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Valtorno-Mourão Dam. Reinforcement of the foundation grout due to problems detected during the first filling

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Abstract

The Valtorno-Mourão dam in the municipality of Vila Flor is intended to create a reservoir with the total volume of 1.12 x106 m3 for water supply. The embankment has a crest length of 150 m and 32 m of maximum height. It as a homogeneous profile including a sub-vertical filter. The construction of the dam took place between July 2004 and January 2006.
During the first filling, the comparison of the results of monitoring with the predictions from the Monitoring Plan lead to the conclusion that the dam was not having the expected behaviour, both for the amount of flow, which was roughly ten times higher than it was expected, and for the pore pressures measured in some piezometers. The Tras-os-Montes region in Portugal has normally severe conditions of water supply and the amount of loss in the dam was not compatible with normal supply to the populations. Given this scenario, it was decided to stop the first filling of the reservoir to allow the diagnosis of deficiencies. As a result, a new grouting treatment of the foundation was made, so that currently, the dam exhibits the desired behaviour. This paper seeks to describe the fundamental characteristics of the dam and foundation, some aspects of the construction, the diagnosis of disabilities, the treatment performed and, finally, the behaviour observed up to the date.
Keywords: fill dam, reinforcement, first filling, monitoring

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1 Introduction. Description of the dam

The Valtorno-Mourão earth dam is located in the municipality of Vila Flor. Its main purpose is to supply water to Vila-Flor and other towns located nearby. The dam has a homogeneous profile with a maximum height of 32 m above the foundations, and includes an inclined filter and a drainage blanket to control the seepage (Figures 1 and 2). The fill material came from reclamations located in the local area of the reservoir is mainly constituted of soils resulting from schist decomposition.

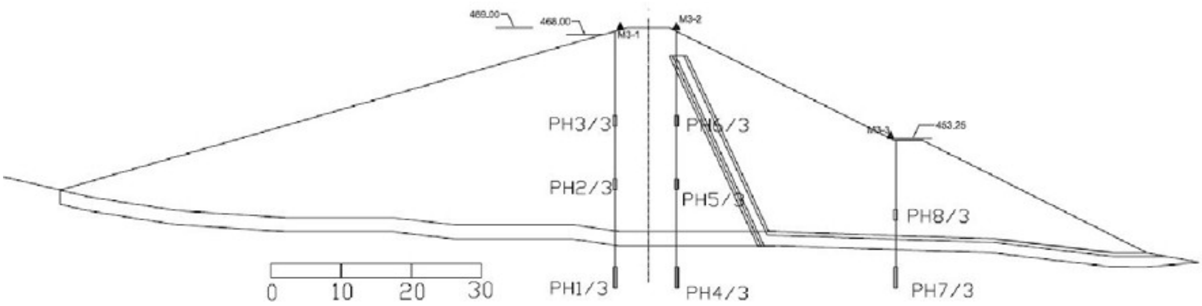

Figure 1: Cross-section (3-3) of Valtorno-Mourão dam

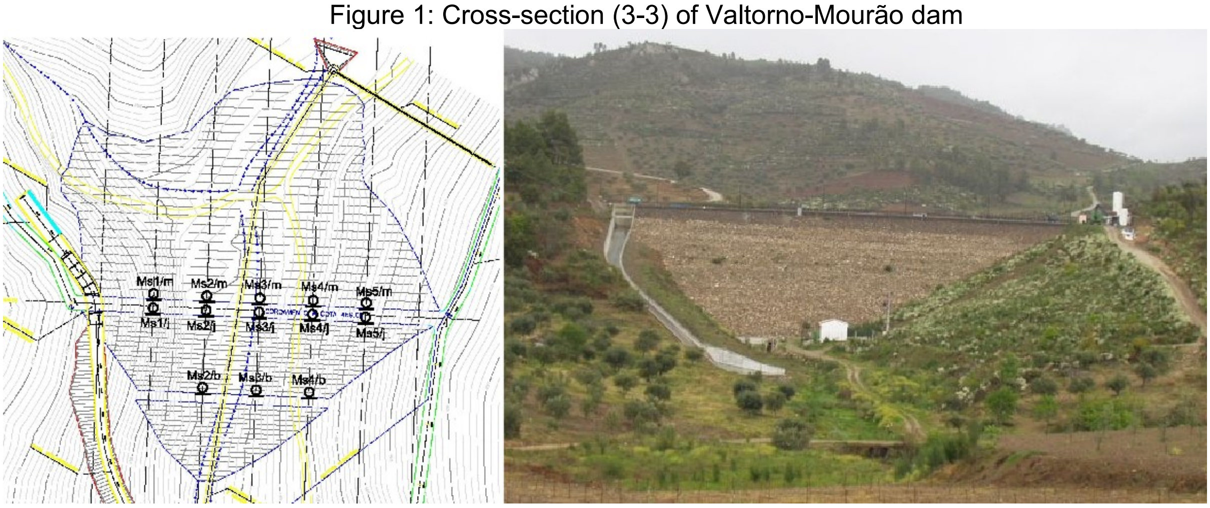
Figure 2: Plant and downstream view of Valtorno-Mourão dam

