

TRANSIENT ANALYSIS AND WATERHAMMER PROTECCION.

A CASE STUDY

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ABSTRACT

Transient analyses for different emergency scenarios for the biggest pressurized aqueduct ever built in Spain are presented. The duct is 70 Km long, 1.6 m of diameter and has a transport capacity of 11 m³/s. It has been designed to supply quality water to the city of Zaragoza and to irrigate several thousands of hectares of land. The gross budget is slightly under 200 million USD dollars.

The characteristics of the whole construction allows the application to a case both real and of great interest of several developments carried out by the authors, which have been presented in the two IAHR Conferences about Hydraulic Machinery and Systems previous to this of Charlotte. In particular, the subject of entrapped air was addressed in Singapore in 1998, while the selection of the optimum closure valve was considered in Valencia in 1996. This paper clearly evidences the important improvements that insight analyses of the subject can offer. Also, the necessity of avoiding unexpected failures, especially for a big construction like the one object of this paper, is stressed.

1. Introduction

This paper presents the most important aspects of the analyses carried out for different emergency scenarios regarding transients for the biggest pressurized aqueduct ever built in Spain. This study is the result of an agreement of co-operation between UTE, formed by EUROESTUDIOS from Madrid and BS Ingeniería from Zaragoza, and ITA-GMF from the Polytechnic University of Valencia.

The layout of the system, made out of three main pipelines, can be observed in Figure 1. Pipelines labeled as 1 and 3 transport water by gravity, while pipe number 2 needs a booster pumping station of considerable importance. The main data can be summarized as follows. The diameter of the pipes varies from 2 to 1.6 m. The total length of the system is 70 Km. and it has a transport capacity of 11 m³/s. It has been designed to supply quality water to the city of Zaragoza and to irrigate several thousands of Hectares of land. The gross budget is slightly under 200 million USD dollars.

But, the most outstanding feature from the point of view of its security comes from its profile, which is considerably irregular, as can be observed in Figure 2.

In order to cover the range or risks to which this system is exposed, different scenarios have been considered:

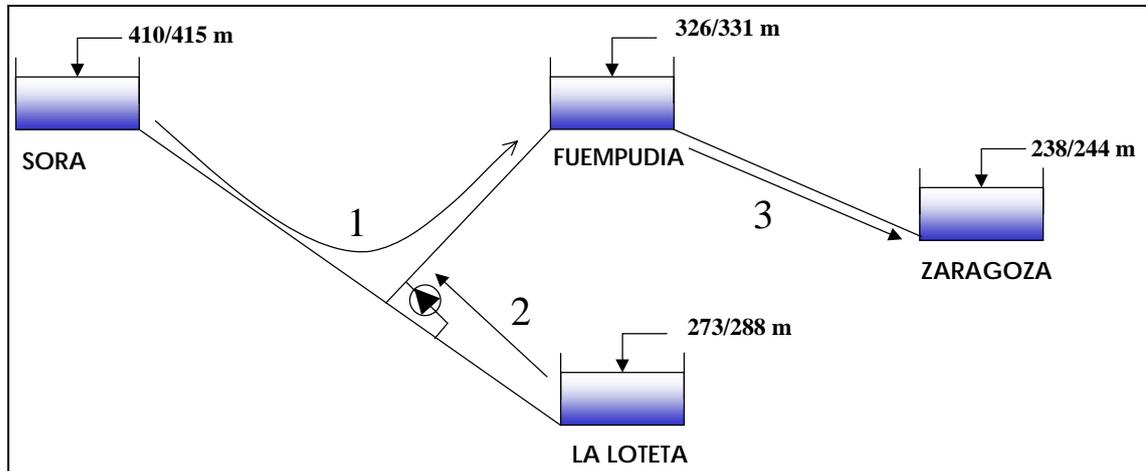


Figure 1. Layout of the system

- One of the most important risks comes from the potentiality of entrapped air at the relative maxima of the profile. Dimensioning of the systems of air admission and release have been considered.
- Due to the fact that the duct must go across deep valleys, several low points are prone to pipe breakage. The subsequent collapse of the pipe next to a breakage point is another aspect that must be addressed.
- In order to avoid overflows following eventual pipe breakage, velocity-limiting valves have been proposed and programmed to close automatically if the velocity exceeds a percentage of the steady state velocity. Different simulations must be performed to establish a correct velocity threshold.
- Valve closures are always a source of risks. Thus, some effort has been given to optimize the time closure of control valves, taking into account several kinds of restrictions, namely pressure and flooding restrictions mainly.
- Finally, water hammer effects should be avoided at the booster pumping station. A bypass line around the pumping station gives insufficient protection for all the loading conditions determined by the variable elevation both at the upstream and

downstream reservoirs. As a consequence dimensioning of air vessel protection both for the suction and the discharge lines have been considered.

