

PRACTICAL EVALUATION OF LUGEON'S AND PAUTRE'S CRITERIA FOR LEAKAGES THROUGH CONCRETE DAMS

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1. INTRODUCTION

One of the difficulties arising in the design phase of concrete dams is the evaluation of leakages, through either the foundation or the concrete structures, which will be drained and pumped through the foundation drainage galleries. Because of the uncertainties affecting the theoretical forecast of these leakages, an alternative is to use some criteria that make it possible to forecast them in a faster and more practical way, which periodically need, however, some experimental evaluation by the comparison of the forecast flows with those ones really measured.

Based on real infiltration data verified through 10 (ten) concrete gravity Brazilian dams – seven of them of conventional type and three of them of roller compacted concrete (RCC) –, it was tried to make a comparison between the maximum observed flows at the end of the reservoir filling and the flows forecast by Lugeon's and Pautre's criteria, whose basic principles of application are presented afterward.

2. LUGEON'S AND PAUTRE'S CRITERIA

Maurice Lugeon, who lived from 1879 to 1953, was a Swiss geologist specialized in the study of hydraulic transmissivity through rock masses. The unit of transmissivity through rock masses is called nowadays Lugeon and was named after him.

Lugeon's criterion was developed to analyze infiltration through sections of boreholes and corresponds to the infiltration flow of 1 l/min per meter of borehole under a pressure of 10 atmospheres, i.e.:

$$1 \text{ Lugeon} = (1,0 \text{ l/min}) / (\text{m} \cdot 10 \text{ atm})$$

For leakages through concrete drains, the following control values were used:

- ✓ "Attention" Limit: 0,2 Lugeon, above which a possibility of treatment should be considered;

- ✓ “Warning” Limit: 1,0 Lugeon, above which an immediate treatment should be done to reduce the leakages.

The empirical Pautre’s method defines as expected leakage the one corresponding to the infiltration flow of $1,0 \text{ cm}^3/\text{s} \times \text{m}^2$ of wetted area and it is applied then to the surfaces in touch with water, like the upstream face of a dam. The control values recommended by Pautre are those presented next:

- ✓ “Foundation” Limit: 0,2 Pautre (considering the grouting curtain area in m^2);
- ✓ “Concrete” Limit: 0,02 Pautre (considering the upstream face area in m^2).

Based on the fact that Lugeon’s criterion was conceived for estimating leakages through bore holes in rock and, on Pautre’s criterion, for estimating leakages through surface in contact with water, one can initially predict that the former would be applied more specifically for infiltration through the foundation and the latter would be more appropriate for infiltration through the dam itself. This will be investigated afterward by the application of these two criteria for a total of 10 (ten) Brazilian concrete gravity dams and by their comparison with the maximum leakages observed just after the first reservoir filling.

According to what can be observed on Fig.1, which illustrates the evolution of the drainage flows of the weir gauges installed at the drainage galleries of Três Irmãos dam, belonging to CESP – Energy Company of São Paulo –, the observed leakages pass by a maximum value, immediately after the final period of the reservoir filling, and then start decreasing, as a consequence of a natural sediment deposition process upstream. This graph presents the flows measured in four triangular devices installed along the drainage foundation gallery from Feb’1990, the beginning of the reservoir filling, until Mar’2008.

