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hydrolink

Hydraulic Transients

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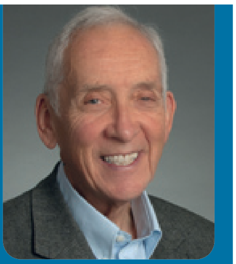
A LOOK AT SELECTED ONGOING WORK ON HYDRAULIC TRANSIENTS IN CLOSED CONDUITS

EDITORIAL BY HAMID BASHIRI & ANGELOS FINDIKAKIS

This issue of Hydrolink includes eight articles on different aspects of research and practice in hydraulic transients in urban and industrial systems. Hydraulic transients result from sudden changes in flow conditions in pipeline systems due to the planned or accidental closure/opening of valves or the start/stop of pumps or hydraulic turbines causing pressure waves through the system and pressure spikes that can be generated by column separation and rejoining.

Hamid Bashiri
Guest Editor



Angelos N. Findikakis
Hydrolink Editor

Failure to properly account for hydraulic transient effects can cause significant damage and accidents that may jeopardize personnel safety. In some cases, transients caused by operator error have resulted in equipment destruction and fatalities, such as the water hammer surge that caused the burst of penstock and three fatalities at the Oigawa Power Station in Japan in 1950. A more severe accident that was likely caused by hydraulic transients is the catastrophic destruction of the turbines of the Sayano Shushenskaya hydropower station in southern Siberia in 2009 killing 75 people, where, as discussed in the article by Hamill in this issue, a quite sudden wicket gate closure caused water column separation in the draft tubes of the turbines followed by extremely large pressure rise.

The systematic study of hydraulic transients in full flowing closed conduits and the resulting pressure waves often referred to as water hammer, goes back to the last quarter of the nineteenth century, starting with research on the flow of blood in arteries, which produced the basic formula relating the change in velocity to the change in pressure in closed conduits, and which later was developed independently by the Russian mathematician and engineer Nikolay Joukowsky working on engineered pipe systems.

Today, hydraulic transient analysis is an essential part of the design of pipeline systems in industrial facilities, including cooling water, firewater, or processing water systems, as well as for the design of pipes carrying other liquids, such as oil or liquified natural gas. The analysis of transients under different operation or accident scenarios produces the maximum pressure in each pipe segment of the system, which is used to select the pipe diameter and material. In addition, as pointed out in the article by Tijsseling in this issue, steep pressure wave fronts can cause structural motion which suggests that designs must account for dynamic fluid-structure interactions.

Equally important to the maximum pressures are the minimum pressures experienced during transients in a pipe system, which sometimes can become as low as the vapor pressure, causing cavitation. The cause and consequences of negative pressures caused by hydraulic transients are discussed in the article by Karney, in this issue.

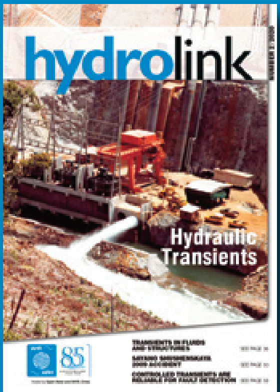
Hydraulic transients are of special interest to the hydropower industry which is supporting research aimed at improving project design and operation.

An example is recent research on hydraulic transient problems in the nearly horizontal upper chambers of surge tanks of underground pumped storage power stations described in the article by Pummer and Richter. Three case studies illustrating the importance of hydraulic transient analysis for the operation of hydroelectric plants are presented in the article by Chaudhry, which also discusses mitigation options for each case. Experimental and numerical model work on hydraulic transients problems in hydropower systems has also been carried out at the Instituto Superior Técnico in Portugal and the Ecole Polytechnique Fédérale de Lausanne in Switzerland as discussed in the article by Ferras, de Cesare, Covas and Schleiss. Their article reports on laboratory tests to study the effect of fluid-structure interaction and air entrapment on the propagation of pressure waves in pipes. The same article also presents the findings of research aimed at using hydraulic transients theory to detect and locate weak zones in pipelines, i.e. parts of lower stiffness.

Hydraulic transients tests have been used by Meniconi, Capponi, Louati and Brunone for the detection of faults in pipelines, such as leaks, blockages, corroded parts or illegal connections. Their article describes laboratory work and the use of this approach to locate faults in two different pipeline systems in Italy.

Sizing structures and devices mitigating the impact of hydraulic transients must ensure the safety of the system but also avoid costly overdesign resulting from simplified analyses that neglect some of the factors affecting the response of such systems. An example of work aimed at avoiding such device overdesign is the work on surge vessels described in the article by van der Zwan and Pothof at Deltares, who are developing models that account for the effect of air temperature inside surge vessels on their performance. An article described their work will be published in the next issue of Hydrolink.

Hydraulic transients can also be of concern for the operation of stormwater systems, where, as pointed out in the article by Allasia, Pachaly, Tassi, Vasconcelos, Hodges, and Dickinson, a combination of poor design and the lack of maintenance allowing the formation of local blockages can cause street damage and dangerous conditions, especially when these systems have to handle rapidly accumulating runoff from strong convective storms.
The articles in this issue show that more than a century after the introduction of Joukowsky's equation, there are still many aspects of hydraulic transients that require further research. Laboratory work, advanced numerical models and new techniques, such as machine learning, are used to continue improving ways to optimize system performance and control the adverse effects of hydraulic transients.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Cover picture: Powerhouse for the Larona Hydro Development on the island of Sulawesi in Indonesia. The photograph shows the operation of the synchronous by-pass valve, which mitigates hydraulic transients in the penstocks during operation. Photograph provided by Dr. Fred Locher.

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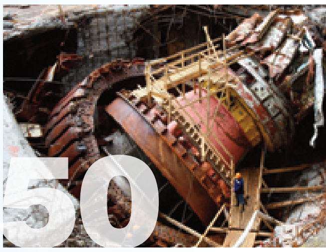

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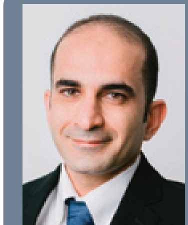

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The Editor wishes to thank Jack O' Sullivan, Fred Locher and Frank Hamill of Bechtel Corporation for their review and comments on parts of this issue.

TRANSIENTS IN FLUIDS AND STRUCTURES

BY ARRIS S. TIJSSELING

Hydraulic transients in liquid-filled piping systems are pressure waves that travel long distances in short times. They are perfectly able to find weak spots and cause damage to pipes, supports, machinery, etc., because the wave fronts are steep, and the pressure rises (or drops) large. It is one of the most severe loadings any piping system will experience during its lifetime. A hydraulic transient causes a structural response, which may cause a smaller hydraulic transient, which causes another structural response, and so on. This is fluid-structure interaction (FSI).

Hydraulic transient analysis is essential in the design of piping systems and even more so in post-accident investigations. Computed transient pressure histories can be used as input to structural-dynamics software in order to find pipe stresses and displacements. This is usually done when the safety standards are high (nuclear industry, chemical industry, dike crossings), when the pipe layout must be light (aerospace industry), when noise must be reduced (naval submarines), when stability is an issue (hydropower stations), for buried pipes during earthquakes, naturally in hemodynamics, for fatigue life or damage prediction, and not in the least for cost reduction. The above procedure of one-way coupling gives useful additional information but maybe wrong when the pipe system has a certain degree of flexibility, mostly encountered in aboveground pipelines (Figure 1). Two-way coupling is then a more accurate approach, noting that FSI causes damping of pressure waves (because energy is transferred to the pipe walls) and has a tendency to mitigate resonance. On the other hand, in free-hanging systems, the classical Joukowsky pressure, calculated with a simple equation which is accurate only for straight uniform-section pipes without any column separation, may be exceeded by a factor of two.


Figure 1. Aboveground pipelines.

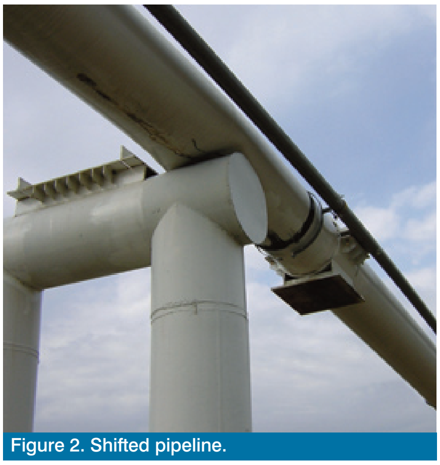
Figure 2. Shifted pipeline.


Figure 3. Broken anchor.

Hydraulic transient loads may cause pipes to move and shift on – or even fall off – their supports (Figure 2 [1]). This is an undesired situation and most frightening for personnel working nearby. The apparent solution would be to fix the pipes rigidly, but – more often than not – this leads to broken anchors (Figure 3 [2]). Some flexibility is always needed to allow for thermal expansion, but also to reduce pipe stresses in a water-hammer event. The locations and strengths of pipe supports are usually obtained from a static analysis based on conservative estimates of the fluid forces. Two-way FSI analysis may help in finding the appropriate way of dynamically supporting the piping system, noting that mass and not stiffness resists to sudden pipe motion. Fluid-structure interaction is always existent to a certain degree and many laboratory experiments on water hammer contain the (undesirable) effects of it. To avoid FSI one might embed the entire pipe in solid concrete [3] or use cubic blocks with cylindrical bores [4].

In general, (very) steep pressure wave fronts are needed to provoke structural motion and justify FSI analysis. The first coupled effect is

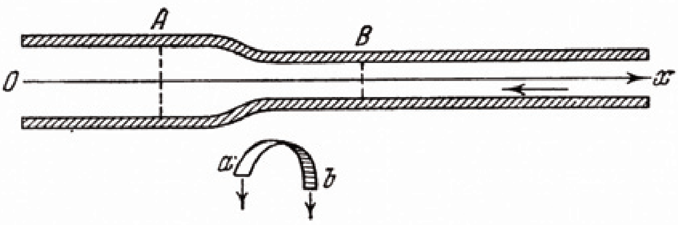

Figure 4. (from Joukowsky himself) Liquid flow from right to left has been arrested at position O and a pressure wave travels from left to right. The increased pressure widens the pipe and causes a dynamic hoop stress proportional to it. Pipe bending occurs only near the wave front.

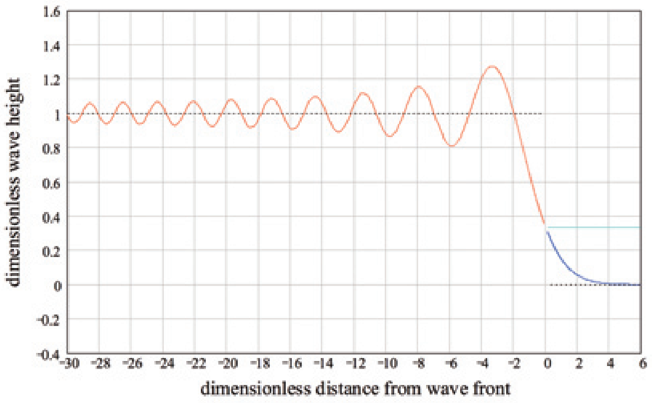

Figure 5. Skalak's theoretical wave front. Instantaneous valve closure causes a step wave front in classical water-hammer (broken line). Fluid-structure interaction disperses the wave front into a "precursor" (blue line) and trailing high-frequency oscillation (red line).

the axisymmetric bending of the pipe wall (Figure 4 [5]) which makes the traveling pressure front less steep and which induces a decaying trailing oscillation (Figure 5 [6]). This is one of the reasons that in pure liquids (without gas bubbles) wave fronts spread over lengths of tens of pipe diameters. The second coupled effect is due to unbalanced pressure forces, which make free pipe bends move; vibrating elbows are the most common generators of FSI. Pipe ovalling occurs, but as this hardly changes the cross-sectional flow area it does not affect pressure waves. The same holds for friction and damping; excluding resonance conditions, these are of less importance for the prediction of extreme pressures and stresses because of the short (acoustic) time scale: inertia and elasticity are the dominant forces such that friction will not affect the very first pressure rise in a water hammer event. It is good practice to have slow valve closures and pump stoppages, but in events of steam condensation and the collapse of column separations – somewhere in the system – almost instantaneous pressure rises are generated.

The oldest FSI formula goes back to Thomas Young [7] and relates the pipe hoop stress to the fluid pressure (linearly via the relative wall-thickness). The radial inertia of the pipe wall is ignored in this formula, which therefore is valid for frequencies well below the pipe's ring frequency. Sudden changes in hoop stress (and strain) cause axial stress waves in the pipe wall, which – due to FSI – are accompanied with changes in fluid pressure. These fast traveling (at the speed of sound in solids) pressure variations have been observed as precursors arriving ahead of the main water-hammer wave [8]. The axial waves in the pipe wall will excite bends if they are not sufficiently restrained and the resulting motion is a sort of pumping action which generates pressure waves in the liquid [9, 10]. It is noted that a traveling pressure wave does not "see" a structurally fixed bend.

To simulate FSI on a computer one needs, in addition to a water-hammer code, a structural-dynamics code, and one must couple them. Regarding the fluid, one might opt for CFD software. Regarding the structure, that is the pipes (and the supports), one may go as far as one wishes: rigid beams, elastic beams, membranes, or shells. One simplified approach is to model only the axial motion of the individual pipes in a system (which is analogue to the vibration of an elastic liquid column and might be referred to as "steel hammer"), and represent lateral and torsional motion by spring-mass-dashpot systems [10]. It has no use to simulate the entire piping system with FSI included, but one should select only those sections that can move as a consequence of unrestrained elbows, tees and U-bends.

Future challenges lie in the analysis of pipes, tubes and hoses made of a combination of different materials, like concrete and steel, and fiber-reinforced plastics. That is non-uniform and non-elastic pipes, with lining and coating, surrounded by soil and/or liquid. In fact, a blood vessel, where all hydraulic transient research started off in the 19th century, is the most striking example. The technical details of hydraulic transients with FSI and some of its history, together with the evidence of laboratory and field experiments, can be found in several review papers [11-15].

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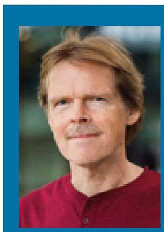

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HYDRAULIC TRANSIENTS AND NEGATIVE PRESSURES – CONSEQUENCES AND RISKS

BY BRYAN KARNEY

Orderly, steady, liquid flows in closed conduit systems can be disrupted in a variety of routine ways. Two crucial disruptions are overviewed here, one arising through the introduction of unsteadiness associated with changes in the system's boundary conditions (typically adjustments to operating conditions at pumps, valves and tanks) and the other by inducing or introducing a second phase, a gas or vapor, into the flow. This article briefly overviews the often-problematic but invariably fascinating nature of these transient water-air or water-vapor flows.

Introduction

Pressurized pipe systems, whether carrying treated water or untreated wastewater, are required to meet a variety of technical requirements, ranging from achieving sufficient hydraulic capacity, to delivering water undegraded in chemical and biological quality, to being economically viable, to having sufficient structural strength to withstand both internal and external loadings. One of the perhaps surprising (and sometimes overlooked) implications of these basic performance constraints is that the pipeline needs to breathe well – that is, that all lines need to limit cavitation and to permit and control the movement of air into and out of the line as the line responds to a range of operational requirements.

The steady-state flow of liquid water in a pressurized conduit system is typically expressed physically in a kind of stately cadence – as the flow progresses downstream, mechanical energy is transmitted farther along the line but is also gradually converted into thermal form. Even for turbulent flow, this progression in a single-phase system generally sees the total mechanical energy of the flow diminishing downstream, even while experiencing many local variations in the component velocity, elevation, and pressure heads. But even though these three-component heads do change, they do so quite predictably in response to obvious local changes induced by things like undulations in the pipeline profile or local changes in the flow's cross-sectional area. Significant adjustments in mechanical energy sometimes occur too, as for instance when a flow passes through a pump or turbine.

But transient or unsteady conditions disrupt this orderly progression, creating sudden local changes in flow and pressure that are subsequently propagated throughout the connected system via coupled acoustic pressure and velocity waves. As much as the overall system response can be dramatic, usually associated with some initiating cause followed by the system's sometimes complex response, what happens within any individual pipe is fundamentally more limited. Under steady flow, the inflow and outflow of water to a pipe segment must be equal, since an imbalance in flow rates would imply an accumulation or depletion of matter over time, and thus a violation in the steady assumption. But under unsteady flow conditions, a pipe segment can experience any combination of only four primary events: the inflow rate can increase or decrease and/or the outflow rate can increase or decrease, with each change initiating a propagating pressure/velocity wave.

With one of these pairs – namely, either an increase in inflow or a decrease in outflow – a transient increase in the mass contained in that pipe will occur, and thus the pressure within the segment will necessarily rise due to the mobilization of a tiny (but significant) compressibility effect. Either or both of these induced changes causes a transient pressure increase and a so-called positive wave to be initiated at the location of the imbalance. These positive-pressure transient waves increase other things too, such as inducing stresses or movement in the pipe wall or its supports, and thus leading to an increased chance of a pipe burst or other component failure. This sequence of consequences is indeed at the heart of the conventional concerns with water hammer.

But the opposite imbalance can lead to other less-well appreciated issues. Thus, if, for any reason, either the flow into a pipe section is decreased, or the outflow increased, the

Figure 1. Cavitation on an impeller (National Technical Museum, Prague).

pressure in the segment quickly drops, sometimes to values below atmospheric, or possibly even to the vapor pressure. Such pressure drops tend to either induce a phase change in the flow or to draw foreign material into the pipe (whether air or water, possibly along with dissolved substances or entrained solids) through any available cracks or openings.