The crest of the dam is straight and has a length of 150 m and a width of 6 m. The downstream slope has 1(v):2(h) gradient and includes a bench at an elevation of 453 m. The upstream slope is less steep having with a gradient of 1(v):3.5(h).
The foundations of the dam are constituted of schist and granite. The former occurs in the right abutment, where they are very weathered. Schist also appears in the left abutment, upstream of the grout curtain. Granite appears downstream of the curtain in the left abutment.
Seepage control in the foundation is achieved by a grout curtain, formed after the cleaning of the foundation surface and the creation of a plinth.

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2 Behaviour during first filling

2.1 Monitoring and First Filling Plans

According to Portuguese dam regulations (RSB, 2007), the dam has to be monitored during its entire life and especially during the first filling. This particular phase of the dam's life also has to comply with a first filling plan (LNEC 2006),where the filling stages, maximum rates for raising the level of the reservoir, and monitoring frequencies are also defined.
Considering the dam type, and the failure mechanisms usually associated with dams like Valtorno/Mourão, it was decided to monitor the following parameters:

- reservoir level;
- pore water pressure in the dam body due to reservoir level and construction;
- pore water pressure in the foundations;
- surface displacements;
- total seepage flow.

To accomplish this task, the dam was monitored with level meters, open standpipe piezometers (20 piezometers in three different cross-sections), vibrating wire piezometers (6 units), surface marks (13 in the crest and bench), and weir flow meters (2, one receiving the flow from the drainage blanket and other receiving the flow from the foundations).
The Monitoring Plan (LNEC 2005) also indicates the frequency of data collection for each phase of the dam's life. In particular, for the first filling phase the frequencies in Table 1 were recommended.
When establishing the first filling plan, in the first place, one should consider the dam's safety but also other issues such as the incoming flow and the water supply needs, among others. In the case of the Valtorno/Mourão dam, as there was a severe drought in the interior north of Portugal, it was decided to maximise the availability of water, considering only one filling step.
This step corresponds to 41.3% of the reservoir's storage capacity and to 72.4% of the maximum hydrostatic load (Figure 3). According to the plan, the water level should be kept within the range of 456.5 m to 459.5 m during 2 months, to permit an assessment of the structural and hydraulic behaviour.

Table 1: Monitoring frequencies for the first filling

Parameter	Minimum frequency	Required readings
Reservoir level	Daily	non applicable
Surface displacements	fortnightly	start, end of each filling step, end of filling
Piezometric levels	fortnightly	start, end of each filling step, end of filling
Total flow	Weekly	start, end of each filling step, end of filling

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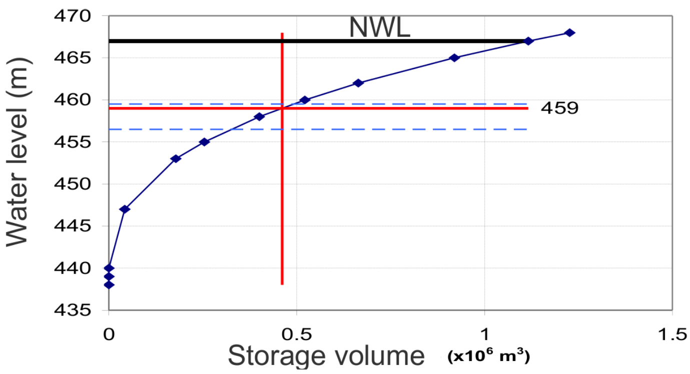

Filling step	Level (m)	% of the height	Stored volume x10^6 m^3	% of the volume
Ideal value	459	72.4	0.461	41.3
Minimum value	456.5	63.8	0.327	29.3
Maximum value	459.5	74.1	0.492	44.0
Water volume avaliable to supply			0.134	x10^6 m^3

