahashi, M. (2004). This methodology allows to assess the dimensions of the steps to guarantee the most suitable skimming-flow conditions and the maximum energy dissipation.

STEP DIMENSIONS

Using the above mentioned considerations, Table 1 summarizes the magnitude of different variables that were taken into account to dimension the stepped structure. The final values were obtained from a trial and error process of variables such as slope, tread and riser length. The selected combination would then be the one that guarantees an adequate energy dissipation using the skimming-flow design methodology. Figure 3 summarizes the whole process.

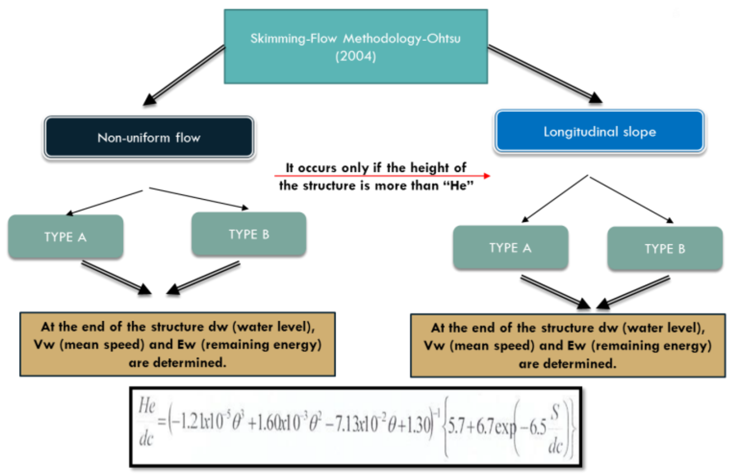

Figure 3. Flow chart for skimming-flow stepped-structures dimensioning. Ohtsu (2004)

The analysis considered the constructive process limitations of the structure. Table 1 shows the results of the analysis.

Table 1. (a) Skimming-flow stepped-structure design for the Caño Piedras stream. Design parameters and dimsnsions. Methodology by Ohtsu, I; Yasuda, Y; Takahashi, M. (2004).

H_{total} =	2.17	m
Q =	55.10	m^3/s
B =	8.0	m
θ =	8.13	º
g =	9.81	m/s^2

Table 1. (b) Skimming-flow stepped-structure design for the Caño Piedras stream. Design parameters and dimsnsions. Methodology by Ohtsu, I; Yasuda, Y; Takahashi, M. (2004).

Canal con Flujo Rasante				
Variable	**Símbolo**	**Unidad**	**Expresión Usada**	**Cálculo**
Altura del escalón	S	m	De Tabla 9.1 (interpolado)	**0.30**
Profundidad crítica	yc	m	$y_c = \left[\frac{(q)^2}{g}\right]^{1/3}$	**1.69**
Condición de flujo rasante			$\left[\frac{S}{y_c}\right]_s = \frac{7}{6}[\tan(\theta)]^{1/6}$	**0.84** OK
Tipo de Flujo	---	---	Si $\theta > 19°$	**NO**
	---	---	$\frac{S}{y_c} \leq \left[\frac{S}{y_c}\right]_B$	No
	---	---		
	---	---		
	---	---	$\left[\frac{S}{y_c}\right]_B = [13(\tan\theta)^2 - 2.73\,(\tan\theta)] + 0.373$	**0.25**
	---	---		
	---	---		
	---	---	Flujo tipo B (otros casos)	No
	---	---	Flujo tipo	**El flujo es tipo A**

