Monitoring of steel-lined pressure shafts and tunnels

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A new non-intrusive monitoring method to detect the local drop of wall stiffness of shafts and tunnels at hydro plants has been developed in Switzerland. The method is based on the waterhammer wave signal and the fluid-structure interaction phenomenon. An overview is presented here of the status of the ongoing work in this field, and includes a short state-of-the-art-review, a description of the physical scale model with some tests results, and a description of an in-situ measurement system which acquires pressure records from the shaft of a pumped-storage plant in the Swiss Alps.

The current European electricity market offers an excellent opportunity for Swiss hydropower producers to increase their daily peak energy production. In addition to its attractive market price, this energy is essential to avoid blackouts which could cover large areas and cause major economic losses. Switzerland has developed 85 per cent of its economically feasible hydro potential [Schleiss, 2000[1]] to meet approximately 55 per cent of the country's electricity requirements. The Federal Government wants to promote the future use of hydropower to a greater extent, to maintain and increase the strong position of Switzerland in peak hydro production and the export of high value technology.

The research consortium HydroNet, established in 2007 and co-financed by CCEM and Swisselectric research, aims to converge towards a consistent, standardized methodology for design, manufacture, operation, monitoring and control of pumped-storage plants. One of the civil engineering fields involved in this research consortium concerns the design of pressure shafts and tunnels.

1. State-of-the-art review

The actual design criteria and methods for load-sharing calculations for steel-lined pressure tunnels and shafts have been reviewed and discussed by Hachem and Schleiss [2009[2]]. A review of wave speed in frictionless and axisymmetrical steel-lined pressure tunnels has also been discussed by these authors [Hachem and Schleiss, 2011[3]]. In this second paper, general applicable approaches for estimating the quasi-static and frequency-dependent waterhammer-wave speed in steel-lined pressure tunnels are analysed. The external constraints and assumptions of these approaches have been discussed and the reformulated formulae have been compared with commonly used expressions. An enhanced theoretical model for the steel liner has been proposed as a basis of future development, including the application of fracture mechanics, to assess the response of high-strength steel which is used as the lining for shafts of new hydro plants.

The monitoring of existing steel-lined shafts and tunnels is normally done using pressure sensors, water level measurements, and downstream and upstream flowmeters. The water pressure records are usually used to check the amplitude of the transient pressures relative to a critical operation value defined during the design phase. No further advanced analyses and pressure signal processing is done. When a liner failure occurs, the water flow discharge increases and exceeds a predefined threshold. The security shut-off valve at the upstream end of the shaft closes automatically to limit the quantity of water leaking from the shaft towards the rock surface. Nevertheless, catastrophic consequences can occur because of the considerable leakage volume combined with hydraulic jacking of the rock mass. Any further and additional investigation of the steel-liner as regards excessive local deformations and steel yielding requires the interruption of operation and the dewatering of the shaft for visual inspections. Furthermore, no information can easily be obtained regarding the stiffness of the backfill concrete and the rock mass surrounding the steel-liner.

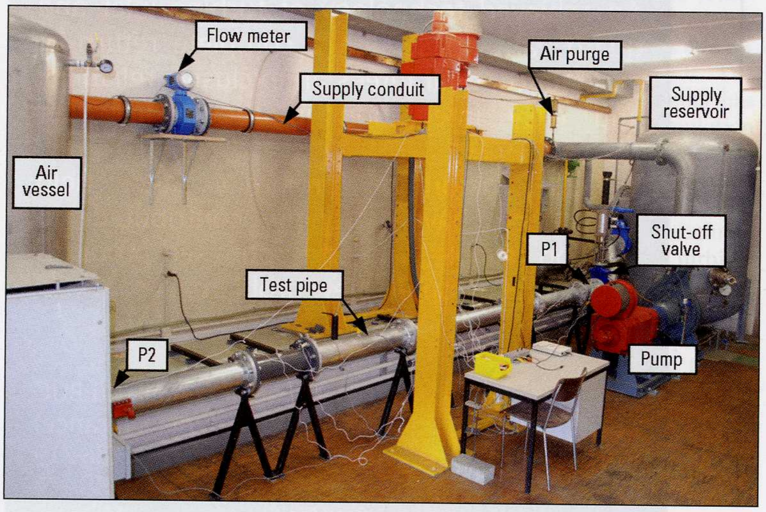
Besides these rather rudimentary hydraulic-based monitoring systems, a number of more advanced techniques for pipeline leak detection, involving transient pressure waves, have been applied in water, gas and oil networks [Misiunas *et al*, 2005[6]; Stephens *et al*., 2008[7]; Taghvaei *et al*., 2010[8]]. Therefore, a new monitoring method for steel-lined pressure shafts and tunnels, based on the fluid-structure interaction and on the processing of the wave reflections during waterhammer, has been developed and is presented here. It is a real time procedure, which can detect the occurrence, severity and location of a change in wall stiffness of shafts and tunnels, based on recorded dynamic pressure signals at both accessible ends.