Figure 3: Characteristics of the filling step of the Valtorno reservoir

2.2 Monitoring of Results

After an initial survey, the Portuguese authority for dam safety (INAG) gave permission to initiate first filling. The level of the first filling step was attained after 40 days, in October 2006, giving an average rise of the water level of 22 cm per day (Figure 4).
The displacement records at that time were quite normal. The maximum settlement was recorded at the cross-section P3, which at the time was about 5 cm. This value was inside the expected range.
On the other hand, seepage flow recorded at the dam's toe was much higher than expected. According to the FEM model established in the monitoring plan (Figure 5), the total flow to the maximum water level, should be about 2.6 l/s. Instead, values recorded were up to 10 times this value.
Figure 6 plots the reservoir's water level and the measured flows against the date. As can be seen from the figure, the flow rates recorded in December 2006 and January 2007 were higher than 20 l/s, but for the first filling step instead than at the MWL as forecasted by the model.
According to a statistical analysis of the data, the following expression was deduced for the seepage flow (SF) (from 2006 to September 2007):

$$SF = 0{,}79204 - 0{,}00555\,N_d + 0{,}0245\,P_{21} + 1{,}3539\,(WL - 446) \qquad \text{(Equation 1)}$$

where N_d represents the number of days from an arbitrary date, P_{21} the accumulated rainfall of 21 days and WL represents the water level in the reservoir.
According to this model, the forecast for the MWL is (perhaps optimistically) roughly 30 l/s. This situation posed two serious issues. The first was safety-related, because with that amount of flow the dam foundations could experience erosion problems. The other issue was related to the storage itself. According to the figures, with no indraught, the reservoir would lose almost all of the stored water in one year time.

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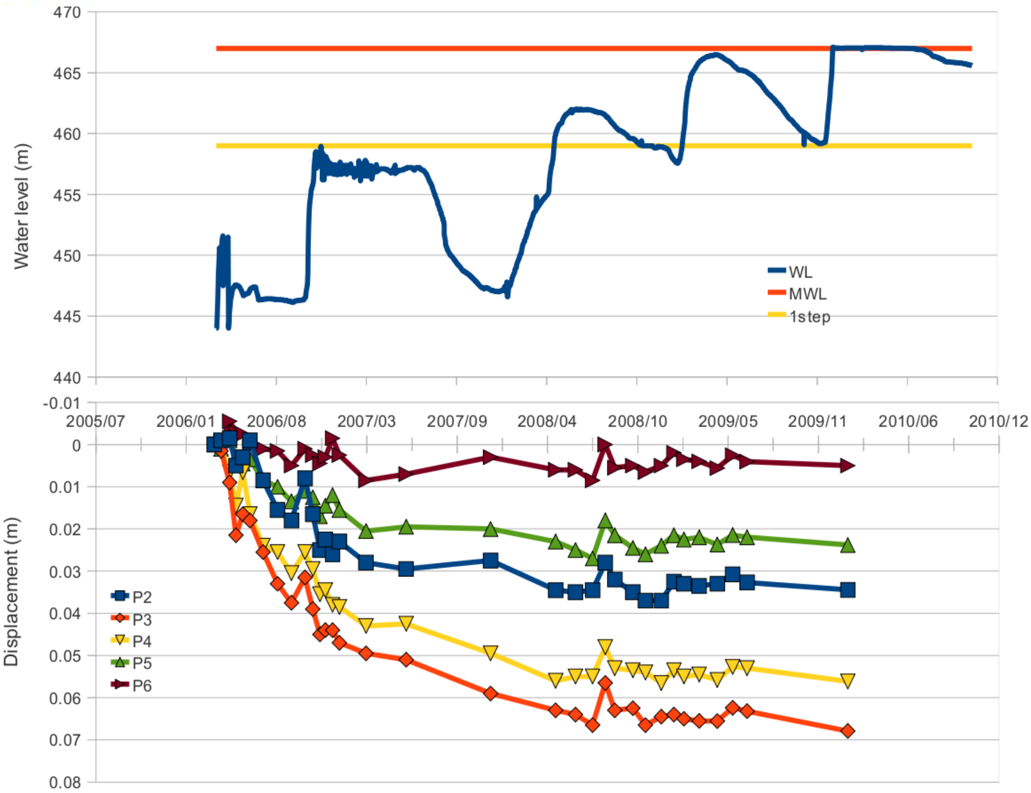

