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Experimental results for guidance and design criteria of horizontal end-dumping type river closure

Resultados experimentais como orientação e critério de projeto para fechamento de rios por lançamento em ponta de aterro

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ABSTRACT

The river diversion involves the construction of cofferdams when dumped material is exposed at high velocities, which may cause the drag of blocks. Classical equations relate the mean rock diameter to the drop of water surface between the upstream and downstream. Results of 283 experimental tests performed in hydraulic models allowed the definition of a relationship between water surface drop and mean diameter in the limit condition of stability. The result obtained was $d = 0.33 \times \Delta H$, consistent with classical equations and validating their applicability, suggesting it use for design and analysis.

Keywords: River diversion; End-dumping closure; Design criteria.

RESUMO

A etapa de desvio de um rio envolve a construção de ensecadeiras, momento em que o material lançado fica exposto a grandes velocidades que pode provocar o seu arraste. Equações clássicas para dimensionamento relacionam o diâmetro médio do enrocamento (d), lançado em ponta de aterro e o desnível (ΔH) entre os escoamentos a montante e a jusante da ensecadeira, no momento do lançamento do material. Resultados de 283 ensaios realizados em modelos hidráulicos reduzidos permitiram a definição de uma relação consistente. Dentre os vários resultados de modelo, foram coletados apenas os referentes à condição limite de estabilidade do material. O resultado obtido foi $d=0,33 \times \Delta H$, consistente com o equacionamento clássico, validando, portanto, a sua aplicabilidade e utilização como orientação para projetos.

Palavras-chave: Desvio de rios; Lançamento em ponta de aterro; Critérios de projeto.

INTRODUCTION

The closure of a river is a step needed before constructions. The river is in fact not closed but river discharge is diverted through a channel or a tunnel and discharged afterwards downstream (SCHREIBER, 1977).

One common method for river closure is the horizontal (or transversal) end-dumping closure (see Figure 1A), which is largely used is Brazil. Loose material such as gravel and stones are release from one or both banks to constrict the flow progressively until it is blocked.

During closure works the hydraulic condition gradually changes and is mainly function of the discharge trough the gap and the diversion, which are also controlled by the river flow conditions upstream and downstream. The flow velocity in the gap increases gradually and this feature is the most important for closure design, which behavior is also common to other closure techniques.

The end-dumping closure advantage is that the materials used in most cases are rock available close to the closure site. Is also may be possible to use smaller stone sizes at the start of operation and bigger ones at critical steps of the closure work (see Figure 1A). The stone/rock size required during the closure increases as functions of the flow velocity through the gap and consequently by the water head drop. The size of stable closure material also depends on the relative buoyant density of the material.

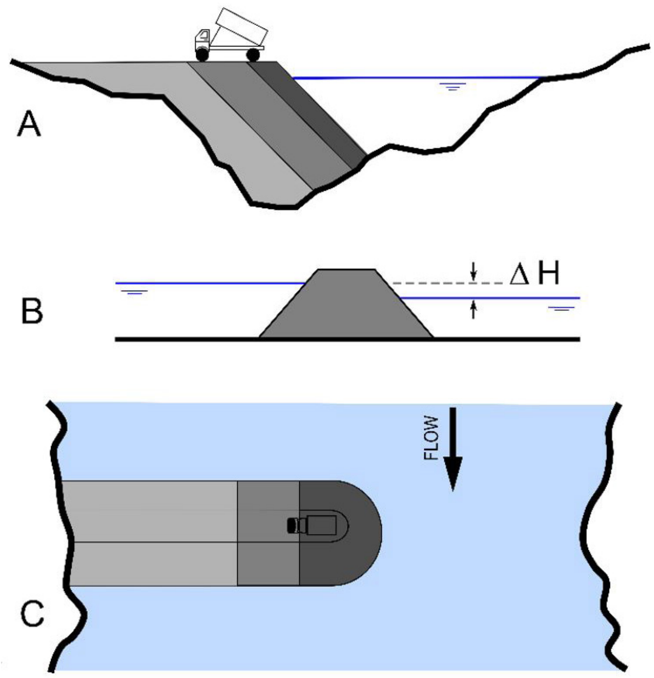

Figure 1. Representation of gradual horizontal end-dumping closure. The gray scale represents different rock sizes. (A) Shows the lateral dumping by trucks transportation reducing gradually the flow gap with different rock sizes using during closure work; (B) Shows the longitudinal cross-section of the advancing embankment (cofferdam) and the water drop from upstream to downstream; (C) Shows a top view of the cofferdam and the gap flow.

As higher the water drop, higher the rock size for closure and higher costs and the closure difficulty. It is common to split the overall differential head over two or three embankments, reducing correspondingly the material size at each embankment.