What is significant as well is that the generic system adjustments that generate negative pressure events are associated with quite routine operational actions. Any or all of the following can lead to a transient negative pressure event, from the failure or trip of a supply pump, to simply closing an upstream valve, to rapidly opening a downstream valve, or having to suddenly satisfy a water demand from the pipe, to draining a line, or to the pipe experiencing a burst event. The design and operation challenges associated with this pressure drop often create many hazardous operational conditions as well as those associated with induced phase changes. Indeed, phase changes, or related air and water ingresses, tend to make pipeline operation and design more unpredictable, more asymmetric, more prone to failure, and generally more pathological, than a quick or uninformed appraisal might indicate [1]. It is to these phase-change-inducing transient events that the remainder of this short article is addressed.

Causes and consequences of negative pressures

Transient imbalances are a notable cause of negative pressures, but not the only one. Even steady state influences and Bernoulli effects can induce negative pressures and phase changes. Any of the following conditions can be problematic in this sense: high elevations such as associated with an elevated pipe profile or siphon structures; flow restrictions such as those associated with partially closed valves or blockages; high velocities in combination with large surface roughness or abrupt changes in the flow direction; or large secondary flows such as those associated with the vortex action and secondary flow of pumps or turbines. Any of these common causes are capable of creating sufficiently low local pressures to induce cavitation, or perhaps to induce air or gas release such as freeing ammonia from solution in certain sewer systems. Any transient event (associated with the local flow imbalances just described) can greatly exacerbate those conditions, superimposing an additional complexity on an already complicated phenomenon.

Few hydraulic engineers will need a reminder of how damaging local cavity creation and collapse can be. When a fluid cavitates, a vapor pocket is formed in the flow, a condition that is almost invariably unstable since higher pressures follow low values, either in space or in time. Thus, cavitation in the suction of a pump (induced by vortex action) evolves into vapor collapse as the outward flowing fluid moves the vapor cavities into the outer reaches of the impeller, while cavitation bubbles generated in the throat of a valve (induced by high local velocities) are swept into regions of higher pressures downstream. The collapse of these cavities is often so violent that extremely high pressures, high temperatures, and even high velocities frequently result [2]. Figure 1, taken at the National Technical Museum in Prague, shows the typical outcome of an impeller having been exposed to a strongly cavitating flow. The material near a repeated cavity collapse is first fatigued and then effectively “eaten away” by a process that is so irresistible that no known material can withstand its attack indefinitely.

The low-pressure conditions that can occur at the highpoints in a pipeline profile, or in the eye of a pump, or in the throat of a valve, can also be generated by the transient imbalances referred to earlier. But it is the conjunction of multiple causes that often creates the greatest challenge to system designers and operators. Thus, for example, a pump trip can generate a negative pressure wave that might be tolerable to the pump but interacts with a high point in the pipe profile to create negative pressures and potentially cavitation. The cavitation can sometimes be so extensive as to effectively split the flow into two segments in an event called water column separation, a phenomenon extensively reported on in the classic water hammer literature. To limit the cavitation risks, air-vacuum valves are often placed at high points to limit the pressure drop to less-negative valves, but at the cost of admitting air into the line, and effectively substituting one two-phase flow challenge (water and vapor) with another (water and air). As is the case so often with cavitation, the most damaging consequence is not the formation of these air or vapor cavities, but their collapse, a transient event that has frequently damaged not only air valves but also their adjoining conveyance system [1], [2].

Before considering air-related transient events in slightly more detail, it is useful to briefly mention an interesting and sometimes forgotten reality about cavitation: the transition between liquid and vapor states is not automatic as soon as saturation pressures are reached. In fact, this transition is greatly facilitated by the presence of nucleation sites, sites that are often associated with small particles or nucleation sites in the flow and give a kind of hint or nudge to the flow about where to focus or concentrate the phase change. The complexity and randomness of this nucleation process can be visually appreciated by a close inspection of almost any vegetated surface after a dewfall. As Figure 2 indicates, both the size and distribution of the resulting condensation droplets are highly variable. This complexity of this distribution is present whenever phase change occurs, though usually, the results are much more difficult to visualize than when dew on the grass. However, in most commercial pipeline applica-


Figure 2. Complexity of nucleation visualized by dew on grass.

tions many nucleation sites are presented and the transition between phases is not unduly inhibited.

Of course, cavitation is not the only possible consequence of negative pressures. Negative pressures can in some cases can lead to the release gases, many of which are corrosive, or can induce the pipe wall to buckle, with often grave structural and hydraulic consequences. Negative pressures can also induce ingress into the pipe from the surrounding soil or water, creating a water quality threat in potable water systems. Moreover, negative pressures can draw larger quantities of air into the pipeline, creating an air pocket that can pinch the flow, increase hydraulic losses, generate air removal issues, and possibly intermittent and pulsatile action in the flow.

The complication of air in a water line – its presence, admission and expulsion

The devices that help to facilitate this air exchange are the set of a line's air valves (which let air out), vacuum valves (to let air in), and combination air valves (which permit a two-way air flow). For simplicity, all these roles are collected here under the general term of "air exchange valves". The process of design for these devices generally involves choosing the valve manufacturers, selecting the kind and number of valves, selecting the location and specific mounting of each valve, and sizing all their exchange orifices of each valve. One of the great challenges of selecting an appropriate set of air valves for a given pipeline system is that the function of these valves must generally cover a broad range of requirements, and there is actually remarkably few data about the long-term performance of these valves over the range of environments commonly encountered in pressurized pipeline work. Several publications by Ramezani and others highlight these challenges [5], [6].

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Before considering air valves in slightly more detail, it is worthwhile emphasizing that merely the presence of air can be problematic. When, say, an air pocket is present, not only are buoyancy forces mobilized but the compressibility of the line is increased, a fact that can allow the fluid to accelerate in ways that would not be possible if only liquid were present [7], [8], [9]. Figure 3 shows a typical case where a line containing an air pocket is rapidly pressurized; in this plot, VF represents the void fraction occupied with air, a measure of the system's capacity to allow acceleration as the air is compressed. Since the original pocket is not under significant pressure, its density is low and it can be compressed with only a moderate change in pressure. This allows source water to accelerate to high velocities before compressing the air sufficiently to provide the pressures needed to decelerate and eventually arrest the water's forward motion. In general, rapidly pressurizing spaces containing air pockets can have dramatic and sometimes even explosive consequences.

The roles that air exchange valves have to perform are quite varied, ranging from allowing air to be removed during line filling operations to allowing air to re-enter the line when it is drained. But they also extend to what amounts to temporary or transient local filling and draining operations under water hammer or surge conditions, such as the pressure waves induced by power failure to a pump or the rapid closure of a valve. That is, if the local pressure drops below atmospheric conditions, a suitably-sized vacuum valve should open to admit air to maintain pressures, and then this admitted air should be safely discharged at a controlled rate when internal pressures again rise above atmospheric values. Finally, air valves need to remove the small amount of air that can evolve or be present in the line even under otherwise steady conditions. What makes these roles particularly problematic is that the sizing and location choices for the different design conditions can be in conflict, and it is not always easy to know how to achieve a suitable compromise, let alone to know how frequently their action is called for in practice.

A hint of this air-induced complexity is providing by considering the simple act of filling a line with not untypical profile. Figure 4 shows a case where a line with a V-shaped elevation profile is being filled. Intuitively one might expect little problem with negative pressures since the line is filled from a water source at a higher elevation than any point on the pipeline itself. However, there is roughly a

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Figure 3. Pressure and velocity during air pocked compression after pressurization. [4]

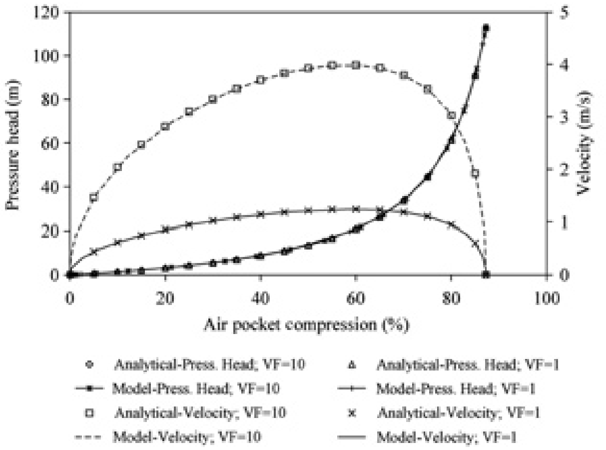
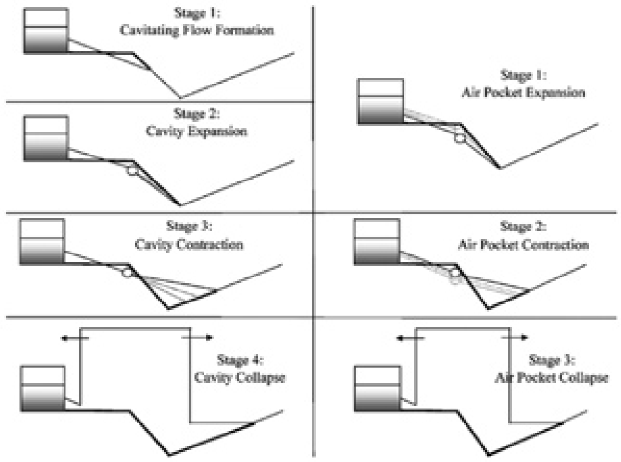


Figure 4. Air or vapor pocket growth and collapse due to line filling in a V-shaped profile. [3]



INNOVATIVE STRATEGIES FOR CONTROLLING HYDRAULIC TRANSIENTS IN PUMPING SYSTEMS AND HYDROELECTRIC POWERPLANTS

BY M. HANIF CHAUDHRY

To account for uncertainties in the system parameters and in the computed results for hydraulic transients in pumping systems and hydroelectric power plants, liberal factors of safety were used in the past while designing or operating such systems. However, modern computational procedures and general-purpose, commercial computer codes have made it possible to simulate hydraulic transients in complex piping systems, producing computed results that can be used with confidence. In addition, advances in the sensor and wireless technologies, along with the utilization of real-time data, make it possible to develop innovative strategies for transient control for efficient system operation in spite of uncertainties in the system parameters. These concepts are discussed, and four casestudies on which the author acted as a consultant are presented for illustration purposes.

Hydraulic transients are produced in piping systems whenever the rate of discharge or inside pressure changes in time at any location in the system. These changes, planned or accidental, may be due to the opening or closing of control valves, starting or stopping of pumps, and starting or stopping and acceptance or rejection of load on hydraulic turbines, etc. The pressure waves produced by these operations travel back and forth in the system until they are dissipated.[1]

Piping systems are designed to keep the maximum and minimum transient pressures, maximum and minimum rotational speed of turbomachinery, and maximum and minimum water levels in the surge tanks within the specified design limits. If necessary, protective devices are provided or system configuration and layout and operations are modified to meet design objectives and develop economical systems having efficient operations and reduced maintenance costs.

The development of modern analysis procedures utilizing the latest numerical methods for machine computation and general-purpose computer codes have made the analysis of large and complex systems possible. This has been useful for designing new systems or renovating or upgrading existing systems. In the past, liberal factors of safety were used because of doubts about the accuracy of the computed results. Thus, it is possible to modify operations for increased power production or increased pumped flows. However, the analyst must understand the limitations of these codes. They should not be used as black boxes, and proper attention must be paid to the limitations of the boundary conditions and to the validity of the assumptions on which the governing equations utilized in the model are derived. The use of general-purpose codes as black boxes without understanding their limitations has resulted in incidents, accidents, failures, and unnecessary litigation on many occasions.

In addition, recent advances in sensor design, ease in wireless transmission, and communication of measurements may be utilized for transient control and for safe and efficient operations utilizing real-time data. This allows minimized construction costs, optimized utilization of limited available water resources, and the production of reliable computed results in spite of uncertainties in the system parameters. For example, no reliable methods for computing the dissipation of oscillations in transient flows are currently available. Similarly, the wave speed in various conduits cannot be computed precisely. The presence of entrained or entrapped air could result in reducing the wave speed significantly. As a result, the use of real-time data for systems operations could be useful, especially in multiple operations, e.g., the starting of pumps following power failure and load acceptance following load rejection on hydraulic turbines. Figures 1 and 2 show the variation of water level in the upstream surge tank of a power plant for dual operations in a

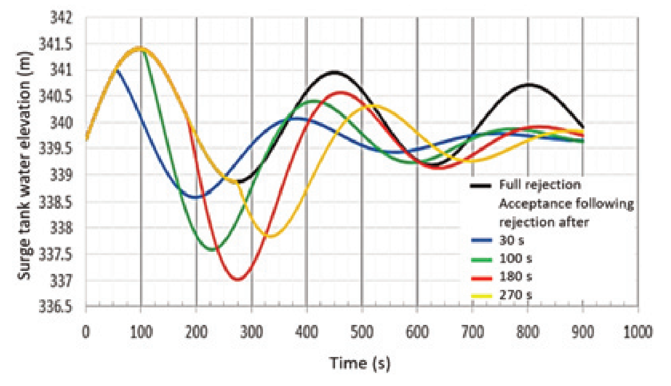


Figure 1. Water level variation in upstream surge tank for load acceptance at different times following load rejection.

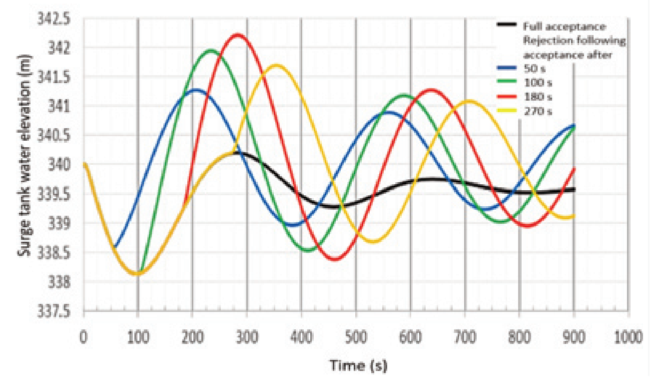


Figure 2. Water level variation in upstream surge tank for load rejection at different times following load acceptance.

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sequence, computed using the computer code WH[5]: Figure 1 depicts the load acceptance following full load rejection at different times and Figure 2 shows the load rejection at different times following full load acceptance. Note that the maximum upsurge for load acceptance following rejection and the minimum down-surge for load rejection following acceptance depend on the time of the second operation and that critical cases for the second operation do not result by initiating them at the peak or valley of the water level oscillations produced by the first operation. Ordinarily, it would be difficult to compute the suitable timing of the second operation due to the uncertainty in the wave velocity, and for this reason a sensitivity analysis and suitable factor of safety are needed. However, if real-time data for the surge tank water level variation were available, the second operation could be initiated to achieve desired objectives in spite of uncertainties in the system data.

A number of case studies for illustration purposes follow.

Utilization of Real-Time Water Levels

Yukon Energy, Yukon Territories, Canada added to the existing Mayo A Hydroelectric Power Plant a second powerplant called Mayo B. Figure 3 shows the schematic of both power plants. The upstream conduit of this new power plant is flat over a considerable length near the intake, and the hydraulic grade line during the steady state for a surface conduit with the existing topography is slightly above the conduit, allowing a small pressure drop during transient conditions without column separation. For economy, an inclined surge tank comprised of two conduits of the same diameter as the penstock and connected in a Y-branch is provided. Analyses, using the computer program WH[5], showed that the pressures may drop to sub-atmospheric levels over a considerable length of the conduit upstream of the surge tank following load rejection or load rejection during load acceptance. The project is located in North Canada, and the upstream reservoir surface is frozen during considerable periods of the year. Thus, it is difficult to precisely predict the steady state and transient state hydraulic grade lines in the upper parts of the upstream conduit, and a liberal factor of safety would be justified. This would have required deep excavation to lower the conduit. Instead, it was decided to install a vent near the critical point of the conduit and the water level in this vent is monitored continuously with the signal transmitted to the operator in the plant. Depending upon this level, the loading and unloading operations in the plant are restricted. Also, it is assumed that the vent would act as a back-up to provide air inflow in case the pressures become sub-atmospheric in some unusual situations. The plant has been operating satisfactorily for several years. The monitoring of the water level in the air vent has allowed some relaxation of the restrictions on the plant operation, which would not have been possible otherwise.

Downstream Control Valve Operation as Surge Control

The McCall effluent pipeline in Idaho, USA is designed for a discharge of 0.093m^3/s during Phase I and 0.11m^3/s during Phase II. Transient analysis[5] indicated column separation near the summit following pump shutdown or power failure. Normally, a surge tank, or a one-way surge tank would be provided at the summit to prevent column separation. Since the liquid being pumped is treated sewage, these devices were not considered as suitable alternatives. In addition, during the winter, temperatures drop significantly below freezing and this would require heating of the surge tank. A large air valve was not considered suitable for total surge protection because it would require significant downtime in the pipeline to evacuate air in the case of activation of the air valve. Instead, a discharge valve was recommended and installed at the downstream end of the pipeline that would close as soon as there is power failure at the pump station. This creates a positive pressure wave at the valve that propagates towards the pump; and thus, the entire pipeline remains pressurized and there is no column separation (Figure 4). The project has been operating satisfactorily for many years.