Figure 4: Water level and crest displacement records

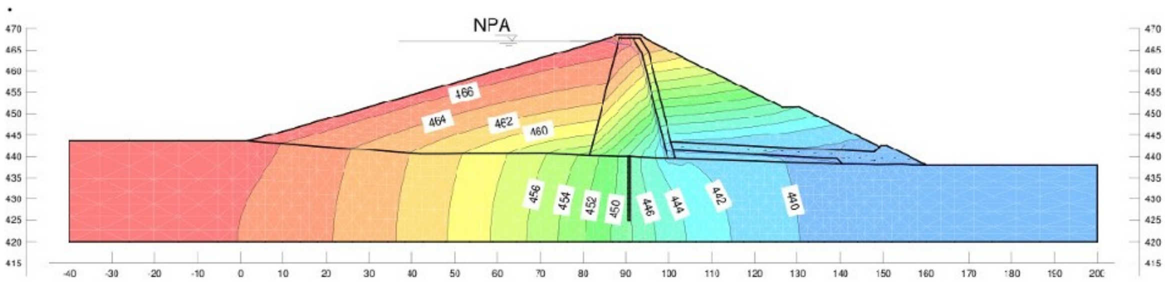

Figure 5: FEM model results (equipotential lines)

In addition to these issues, there were other symptoms of poorly functioning foundations. The standpipe piezometers located in the foundation, downstream of the grouting curtain, exhibited high water pressures, and the piezometers located above the drainage blanket also recorded pressure. These piezometers should never record pressure, under normal conditions, because the drainage blanket should contain all the seepage.

It was then decided to stop the first filling of the reservoir and proceed to the reiforcement of the foundation treatment. The works were carried out from September 2008 to February 2009, after which it started again the (second) first filling of the reservoir, ie, the first filling was retaken.

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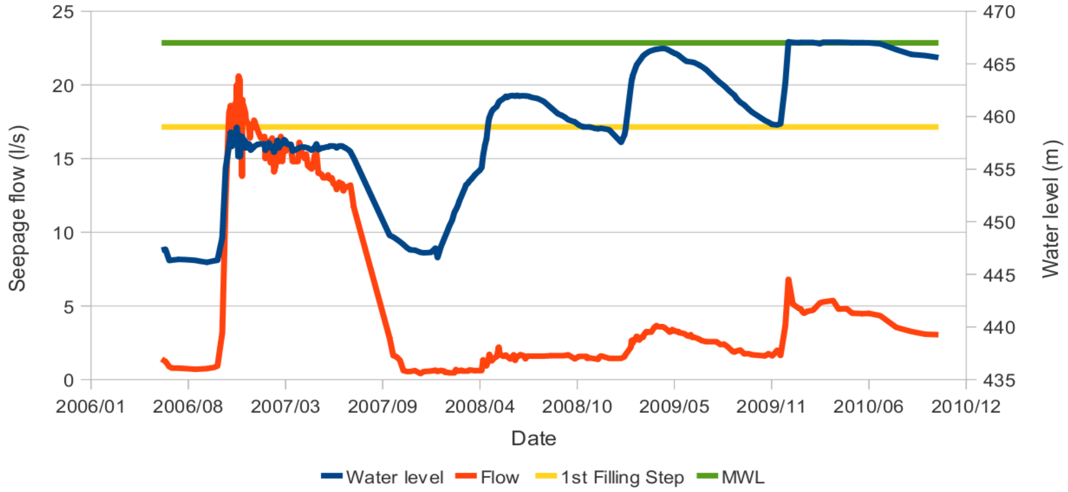

Figure 6: Water level and seepage flow against date

3 Reinforcement of foundation grouting

3.1 Geological Characteristics of the Foundation

The dam is located in the complex of metamorphic formations of the formation of Ervedosa, in very close contact with the granite of Mourão. The rock around the curtain mainly consists of various types of schist, from very hard graywacke schist to soft clayey schist. At the right abupment, the schists are traversed by numerous veins and enclaves of migmatites, granulites and on occasion pegmatites. A mass of coarse-grained granite appears at the base of the left strand. The quartz veins, either compact or very fractured, are also common in the schists along the curtain.

Increasing the lithologic complexity of the rock, there occurs a pronounced partitioning characterised by open and intense fracturing and numerous tectonic faults and tectonics bands of variable thickness. The fill material of these tectonic fractures consists of crushed material of with variable resistance, consisting of clay, breccia and micro-cracked rock fragments. In the valley, in a band about 20 m wide, the solid rock is very homogeneous and strongly tectonized, and it was presumed to be a regional fault with a NNE-SSW direction.

In the slopes, the schists present a profile of quite evolved rock stratum disintegration, with decomposed rock, which is on average about 5 to 6 m deep. Below this horizontal surface, the rock is slightly altered or sound with decomposed parts vanishing with depth.

Signs of water movement in the fractured rock are apparent on the slopes up to the riverbed. On the righthand slope a band where the oxidation of the fractures is deeper and results in a more permeable zone was identified. This singularity behaved as a path of preferential seepage through the foundation with significant contribution to the downstream flow of the dam, as noted during the injection process.