Energía residual	$\left(\frac{E_{res}}{y_c}\right)_u$	m/m	Para Flujo Tipo A $\left(\frac{f}{8\text{sen}\theta}\right)^{(1/3)}\cos\theta + \frac{1}{2}\left(\frac{f}{8\text{sen}\theta}\right)^{(-2/3)}$ Para Flujo Tipo B $\left(\frac{f}{8\text{sen}\theta}\right)^{(1/3)} + \frac{1}{2}\left(\frac{f}{8\text{sen}\theta}\right)^{(-2/3)}$	**2.86**
	Eres_cuasiuniforme	m	Para 5.7º ≤ θ ≤ 19º D=0.300 Para 19º ≤ θ ≤ 55º Eres= **2.86*yc**	**4.83**
	Eres_NOcuasiuniforme	m	$5.0 \leq \frac{H_{Total}}{y_c} \leq \frac{H_e}{y_c}$	OK
			$\frac{E_{res}}{y_c} = 1.5 + \left[\left(\frac{E_{res}}{y_c}\right)_u - 1.5\right]\left[1 - \left(1 - \frac{H_{Total}}{H_e}\right)^{\frac{\theta}{25}+4}\right]$	**2.06**

GENERAL CHARACTERIZATION OF THE STRUCTURE. DIMENSIONS.

The following is the outline of the design considerations that served to establish the structure elements’ dimensions, apart from the tread and riser.

The delivery structure of the Caño Piedras stream consists of a rectangular cross section of 8.00 m width, a rise of 0.30 m height, a tread of 2.10 m long and a final step with a rise of 0.37 m height. Figure 4 shows the detailed dimensioning of the structure.

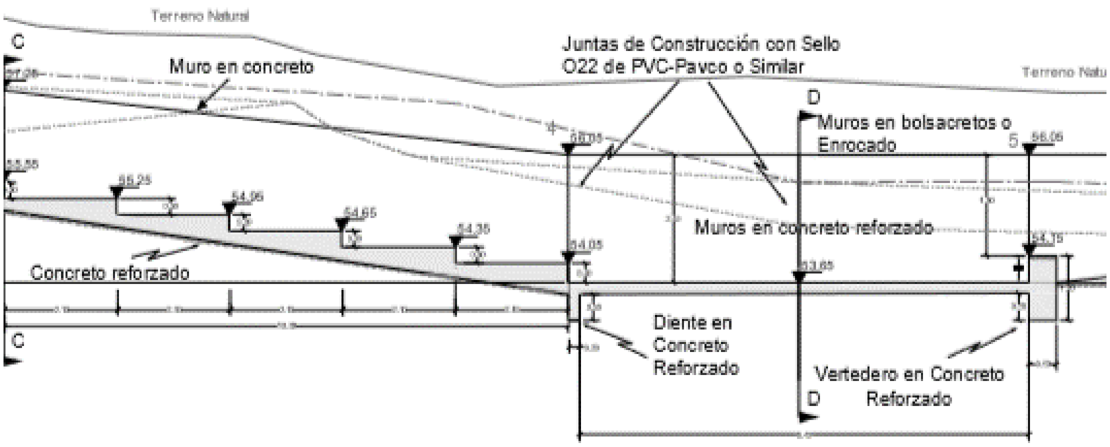

Figure 4. Longitudinal profile of the dissipation structure. Caño Piedras.

Considering the alluvial material characterization that conforms the foundation for the structure, construction joints were defined to guarantee the impermeability of the structure even if it's subject of shifting.

STILLING BASIN

In order to dissipate the remaining energy in the lower level of the structure, it was necessary to design a stilling basin to assure subcritical flow conditions in the inflow to the realignment channel. The formation of a hydraulic jump in the tank is favored by the presence of an end sill. Figure 5 shows a general drawing of the tank.

Due to the permanent impact forces and secondary flows that take place in the structure, it was necessary to design anchoring elements of 0.50 m height under the slab.

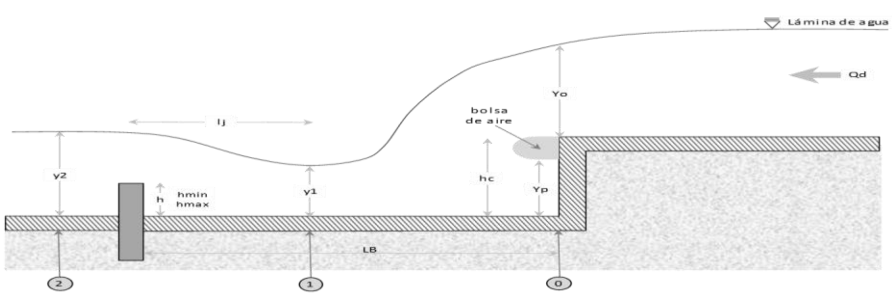

Figure 5. General design of a stilling basin with hydraulic jump.