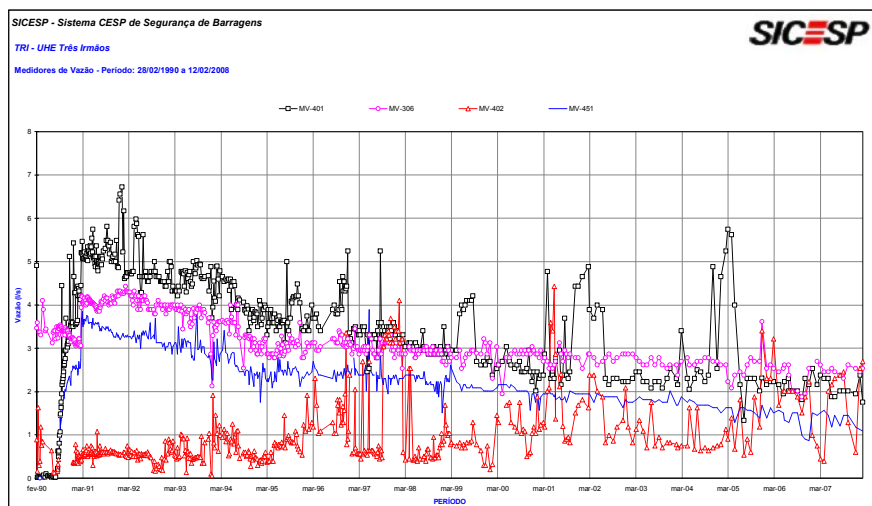


Fig. 1
Evolution of the leakages measured at Três Irmãos dam – CESP

3. APPLICATION OF LUGEON'S AND PAUTRE'S CRITERIA FOR THREE RCC DAMS

In this item, it is presented a comparison of the leakages observed in three RCC gravity dams, recently built in the state of Rio Grande do Sul, in the south region of Brazil. These structures have between 27 and 60 m of maximum heights and between 230 and 600 m of lengths, whose operation of the respective hydropower plants occurred between 2000 and 2008.

The application of Lugeon's criterion was done drain to drain, not only along the foundation drainage curtain but also through the internal concrete drains. On the other hand, Pautre's criterion was applied to the area corresponding to the drainage curtain, to the foundation and to the upstream dam facing, in its underwater part.

On the following Table 1, the results obtained by the application of these two criteria are presented, with a comparison of the predicted flows with the real maximum flow obtained "in situ", immediately after the first reservoir filling, when the measured flows reached a maximum value.

Table 1
Lugeon's and Pautre's criteria application to RCC dams

Criteria	Infiltration flows (l/min)	RCC Dam		
		Dona Francisca	Monte Claro	Castro Alves
Pautre	Concrete	40,5	4,1	11,8
	Foundation	341,5	18,2	91,9
	TOTAL	382,0	22,3	103,7
Lugeon (Attention/ Alert)	Concrete	235,5 / 1178,0	8,6 / 43,0	99,1 / 495,4
	Foundation	1214,3 / 6071,6	40,4 / 245,0	211,3 / 1056,7
	TOTAL	1449,8 / 7249,6	49,0 / 245,0	310,4 / 1552,1
"In situ" measurement after reservoir filling		2 240	385	210

The high leakages observed in the foundation of Dona Francisca dam, as emphasized in this table, is a consequence of the sandstone rock mass, hence more pervious than the basalt of the other two dams. Besides, the drainage system of this dam was very strengthened by the execution of three drainage curtains, two upstream and one other downstream, to guarantee suitable stability conditions.

With regard to Monte Claro dam, it is highlighted that the measured leakages overtook Lugeon's criterion for the "Alert" value and this demanded the carrying out of an intense grouting campaign, to reduce the leakages occurring mainly through the concrete (RCC).

4. APPLICATION OF THE LUGEON'S AND PAUTRE'S CRITERIA FOR 10 CONCRETE GRAVITY DAMS

In addition to the three RCC dams already mentioned, Lugeon's and Pautre's criteria were applied to other seven concrete gravity dam, of conventional concrete. On Table 2 the main characteristics of these dams are presented, all of them placed on basalt rock masses, except Xingó, which is situated on granite-gneiss.

Table 2
Basic characteristics of the investigated concrete dams

Dam	Structure type	Maximum height (m)	Length (m)	Foundation
Jupiá	Gravity	53	895	Basalt
Ilha Solteira	Gravity	74	970	Basalt
Promissão	Gravity	35	177	Basalt
Água Vermelha	Gravity	90	400	Basalt
Três Irmãos	Gravity	67	485	Basalt
Itaipu – Section H	Gravity	142	160	Basalt
Xingó	Gravity	71	475	Granite
Dona Francisca	Gravity	51	610	Sandstone
Monte Claro	Gravity	27	232	Basalt
Castro Alves	Gravity	48	341	Basalt

On the following tables and graphs, a comparison of the leakages obtained in these seven dams is presented, in addition to the flows of the RCC dams already commented, and also a comparison of the leakages forecast by Lugeon's and Pautre's criteria and those flows measured after the reservoir filling.