3.2 Waterproofing reinforcement

The waterproofing reinforcement consisted of the injection of grout via 29 holes from the crest, with an initial spacing of 3.0 m and inclined by 60º to the abutments, except for three holes in the central zone that due to the presence of the bottom discharge conduit were vertical. To avoid damaging the earthfills, filters and drains, the drilling of the embankments was made in dry conditions by continuous auger and using coating. In rock, the drilling was carried out by rotation with continuous recovery of samples and systematic Lugeon tests.
To protect the earthfill against water return circulation during drilling, it was decided that the coating tubes should penetrate about 0.50 m into the foundations on solid rock and the connection was to be sealed by cement grout.
The treatment by injection of the curtain in the dam's foundations was carried out over 170 m of length, between the right and left abutments, with a height ranging between 15 m at the bottom of the valley and left abutment and 30 m on the right abutment. The total area of the curtain created by this treatment was 3200 m^2, including the area under the spillway (Figure 7).
The injections were made by the successive approximations method. Initially the treatment consisted of injections via the primary and secondary holes provided for in the project and still some holes to the reinforcement of the abutments, where a lot of uncompressed solid rock with open joints was detected.
Given the difficulties in obtaining refusal and the high consumption of cement, resulting from the poor quality of the rock foundation, it was decided to continue treatment with a second phase of injections with tertiary and quaternary holes in the most critical zones, near contact with embankments and those identified by the geotechnical zoning.

3.3 Geotechnical Zoning

The analysis of the waterproofing treatment res3.5 Grout Cement Compositionults in real time, was done by a geotechnical zoning of the rock foundation, which allowed the most critical areas of the curtain that required particular injection procedures to be individualised. This zoning divided the area of the curtain into six geotechnical zones. Zones A, B and C are in the right abutment (RA), the zone D in the valley (V) and zones E and F on the left abutment (LA). The partial areas of each zone are shown in Table 2.
The most permeable zones, where higher intakes of cement were observed and/or it was difficult to achieve the prescribed pressure or refusal, were zones A and E and, to a lesser extent, zone B, totalling 30% of the curtain. The remaining 70% was related to zones C, D and F, with low to moderate permeability, but with high grout consumption, which includes the lower horizon of the curtain, and corresponded to about 30% of the overall treated area.

Table 2: Areas of geotechnical zones

Geotechnical zone	A	B	C	D	E	F	Total
Parcial area (m^2)	310	250	1140	52	400	580	3200
Percentage	10	8	36	2	13	18	100
Location	RA	RA	RA	V	LA	LA	