2. Physical scale model

2.1 Description of the experimental set-up

If the hypothesis of an axi-symmetrical deformation of the multilayer system (steel-concrete-rock) of the pressure shaft is accepted, the shaft can be modelled by a single-layer system. The experimental facility shown in the photo on the left was built at the

View of the experimental facility.



Laboratory of Hydraulic Machines (LMH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). Waterhammer events can be generated inside the multi-reach test pipe by closing a shut-off valve at its downstream end.

The test pipe has an internal diameter of 150 mm and a length of 6.25 m, measured from the shut-off valve to the upstream air vessel. It is supplied with water from a reservoir through a variable speed pump and a 10 m-long PVC supply conduit. The test pipe is divided into several reaches 0.5 m and 1 m long, fitted together with flanges having an external diameter of 285 mm and a thickness of 24 mm. The flanges are also used to fix the test pipe rigidly along its length, to minimize any longitudinal and transversal movements during the tests. An electromagnetic flowmeter is placed on the supply conduit to measure the steady-state flow inside the facility. On the highest point of this conduit, an air purge valve is installed to evacuate the captured air inside the test rig. The first control and security valve, followed by an elastic deformable joint, are located at the downstream end of the supply conduit, which is protected against waterhammer by the pressurized air vessel.

The shut-off valve is operated automatically by an air jack with input and output electro-valves. The volume of air needed to activate the jack is provided by an air compressor with a constant pressure of 10 bars. The shut-off valve is followed by a purge valve, two elbows, an elastic joint and a second control valve located at the entrance of the supply reservoir. The total length of the test pipe made up of all these pieces is about 2 m. The opened and closed states of the shut-off valve are detected by two infrared diffuse sensors. The data acquisition system includes:

- two pressure transducers (HKM-375M-7-BAR-A, Kulite) with a pressure range from 0 to 7 bars and an accuracy of 0.5 per cent;
- an NI-USB-6259 acquisition card M series with 32 analogue input channels and two analogue output channels to activate the two electro-valves of the shut-off valve; and,
- a notebook computer connected to the acquisition card through a USB cable.

The sampling frequency was fixed at 15 kHz. LabView 8.6, MATLAB 2008b and Diadem 11.0 software were used for acquiring, controlling and processing the experimental data.

The different test pipe configurations are shown schematically in Fig. 1. All the tests were carried out with an initial steady flow of 58 l/s and an initial mean water pressure of 0.2 bar measured at the sensor position P2.

2.2 Tests results and analysis

An example of the measured pressure records at P1 and P2 is shown in Fig. 2 for three test pipe configurations. The waterhammer wave speed is the ratio of the distance separating the pressure sensors (equal to 5.88 m) and the wave travel time between them. In case of steep wave fronts, the travel time is the one that separates the time at the maximum values of these fronts. The mean and standard deviation of the computed wave speeds for 84 tests carried out on the seven test pipe configurations are shown in Fig. 3. A significant decrease in the wave speed is observed in 'Steel+PVC' configurations. This is an indicator of the presence of weak reaches in the pipe or in the shafts of hydropower plants. This decrease of the wave speed is

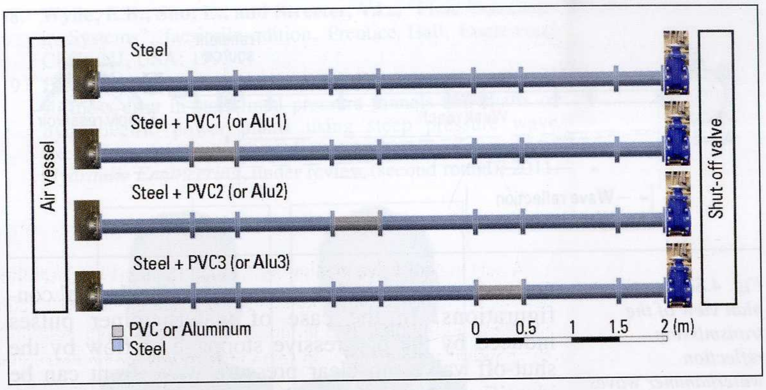


Fig. 1. Four configurations of the test pipe.