SIDEWALLS

The sidewall height for the stepped structure was defined by the highest water level obtained from different analysis. Taking into account the amount of air entrapped in the skimming flow, the sidewall height considered the water level plus a 40% in addition to the estimated height.

Besides the definition of the sidewall height, the topographical characteristics of the area had to be taken into account, generating a gradual transition between the structure and the natural field. Along the dissipation structure and the stilling basin, reinforced-concrete walls were projected. Finally, it was necessary to “comb” the side slopes of the natural valley, using rock material, with a recommended slope of 2H:1V.

GRADUAL TRANSITIONS

As the stepped structures do not have the same width as the cross section of the stream, it was necessary to design gradual transitions between the original cross section of the stream and the delivery structure in both the inlet and the outlet.

The transition side slope was defined as 2H: 1V built in rubble and bolsacretos or gabions, for the easiness of construction, letting a better adaptation of the structure to the dynamic conditions of the stream.

In order to establish a better stability, two side baffles were designed at each ending of the sidewalls, to create an additional anchoring of the structure, making it support adequately the shear stresses that may destabilize the structure. Figure 6 shows the plain view of the structure with its final dimensions, taking into account the foregoing considerations.

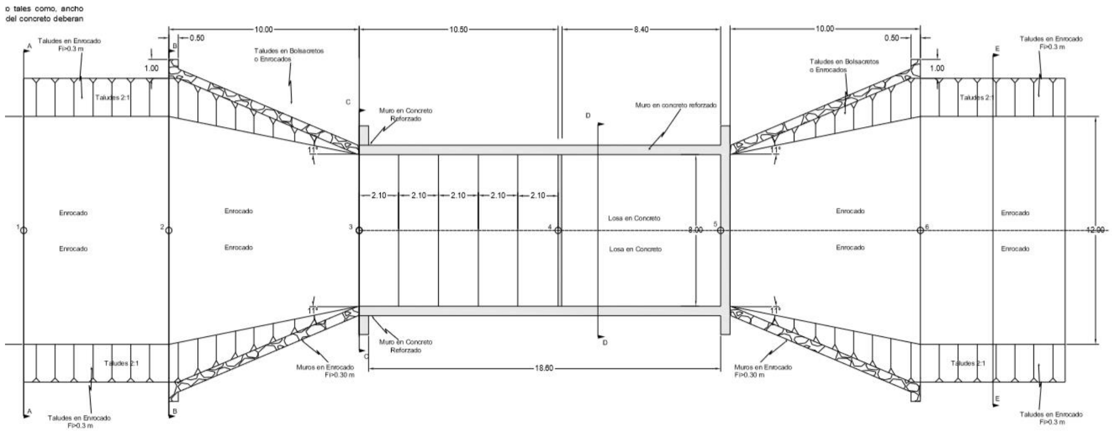

Figure 6. Plain view of the energy dissipation structure of Caño Piedras stream.

PHYSICAL AND NUMERICAL MODEL FOR FLOW IN STEPED STRUCTURES

Currently, the *Centro de Estudios Hidráulicos* (Hydraulic Studies Center) of the *Escuela Colombiana de Ingeniería Julio Garavito*, is making research in this kind of structures. As the research takes place, it is expected to be able to validate the equations that define the skimming flow over stepped structures.

Three different tilt configurations are being assessed and physically modelled for a wide flow range, aiming to analyze the behavior of the "step by step" flow (nappe flow), the transition flow and the skimming flow. Figure 7 shows the actual physical model of one of three selected configurations of a stepped structure with skimming flow.