Computer Analyses of Series Power Plants with 8 Surge Tanks

The Agoyan Hydroelectric Power Plant is an existing plant in Ecuador and a new power plant, San Francisco, was planned at the time of these studies (Figure 5). With the proposed layout, both plants would have a total of eight surge tanks, including the inter-connection chamber between the two hydropower plants. Both plants were to be operated synchronously as a closed system. The large number of surge tanks, the unusual layout of the main upstream tanks of both plants and the large number of system parameters made the

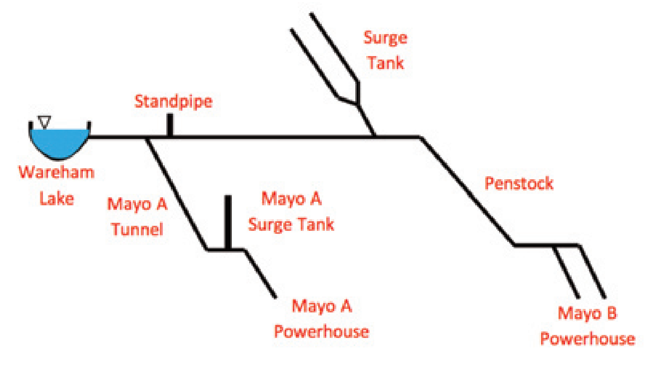

Figure 3. Schematic of Mayo A and B Hydro-electric Power Plants.

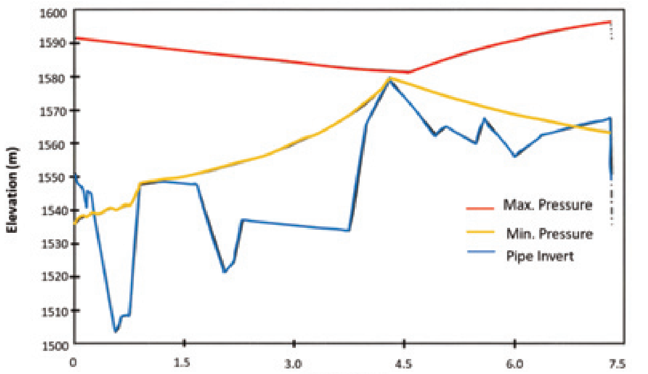

Figure 4. Maximum and minimum transient state pressures following power failure and downstream valve closure.

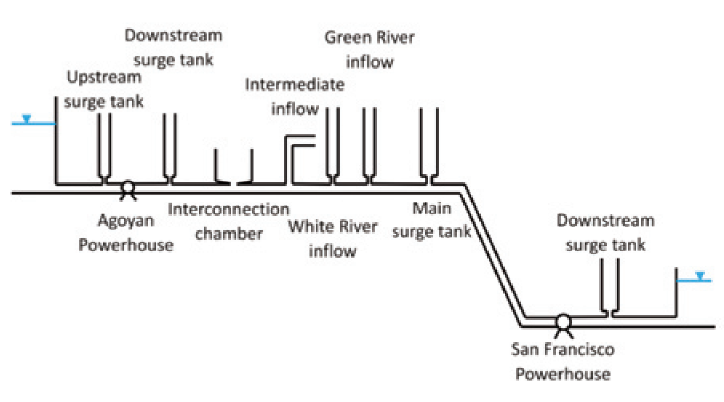

Figure 5. Schematic of Agoyan, San Francisco Hydroelectric Power Plants.

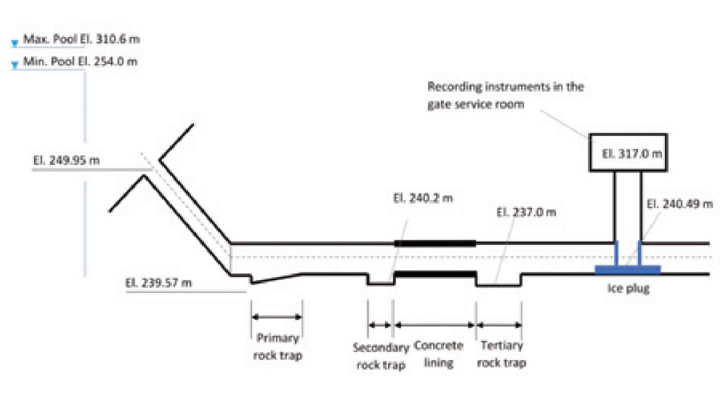

Figure 6. Profile of the intake tunnel at Snettisham Hydroelectric Power Plant.

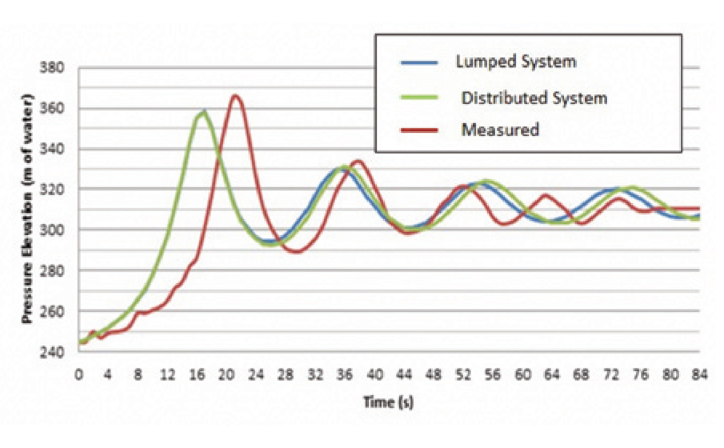

Figure 7. Variation of transient-state pressure with time following blasting of last rock plug.

investigation of the transients in the system challenging.

A computer program, SUR[4], based on the lumped-system approach was used to determine the maximum and minimum tank levels, as well as investigate the stability of the system of surge tanks. Commonly used standard stability criteria and analysis procedures could not be employed because of the large number of surge tanks. These studies indicated that the main surge tank of the San Francisco power plant would drain if the drill and blast method were used to bore the tunnel; two drop shafts that act as surge tanks had continuous oscillations, and it became apparent that it might be difficult to operate the two plants synchronously. The following recommendations were made to handle critical transient conditions: To avoid oscillations becoming too large and unstable, the inter-connection chamber was modified to a free-flow tunnel and a side over-flow weir was provided as a fail-safe back-up. A lower gallery was provided at the main surge tank of the San Francisco power plant to avoid tank drainage and orifices were included at the drop shafts to reduce the amplitude of the water level oscillations in these shafts.

Computer Modeling of Lake Tap

Intakes of pressurized conduits are normally built in the dry behind cofferdams. To reduce construction costs and to provide better rock conditions, a new procedure was selected for the construction of the power intakes of the Snettisham Power Plant, Alaska. In this procedure, the tunnel is constructed from the powerhouse towards the upstream reservoir. Then the last remaining rock plug is blasted allowing the water to rush into the tunnel, with the tunnel closed at the lower end with the intake gate (Figure 6).

To compute the pressure on the intake gate as the advancing water front moves towards the gate and compresses the enclosed air, a computer model was developed[3] in which the contraction and expansion of air was assumed to be adiabatic, and the varying length of water column representing the pressurized part of the tunnel was analyzed considering it both as a lumped and as a distributed system. The computed results from the lumped- and distributed-system approaches compared satisfactorily with each other [3]. During construction of the project, the air pressures were recorded as the last rock plug was blasted. As shown in Figure 6, the measured pressures in the field compare well with the computed results [2].

Acknowledgements

The author would like to extend his thanks to KGS, Winnipeg, Canada and Yukon Energy Corporation, Canada for Mayo B Hydropower Plant Project; US Army Corps of Engineers, Anchorage, Alaska for Snettisham Project; JUB Engineers, Boise, Idaho for McCall Effluent Pipeline and INECEL, Quito, Ecuador for Agoyan-San Francisco complex. Special thanks are due to Dr. Mohamed El-Kholy for Figures 1 and 2, Fuad Curi of KGS Group for Figure 3, and Dr. Melih Calamak for Figures 4 and 5. ■

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HYDRAULIC TRANSIENTS IN HYDROPOWER SYSTEMS: FROM THEORY TO PRACTICE

BY DAVID FERRAS, GIOVANNI DE CESARE, DIDIA I.C. COVAS & ANTON J. SCHLEISS

What do we know about transients in hydropower conduits?

Hydropower conduits may be engineered to perform either unpressurized (free-surface) or pressurized (without free-surface). Not only regime transitions and two-phase flows, but also hydraulic transients with associated phenomena, such as fluid-structure interaction, unsteady friction, cavitation or mass oscillation imply strong limitations and uncertainty to water conduits design and operation. Engineers have to be able to identify, to distinguish and to assess the relevant phenomena not accounted for in classic hydraulics, as these may be the cause of ill-defined calculations and subsequent operation problems. Our mission as researchers on the engineering and technology field is to develop and provide the right tools to enhance and empower engineering designs.

Hydraulic transients in pressurized flows is an active research area at the Laboratory of Hydraulics and Environment (LHE) of the Instituto Superior Técnico (IST) in Portugal and the Platform of Hydraulic Constructions (PL-LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. Both institutions have been working jointly over the past 10 years for the enhancement of the fundamental theory and its applicability to real engineering problems in the field of hydropower. The highlights of this collaboration are described hereby.

Fluid-structure interaction and the extended water-hammer theory

The origin and development of the classic water-hammer theory is based on the fact that during unsteady pressurized flows the fluid and the piping structure behaviors are interconnected. In Fluid-Structure Interaction (FSI) all the potential pipe vibration modes that may affect the water-hammer wave propagation are considered and the two-way coupling between fluid dynamics and structural mechanics is described. It is a reasonable assumption to consider that, in common pipe systems, up to eight degrees-of-freedom or pipe vibration modes may be excited under unsteady flow conditions [1]. Large hydropower conduits though are slender single elements and, if their junctions are aligned with the flow direction, axial vibrations outweigh other eventual vibration modes. Consequently, the description of the dynamic interaction between the water-hammer waves in the fluid with the axial stress waves in the pipe-wall is of primary importance in such systems [2].

Experimental and numerical work, using an in-house MoC (method of characteristics) code, has been carried out at LHE (IST) and PL-LCH (EPFL) aiming at investigating the behavior of pipelines constrained against longitudinal movement using pipe supports, anchorages and thrust blocks. In [3], for instance, a robust and accurate MoC code for both the fluid and the structure to simulate anchoring blocks taking into account their inertia and dry friction was presented. The blocks were nested in the numerical scheme as internal conditions, for which junction coupling was considered. Figure 1 shows the experimental pipe rig used to test different pipe anchoring setups on the basis of the classical reservoir-pipe-valve system in which the downstream valve is rapidly shut-down. The validation of the numerical model is shown in Figure 2, where measured *vs.* computed pressures next to the downstream

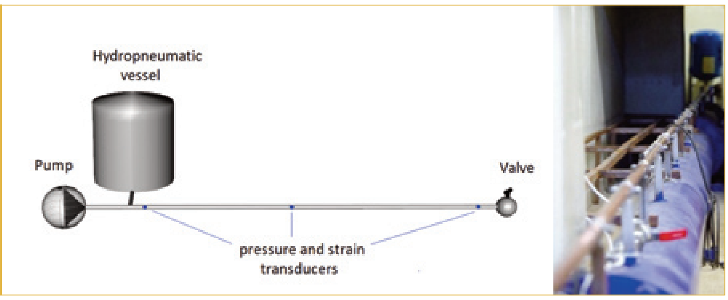


Figure 1. Experimental pipe rig assembled at LHE (IST) used for FSI analyses in straight pipes [2].

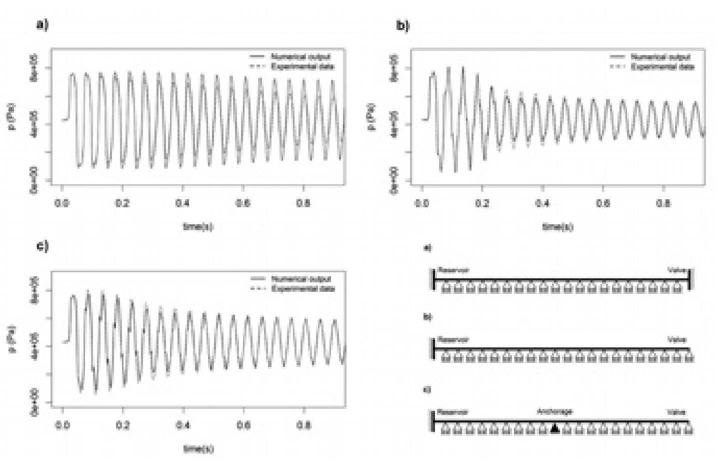


Figure 2. Validation of the numerical model developed in [3] for: anchored pipe ends (a); non-anchored downstream end (b); and non-anchored downstream end but anchored midstream (c).

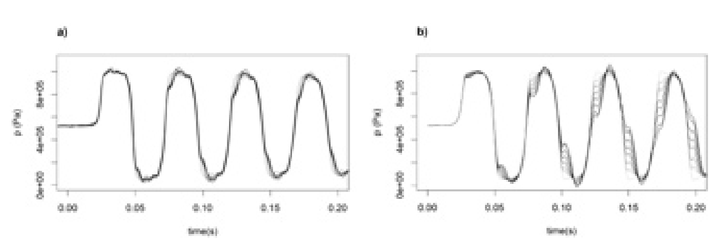


Figure 3. Series of water-hammer tests while releasing the conduit anchorages from the downstream to the upstream pipe ends from: experimental measurements (a); and numerical output (b) [3].

valve are depicted. The model proved to be more accurate when the pipe was not anchored (Figure 2-a). The research suggested that the pipe support effect, dry friction dissipation and the associated assumptions (*e.g.* stick-slip instability) have to be considered when aiming at accurate descriptions of water-hammer events in hydropower conduits. When incorporating FSI there is a substantial increase of computational effort in the numerical simulations. For certain setups though (e.g. valve released) maximum pressures, wave shape and damping are highly altered, hence FSI computation becomes justified.

In [3] the model was also tested and validated using insightful series of experimental tests consisting of releasing, from downstream to upstream and one at a time, the pipe anchorages of a conduit initially fully anchored while launching water-hammer events. Figure 3 depicts both experimental measurements and numerical output, depicting the same trend in the pipe response while anchorages are being released. The numerical implementation proved therefore to be consistent with the empirical data, confirming that the main fluid-structure interaction phenomena is well described by the modelling assumptions.

The research brought valuable insight to the importance of considering FSI phenomena in the engineering designs of straight pipes affected to longitudinal movement, as maximum transient pressures may surpass the ones expected by the classical theory (Joukowsky pressure pulse), while the water-hammer wave damping and timing may be also affected by the dynamic response of the overall structure. A novel, accurate and efficient numerical model that enables the description of the FSI effects of anchoring blocks when considering their resistance to movement due to both inertia and dry friction was successfully developed aiming at providing engineers with a useful tool for improved hydropower conduit designs.

Experimental and CFD modelling of entrapped air during transients events

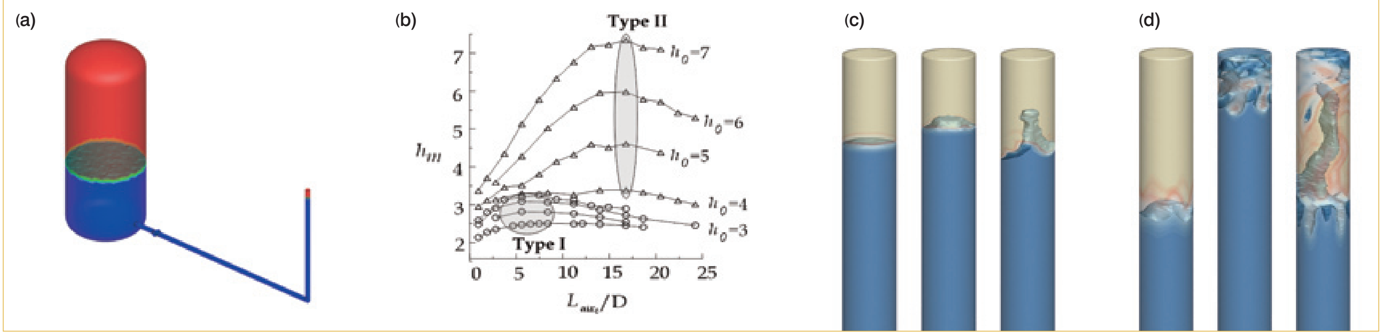
Gases naturally accumulate in pressurized pipes transporting liquids due to inadequate design or operation of valves or pumps, the rapid depressurization and pipe filling after a disruption or the occurrence of transient events [4]. Air is typically entrapped in higher elevation pipe locations or sections with valves and fittings and in quasi-horizontal pipes. The air tends to be accumulated and released by air valves, if they exist and adequately operate. Air pockets create additional losses during normal operation and introduce significant changes in the dynamic response of the liquid-pipe system during transient events. Severe transients combined with entrapped air are responsible for numerous accidents in pressurized pipes. Air pocket volumes are quite difficult to determine, even when using direct pressure measurements. The aim of the research carried out at IST consisted of analyzing the effect of entrapped air in the pressure wave signal during the occurrence of fast transient events both by experimental and CFD modelling for the rapid pipe filling [5] and by experimental analysis for the occurrence of a fast-transient in pipe system with entrapped air [6].