Table 3
Comparison between theoretical and measured leakages for the concrete and the foundation

Dam	Theoretical leakages Pautre's criterion (l/min)			Measured leakage after filling (l/min)
	Concrete (0,02)	Foundation (0,2)	Total	
Jupiá	38,0	200,1	238,1	560 ^(*)
Ilha Solteira	10,1	232,7	242,8	3.300
Água Vermelha	76,9	661,4	738,3	5.200
Três Irmãos	1,2	70,8	72,0	1.770
Promissão	0,42	85,6	86,0	1.110
Itaipu - DS	-	900,0	900,0	1.620
Xingó	5,0	273,0	278,00	890
Dona Francisca	40,5	341,5	382,0	2.240
Monte Claro	4,1	18,2	22,3	385
Castro Alves	11,8	91,9	103,7	210

^(*) Flow about 13 years after the reservoir filling

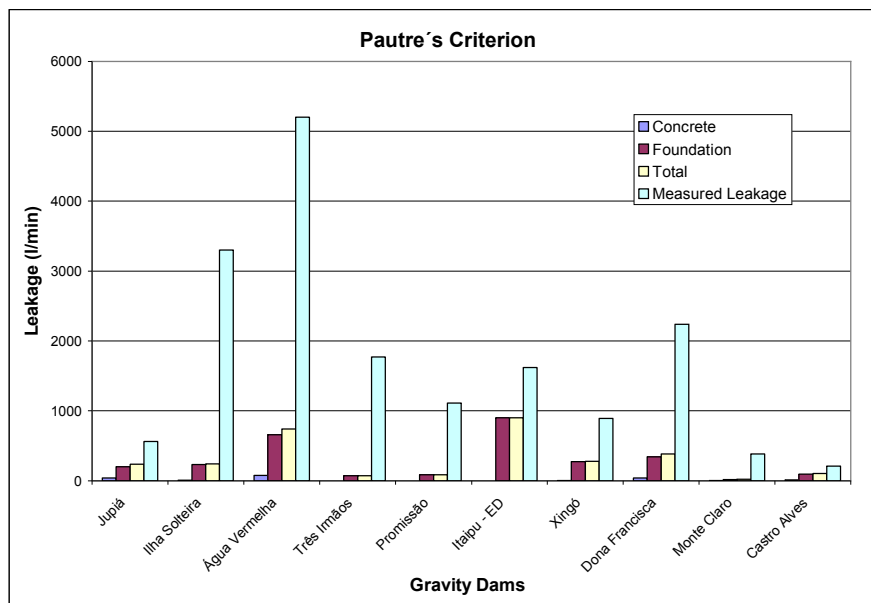


Fig. 2
Pautre's criterion for these dams

Pautre's criterion appeared very conservative, as it can be observed on Fig. 2, because the measured flows showed generally much higher than the forecast values, particularly to the dams situated on basaltic rock masses. This is not considered

therefore a good criterion for the control of leakages through concrete dams, which could probably explain why this criterion is little known in the national technical sphere.