The characteristics of the whole construction allows the application to a case both real and of great interest of several developments carried out by the authors, which have been presented in the two IAHR Conferences about Hydraulic Machinery and Systems previous to this of Charlotte. In particular, the subject of entrapped air was addressed in Singapore in 1998 (see Fuertes et al. (1998)), while the selection of the optimum closure valve was considered in Valencia in 1996 (see Abreu et al. 1996)). Aspects related to entrapped air have been studied by using the model presented in Singapore and developed further in Izquierdo et al. (1999). This model has been programmed using the package VisSim (Visual Solutions, 1994). To address the problems in which there is no column separation the package DYAGATS (Izquierdo et al.1996), devoted to hydraulic transient simulation and developed within the GMF-ITA, has been used. Several simulations allow identifying optimum closing maneuvers for control valves and obtaining maximum velocities reached after pipe breakage, as well. Also, simulations of the performance of the air vessels have been carried out using DYAGATS.

The study clearly evidences the important improvements that insight analyses of the subject and suitable tools can offer. Also, the necessity of avoiding unexpected failures, especially for a big construction like the one object of this paper, is stressed.

2. Gravity mains

For the two pipelines, Sora-Fuempudia and Fuempudia-Zaragoza we study:

- Optimization of the closure time of the valves to minimize peak pressures.
- Programming of the valves to avoid flooding in case of breakage.
- Possibility of pipe breakage at low points with the subsequent pipe collapse nearby. Two types of breakage, namely full and minor, are simulated.
- Dimensioning of the systems of admission and release of air.

The process of filling the pipeline with entrapped air is also considered, even though likelihood of such an eventuality is, in practice, very low since the pipe remains

pressurized as a consequence of the valve closures following a potential accident. In any case, the risks associated to the filling of the pipeline with entrapped air are underlined.

2.1 Valve closure simulation

It is a well known fact that valve regulation capacity on pipelines with great inertia is very low. Thus, to avoid water hammer effects extended closure times are required. But it necessarily implies that large amounts of water go through the valve before it completely closes. In case of valves closing following a breakage this would produce undesirable overflows. One way to avoid such an inconvenience consists on programming two-stage maneuvers. Total maneuvering time was devised to be 10 minutes.

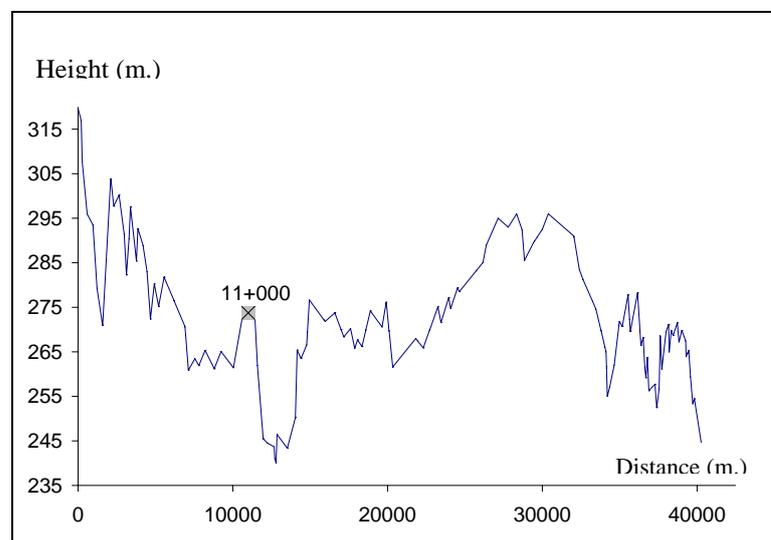


Figure 2. Layout of one of the pipes and location of the valve studied

In Abreu et al. (1996) it is shown that for two-stage valve closures a strategy, given by intermediate time t_p and degree of opening τ_p , exists for which water hammer effects produced by the closure are minimized. In order to identify this minimizing point several simulations have been carried out. Intermediate times and openings have been made to range around a discrete set of values. For the simulations, the valve located at point 11+000 (Figure 2) has been selected since, among the valves, it exhibits the highest steady state pressure. Figure 3 presents the relative maximum pressure versus the opening for different intermediate times. A commercial butterfly valve has been used.