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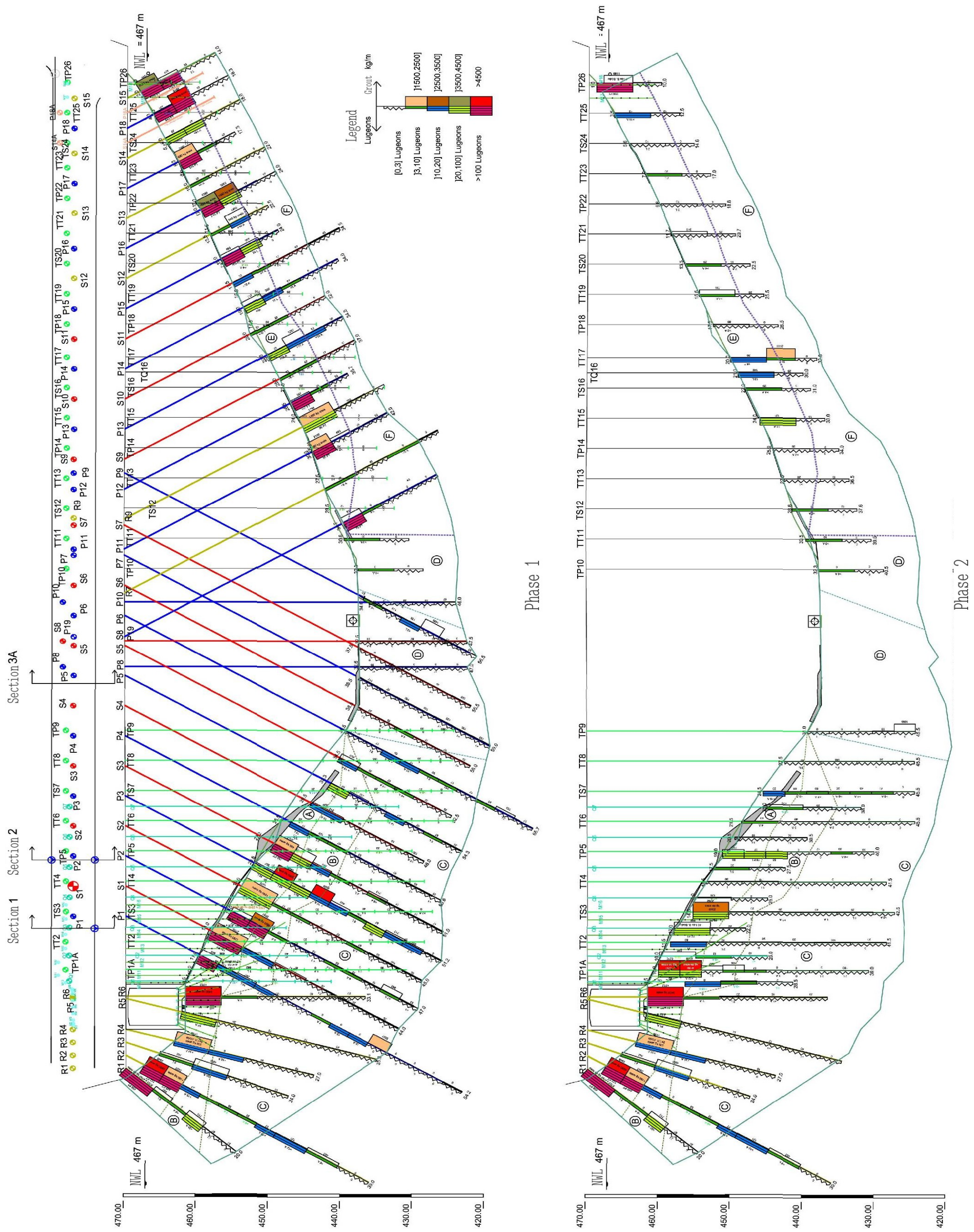

Figure 7: Results of the waterproofing reinforcement injections, 1st and 2nd phases

3.4 Grout

Three compositions of cement and water, without bentonite were used. Table 3 indicates its composition. Where very high intakes of water were registered it was decided to join fine sand in the grout composition. This was a quartz sand, calibrated with dimensions 0–2 mm. The composition of the sand is presented in Table 4.

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Table 3: Grout composition based on cement and water

Trace C/A	Water	Cement	Values of control tests during manufacturing	
	(l)	(kg)	Viscosity (s)	Density
1/2	200	100	28 - 29	1.24 – 1.26
1/1.5	200	135	30 - 31	1.34 – 1.36
1/1	200	200	32 - 33	1.44 – 1.46

Table 4: Grout composition based on cement, sand and water

Trace C/W	Water	Cement	Sand	Values of control tests during manufacturing	
	(l)	(kg)	(kg)	Viscosity (s)	Density
1/0.7	140	200	40	37 - 38	1.56
1/0.6	120	200	40	42	1.66
1/0.7	140	200	60	No injection	

For the reinforcement injections for the curtain 513820 kg of solids (cement and sand) were consumed, which corresponds to an average specific consumption of 393.7 kg per metre, of which 474.2 kg/m was in the 1st phase and 264.2 kg/m in the 2nd phase.

In the 1st phase, the average specific consumption of solids per square metre of curtain was 119.3 kg/m^2. These generic data show that the consumption was very high, both in the 1st and 2nd phases. There are many sections with several tons of injected cement. In relative terms, the consumption was higher in zones A, B and E, with values of between 418 kg/m and 2050 kg/m in the 1st phase. In the 2nd phase there was a sharp reduction in consumption, however it remained high in some sections for the quaternary holes. Although there are sections of the quaternary holes with high consumption, it was decided to finish the treatment, leaving in the most critical areas, some holes reserved for possible future grout reinforcement.

This high consumption resulted from easy penetration of the grout into the rock mass, filling the voids, which were sometimes quite open, and from the migration of grout at the remote areas of the curtain. On the other hand, there were no signs of any damage to the filters and drains due to the grouting operations.

4 Observations during and after the reservoir refill

After conclusion of the treatment, the filling of the reservoir re-started according the same plan that was initially established. As regards to seepage flow, the behaviour of the foundations was substantially different than that previously registered. It was verified that, although the total flow was slightly higher than predicted by the model, an acceptable behaviour of the foundations had been achieved.

Indeed, the maximum flow rate measured for the MWL is 4-5 l / sec (except for a peak value of about 7 l / sec), while in the initial flow rate was about 20 l / s at the first filling step. The hydraulic behavior of the foundation it is now compatible with the safety of the dam.