The first tests focused on the rapid pipe filling. A pressurized system, composed of a "tank–pipe–valve–pipe-dead end" (Figure 4-a), was used. Pipes were made of polyvinyl chloride (PVC) and with an inner diameter of 0.0536 m. The pressurization source was a 1 m^3 steel air vessel. The valve that connected the air vessel to the pipes, a quarter-turn ball valve pneumatically actuated, was initially closed and, then, opened in 0.23 s, creating an upsurge at downstream that compressed the air pocket. The initial air pocket size varied for each transient test. In addition to the experimental tests a 3D-VOF model in CFD was developed and used to simulate the rapid filling, since the maximum transient pressures were higher than those that the facility could sustain, putting at risk the pipe system. The model was calibrated and validated using collected data. Based on the CFD model and using the Joukowsky pressure rise as a reference, the dimensionless maximum transient pressures, h_m, were determined for different air pocket sizes, L_{air}/D, and initial differential pressures, h_0 (Figure 4-b). Maximum pressures attained for each pressure difference created, h_0, and the respective volumes are depicted in Figure 4-b with the ellipse shaded area. Two different types of behaviors of the water-air system were observed: Type I in which air and water do not mix and Type II in which air mixes completely in water (Figure 4-c,d).

The second set of tests was carried out in the experimental pipe-rig depicted in Figure 1, where an acrylic device was assembled to simulate the air pocket inside the pipe and installed at the pipe mid-length (Figure 5). This device has a cylindrical hole with an inner diameter of 5 mm and a total drilled length of 51 mm; it has a lateral inlet at 25 mm from the bottom to control the air pocket volume between each test. Transient tests were carried for eight flow rates ranging from laminar to smooth-wall turbulent flow, with a pressure acquisition frequency of 1 kHz during 5 s. Each initial flow rate was tested with five initial air pocket volumes and for the no-air pocket situation.

Several features are identified in the transient pressure signal analysis. First, a major pressure drop is observed in the pressure transducer near the downstream valve after the Joukowsky overpressure is generated. This drop is created by the air volume compression and subsequent expansion. A series of reflected pressure waves are created. The pressure drop increases with the size of

Figure 4. (a) Rapid pipe filling system with trapped air (water=blue; air=red); (b) Maximum pressure and critical air volumes. Air dynamic behavior (c) Type I and (d) Type II [5]



the air pocket for the same initial flow rate (Figure 6-a) and with the initial flow rate for the same initial air pocket size [6]. Second, an overpressure higher than the Joukowsky pulse is observed. After the initial compression, the air pocket starts the compression-expansion cycle. As this cycle is slower than that of the propagation of the main pressure wave in the pipe, maximum overpressures at the downstream end pressure transducer are not reached in the first wave cycle but in the second cycle after the air pocket expansion (Figure 6-b). These overpressures can be as high as 30% of Joukowsky's pressure variation. Thirdly, air pockets also contribute to higher damping of transient events due to the massive energy dissipation in successive compression and expansion of the air, this damping increases with the air pocket size due to the energy dissipation in the compression and expansion of the air cavity [6]. Some combinations might have a resonance effect due to the superposition of pressure waves, which should also depend on the air pocket position in the pipe.

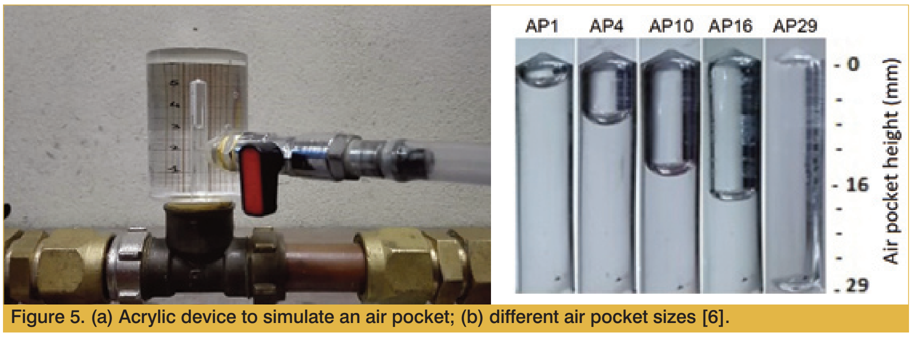


Figure 5. (a) Acrylic device to simulate an air pocket; (b) different air pocket sizes [6].

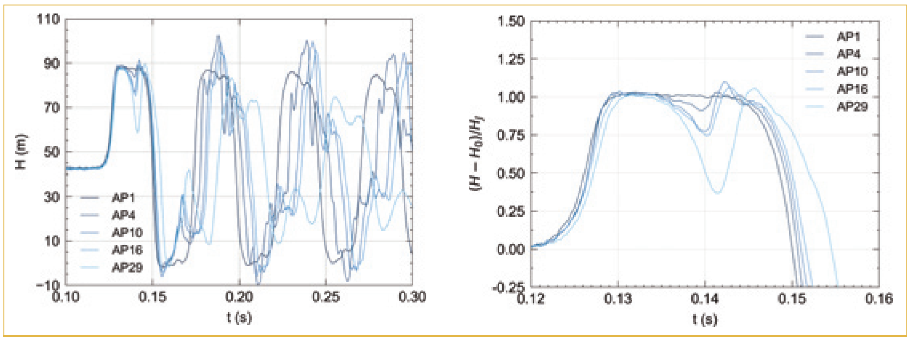


Figure 6. (a) Pressure wave signal and (b) dimensionless transient pressure data collected for five analyzed air pockets situations and initial flow rate Q= 400 l/h [6].

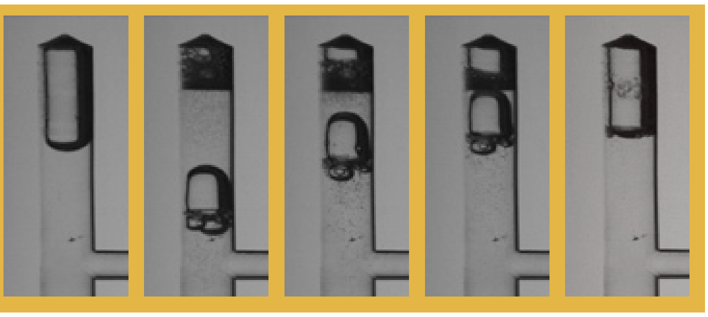


Figure 7. High-speed camera pictures of entrapped air during a hydraulic transient event.

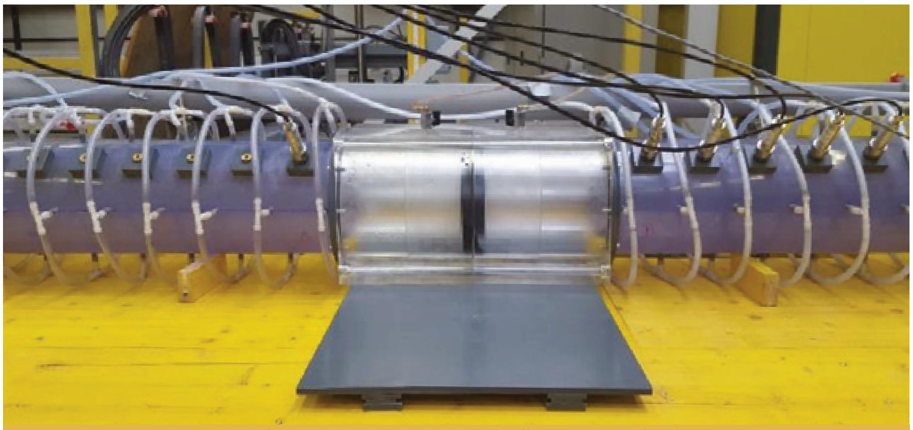
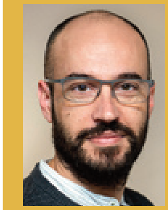


Figure 8. Experimental set-up for the systematic testing of different types of orifices with reversible flow direction.

Experimental tests carried out at IST were used to analyse the effect of an air pocket volume in the transient pressure signal. Several initial flow rates for five entrapped air volumes were tested. Four pressure wave features were analyzed: initial pressure wave drop, maximum observed overpressures, pressure wave damping and phase shift. The pressure drop was higher for larger initial air pocket volumes. Maximum overpressures had a maximum value that was 30% higher than the Joukowsky pressure pulse. Pressure wave damping and phase shift significantly increased with the air pocket volume. On-going research is currently focusing on a better understanding of the observed phenomena by means of video recording of the air pocket compression and expansion during the transient event (Figure 7). An extended explanation of the air pocket behaviors for different flow regimes was presented in [6].

The potential of increasing hydropower plants flexibility through surge tanks throttling

Surge tanks in high-head power plants ensure safe and flexible transient operation of the hydraulic machinery. Orifices or throttles are often critical structural elements for the good performance of surge tanks and the stability of the whole waterway system combined with the hydraulic-mechanical equipment. The design and the dimensioning of orifices or throttles placed at surge tanks have to be carried out with great care since a non-functioning of these critical structural elements can endanger the safe operation of the whole hydropower scheme. Orifices or throttles have to produce a distinct head loss for flow entering and leaving the surge tank. In the design the best geometry has to be found which produces the wished-for head losses. The search of the most adapted geometry of the orifice or throttle is often difficult and has often to be done with hydraulic model tests in real world projects. In order to allow a fast, preliminary design of orifices, a systematic research campaign comprising laboratory experiments (Figure 8) and numerical simulations, was carried out. As part of this research a large number of different geometries of throttles, i.e. orifices,



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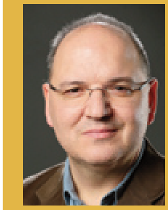

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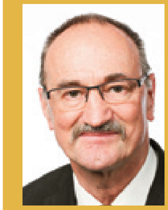

Anton J. Schleiss obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design in 1986. He worked for 11 years for Electrowatt Engineering Ltd (now Pöyry-AFRY). In 1997, he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) of the EPFL. After retirement from teaching, he became Honorary Professor at EPFL in March 2018. He is the honorary President of the International Commission on Large Dams (ICOLD). With more than 40 years of experience he is regularly involved as a consultant and expert in large water infrastructures projects including hydropower and dams all over the world.

were tested. Based on the extensive catalogue of the orifice geometries tested and the developed empirical relationships, efficient design guidelines based on empirical formulae could be given. They were incorporated in an easy to use sheet, which allows finding efficiently the appropriate orifice geometry for a wished-for head loss. Furthermore, the systematic experiments and numerical simulations allowed also a better understanding of the hydraulic behavior of orifices in view of the influence length of the orifice, i.e. the reattachment length of the jet leaving the orifice and associated risk of cavitation [7].

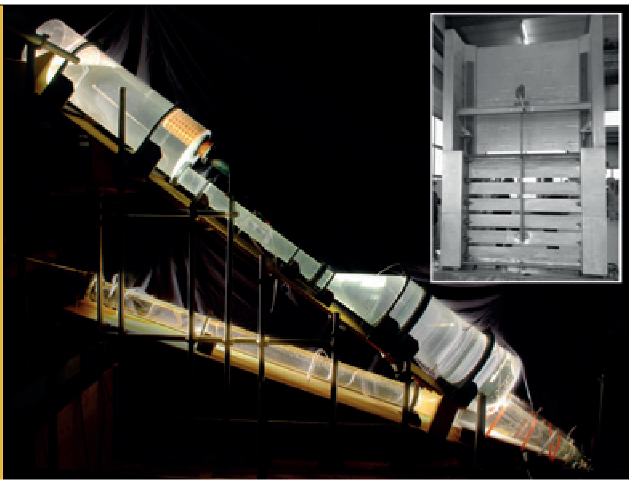

Figure 9. Gondo HPP power and flexibility increase. Physical-scale modeling (big picture) was performed to validate the design of the grid throttle (prototype under construction) placed at the bottom of the lower chamber of the existing surge tank.

The implementation of throttles in existing surge tanks of hydropower plants is an economical measure to enhance capacity and consequently flexibility in generation [8], such as the hydraulic model tests of the surge chamber and throttle for the Gondo hydropower plant (HPP), which led to an increase in power generation and flexibility of operations (Figure 9).

Can we detect, locate and quantify weak zones in pipes with the help of the water-hammer signal?

This question is especially relevant for high head pressure tunnels and shafts of hydropower plants which have to be steel-lined if rock overburden is not sufficient. Since the water can reach in an uncontrolled way the rock surface in case of failure of these water-conveying systems, high damages due to landslides and debris flow can occur. Furthermore, high strength steel is used nowadays for such steel liners, which have an increased risk of brittle and fatigue failure. Storage hydropower plants and especially pumped-storage power plants are operating today more and more under challenging conditions as they try to satisfy the highly volatile peak energy demand due to the integration in the grid of new renewable energies, like wind and solar. Therefore, an enhancement of the existing theoretical design model for steel-lined pressure shafts and tunnels as well as new monitoring approaches are necessary to manage the considerable risk in case of failure [9]. Normally the operation of hydropower plants cannot be stopped without significant generation losses and thus non-intrusive and continuous monitoring is required.

Early detection of any weak zones in pipes and steel lined tunnels is vital but also a challenge. This challenge was addressed in a research project with an experimental set-up at LCH-EPFL (Figure 10), which aimed at quantifying the influence of a local drop of wall stiffness on the pressure wave speed and wave dissipation during transients in a pipe. A complex data acquisition system was designed for this project [10]. A large number of different pipe configurations were tested. The weak reaches in the pipe were simulated by replacing the steel reaches with Aluminum and PVC materials (Figure 11). Besides pressure sensors also for the first-time geophones were used for the acquisition of water-hammer signals. The acquired data was assessed using, amongst others, the Fourier Transform, wavelet decomposition, and cross-correlation techniques [10].

The detection of a weak reach in the pipe, that is its location and drop in stiffness, is based on the following principle. When a wave (water-hammer) hits a junction, where there is a change of the hydroacoustic parameters, such as a change of section or a difference in wall stiffness, it is divided into transmitted and reflected parts (Figure 12). By comparing the outgoing wave (water-hammer) with the reflected signal, with the help of a detailed wave decomposition time analysis, the location of the weak reach and its stiffness can be back-evaluated. The measured transient pressures at the two end positions of the test pipe can be used to predict the front wave speed of an excitation traveling between them. Three different methods were applied to estimate this crucial parameter required in the time–distance transformation process: (i) the determination of the time separating the maximum front peaks of the signals, (ii) the time separating the intersection point of the regression line for the steady-state pressure and the regression line for the first pressure front, and (iii) the cross-correlation method.

The experiments showed that the wave speed and the wave dissipation ratio are good indicators of the presence of local and large changes in stiffness. When a steep front wave was generated inside the test pipe by the fast closing valve, the weak reaches represented by PVC could be located by a maximum relative mean error of about 6 % taking as reference the position to the pipe end. The local stiffness change could be quantified with a maximum relative mean error of 21% of the actual Young modulus of the pipe wall material [10]. Since the water-hammer is a complex signal, the analysis allowed only to detect important drops of stiffness (around 98% as the case for PVC). Therefore, in a further study an underwater spark generator was developed which allows to produce cavitation bubbles in the pipe resulting in very steep shock waves having a clear signal [11]. The analysis of the pressure wave reflections due to the cavitation bubble explosion, recorded by two hydrophones placed at the extremities of the test pipe, allowed identifying very precisely the wave front and correspondingly the wave speed and the weak reach location. Compared to the wave analysis from water-hammer signals, the active cavitation bubble generation in the pipe is an innovative method that significantly increased the effectiveness of the detection of wall stiffness drops.

In-situ measurements at the pressure shaft of the pumped-storage powerplant Grimsel II were carried out to validate the new water-hammer signal processing procedure [12]. The water-hammer signal was measured continuously at the downstream and upstream end of the pressure shaft (Figure 13). Monitoring charts were established based on the statistical quality control of the two indicators namely the water-hammer wave speed and the wave dissipation coefficient (see reference [12] for details on the monitoring charts). The wave speed was assessed from the Fourier transformation spectrums (F) while the dissipation coefficient was determined by computing the root mean square (RMS) of the signal followed by an exponential regression fitting. Three control limits representing the actual state of the steel lining in the pressure shaft were set on these charts obtained from the acquired and processed pressure data. These limits and the overall behavior of the pattern of future measured points could be used for on-line monitoring of the shaft.

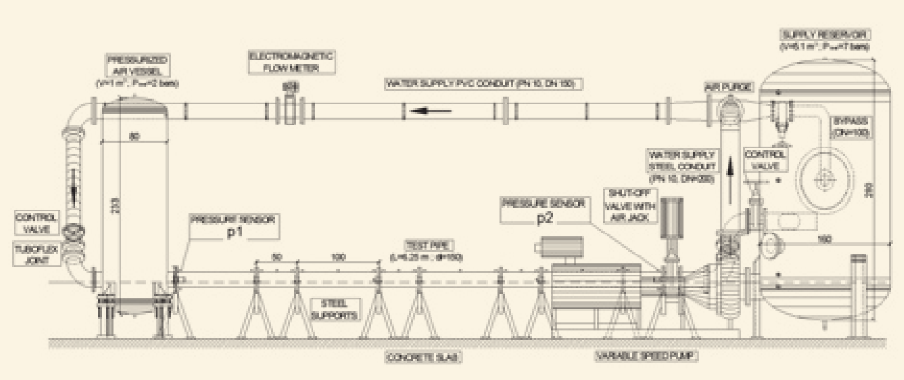

Figure 10. Experimental set-up assembled at the EPFL for the assessment of the local drop of pipe-wall stiffness dynamics.