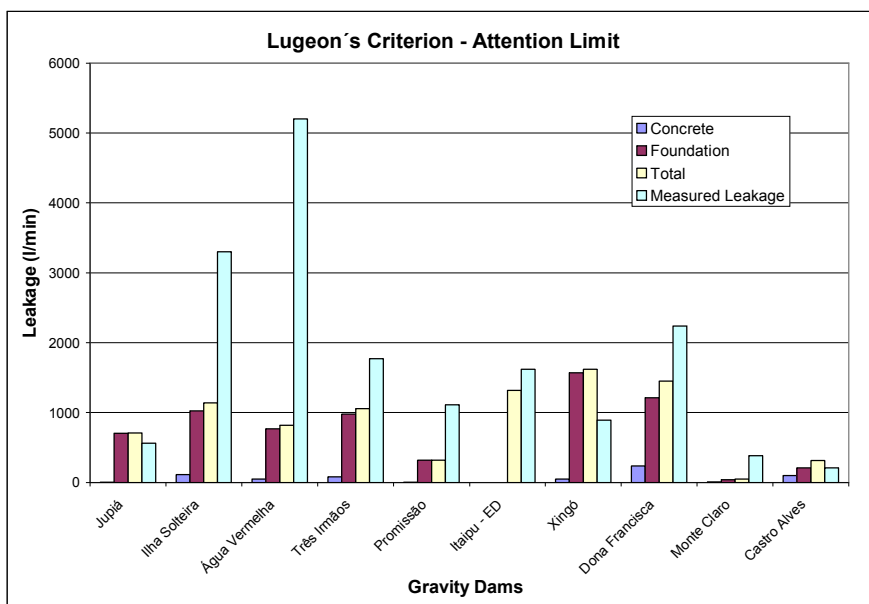


Fig. 3
Lugeon's criterion – "Attention" values to the leakages

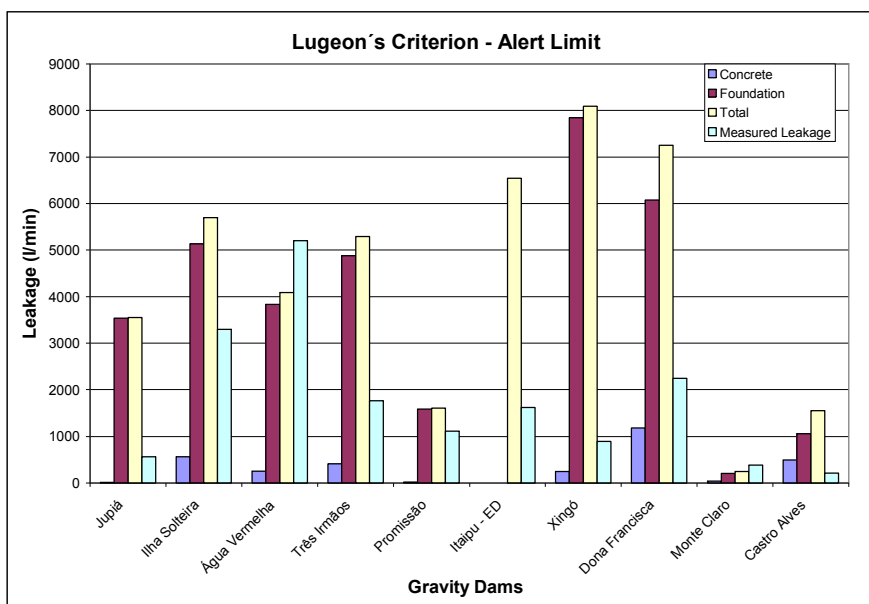


Fig. 4
Lugeon's criterion – "Alert" values to the leakages.

Lugeon's criterion for "Attention" values was overtaken in 70% of the cases and it must be thus considered only as a basic reference value, which would not demand however any treatment, because all the dams that overtook it showed a behavior inside normal patterns.

With respect to the Lugeon's criterion for the "Alert" value, it appeared as a suitable criterion for indicating the need of treatment and was overtaken by the leakages in the case of Água Vermelha and Monte Claro dams. In Monte Claro RCC dam, the high flows were a consequence of the infiltration through the concrete structures, which demanded an intense treatment by grouting of cement and of hydro-activated polyurethane.

In Água Vermelha dam, the high leakages were a consequence of a geological anomaly that occurred in the foundation rock mass, named "circular geological structures", in which the basalt layers appeared very fractured and weathered. This fact demanded in some spillway blocks the incorporation of a transversal gallery, in addition to the upstream and downstream longitudinal galleries, ending up to create high leakages. There was no need for any treatment to reduce the infiltration flows; only a partial (30%) closing of the foundation drains was done in the region where the higher leakages happened, based on the low uplifts pressures observed in it.

For Jupuíá, Ilha Solteira, Três Irmãos, Promissão, Itaipu, Xingó, Dona Francisca and Castro Alves dams, the maximum flows measured just after the end of the reservoir filling appeared always lower than the "Alert" value, which corresponds to 1,0 Lugeon, and this proves that it constitutes a good criterion in order to indicate the need of immediate treatment.

5. MAIN CONCLUSIONS

The application of Lugeon's and Pautre's criteria to a total of 10 concrete gravity dams, being three of them of RCC – Roller Compacted Concrete –, allowed to know the practical representativity of them, by the comparison between forecast and measured leakages after the phase of reservoir filling.