On average, at the highest levels for the reservoir, the flow was reduced to about one fifth of the initial value.

Figure 8 presents all the flow readings taken following treatment. The best fit curve obtained can be expressed by the equation:

$$SF = 1.1543 - 0.00544\,P_7 + 0.00092\,P_7^2 - 0.2245\mathrm{WL} + 0.0172\mathrm{WL}^2 \qquad \text{(Equation 2)}$$

where P_7 stands for rain fall over 7 days and WL for water level in the reservoir.

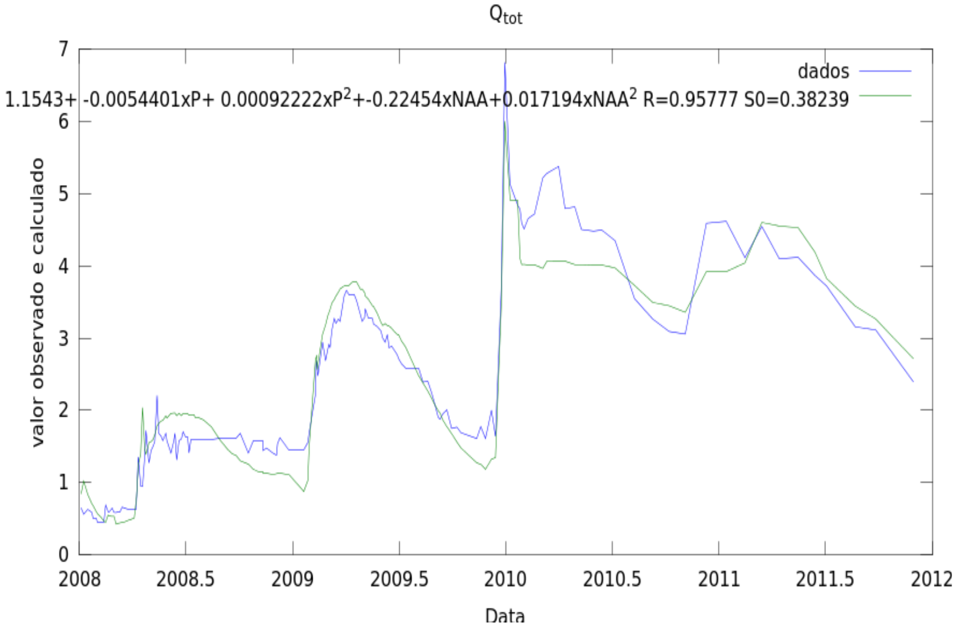

Figure 8: Valtorno dam seepage flow measurements and model

Some significant changes were also noticed at the pore water pressure in the foundation and in the dam. For example in profile 3-3, (Figure 1), the pore pressure in the foundation is shown in Figure 9. The first plot presents the head in piezometers 1, 4 and 7, all in the foundation. The second plot presents the relative hydraulic load defined as:

$$R_{hl} = \frac{PWL - FTL}{WL - FTL} \qquad \text{(Equation 3)}$$

and expressed in percentage. In the expression PWL represents the piezometer water level, WL the reservoir water level and FTL the filter tip level. It is noticeable that, before the treatment of the foundation, the piezometers 1 and 4 had relative hydraulic load (RHL) of about 70% and 60% of the reservoir's load. After the treatment, the RHL is about 60% and a little less then 40%, respectively. A similar scenario is observed for piezometer 7, where the relative hydraulic load dropped from 20 to 10%.

Considering the readings from cross-sections 3-3 and 4-4 the actual RHL can be compared with the predictions shown in Figure 10.

As it can be deduced from the figure, the f.e.m. model predicts very well the pressure in the foundation but in the dam body the predictions are far from the actual values. As the actual values are much higher that in the model, it is probably a sign that the material is more impermeable (and / or less anisotropic) that what considered in the model.