Important considerations for river closure planning are the seasonal discharge and water level variation. Closure is easy, and risk is reduced during low flows conditions and dry season, giving a construction time window during the flow seasonality. Critical restrictions are the distances dump trucks have to travel to bring material to the closure site and the need to provide a haulage road wide enough for trucks.

This paper contributes with a compilation over 44 years of experimental results from laboratory studies of real cases hydraulic models to build a practical design curve to directly determine the stable size of closure material. A functional relationship can be used to design guidance and aspects of rock works applied for horizontal closure. The design curve is based only on data obtained at the critical condition for material movement.

COMMON DESIGN CRITERIA

The main concern for closure work design is the velocity or the maximum velocity at the gap that induces the rockfill transport. This critical velocity is a function of local hydraulic conditions as: (i) discharge through the gap and the river diversion structures, (ii) water levels at both sides of the closure gap, (iii) and hydraulic head differences. A design criteria should define the rock size (median material diameter, d) for a stable cofferdam construction, at each step of the closure work, considering those hydraulic conditions.

Due to the flow contraction (constriction) at the gap the subcritical flow from upstream is accelerated and experiences the maximum current velocity near the embankment alignment. Downstream the gap, the flow expansion reduces velocity, dissipate turbulence and loses mechanical energy (head loss). The hydraulic head difference at both sides, according to Figure 1B, is named ΔH.

It is possible to relate the velocity downstream the gap, V, with the head drop between upstream and downstream the cofferdam, ΔH, by simplifications of the energy equation considering: (i) uncompressible and steady flow, (ii) energy conservation, (iii) negligible upstream velocity and (iv) depth average velocity. This simplified flow analysis gives $V = \sqrt{2g\Delta H}$. The critical velocity for the block incipient movement is given by (IZBASH, 1936)

$$V = \eta\sqrt{2g\frac{\rho_s - \rho}{\rho}d} \tag{1}$$

where V is the critical velocity (m/s), η is an experimental coefficient; ϱ_s is the block density (kg/m^3); ϱ the water density (kg/m^3); g is the gravity acceleration (m/s^2); and *d* is the nominal diameter which corresponds to a same volume sphere diameter (m).

Considering the incipient condition for motion and equaling the critical velocity to the velocity at the gap it is possible to relate ΔH and d. For Izbash (1936) the η coefficient ranges 0.8-1.2, for exposed and embedded stones, respectively, which yield for final relation as $d = 0.4 \times \Delta H$ and $d = 0.8 \times \Delta H$. Other relations presented in Table 1 are also based on experimental coefficients. Blanchet (1946) presents the Izbash equation considering a recuperation of the kinetic energy downstream and the angle of repose, obtained lower coefficients. Eletrobrás (2003) considered additional parameters as the Froude number, the angle between the cofferdam and the flow direction, contraction and friction.

LABORATORY STUDIES

The data are results of 61 experimental configuration tests of 15 scale models (of real constructions) of horizontal end-dumping method. From those experiments 283 data were obtained for different material dimension at the stability limit condition during the stages of closure work. The scale of the models ranged from 1:100 to 1:70, making it possible to obtain data for different mean diameters.

Data were collected from laboratory reports from real closure studies in models. The data represent the stability limit (critical condition) before movement were observed. In this study the closure material stability diameter is defined at the critical condition. Those data include the material mean diameter, the water head drop, and the higher velocity measured in this condition. Table 2 show the main characteristics in prototype scale of each closure site study and it reference.

Figure 2 illustrates an intermediate step of one test which shows different material sizes used during horizontal end-dumping closure. During the tests, when a critical condition was observed the material size was changed to a higher one and all hydraulic informations were measured. The critical condition which represents the stability limit was considered when material started to be carried downstream consistently, and not only by individual rocks that rolled down the steep bank.

Table 1. Classical equations developed for material dimensions as function of the water drop upstream and downstream.

Reference	Equation	Conditions
Izbash (1936)	$d = 0.4 \times \Delta H$	embedded stones on a sill
Izbash (1936)	$d = 0.8 \times \Delta H$	exposed stones on a sill
Blanchet (1946)	$d = 0.327 \times \Delta H$	selected material
Blanchet (1946)	$d = 0.412 \times \Delta H$	rockfill
Bouvard (1960)	$d = 0.436 \times \Delta H$	-
Eletrobrás (2003)	$d = 0.3 \times \Delta H$	-

RESULTS AND DISCUSSIONS

All data collected from Table 2 are shown in Figure 3. Those results indicate the linear relation between head drop and material diameter. The slope coefficient fitted with the median value in each box plot gives the relation $d = 0.33 \times \Delta H$. This result is close to those proposed by Blanchet (1946) for a well selected material, which is also the case of the experimental results. The linear trend and comparison with other equations (slope coefficients) also confirms the traditional approach and prediction equations. The data dispersion indicated by the box-plot is due to other

Figure 2. Example of a closure work in a 1:70 model of a mountain river. Observe different rock size used during closure and the material carried downstream specially at the stage the gap is small. Source: Tomaschitz (2017).