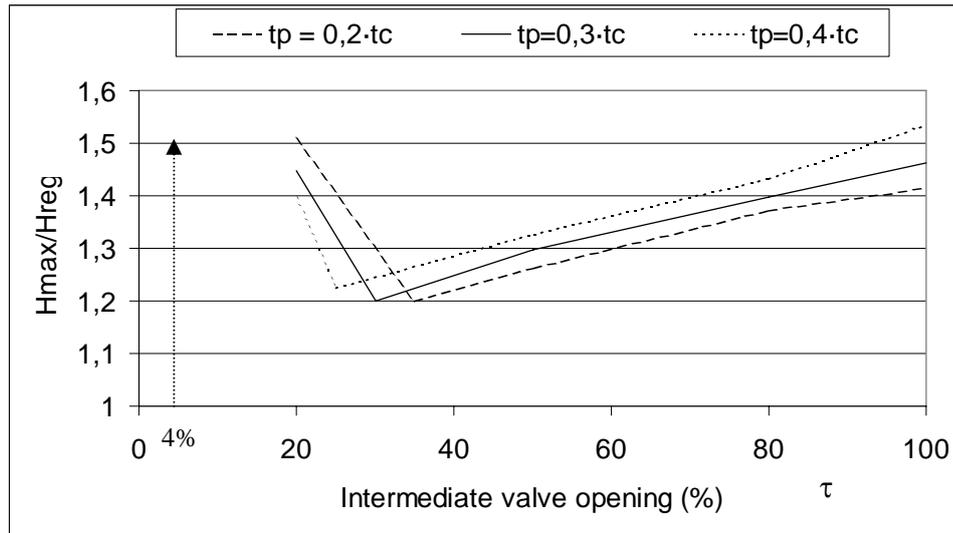


Figure 3. Optimization of the valve maneuver

The fact that simulations have been performed for only a discrete set of τ values gives the polygonal -instead of smooth- aspect to the graph in this chart. Only graphs for $t_p = 0.2, 0.3$ and 0.4 times the closure time t_c has been included, since other intermediate times give minima that are higher than the corresponding to the selected graphs.

Since the minima for these graphs are quite similar, the final decision must be taken according to other criteria. An important aspect to consider when dealing with a valve designed to prevent floods is certainly the amount of water it lets out before it closes completely. Thus, the volume of water through the valve during the maneuver has been calculated for the three candidate strategies. The results are the following

	$t_p=0,2 \cdot t_c$	$t_p=0,3 \cdot t_c$	$t_p=0,4 \cdot t_c$
Volume through the valve in m^3 along the maneuver	1198,258	1189,890	1191,457

As can be seen, there are not important differences. As a consequence, a third criterion is used to take a final decision on the closure maneuver. We have decided to study the flowrate variation, what means velocity variation, since it has important effects on the transient.

The chart in Figure 4 presents graphs of the flowrate variation for the three maneuver candidates.

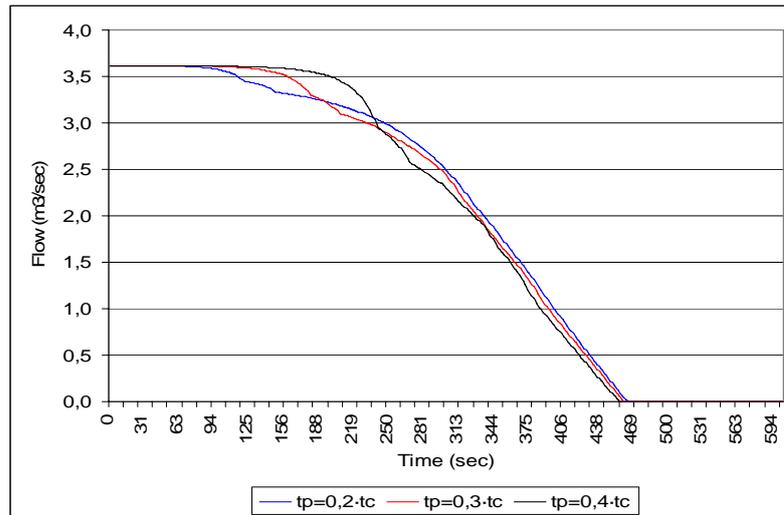


Figure 4. Flowrate evolution for the three closures considered

The analysis reveals, as expected, that the more rapid initial variation corresponds to the closure having the shorter intermediate time. Obviously the subsequent reduction is lower, giving a simple explanation to the fact that the amount of water for the three closures are almost the same. Nevertheless, an initial rapid variation is desirable since it creates greater and earlier waves that have more time for transmission and reflections, what is usually beneficial for the transient since they compensate with later waves, thus minimizing water hammer effects. In the present case it can be shown that this shorter intermediate time allows a better performance for the whole system.