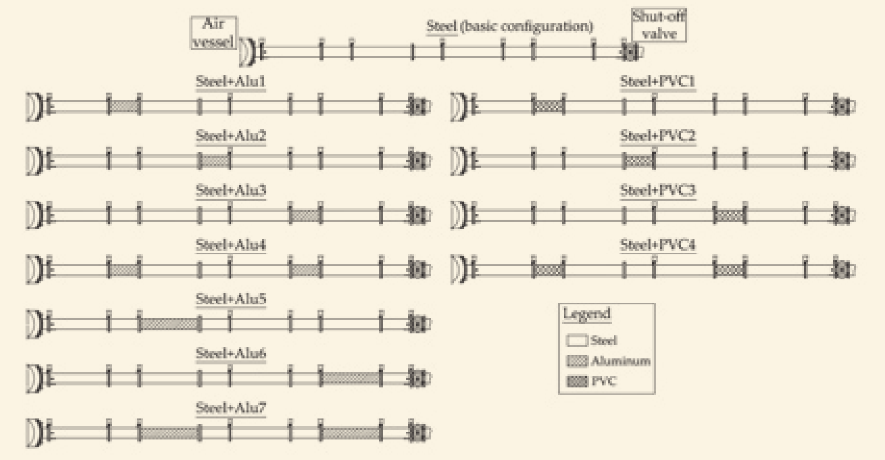

Figure 11. Tested pipe configurations. The weak reaches in the pipe are simulated by replacing the steel reaches with Aluminium and PVC materials.

Conclusions

Fluid-structure interaction affects the water-hammer signal shape, damping and timing in above-ground or non-buried pipelines, not only in hydropower systems, but also in long oil and gas pipes, cooling systems of nuclear and thermal plants, or any fluid distribution system in industrial compounds. Air entrapment has a similar effect on transient wave propagation. The collected data at LHE-IST have shown a wave shift and an increase of the wave amplitude and damping. Although undesired, the presence of air in pressurized water conduits is a frequent cause of hydraulic underperformance. Better understanding of the dynamic phenomena associated with hydraulic transients is essential for the improvement of the design and operation of hydraulic systems, and likewise for the investigation of accidents and incidents caused by water-hammer events. There is a need for both fundamental and applied research in this field and the collaborative work between LHE (IST) and PL-LCH (EPFL) represents a substantial advancement in this direction.

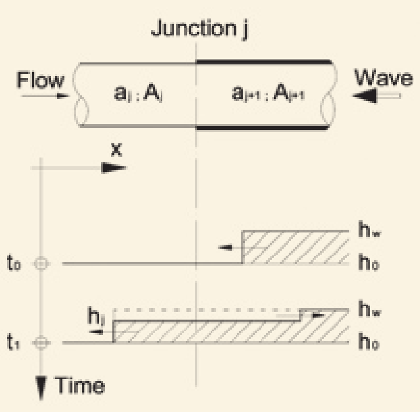

Figure 12. Schematic of a pressure wave h_W passing by a junction j representing a change in section A_j. or stiffness, which influences wave celerity a_j.

Water-hammer theory may be used for the protection, diagnosis and flaw detection of pressurized conduits. An example is provided hereby concerning throttled surge tanks, which aim at the dual purpose of anti-surge protection and flexibility in system operation.

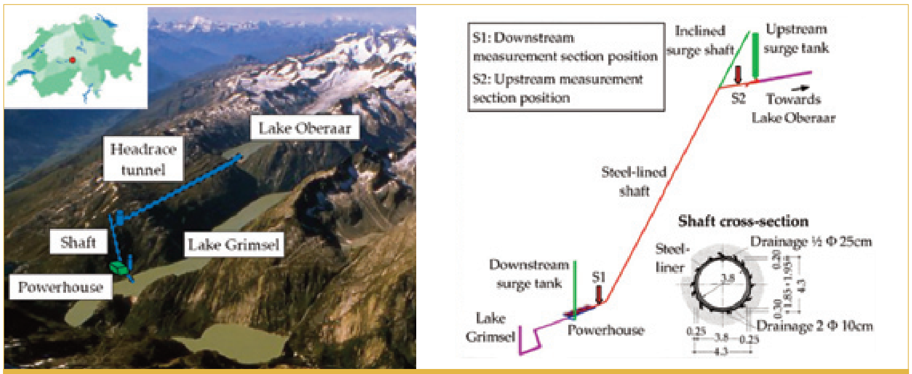

Figure 13. Grimsel II pumped-storage scheme, Left: aerial view of the site with the upper and lower reservoir, Right: schematic 3D view of the waterway system with the two positions of the data acquisition systems and a cross-section of the steel-lined shaft.

The head losses generated by throttles may reduce the water-hammer wave amplitude and increase its damping rate, safeguarding the main conduit from failure and, additionally, reducing mass oscillation phenomena. A second example of the application of water-hammer theory in hydropower conduits focuses on the detection of weak zones in steel-lined tunnels and shafts. A methodology based on the analysis of water-hammer wave transmission and reflection through pipe sections with a change of the hydroacoustic parameters is proposed. This essential principle can be applied to assess pipe defects such as leaks, bursts or obstructions. Transient based techniques for pipe flaw detection are currently an active field of research, as they require improvements in their efficiency, accuracy and robustness in order to become useful tools for standard engineering practices.

Acknowledgements

The authors acknowledge their colleagues at EPFL and IST who contributed to the research work described hereby, with special emphasis on Pedro Manso, Nuno Martins, João Ferreira, Fadi Hachem and Nicolas Adam. ■

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HYDRAULIC TRANSIENTS AND NEGATIVE PRESSURES – CONSEQUENCES AND RISKS

BY BRYAN KARNEY

continued from page 40

straight-line hydraulic grade line from the water source to the advancing filling interface. When the filling interface descends into the first part of the V, the high point in the profile will often experience negative pressures, with either a vapor cavity or an air cavity forming, depending on whether or not an air-vacuum valve is present at the knee. When the advancing front then ascends to the second half of the V, this air or vapor cavity will tend to collapse, sometimes with serious consequences [3].

However, if these air-exchange devices are well-designed and well-maintained they can perform their roles effectively and, in that way, assist the overall system to achieve its hydraulic and economic roles, even under transient conditions. Yet, if poorly chosen, or inappropriately installed, or if neglected once they are installed, the same devices can make matters worse, becoming the source of much misbehavior or even the cause of system failure. A poorly performing air valve can leak water or sewage, can severely exacerbate transient pressures, or can fail to exchange the very air which justifies its existence.

Summary

This article is not a comprehensive or complete treatment of transient negative pressures or of the associated phase changes such pressures often induce. The goal is merely to collect a few of the crucial ways transient events can complicate the pressurized flow systems, particularly through the introduction or expulsion of air, or through the creation and collapse of vapor pockets. The practical consequence of the presence and dynamics of these two-phase complications can be profound, troublesome, and highly damaging, but are also almost invariably fascinating, both physically and mathematically. At the very least, negative pressures are a warning or alert sign: whenever such pressures are, or might be, present, owners, operators, and designers need to take special care to avoid or mitigate both their presence and their often-vexing and confounding implications. ■

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SAYANO SHUSHENSKAYA 2009 ACCIDENT UPDATE

BY FRANK A. HAMILL

17 August 2019 marked the tenth anniversary of the catastrophic accident at RusHydro's Sayano-Shushenskaya Dam and power station (Figure 1). The accident destroyed or severely damaged all the hydraulic turbines contained in the large powerhouse located at the toe of the dam (Figure 2). The Project is located on the Yenisei River in the village of Cheryomushki, which is near the city of Sayanogorsk, Khakassia in southern Siberia. In the ten years since the event, numerous writers have expressed opinions as to the probable cause of the accident. The owner of the plant, RusHydro, and the national industrial safety agency, Rostekhnadzor, have both issued findings as to the probable cause. None of the official reports or findings have discussed the governor wicket gate closure time or its possible relation to the accident.

In November 2010, this writer prepared an article for the magazine International Water Power and Dam Construction in which he presented an hypothesis as to the direct cause of the accident. The hypothesis was that a very fast governor time resulted in a quite sudden wicket gate closure upon the unit shut down due to total load rejection. This caused water column separation to occur in each of the affected turbine draft tubes. When the resulting vapor cavities collapsed, there was an extremely large draft tube pressure rise in each case as the water column collided with the underside of the turbine head cover, causing it to rise several meters and destroying the turbine and generator supported by the head cover. Unit 2 failed first and showed the most extreme damage. The writer's hypothesis was based on the published data in the Rostekhnadzor report of 3 October 2009. Neither Rostekhnadzor nor RusHydro mentioned this hypothesis as a possibility. It was possible that neither operations personnel nor management were sufficiently familiar with the fluid mechanics of unsteady flow in closed conduits to entertain the idea of such a phenomenon [1].

Nothing has appeared since then to change the writer's opinion as expressed in that article.

That reinforces the lesson from this disaster that the design limitations of the plant MUST be respected. Operator training should emphasize design limitations with particular emphasis on the operation of turbine governors, and younger operators replacing retired experts should undergo a detailed examination of the behavior of the equipment under all conditions. If necessary, manage-

Figure 1. Sayano-Shushenskaya powerhouse machine hall operating floor prior to accident.

Figure 2. Part of the damage to the powerhouse after the 17 August 2009 accident. Unit 2 as seen on 3 September 2009 after dewatering.

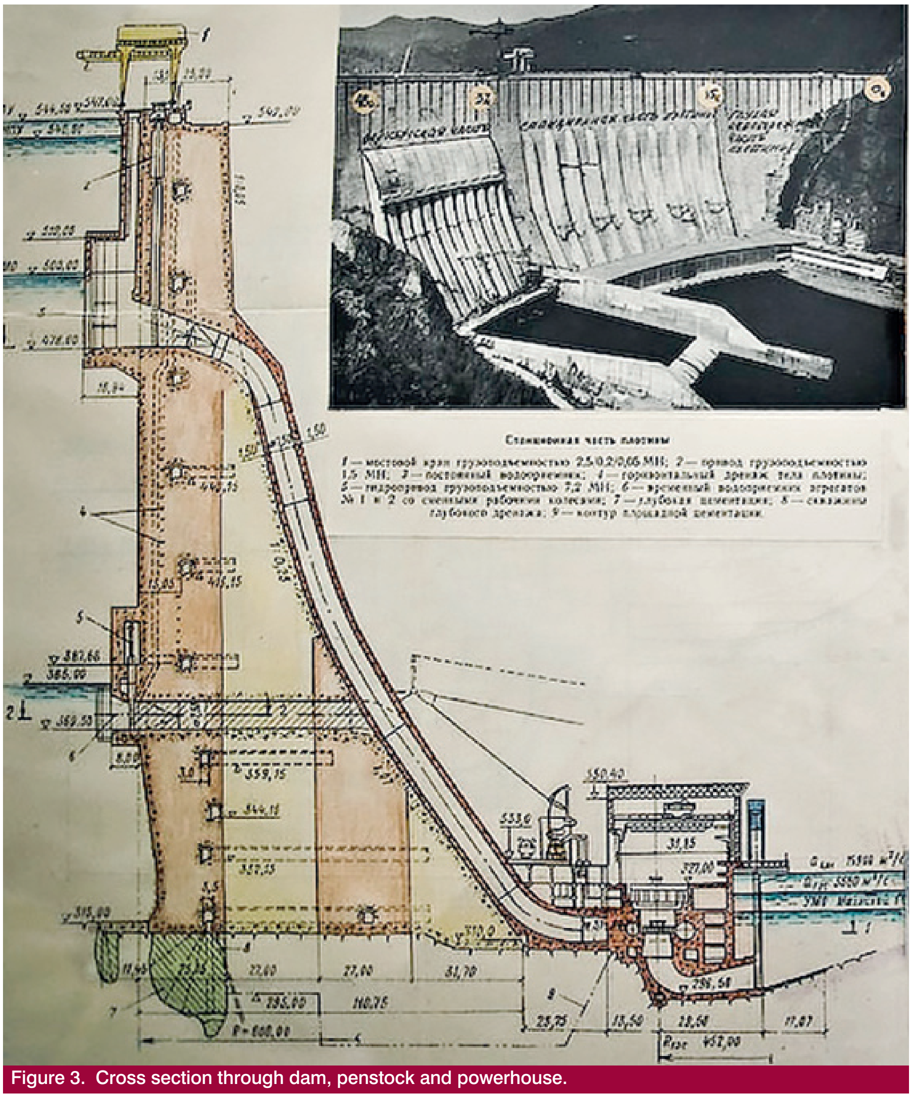


Figure 3. Cross section through dam, penstock and powerhouse.

ment personnel should also undergo detailed training. If an operator is ordered to perform unsafe actions, he or she must be permitted to refuse such an order.

Background

The Sayano Shushenskaya installation (Figure 3) was and remains the largest hydroelectric power station in the Russian Federation. It was the sixth largest in the world at the time of the accident with 6400 MW installed capacity. The powerhouse contained ten turbine generating units rated at 640 MW each. The turbines were of the Francis type (Figure 4) with a rated net head of 194 m and a rated discharge of 358.5 m^3/s. The rotational speed of each unit was 142.86 rpm [1].

The primary loads served by the Sayano Shushenskaya power station were a series of aluminum smelters located in the region of Siberia served by the regional electrical grid. This type of load is significant to the failure condition since such smelters are known to have rapid and unpredictable load changes. This is due to the loads having no significant inertia. The result is that the generating station must be able to adjust to load changes very rapidly to maintain electrical frequency stability. Sayano Shushenskaya had normally served as a base-load plant, with frequency control coming from other stations. Unfortunately, a fire at the Bratskaya station, which normally provided frequency control in the same service area, the night before the accident required that the Sayano plant shift to frequency control duties, for which it was not suited [5].

At 08:13 and 25 seconds on the morning of 17 August 2009, Unit 2 in the plant suffered a total load rejection. This was followed by a violent eruption of water in the draft tube lifting the turbine head cover, turbine runner, shaft, turbine and generator bearings upward several meters (a witness estimated three meters rise). This destroyed the generator rotor spider and permitted water to flood the turbine pit and spill out into the powerhouse operating floor (Figure 5). The sudden failure of Unit 2 was followed immediately by similar failures of Units 7 and 9. In all, nine of the ten operating units were either destroyed or severely damaged. Only Unit 6, which was out of service at the time, was spared from severe damage, although it was flooded by water from the other failed units. In all, 75 people died and 13 were injured in the powerhouse as a result of the flooding, which raised the event to the level of a national scale disaster.

The accident was studied by Rostekhnadzor, which issued a preliminary report on 3 October 2009. The tentative conclusion was that the studs which attach the head cover outer flange to the unit stay ring failed due to fatigue related to the observed severe vibration of Unit 2. The report did not address the failures of the other units in the station, nor did it attempt to explain the source of the very large upward force necessary to cause the damage that was observed. It was expected at the time the report was issued that it would be expanded later. In fact, the report, which included a significant amount of technical data such as turbine loads versus time for each unit leading up to the failure, was withdrawn a few months later [5].

Update post reconstruction of the station

Repairs commenced as early as November 2009. In 2010, the four least damaged units (Units 3,4,5, and 6) were put into operation on a temporary basis. In December 2011, the first new unit (Unit 1) was launched, with repairs and replacements taking place over the next three years. By the end of 2014, all 10 units were replaced with new ones and the new ones were in operation. By 2017, new control and safety equipment was installed and put in operation [3], [4], [6], [7].

Technical studies

The technical aspects of the failure were discussed by several writers since the accident, although none drew definitive conclusions.

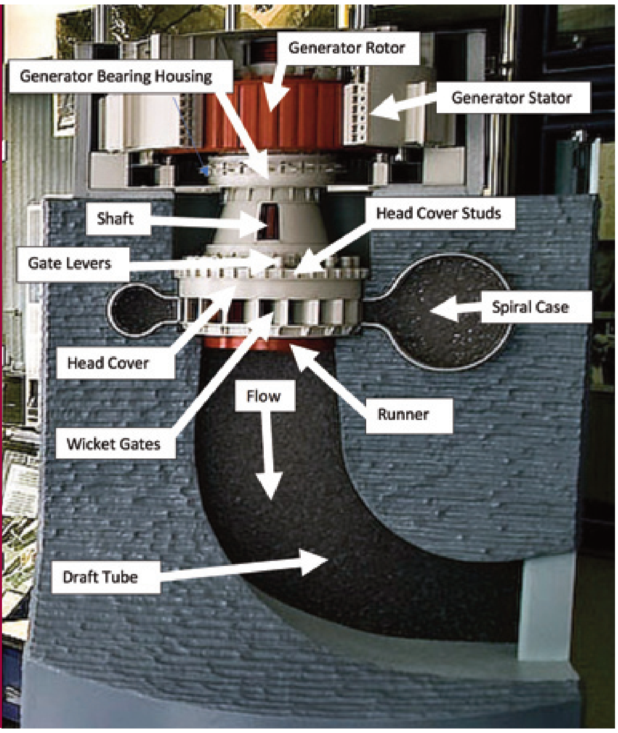
In March 2010, the magazine Hydro Review published an article that quoted Donald Erpenbeck, a vice president of MWH Americas, Inc., who agreed with the conclusion of Rostekhnadzor that fatigue failure was one of several causes of the accident. He rejected the possibility of waterhammer from a governor closure, stating that “there are other things in the system that should not have allowed the wicket gates to close that fast." He theorized that a possible generator short circuit may have been involved but did not explain the similar failures of Units 7 and 9 [2].

In an extensive article in Power Magazine dated 1 December 2010, Alexander Boyko and Sergey Popov, both relay protection engineers with EKRA-Sibir Ltd., and Nemanja Krajisnik, a power systems consultant for Siemens Transmission and Distribution Ltd. described the events that occurred immediately prior to and during the accident. They described the 1860 ton head cover being blown off leaving the Unit 2 turbine in its pit with no turbine mountings but with its wicket gate and head gate opened. The claim was made that the 212 m water head ejected the turbine rotor from the pit. This explanation is not convincing in light of the type and extent of the damage [5].