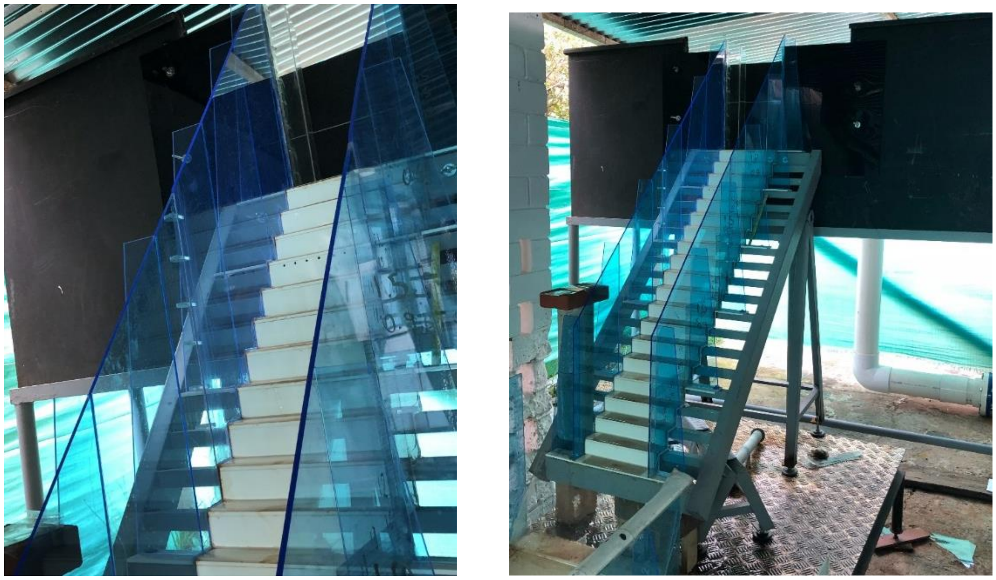

Figure 7. Skimming-flow stepped structure prototype general view. Centro de Estudios Hidráulicos (Hydraulic Studies Center)

Based on the experiences that were gathered from the real structure functioning, whose dimensions were obtained from the skimming-flow methodology, a physical and numerical modelling is going on to make research on cuasi-steady flow.

1. Tread and riser geometry.
2. Validation of a general equation representing the flow over the stucture.
3. Mixture's viscosity and specific weight determination. Apparent roughness coefficient.
4. Remaining energy assessment (stilling basin dimensioning).

The aim is to define a basic design methodology to select the structure that dissipates the highest amount of energy, considering the three type of flow that can occur in these structures.

CONCLUSIONS AND RECOMMENDATIONS

In order to surpass an important height difference in a short section of the discharge of the Caño Piedras stream to the realignment channel, a skimming-flow stepped structure and a stilling basin were projected.

The stepped structure is shorter when it is designed with the skimming-floe methodology, compared with the falling number methodology. However, in both cases it is necessary to project a stilling basin to favor the remaining energy dissipation.

From the point of view of the flow conditions, the skimming-flow allowed to pose a short stepped structure. The skimming-flow methodology assumes that, at the end of the structure, uniform and supercritical flow are found.

The performance of the structures that were already built is sufficient and the measured values obtained in the field are compliant with the values obtained in the design process.

Three-dimension modelling is expected to be achieved from the results of the physical modelling, the theoretic basis and the field performance results of the structures that were built and started-up.

REFERENCES

Centro de Estudios Hidráulicos. (2016). "Consultoría Para El Diseño del Realineamiento No. 4 y Factibilidad del Realineamiento Definitivo del Arroyo San Antonio en el Departamento del Cesar". Bogotá, Colombia. Escuela Colombiana de Ingeniería.

González, C. Chanson, H. (2007). "Diseño hidráulico de vertederos escalonados con pendientes moderadas: metodología basada en un estudio experimental". Universidad de Queensand, Australia.

Ohtsu, I; Yasuda, Y; Takahashi, M. (2004). "Flow Characteristics of Skimming Flows in Stepped Channels". Journal of Hydraulic Engineering, ASCE, Vol. 130, No. 9, September 2004, pp. 860-869.

Ven Te Chow, Maident David R., (1994). "Hidrología Aplicada". Mc. Graw Hill.