Thus, the final recommendation advises the maneuver with intermediate closure $0.2 \cdot t_c$ (corresponding to 120 seconds) to reach 35% of opening and the full closure from 35% to 0% carried out in the final 480 seconds. The relevant data are the following.

	Maximum pressure (m)	Minimum pressure (m)	Volume through the valve (m ³)
Recommendation	56	10	1203

It is clear that these values strongly depend on the type of valve used.

2.2 Pipe breakage simulation

A pipe breakage affects the whole installation due to the velocity rise it originates. This velocity rise easily generates lower pressures possibly triggering cavitation and pipe collapse. To simulate a breakage different hypothesis can be considered ranging from a

minor breakage to a full one. Even though this last circumstance is almost impossible, except in case of accident or terrorist action, it has been considered in order to predict the behavior of the installation in face of such an eventuality. These emergencies must be controlled by valve closure automatically activated by over-velocity.

2.2.1 Full breakage

By full breakage we understand that accident leaving a whole straight section of the pipe discharging to the atmosphere. So, the discharge area is $\pi D^2/4$. It originates very low pressures at points close to the breakage, which extends far and far unless a suitable air admission device is reached. Since abundant air admission has been designed every 5 Km, the longest reach of the pipe affected by underpressure is relative reduced. Simulations of full breakage at point 12+800 have been performed. Head envelops are shown in Figure 5.

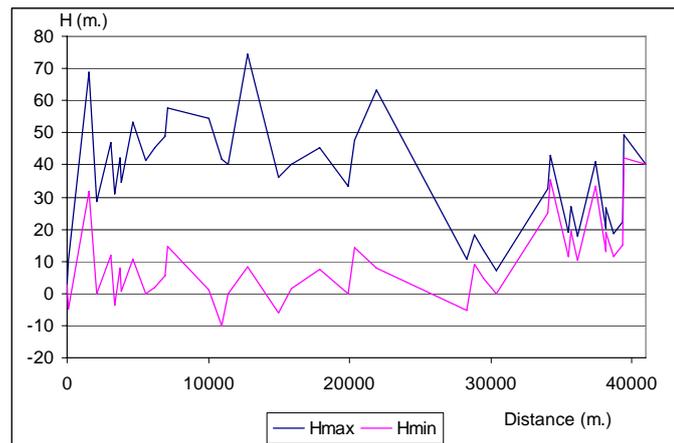


Figure 5. Head envelops for full breakage

2.2.2 Minor breakage

In order to determine the right threshold for the velocity limiting valves several simulations of minor breakage cases have been performed. The objective is twofold:

- To ensure that the valves really close if a breakage event risking the system safety occurs.
- To leave the system under the better hydraulic conditions after an emergency, thus minimizing the number of necessary operations to start it up again and, as a consequence, helping to restore the service rapidly.

The ideal situation would be that of the system reacting in an intelligent way in face of a breakage. This means that after a breakage only the first valve among the upstream valves of the breaking point should close to prevent flooding. Also, the valve directly downstream of the breaking point should close if flow reverses. Due to the fact that transient waves propagate very rapidly while valves react very slowly it is practically impossible to achieve that only the valve directly upstream closes while all the other remain unaffected. The study of minor breakage events carried out clearly reveals this fact in general. To perform the simulations an open surface of 500cm^2 (corresponding to a leak section of an annulus 1cm high of a 1600mm pipe) leaking to the atmosphere and with a discharge coefficient $C_d = 1$, has been considered. Thus, we are on the safety side since this is the maximum value C_d can take. The critical points of the system have been identified and a minor breakage has been simulated for them using DYAGATS. Then, velocities at the valves have been monitored. Figure 6 shows velocity graphs for the upstream valves of one of the breaking points. If the graph corresponding to a valve reaches the 10% line the valve will begin its programmed closing maneuver. Velocities are referred to the maximum values at any operating point. In this particular case these maximum values are attained when there exists consumption from several side lines fed by the main. Nevertheless, the simulation have been performed without taking into account those consumptions, since it represents the most unfavorable case from the point of view of transients. This is the reason why several graphs start bellow zero.