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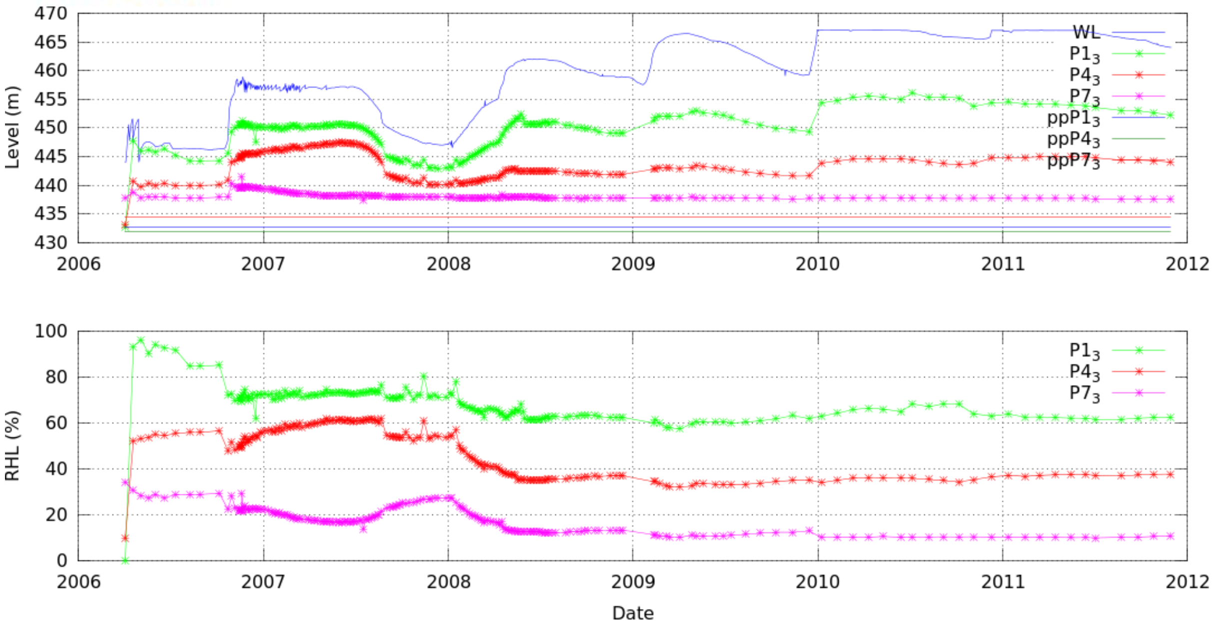

Figure 9: Profile 3-3. Pressures measured in the foundation

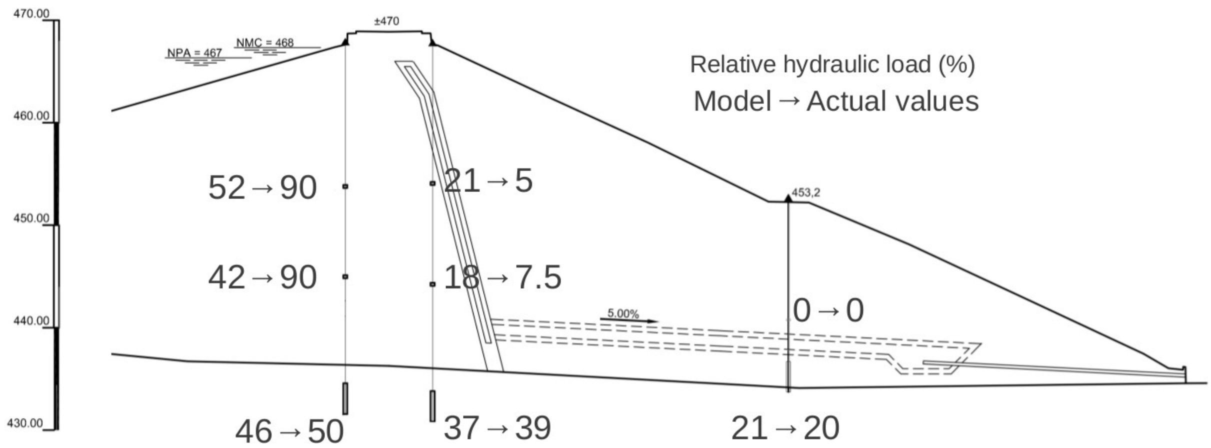

Figure 10: Comparison between model and actual values of RHL

5 Final Remarks

The Valtorno-Mourão dam became an important case study, showing that an Monitoring Plan and First Filling Plan are fundamental documents in safety control. Beyond this, it is also necessary to emphasise that for these plans to meet their objectives, the owner of the work must have an accurate idea of their responsibilities and skills, as it was the case here.

The importance of how the processing operations of the foundation were undertaken should also be noted. There is a need to ensure the technical capacity to adjust the treatment to the actual conditions of the foundation and the dam, to optimise treatment at minimal cost.

The Valtorno-Mourão dam is currently operating in appropriate and satisfactory conditions of safety. As yet, due to the its history, there are concerns about the behaviour of the foundation, it is imperative to maintain the observation activities with at appropriate frequencies, in particular at the higher levels of the reservoir.

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