Table 2. Data characteristics from laboratory studies (from real constructions) and it sources where the hydraulic head difference (ΔH) and the rock mean diameter are shown in prototype values.

River	Scale	No of tests	ΔH (m)	Diameter (m)	Reference
Paraná	1:100	9	6.17	0.14 to 1.50	Neidert (1973)
Parnaíba	1:100	6	5.58	0.20 to 1.50	Neidert (1975)
Manso	1:75	10	3.07	0.15 to 1.19	Carneiro (1986)
Araguari	1:100	2	1.76	0.20 to 1.11	Ota and Neidert (1986)
Uruguai	1:100	7	3.94	0.53 to 1.50	Fabiani (1989)
São Francisco	1:100	3	3.94	0.38 to 1.11	Guetter (1989)
Araguari	1:100	5	2.59	0.20 to 079	Olinger (1991)
Jordão	1:100	4	1.93	0.09 to 0.59	Ota (1994)
Iguaçu	1:100	3	1.95	0.20 to 0.79	Olinger (1995)
Jacuí	1:100	4	3.23	0.09 to 0.79	Terabe (1997)
Canoas	1:100	2	3.45	0.38 to 1.11	Friedrich and Fabiani (2000)
Jequitinhonha	1:100	1	2.15	0.38 to 0.56	Terabe, Ota and Groszewicz (2000)
Canoas	1:100	3	3.13	0.38 to 1.11	Terabe, Ota and Groszewicz (2002)
Jequitinhonha	1:100	3	4.27	0.38 to 1.11	Povh, Ota and Groszewicz (2003)
- - -	1:70	2	4.20	0.56 to 1.80	Tomaschitz (2017)

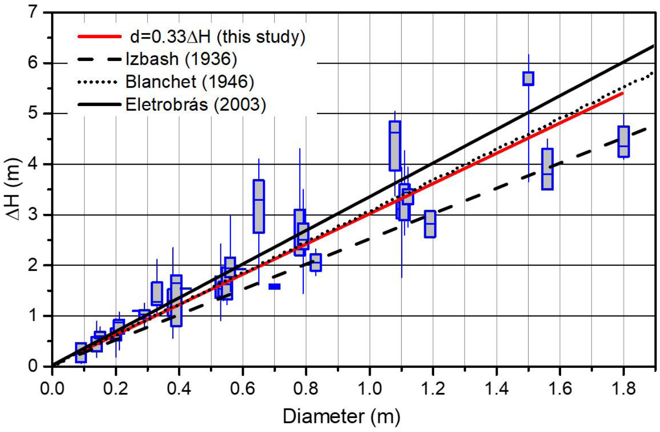

Figure 3. Relation between mean rock diameter and head drop from 283 data obtained from real cases laboratory studies presented in Table 2.

variables that influence the process as water depth, repose angle, flow curvature around the cofferdam and others.

The Izbash (1936) equation showed a fear agreement with the lower values of ΔH and it can be considered as a cautious design method, which means its equations returns the lower water head drop achieved with each material diameter. In the other side, Eletrobrás (2003) returns higher drop head achieved with the same material diameter. Other equations (slope coefficients) are also shown in Figure 3.

CONCLUSIONS

A relation between material diameter and the water level drop downstream of a gap during end-dumping closure works in rivers was obtained from laboratory studies at the critical limit of stability. The relation $d = 0.33 \times \Delta H$ confirms classical equations proposed by Blanchet (1946), Eletrobrás (2003), and Izbash (1936).

The dumping material diameter and the water drop head relation becomes from simplified energy equation and the critical velocity, formulated for averaged depth velocity. Experimental results showed a wide data dispersions, related to other parameters and flow patterns not considered in the simpler approach. Those results also reinforce the importance of laboratory studies for an accurate closure works design that involves all parameters of this particular case of sediment transport problem.

Besides the influence of other parameters the relation obtained can be used as a guide for preliminary designs as well the extreme values can be considered for carful designs approaches.

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Authors contributions

Joice de Oliveira Petrecca Tomaschitz: Literature review, data collection, data analysis, perform laboratory experiments, paper writing and review.

Michael Mannich: Paper conception, literature review, discussion, paper writing and review, figures preparation.

José Junji Ota: Paper writing and review.