Some writers have suggested that something else other than simply the fatigue failure of the studs must have been involved in order to lift the head cover of Unit 2. An article in Engineering and Technology Magazine published on 11 July 2011 suggested that the studs connecting the head cover to the stay ring were primarily there to effect a water and air tight seal, while the main upward force that was expected during operation would be resisted by the large downward thrust caused by the weight of the generator and turbine supported by the thrust bearing, which, in turn, was supported by the head cover. The article proposed that the studs could not have been expected to resist the expected upward thrust even if they had been in pristine condition. The article also noted that the turbine, generator and thrust bearing, weighing nearly 1600t were thrust vertically several meters in the air flooding the powerhouse. The article did not speculate as to the cause of the waterhammer pressure that lifted the head cover, however [8].

An article dated 19 December 2014 in Hydro Review by Enes Zulovic of Hydro Tasmania discussed several cases where failures were experienced due to hydro knowledge transfer deficiency. This was shown to be related in part to the retirement of experienced hydro personnel leaving young engineers with fewer opportunities to gain experience. The Sayano Shushenskaya accident was an example used in Zulovic's article. Unlike many other writers, Zulovic accepted the premise that draft tube water column separation was a likely cause of the accident [12].

Figure 4. Cutaway turbine-generator model.



In May 2015 at a World Hydropower Congress held in Beijing, a group of representatives of RusHydro made a presentation which concluded that the accident was NOT caused by a shock or hit, but rather attributed the accident to the destruction of the studs due to the long term influence of high frequency vibration. This finding is very strange, given the evidence in the Rostekhnadzor report, and the failures of the other units in the station. No mention was made of the effects of a rapid governor shut down on load rejection [13].

A brief article in Tayga Info dated 22 November 2017 reported that the power station had been restored to full operation. The article referred to the Rostekhnadzor finding that the accident had been caused by destruction of the studs in the head cover but indicated that many experts believed that the conclusions were incomplete and inaccurate since a complete study of the reasons was not carried out. Moreover, the fact that the break of the head cover mounting and pushing the multi-tonne unit upwards contradicts all physical principles of operation of a hydraulic turbine [14].

The tenth anniversary of the accident gave rise to several articles about the incident. Of these, there were both technical and historical presentations [9],[10],[11],[16],[17].

In an emotionally moving article in Siberia Realities dated 16 August 2019, journalist

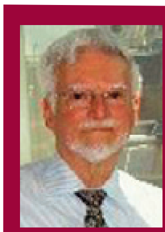
Figure 5. Unit 2 several hours after failure.

Julia Starinova interviewed several of the people who had been affected by the accident ten years previously. She reported that a number of the affected people remained quite bitter about the accident and about the reaction of the officials in the years that followed. The title of the story was a quote from journalist Mikhail Afanasyev, who in 2009 was charged with libel by the local prosecutor for his coverage of the story: "The true culprits will never be punished." In general, the technical claims of the officials were not believed by the people who were there [15].

A more technical evaluation of the failure was discussed by power engineer Gannady Rassokhin in a brief article in the Russian website ProAtom dated 16 August 2019 recognizing the tenth anniversary of the accident. He looked at the plots of pressure in the spiral case and in the draft tube at the time of the accident. His conclusion was a rather complex event involving flow around the rotor rim deflecting flow into the station's engine room. Although this analysis appears to be closer to the true conditions, it still fails to define the source of the enormous upward thrust that caused the massive rotating turbine to be projected several meters into the air. The large cover of the generator air housing was observed by a witness to have been blown up to the roof by the water column (geyser). The roof was blown off the building by the event [18].

Legal investigations and findings

Legal investigations into the causes of the accident were started as early as October 2009, when the regional Investigative Committee at the Prosecutor's Office for the Republic of Khakassia opened a criminal case under a provision of the Criminal Code of the Russian Federation that governed labor protection rules. This was quickly transferred to the Main Investigative Department of the Investigative Committee under the Prosecutor's Office of the Russian Federation. The investigation centered on the increase in the amplitude of vibration of the turbine bearing supported on the head cover of Unit 2. This was reported to be a significant factor in the hours immediately preceding the failure. The conclusion was that the studs holding the head cover to the stay ring failed due to fatigue caused by the serious vibration. In June 2013 the Main Investigative Department completed an investigation into the criminal case of the accident. As a result, seven managers and engineering workers of the station were tried at the Sayanogorsk City Court of the Republic of Khakassia. A verdict was reached on 24 December 2014. The director of the station and the chief engineer were both sentenced to six years in prison. Two deputy directors were sentenced to over five years imprisonment each. Employees responsible for monitoring equipment in the station were given 4.5 years probation. Another employee was sentenced to 4.5 years but was released under an amnesty [19]. Apparently, none of the legal investigations fully evaluated to the technical aspects of the incident. Both the failures of the other units (particularly Units 7 and 9) and the unexplained source of the very large upward force that was necessary to cause the type of failure that occurred were not pursued by the courts.



Frank Hamill has worked 50 years for Bechtel Corporation as technical advisor, project manager and project engineer for concept planning and design of water supply and hydroelectric projects, powerhouses, dams, tunnels, penstocks, canals, large diameter pipelines and pumping stations. Expertise in site evaluation, project concept development, feasibility studies, licensing, economic analysis, planning, hydraulic analysis and design of dams, hydroelectric facilities, and pumping stations. He has been recognized as Bechtel Distinguished Engineer.

Tentative conclusions remain unchanged

In reviewing these articles and several other short pieces recognizing the tenth anniversary of the accident, this writer has not found any reference to the original or to the present-day turbine governor settings. Of particular interest would have been the wicket gate closure time when the governor was saturated due to a full load rejection. There was also no reference to the extent, if any, of a "cushion stroke" in the final stage of gate closure between the speed-no-load setting and fully closed. Such cushion stroke settings are slowed-down gate movements usually used to prevent extreme waterhammer pressure changes in the zone where flow rate changes very rapidly in response to relatively small gate position changes. Since this normally applies only in the zone where there is no load on the machine (near shut-down), it does not affect the machine's response to load changes. Thus, the governor may have had two speeds: a fast one for load changes, and a slow one for the last stage of shut down. The fast speed is the one of significance to this event, and the record seems not to indicate what it was.

A very significant point was made in the March 2010 Hydro Review article, wherein the author indicated that "There are other things in the system that should not have allowed the wicket gates to close that fast." If these "other things" had been adjusted to permit faster responses to load changes, this could have caused the accident. This had been the tentative conclusion reached in this writer's December 2010 article in International Water Power and Dam Construction. As mentioned above, nothing in the literature since the 2010 article has surfaced to cause a change in this conclusion [1], [2].

This issue remains very important for designers, builders, operators, and owners. The physical limitations of any hydro power installation cannot be ignored regardless of the short-term economic benefits that may be expected by managers or operators who may be unfamiliar with the fluid mechanics of unsteady flow in closed conduits. There may be an opportunity to start a conversation among interested technical personnel on this vital issue. It is hoped that this can make the issue more transparent to the industry. ■

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SURGE MITIGATION FOR PUMPED STORAGE HYDROPOWER

BY ELENA PUMMER & WOLFGANG RICHTER

Spectacular surge waves can occur in hydraulic underground structures such as surge tanks and tunnel systems in pumped storage plants. The flexible way of operating these types of plants may cause pressure surges to be transferred to free surface waves and vice versa. The mitigation of these surges is the topic of the research discussed in this article. We aim to optimize the safe and reliable operation of pumped storage plants under the most unfavorable load cases that may appear over their life. This article describes some innovative developments in this field. The first part focuses on hydraulic research on surge tanks and the second part highlights free-surface waves in storage tunnel systems.

Pumped storage hydropower plants, as an important energy storage system, use head differences between open surface reservoirs or underground tunnel systems to efficiently store vast amounts of electric energy. Massive amounts of sustainable energy storage are needed to ensure an economic transition to an expanded renewable energy-based system. This requires the flexible operation of the hydro storage plants with high water discharges in pipes and high heads and that demand damping facilities such as surge tanks to balance the water inertia and to enable the best possible control of the hydraulic turbomachines. Complex surge tanks may consist of a combination of shafts and chambers. Storage tunnels and cavern storage systems are becoming the subject of research seeking ways to improve the utilization of energy storage in underground structures that are not constrained by the topography [1].

Surge Formation

Pressure surges result from rapid changes in the operation of hydraulic turbomachines and flow control devices. These operation changes may be due to load variations causing rapidly forced disconnections from the grid or by providing flexible power production. Full load rejection in generation mode or pumping mode may lead to extreme pressure surges and unpredicted failures. Pressure surges and water inertia demands must be mitigated and captured, which is safest done by surge tanks. Surge tanks provide free water surface and often have side chambers where the surging water is transferred and forms free surface surge waves. These waves can be large, and reflections and superposition can occur. To dissipate high pressure surges a robust

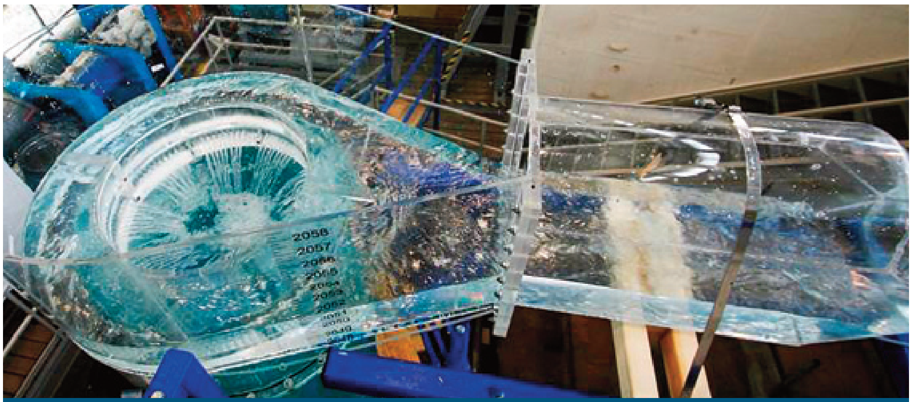


Figure 1. Laboratory scale model at Graz University of Technology of the waterfall dampening device for Obervermuntwerk II pumped storage plant [2], Photograph: Wolfgang Richter.

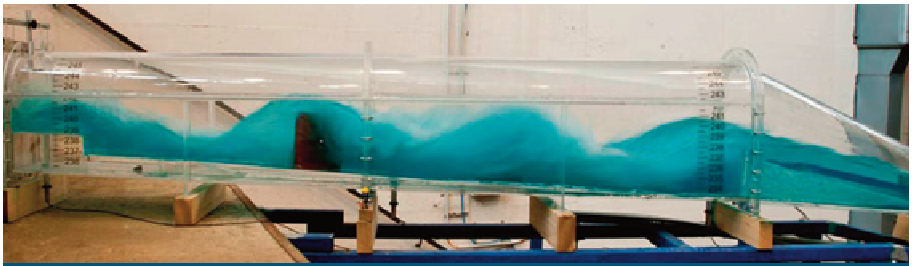
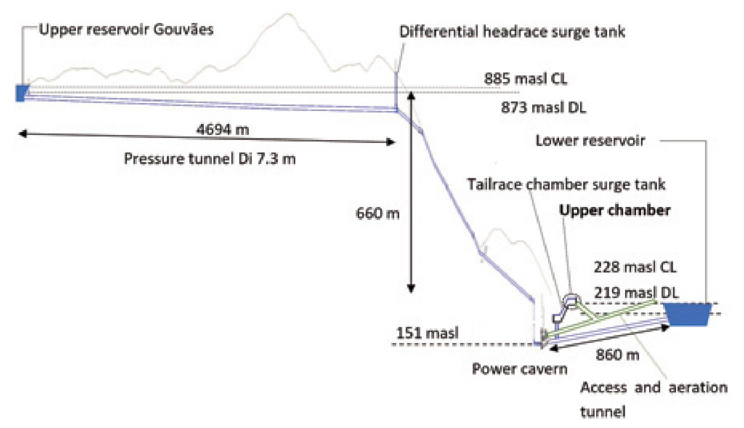


Figure 2. Upper chamber surge wave dissipation for an unfavorable design load case in the tailrace surge tank of the pumped storage plant Gouvães from Iberdrola, Photograph: Franz Georg Pikl [3].

Figure 3. Longitudinal section of Gouvães pumped storage hydropower scheme by Iberdrola, surge tanks hydraulically tested at Graz Universtiy of Technology.



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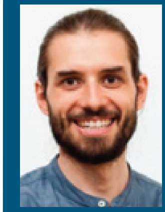

Wolfgang Richter is a Project-Senior Scientist at Graz University of Technology, since 2010. His research is mainly associated with transient physical model tests of surge tanks for large and flexible pumped storage hydropower plants.

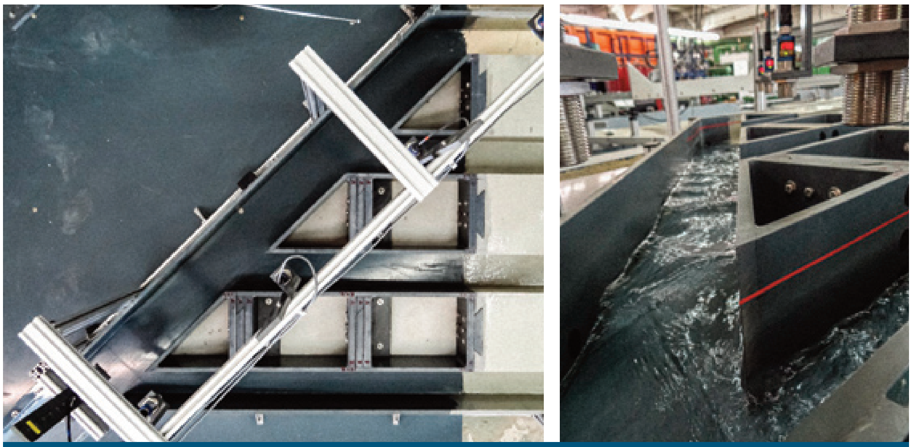

Figure 4. Extract of an open tunnel system model with modular design at RWTH Aachen University. Photograph: Elena Pummer.

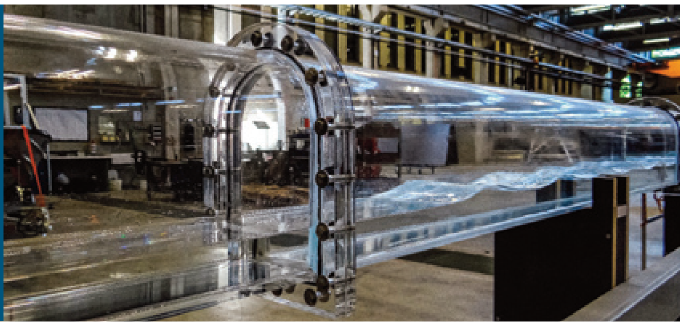

Figure 5. Surge wave formation in a tunnel system model at RWTH Aachen University. Photograph: Elena Pummer.

hydraulic system design is needed. Such a system must allow the flow to transition back to pressurized flow in the pipes, as the oscillating water mass fills and empties the surge tank structure.

Controlling Surges with Innovative Surge Tanks

Structures to mitigate pressure surges are most of the time the subject of unique designs. The flow phase interchange between pressurized flow and free surface flow in the chambers of the surge tank represents a design challenge. Because, hydropower plants are connected to the electrical grid, this hydraulic effect influences the surge tank design by requiring a stability criterion expressed by minimum horizontal cross-section in contrast to surge tanks for water pipelines. Surge tanks that consist of a vertical shaft and an nearly horizontal upper chamber face the additional challenge of air entrainment when the water surface in the main shaft drops while water remains in the upper chamber and plunges in the shaft as a waterfall down the main shaft. In such cases, air bubbles must de-aerate in the surge tank structure or in a controlled way in the power water system to avoid causing any damage.

Surge tanks in pumped storage hydropower plants are designed for several main purposes:

a) To enable machine controllability when pressurized pipes are utilized by mitigating the direct elastic inertia acting on the units
b) To allow quick loading with water supply from the surge tank reservoir
c) To mitigate pressure surges from valves, extreme loads at load rejection in turbine or pumping mode

Due to the vast demand for power control in the electrical grid and the demand for electrical energy time-shifting, i.e. storing power when demand is low and using it during peak demand hours when also prices are highest, pumped storage plants are designed increasingly larger with higher discharges, which increases the demand for flexible operation and surge mitigation. One example of a modern pumped storage plant is the *Obervermuntwerk II* scheme by Illwerke VKW AG in Austria with 360 MW of installed capacity. This plant is equipped with a large surge tank and an upper chamber that can generate massive surge waves creating waterfalls into the main shaft. A waterfall dampening device was developed to force the surge wave into several small openings, which lead to many small jets mitigating the air bubble entrainment by 2/3 compared to a concentrated waterfall jet. Figure 1 shows a snapshot of the transient physical model test of the waterfall dampening device that was investigated in the hydraulic laboratory of Graz University of Technology and has already been successfully constructed at the plant and is in operation. It consists of a balcony structure with defined small vertical and horizontal holes that create multiple small jets instead of one waterfall to spread the jet impact and thus mitigate the air bubble entrainment.

Major hydraulic loading on pipe systems in pumped storage schemes may be generated by pump trips. Due to high heads and large discharges, the flow in the high-pressure section of the system may reverse in a very short time before the guide vanes are fully closed. Such events demand a very quick reaction of the headrace surge tank to prevent sub-atmospheric pressures. On the tailrace side, such a pump trip may cause a significant pressure surge, when filling the surge tank. At this point, the pressure surge is transferred to a free surface surge wave in an inclined upper chamber connected to the surge tank. Figure 2 shows the transient physical model test investigation of the upper chamber from the tailrace surge tank of the *Gouvães* pumped storage scheme in Portugal with 880 MW installed capacity by Iberdrola. To avoid spilling of the aerated chamber into the access tunnel, massive baffles were developed to efficiently dampen even the most severe surge wave. The design developed with the aid of the physical model was adopted by the project, which is still under construction and due to be commissioned in 2021. Figure 3 shows the hydraulic system of the pumped storage scheme and the position of the upper chamber.