The application carried out involved gravity dams on basaltic rock masses, with lengths of until 500 to 1000 m and heights between 30 and 140 m. It was done structure by structure, i.e., computing the leakages through the Spillway, the Intake, the Powerhouse etc. separately. In this work, however, the data were presented in terms of total leakages observed in each dam, trying to synthesize in this way the results obtained.

Pautre's criterion appeared extremely conservative, not applicable to the dams in study, most of them placed on basaltic rock masses. Lugeon's criterion for "Attention" value corresponding to 0,2 was overtaken by the maximum observed flows at the first filling in 70% of the observed dams. It is not considered then a

suitable value for the need of treatment. Even though it has been seen in Brazilian dams on basalt a significant reduction of the leakages in the initial period of dam operation, generally with reduction in the range of 30% to 50% in the first 10 years. For the possibility of an eventual treatment, this value should be adjusted to 0,5 Lugeon.

Lugeon's criterion for the "Alert" value corresponding to 1,0 Lugeon was overtaken in two dams studied, which are Água Vermelha and Monte Claro. The latter one indicating the need of immediate treatment, as a consequence of the high leakages through the concrete. The grouting carried out in this dam used both cement grout and polyurethane foam to reach a substantial leakages reduction. On the other hand, for Água Vermelha Dam, there was no need of treatment, as high leakages were processed through the foundations, as a consequence of the existence of a geological anomaly named "Circular Geological Structure", in which the basalt rockmass appeared extremely fractured, weathered and with high permeability.

To synthesize it, therefore, this practical study of Lugeon's criterion ended by showed that it appeared a good criterion for establishing "Alert" values to take a decision about the need of treatment, for leakages through the concrete gravity dams, involving infiltration through both the concrete and the foundation. As it can be observed in the graphs presented in this work, normally the leakages through the basaltic rock foundation are preponderating over those ones through the concrete.

ACKNOWLEDGMENT

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ITAIPIU Binacional: Itaipu dam Diversion Structure
CESP: Energy Company of São Paulo: Jupia, Ilha Solteira, e Três Irmãos dams;
AES Tietê Company: Promissão e Água Vermelha dam;
CERAN: Energy Company Rio das Antas (state of Rio Grande do Sul): Monte Claro and Castro Alves dams;
DFESA: Dona Francisca Energy and CEEE: Electric Energy Company of Rio Grande do Sul State: Dona Francisca dam.

SUMMARY

The difficulties in forecast, in a reliable way, the infiltration through concrete dams, through the foundation and the concrete structures, have turned feasible the use of empirical criteria. These criteria are also useful, when, after the measurement of the observed leakages at the end of the reservoir filling, one must take a decision about the need of application of some eventual treatment, in order to reduce the total infiltration.

Having into account Lugeon's and Pautre's criteria to establish control values for the infiltration through concrete dams, a comparison between the forecast and measured leakages is presented in this paper, involving 10 (ten) concrete gravity dams, with three of them in CCR and the others in conventional concrete.

Through this comparison it was possible to verify that Pautre's criterion is not adequate, particularly for dams in area of basaltic lava flows, while the Lugeon's criterion appeared more adequate to establish control values for leakages through the foundation and the concrete of solid gravity dams.

RÉSUMÉ

Les difficultés à se prévoir de manière fiable les infiltrations à travers des barrages en béton, à travers de la fondation combien du béton, il vient favoriser l'emploi de quelques critères empiriques, pour l'estimation des infiltrations à travers de cetttes barrages de béton.

Ces critères sont aussi important, quand après la mesure des sorties observées après le remplissage de reservoir, quand il fout décider sur la nécessité d'un éventuel traitement, pour la réduction des infiltrations. En ayant par base les critères de Lugeon et de Pautre, pour l'établissement de valeurs de contrôle pour les infiltrations à travers des barrages en béton, se présente dans ce travail une comparaison entre les infiltrations prévues et les réellement mesurés, dans un total de 10 (dix) barrages type gravité, avec trois d'elles en CCR et les autres en béton classique.

À travers de cette comparaison il s'est pu vérifier que le critère de Pautre ne se présente comme approprié, tandis que le critère de Lugeon se présente plus approprié, de telle façon pour l'établissement de valeurs de contrôle pour les infiltrations à travers la fondation, quand des structures en béton d'une barrage.