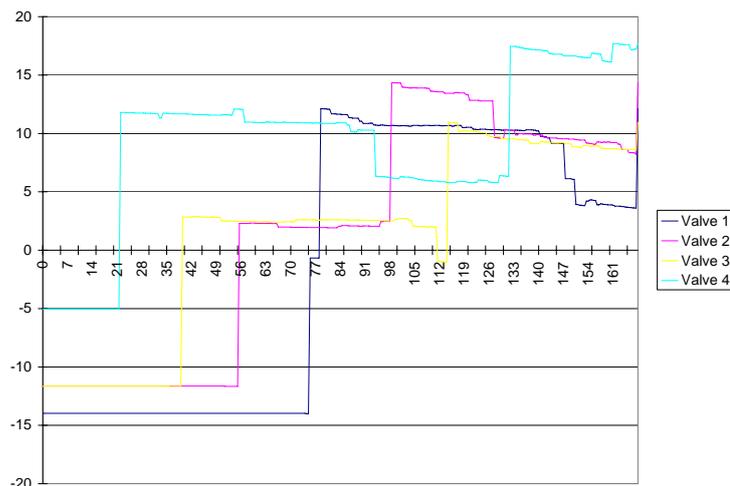


Figure 6. Velocity graphs for the valves upstream of a breaking point

2.3 Final recommendation to control system watertightness

Taking into account that a small leak through a joint or a crack, for example, will not produce a velocity rise of 10%, which is the lower threshold the valves can detect, it is of paramount importance to audit periodically the system. For example, for a flow rate of $7\text{m}^3/\text{s}$, this 10% would boil down to a leakage of $0.7\text{m}^3/\text{s}$. The velocity-limiting valves could detect such a loss in no way. But the leakage would rise to 50000m^3 per day, which evidently is an inadmissible loss.

3. Filling of the pipeline

The air introduced into the pipe through the air valves as a consequence of a pressure drop must be expelled either automatically through the same air valves as a part of the transient process or as a step of the start-up of the system if it was admitted as a consequence of a breakage. The systems of air admission and release have been suitably designed for both cases. Then, our concern focuses on the likelihood that the air valves do not let out the air suitably during the filling process. In effect, the filling of a reach of a 2m-diameter pipe of some 5Km with a driving head of some 200m must be considered as prone to risk. Calculations involve dimensionless variables (see Abreu et al. (1999)) and have been programmed using VisSim. It can be shown that the maximum value for dimensionless head h^* is 1.8. Thus, the maximum absolute head would reach $H_{\max}^* = 1.8 \times 200 = 360\text{m}$, and the maximum head $H_{\max} = 350\text{m}$, clearly over the 200 or 250m the pipe can stand. If the air valves work properly this situation will never happen. As a consequence a good maintenance practice is definitely advised.

4. Loteta-Fuempudia pumping station

The layout of the line is shown in Figure 1.

Four different load conditions, determined by the extreme water elevation in the upstream and downstream reservoirs, have been considered.

The start presents no problems at all, even without protection. So, we concentrate on the accidental trip of the pumping station. For some of the loading conditions it can be seen that simply a by-pass arrangement around the pumps would represent suitable protection. See, for instance, in Figure 8 the hydraulic grade line envelopes for the case in which both reservoirs are at their maximum level. Nevertheless, to give protection for the most critical cases air vessel protections is devised.



Figure 8. Maximum and minimum envelopes after pump trip

Cavitation does not show up, while the sub-atmospheric pressures near the downstream reservoir can be easily laminated by means of air valves. Dimensioning of the air vessel capacity for both the suction and the discharge can be carried out by standard methods.

5. Conclusion

The results and/or proposals more relevant of this study can be summarized as follows:

- A permanent audit of the system is advised to prevent leaks that cannot be detected by the limiting-velocity valves but should be considered unacceptable.
- Suitable maneuvers for the anti-flood valves have been proposed, which minimize the impact of breakage events from different points of view.

- Air admission and venting have been suitably dimensioned, thus guarantying both normal operation during transient events and programmed release of the air after a breaking event and prior to the start-up of the installation. The necessity of a suitable maintenance program of the air admission systems has been stressed by pointing out that its failure could put at risk the installation.
- Finally, air vessel for both the suction and the discharge of the pumping station have been devised and their characteristics calculated.

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