Designing Tunnel Systems to Minimize Surges

Tunnel systems and caverns could be used instead of, or in addition to classical free surface reservoirs in pumped storage plants. They might even substitute surge tanks by serving multiple hydraulic purposes. Classical surface reservoirs have a large continuous area, which is not the case for tunnel systems. Their site-specific conditions are always unique, and the tunnels need to be specifically designed for each plant. Since very few plants of this type have been built, the current state of the research is the state of the art.

At the laboratory of RWTH Aachen University, model plants of many different tunnel system designs and operation modes were tested. Figure 4 and Figure 5 show photo extracts of different physical models in the laboratory [4]. Figure 4 shows the modularity of the system and the possibility of design changes in one of the models.

The results show the increased intensity of surges in comparison to classical surface pumped storage reservoirs (Figure 5). Thus, the classical approach of neglecting wave generation by pressure surges is not appropriate for tunnel systems. Also, classical formulas for tunnel dimensions cannot be used, because of complex tunnel filling and emptying processes related to the plant operation. Plant operation and design depend strongly on the local site conditions, including rock quality, operational objectives and cost. Thus, the authors developed new calculation approaches and recommend using numerical and physical modelling to design this type of plants [5].

Conclusion

The mitigation of hydraulic surges has always been a great challenge for the design of pumped storage plants and will be even more crucial with the increased need of flexible operation and higher capacity in these sustainable energy storage systems due to the vast integration of fluctuating renewable energy sources. To overcome topographic limitations for the siting of pumped storage projects, the concept can be economically transferred fully to underground structures. The engineering and research experience gained so far and the ability to build suitable small-scale models and perform numerical simulations makes it possible to address the hydraulic challenges in the design of surge mitigation structures in underground caverns and tunnel systems. ■

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ISHS 2020

The 8th IAHR International Symposium on Hydraulic Structures (ISHS2020) was scheduled to take place on 12-15 May 2020 in Santiago, Chile. Because of exceptional circumstances, i.e. the COVID-19 virus pandemic, the event had to be cancelled in late March 2020.

The ISHS series is the flagship event of the Hydraulic Structures Technical Committee (HSTC) of IAHR. The symposium is organised in different parts of the world every 2 years, aiming to facilitate the sharing of information among water engineers coming from different regions, industries and background, including developed and developing countries, and hydraulic engineering students, young and senior professionals.

ISHS2020 would have been the eighth in a successful series of Hydraulic Structures symposia organised by the HSTC, in cooperation with other Committees, Associations and Institutions. The event aim to facilitate the sharing of information among water engineers coming from different regions, universities, industries and background, including developed and developing countries, and hydraulic engineering students, young and senior professionals. The first was held in Tehran, Iran, in 2004; the second was held in Ciudad Guayana, Venezuela, in 2006; the third took place in Nanjing, China, in 2008; the fourth was held in 2012 in Porto, Portugal; the fifth in Brisbane, Australia, in 2014; the sixth in Portland, Oregon, USA, in 2016; and the seventh was held in Aachen, Germany, in 2018.

The organisation of ISHS2020, in association with the Sociedad Chilena de Ingeniería Hidráulica (SOCHID) was well underway when the unfortunate decision had to be made to cancel the event. Key activities planned for the event included two days of technical presentations, keynote and invited lectures, a site visit to Instituto Nacional de Hidráulica (INH) laboratory and the Rapel hydropower dam, a master class on open channel hydraulics to be held at the Pontificia Universidad Católica de Chile, and short courses on energy dissipators and non-linear weirs, and last but not least the internationally famous water games.

In spite of the cancellation of ISHS2020, the Chairs of the Scientific Committee, Robert Janssen and Hubert Chanson, and Chair of the Local Organising Committee, José M. Adriasola, decided to proceed with the publication of the Proceedings of ISHS2020. The Proceedings focus on many aspects of hydraulic structures and their design, especially in terms of diversity, ecology, energy dissipation, and hydrodynamics relevant to the 21st century.

In response to the Call for Papers which was sent out in 2019, the Scientific Committee received 70 abstracts, followed by 49 full paper submissions. The Panel of Reviewers was drawn from the HSTC community and other international and national experts in fields relevant to the symposium themes. All papers submitted for presentation were peer-reviewed by at least two independent reviewers according to a set of criteria established by the Scientific Committee. Altogether the proceedings contain 36 papers involving 85 authors from 20 countries and 5 continents, including 2 invited keynote papers, 2 invited lecture papers and an editorial paper.

The Proceedings are an University of Queensland publication. Each paper was allocated a direct object identifier (DOI), is accessible open access at the University of Queensland institutional open access repository UQeSpace {http://espace.library.uq.edu.au/} and is indexed by Scopus and Compendex.

The proceedings are available on the Hydraulic Structures Committee webpage which can be found in the Communities section of the **IAHR website**.

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CONTROLLED TRANSIENTS ARE RELIABLE FOR FAULT DETECTION

BY SILVIA MENICONI, CATERINA CAPPONI, MOEZ LOUATI & BRUNO BRUNONE

In the last decades, transient test-based techniques (TTBTs) have been proposed for fault detection in pressurized pipe systems. Such techniques, where pressure waves are injected in pipes "to explore" the system, are competitive with respect to other methods (e.g. inline techniques using sensors inserted into the pipelines). This article discusses the reliability of TTBTs for some real systems based on the results of case studies that fully confirm those of numerical and laboratory experiments.

Transmission mains (TMs) lose an average of 40% worldwide of the transported water in part because of limitations of current leak detections methods. Water losses in conveyance systems cost money and energy, and represent an effective reduction in the available water resources putting more stress on aquatic ecosystems in addition to the climate change impacts. Moreover, leaks could reduce system reliability, lead to infrastructure failures, and allow water contamination thereby decreasing water quality and threatening public health. In recent decades, controlled transient waves in pipes have been shown to be efficient and promising tools for overall system diagnosis.

This article discusses the ability of the TTBTs to detect in TMs not only leaks, but any type of faults (e.g., partial blockages, negligently partially closed in-line valves, damaged pipe sections due to corrosion, and illegal branches). Moreover, they minimize the interference with the regular functioning, without breaking ground or making particular changes in the pipe asset. Like any other technique, TTBTs require a preliminary survey of the system to identify the layout, the geometric and mechanical characteristics of the pipes (to set, for example, a preliminary value of the pressure wave speed), and the location and behavior of known boundary conditions (e.g., reservoirs, and pumps). During a transient test, a pressure wave is injected into the system at a selected location through a rapid change in flow or in pressure; the pressure response is recorded at one or more measurement sections. The transient wave, while travelling along the pipeline at a high speed, interacts with any pipe boundary or defect, being partially or totally reflected. The arrival of these reflected waves at the measurement sections is detected as a sudden change in the pressure signal. The arrival times of the waves, combined with the knowledge of the system topology, allow determining the actual value of the wave speed, the unknown functioning of boundary conditions, and the defect location. The performance of this approach is surely noteworthy in systems with a simple topology. In complex networks, such as water distribution systems, the complicated pattern of wave transmission and reflection makes the analysis of the pressure signal quite difficult, but possible [1]. The difficulties are mainly related to the limited number of measurement locations and they can be resolved by monitoring pressure at the system boundaries regardless of the network [2]. A numerical model (e.g. a Lagrangian model, a model based on the Method of Characteristics or the Transfer Matrix Method) based on the solution of the partial differential equations governing transients, may help in detecting the instances that the pressure waves are expected to pass through the measurement section based on the topology of the system. Such instances are compared – possibly by using an optimization procedure, such as a genetic algorithm or match-field processing [3] – with those detected in the pressure signal to exclude expected wave reflections from system boundaries and junctions and to point out singularities from defects. Recently, the use of TTBTs is increasing, because of the simplicity and time-efficiency of the tests, as well as the modest cost of the necessary instruments (in fact only pressure must be measured). For these reasons, TTBTs are undoubtedly competitive with the invasive techniques that involve the insertion of probes in the pipelines, or the realization of "listening points" for the leak a few hundred meters away from each other. In addition, TTBTs are found to be very efficient at detecting leaks at low pressure whereas the

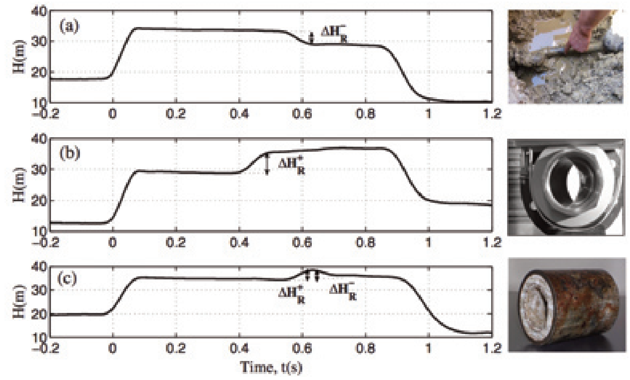

Figure 1. High-density polyethylene pipe system: anomaly effect in the pressure signal during the first characteristic time of the pipe: (a) leak (or branch); (b) partially closed in-line valve; (c) partial blockage.

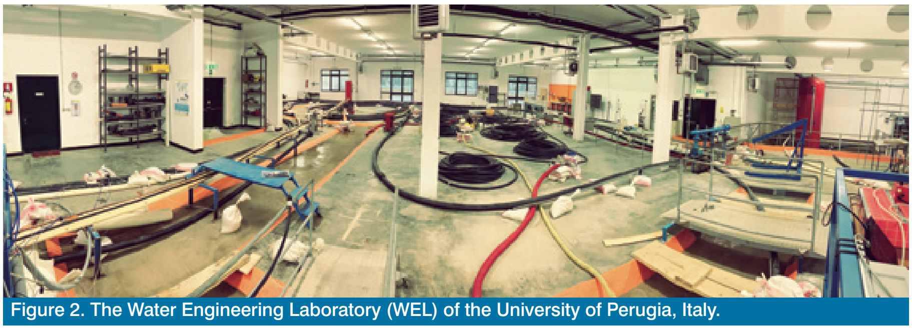

Figure 2. The Water Engineering Laboratory (WEL) of the University of Perugia, Italy.

Silvia Meniconi, Ph.D., is an associate Professor qualified for Full Professorship at the University of Perugia. Her research interests include: the modeling of transients in pressurized pipes, transient test-based techniques for fault detection in pipe systems, and the pressure control by PRVs. She won the Bologna 2016 Water Fair Innovation award for the PPWM device. She was the PI of a Research Project of National Interest - PRIN funded by the Italian MIUR of a Project of Relevant National Interest and she is a co-investigator in the Smart UWSS project at HKUST and in many consultant activities commissioned by some Italian water supply companies. She co-founded and co-organized the special sessions on “Transients in pipes” at the 37th and 38th IAHR World Congresses. Now, this special session has officially become permanent in all future IAHR congresses under her co-leadership. She is the co-chair of the IAHR Transient Flows Working Group.

Caterina Capponi is a research fellow at the Water Engineering Laboratory (WEL) of the University of Perugia, where she graduated and received the Ph.D. degree. She is Co-Investigator in more than 10 research projects, with two of relevant national interest (PRIN) and co-operations with important Italian water utilities. Her research interests include the modeling of transients in pressurized pipes and the development of transient test-based techniques for fault detection in pipe systems.

Moez Louati obtained his Ph.D. degree in Civil Engineering from the Hong Kong University of Science and Technology (HKUST). He was awarded the SENG PhD Fellowship Awards for three years and he received the SENG Overseas Research Award. Currently, he is a Research Assistant Professor at the Civil and Environmental Engineering Department (HKUST) working on the “Smart Urban Water Supply System” (Smart UWSS project) and other funded projects. Since September 2016, he is the Editorial Coordinator of the Journal of Hydraulic Research (JHR) and he is currently an Assistant Editor in this journal. He is a member of IAHR and IAHR-HK-Chapter. He is the chair of the IAHR Transient Flows Working Group.

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accuracy and the competence of steady state-based leak detection methods are mainly dependent on high pressures [4].

In literature, the results of numerical and laboratory/field experiments show that the transient response of leaks [5], [6], [7], [8], partially closed in-line valves and partial blockages [9], [10], internal wall conditions [11] and illegal branches [12] allows their detection. As an example, in Figure 1, the effect (positive or negative reflected pressure waves) of some of these faults in the pressure signals acquired in the Water Engineering Laboratory (WEL) of the University of Perugia is highlighted. In general, a transient test provides the transient-system response (TSR) which represents a transient imprint characterizing the system. A system with defects modifies the intact TSR and each defect type has a specific signature on the TSR.

WEL (for more details see: https://welabpg.wordpress.com), active in this field since 1997, has been recently renovated (Figure 2) with the addition of a pipe network with two loops simulating a Pressure Management Area, and two parallel external straight lines (one buried and one unburied, to evaluate the soil effect), thanks to the support of the Italian Ministry of Education, University and Research (in Italian: Ministero dell’Istruzione, dell’Università e della Ricerca, or MIUR) and the University of Perugia within the program Dipartimenti di Eccellenza 2018-2022, and the Hong Kong (HK) Research Grant Council T21-602/15R Theme-Based Research Scheme and the HK University of Science and Technology (HKUST) under the project Smart Urban Water Supply System (Smart UWSS: http://suwss-dev.ust.hk/).

A crucial role in TTBTs is played by the method used to analyze the pressure signals to improve the detection accuracy: time-domain, frequency-domain, coupled time- and frequency-domain and wavelet analysis methods. Inter alia, within this topic a permanent special session “Transients in Pipes”, organized by two of the authors – at the 37th IAHR World Congress in Kuala Lumpur (Malaysia) in 2017, in collaboration with P. Lee (University of Canterbury), A.S. Leon (Oregon State University), and S. Kim (Pusan National University) and at 38th IAHR World Congress in Panama City (Panama) in 2019 – has highlighted interesting fundamental development and practical applications in the fluid transient field. Moreover, a working group on "Transient flows" has just been created to provide a framework to the transient group community within IAHR.

The following sections present examples where transient analyses are used in real pipeline systems for the accurate location of faults: the quite simple transmission main in Trento (Italy) and the more complex Milan (Italy) water distribution-transmission system.

The Trento transmission main, managed by NovaReti SpA, is an iron pipe with DN 500 mm and length 1.3 km, connecting the “Spini” well-field to the “10000” reservoir which supplies the city of Trento (Figure 3a). The pipeline has few minor branches, quite short and certified by the system manager as inactive (i.e., connecting the main pipe to a dead-end or with a closed valve at about the inlet). The diameter and the length of such minor branches range between DN 80 mm and DN 500 mm, and 0.7 m and 18.5 m, respectively. All branches are steel, except one (marked as E in Figure 3a), which is a high-density polyethylene (HDPE) pipe and consists of two reaches of 3 m and 15.5 m long, respectively. The end nodes of these reaches are the red valve shown in Figure 3a, certified as fully closed, and the inactive San Lazzaro well [13]. The transient is generated by a change of pressure, which is an alternative to the change of the flow rate, the most frequent cause of pressure wave generation (i.e., pump switching off or valve closing). Precisely, such a perturbation is generated by the Portable Pressure Wave Maker (PPWM) device refined at the WEL, which is a vessel filled with water and air. The PPWM has been installed immediately upstream of the “10000” reservoir and connected to the main pipe by a short connection pipe (about 1 m long) and 1/2’’ valve. Just before the transient test started, the pressure at the PPWM was set at a value larger than that in the pipe (about 5 bar of difference), and the pipeline was isolated by closing the valve just upstream of the “10000” reservoir and stopping pumping at the well-field. Precisely, all the pumps were shut down one by one, waiting enough time to damp the transient effects. The manual and fast opening of such a valve allowed injecting a quite sharp pressure wave into the system measured by a pressure transducer installed immediately upstream of the connection valve. It is worth nothing that such a pressure wave injected at 0 s is very small (about 0.85 m) (Figure 3b). The wavelet transform allowed denoising the signal, and pointing out discontinuities. Specifically, the one happening at about 2.51 s after the injection maneuver could be ascribed to the “10000” reservoir and could be used to evaluate the wave speed as equal to 1055.88 m/s. The clear reduction of pressure at 1.52 s was due to the wave reflected by the junction of the E branch and the successive clear increase at 1,62 s could be associated with the San Lazzaro well. A further interview with the water utility technicians revealed that the red valve was not closed as expected. Furthermore, a more detailed analysis [14] pointed out that a small leak of 1 to 2 L/s had occurred at the San Lazzaro well.

The analyzed system in the city of Milan (Italy) is the steel pipe supplied by the Novara pumping station managed by Metropolitana Milanese SpA. As clearly shown in Figure 4d, the topology of the system approaches that of a water distribution network because of the presence of several branches immediately downstream of the pumping station. In the figure, the main pipe, 6.3 km long, and with a nominal diameter DN 800 mm, is highlighted by a bold line; the main connections, as well as the pumping station node, are numbered. The transient was generated by a pump trip. Figure 4a shows the pressure signal at the section immediately downstream of the check valve. The pressure signal was analyzed by the Wavelet Transform (WT) (Figure 4b). The first clear singularity after the pump trip occured at time 9.607 s. Such a wave can presumably be ascribed to junction 8. By associating the discontinuity of the pressure signal with junction 8, the resulting value of the pressure wave speed of the main pipe is equal to 954.26 m/s, which is compatible with its mechanical characteristics. In order to evaluate the other pressure wave speeds, firstly the network was skeletonized and, then, an optimization procedure based on a genetic algorithm was carried out by coupling the WT and the Lagrangian Model (LM). The obtained values of the pressure wave speeds were used in the LM, which integrates analytically the water hammer equations and allows evaluating the causes of the discontinuities. In such a way the defects of the network could be localized more reliably. Because of the complexity of the system and the subsequent inability of knowing the functioning of all terminals, in Figure 4c the impulse response function of the LM is shown for the case that all terminals are closed to emphasize the response of the system to the transients. By comparing the WT and the LM it is possible to evidence a chain of extreme values of the WT, at 10.4 s, that could not be associated with any known boundary condition (i.e. a modification of the TSR). Because of its characteristics, such a discontinuity could be due to an unknown increase in pipe diameter or a change of pipe material, a junction, or a leak. According to the pipe system characteristics, the possible locations of the anomaly pointed out by circles are six in the area highlighted in Figure 4d. It is worth noting that, for a given arrival time of a pressure wave at a measurement section, several paths can be assumed, and then the uniqueness of the solution – in terms of defect pre-localization – is not ensured unless further measurement sections are activated. As a consequence, a fault area was identified with some possible leak locations highlighted inside. The reliability of this procedure has been confirmed since a leak was repaired in the detected area.

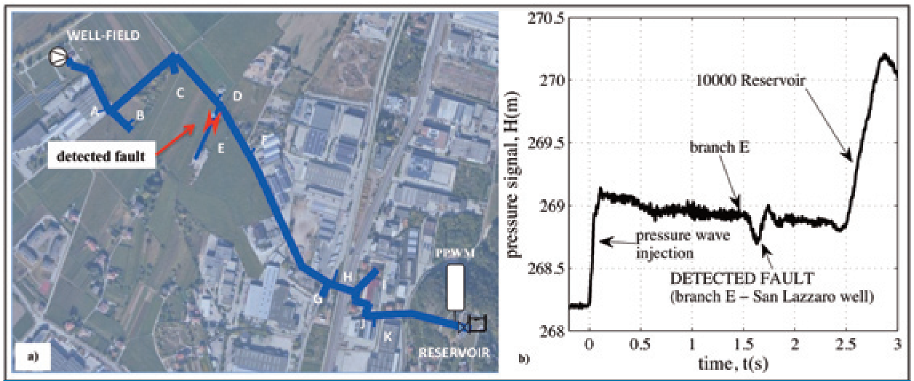

Figure 3. (a) Schematic representation of the Trento supply pipe system (note that letters indicate the branches and a different length scale has been used for the main pipe and minor branches); (b) pressure signal at the section immediately upstream of the connection valve between the main pipe and the PPWM (modified from [14]).

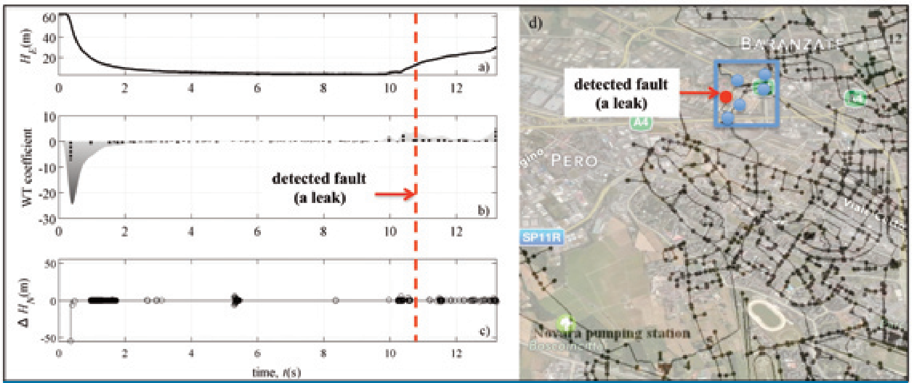

Figure 4. A part of the Milan water distribution system supplied mainly by the Novara pumping station: a) pressure signal, b) time history of the corresponding WT, c) impulse response function is given by the Lagrangian model, and d) schematic of the system [1].

Successful fault detection using controlled transients in laboratories and real networks have been reported in different countries such as Australia, New Zealand, Hong Kong, and US. Recently, the Smart Urban Water Supply Systems project has been analysing the use of actively generated acoustic waves in pipe systems for a superior resolution and damage identification than the described TTBTs, and a promising and noise-tolerant signal processing method called Time-Reversal for pipeline leak localization [15]; [16]; [17]. ■

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CHALLENGES OF MODELING STORMWATER TRANSIENTS IN DEVELOPING COUNTRIES

BY DANIEL ALLASIA, ROBSON PACHALY, RUTINEIA TASSI, JOSE GOES VASCONCELOS, BEN R HODGES & ROBERT E DICKINSON

The rapid urbanization of developing countries has increased population densities and led to a new group of “mega-cities.” This growth has often occurred without adequate planning, resulting in a range of problems including increased flood frequency due to inadequate stormwater infrastructure [1]. Such problems cascade into direct impacts on both people and the economy. For example, some cities in Brazil experience problems caused by inefficient urban stormwater facilities – with both undersized and oversized segments connected in any given system due to unplanned piecewise expansion.

Older segments may have obstacles (e.g., Figure 1) that cannot be accounted for using any standard equations and are poorly documented. The funding to correctly “right-size” the existing stormwater infrastructure is limited. Requests for such funding must compete with those for addressing other urban needs. Consequently, engineers must be creative in developing approaches to improve stormwater management and be aware that existing infrastructure might not follow design standards. This situation has even more serious implications when stormwater systems receive inflows from strong convective storms causing significant hydraulic transients.


Figure 1. Unplanned obstacles in the collection systems’ cross-section in Brazil (source: SUDECAP).


Figure 2. Sediment and litter accumulation in collection systems.


Figure 3. Geyser at a manhole in Southern Brazil.

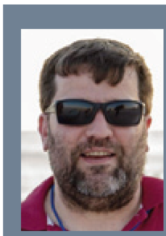
Upgrades of stormwater facilities in developing countries are often designed with very limited data. For instance, the existing system plans may be non-existent or miss key information, the design rainfall criteria may not be specified, watershed monitoring data is usually sparse, and pre-development conditions are poorly documented. Nevertheless, new system additions must be blended with the existing infrastructure, increasing its already complex topology and presenting a system that is far from the “best practices” that would be used when designing on a clean slate. Ill-advised situations can arise in the course of adding new structures to an existing system, such as conduit cross-sectional area contractions, poorly aligned expansions, unplanned shafts, short conduits, and insufficient inlets. In addition, maintenance practices may be poor or non-existent, leading to sediment and litter accumulation in inlets and conduits (Figure 2), thus triggering grade flooding and/or conveyance loss. The resulting systems do not readily propagate a stormwater impulse through the network in the way envisioned in our standard design practices. Sewer transients can lead to damaging and dangerous conditions, ranging from destruction of streets to geysers (Figure 3). Understanding the response of these unorthodox systems to transients is critical to finding designs that efficiently reduce choking points and can thereby reduce flooding.

Accurate and reliable hydraulic models are needed to revise the designs of these complex urban stormwater systems. Due to funding limitations, freely available models such as HEC-RAS or SWMM are usually selected, even though these models have not been designed to simulate hydraulic transients in closed conduits. Unfortunately, the same funding problems typically prevent the collection of an adequate data set for model calibration/validation and may also limit the training available for model users. In the hands of properly skeptical engineers, such free hydraulic/hydrological modeling tools can be valuable despite limited data, but the user-friendly interfaces and robustness of the latest model versions can lead less-experienced practitioners into trouble. Engineers without enough hydraulic training may develop a false perception of the model reliability and its boundaries of effectiveness – particularly where the complex hydraulics phenomena are involved. For example, SWMM unsteady formulation solves the flow conditions in a network of links and nodes through the Saint-Venant equations [3]. This solution well-represents typical stormwater conditions; however, for rapid inflow conditions associated with extreme inflows or complex system geometries, SWMM typically underestimates surges, under-represents sudden changes in sewer flow conditions, and yields significant flow continuity errors accompanied by numerical instabilities [2], [4].

In turn, HEC-RAS incorporates a Mixed Flow Regime option based on the Local Partial Inertia Technique [5]. The LPI method systematically reduces inertial terms in the Saint-Venant equations diminishing the numerical instabilities in the simulation. However, this option introduces simplifications in simulation and should be utilized only after determining that a mixed flow situation exists, which requires judgment from the modeler [6].

Arguably, the low-cost adaptation of the stormwater systems in developing countries is one of the most challenging stormwater infrastructure problems we face, and yet it does not draw the attention and expertise it needs. As cities continue to grow under the pressure of climate change, the need for stormwater systems (and stormwater engineers) that effectively handle transients caused by rapidly changing flows during strong convective storms becomes more pressing.

Comprehensive education of engineers and decision-makers and other stakeholders that adequately explains the usefulness and limitations of freely available models should be a priority as well as robust investment in data collection, analytics, and smarter application of free tools that can help practitioners to cope with hydraulic transients in sewer systems. Using SWMM as an example, these tools can range from analysis tools [7], model's plugins that recommend models setups based on expected dynamic flow conditions, [2] or even more complex numerical models [9].



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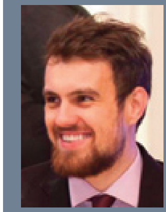
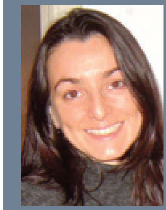


Robson Leo Pachaly is a current Ph.D. student and Teaching Assistant in Civil Engineering at Auburn University, USA. He holds a bachelor's degree in Sanitary and Environmental Engineering and a master's degree in Environmental Engineering, both degrees obtained at the University of Santa Maria, Brazil. He developed open-source plugins for QGIS that aided the acquisition of hydrological data in Brazil and ReSWMM software that improves the hydraulic computations of the EPA Stormwater Management Model (SWMM).



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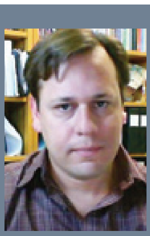
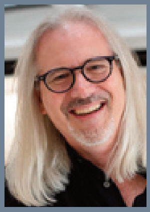
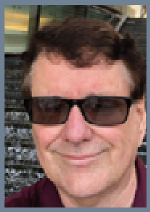


José Goes Vasconcelos is the leader of Hydraulic Research Group at Auburn University, publishing experimental and numerical investigation on unsteady flows in closed conduits, air-water interactions, cavitation effects (TPAcav), extreme flows and surges in urban water systems. His SHAFT model was used in the simulation of large below-grade stormwater storage systems in Washington, DC; London, UK; St. Louis, MO; among other systems. Associate editor in the Journal of Hydraulic Engineering (ASCE), J. of Water Management Modeling (CHI), reviewer for several publications related to unsteady hydraulics and two-phase flows. He is chair of the ASCE EWRI Hydraulic Structures Committee, and the ASCE EWRI Task Committee "Two-phase Flows in Urban Water Systems."



Ben Hodges was educated at the U.S. Merchant Marine Academy (BS), the George Washington University (MS), Stanford University (Ph.D.) and the University of Western Australia (post-doc). He has taught and conducted research at the University of Texas at Austin since the year 2000. His research focuses on water flow and transport behaviour in lakes, rivers, estuaries, and across the urban landscape using advanced 1D, 2D, and 3D models. He is the Principal Investigator for the National Center for Infrastructure Modeling and Management, a 5-year project funded by the US EPA to develop the next generation models of water distribution systems and stormwater runoff management.



Robert Dickinson is the Innovyze Product Sector Leader for ESRI Products InfoSWMM/InfoSewer; Supports InfoWorks_ICM, ICM_SWMM, XPSWMM, SWMM5, Center for Infrastructure Management and Modeling (CIMM); Founder SWMM5.ORG. In the past, he was a Co-Developer of EPA SWMM 3,4,5+, XPSWMM.

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THEMATIC FRAMEWORK | 39th IAHR WORLD CONGRESS

From Snow To Sea (S2S)

Theme 1 Human-water relationships

This theme focuses on bringing together the past and the future, knowledge and experience, with the goal of enhancing enlightened human-water relationships.

a. Dialogue of knowledge: academy and traditional hydro-environment engineering knowledge
b. Hydro-environment cultural heritage
c. Hydro-environment engineering history
d. Sustainable Development Goals
e. Gender balance, youth involvement and leadership
f. Flood management risks from coincident calamities

Theme 2 Snow, river and sediment management

This theme addresses the main management challenges related to the first steps of the water cycle: snow and river processes and their impact on reservoir management.

a. Snow assessment and impact on fluvial processes
b. Sediment transport in rivers: processes, monitoring and modeling
c. Watershed erosion processes and soil conservation
d. River morphodynamics and hydraulic-structure effects
e. River sediment management, basin-scale interactions and impact on the coast
f. River conservation and restoration: nature-based solutions
g. Sedimentation in reservoirs

Theme 3 Environmental hydraulics and urban water cycle

This theme addresses the environmental aspects as well as the urban use of water and its subsequent treatment and reuse.

a. Ecohydraulics
b. Mixing processes
c. Sensors, monitoring and management strategies in urban water and wastewater systems
d. Restoration of water systems in a changing climate
e. Desalination and water treatment
f. Advanced treatment processes for wastewaters
g. Water recycling and reuse
h. Industrial flows

Theme 4 Hydraulic structures

This theme addresses on the design and performance of hydraulic structures, focusing on structures related to the water path from snow to sea.

a. Hydro-environment historical structures: management and restoration
b. Aging hydraulic structures: upgrade and retrofit towards more sustainability
c. Recent advancements to more reliable, sustainable and resilient hydraulic structures
d. Sustainable renewable energy solutions
e. Nature-based solutions as a way towards sustainability
f. Large scale tests and field data - towards the ultimate validation of hydraulic structures design
g. Case studies

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Theme 5 Water resources management, valuing and resilience

Within the framework of sustainable water management, this theme focuses on improving resilience, valuing water, and mechanisms to improve cooperation and water governance.

a. Water resources planning and management under increasing uncertainty and climate change
b. Alternative water resources
c. Advanced water resources systems analyses: improving resilience
d. Water and circular economy: valuing water
e. Water-food-energy nexus: sustainability of water resources
f. Water use efficiency
g. Cooperation, governance of water and transboundary catchments
h. Conflict resolution and stakeholder participation in water management

Theme 6 Computational and experimental methods

This theme focuses on the development and application of both experimental methods and new technologies to improve knowledge of water processes.

a. Computational methods in fluid dynamics and hydro-environmental problems
b. Computational methods in sediment dynamics
c. Computational methods in fluid-structure interactions
d. Computational and experimental methods: towards composite modeling
e. Optimization methods and uncertainty assessment
f. Artificial intelligence in hydro-environment engineering
g. Big data, data mining and high-performance computing under hydroinformatics
h. Instrumentation, experimental facilities and field experiments
i. Water from above: remote sensing and drones technologies

Theme 7 Coasts, estuaries, shelves and seas

Within the framework of sustainable goals, this theme focuses on those aspects of the coast, estuaries, shelf and seas that are most related to IAHR.

a. Hydrodynamics, sediments, and ecosystem services
b. Water quality and pollution
c. Coastal erosion
d. Resilient coastlines in a changing climate
e. Estuaries and shore protection and restoration: green coastal infrastructure in climate change scenarios
f. From the inner shelf to the coastal zone: ecosystem challenges in a changing climate
g. From Snow to Sea: the future of the Mediterranean Sea

Theme 8 Extreme events: from droughts to floods

This theme addresses extreme events, the occurrence and severity of which is expected to increase in the coming years as a result of climate change (among other aspects).

a. Drought prediction and management; impacts of climate change
b. Tsunamis, storm surges and effects of tropical storms under rising sea levels
c. Flood risk assessment, mitigation and adaptation measures
d. Urban flood management
e. Flood recovery and resiliency
f. Impact of global change on extreme environments (cold/arid regions)
g. Adaption to climate change: guidance to engineering design

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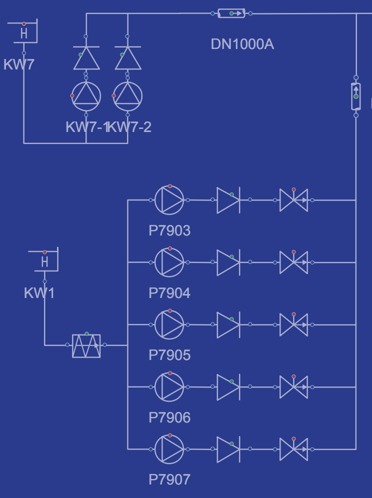
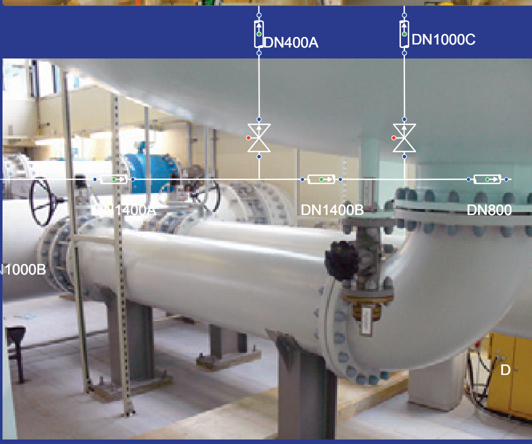
- Extensively tested and validated.
- Python Application Programming Interface (API).





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