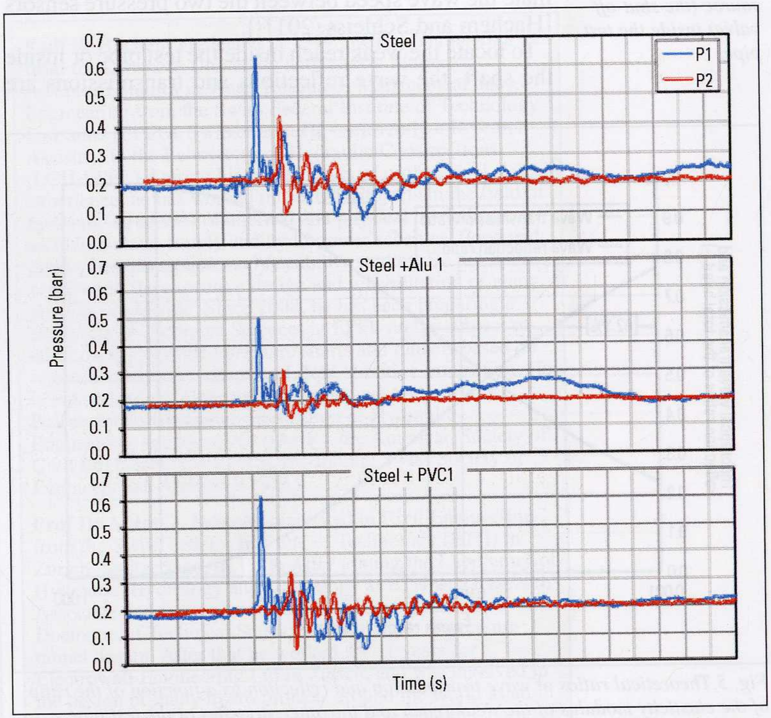


Fig.2. Waterhammer pressure measured at the sensor positions P1 and P2 for three test pipe configurations.

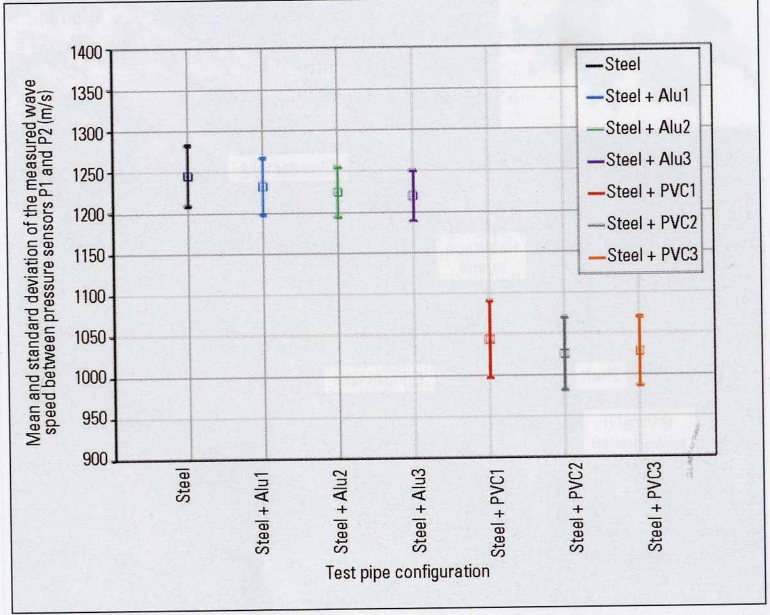


Fig. 3. The mean and standard deviation of the measured wave speed obtained from 84 tests carried out on the seven test pipe configurations.

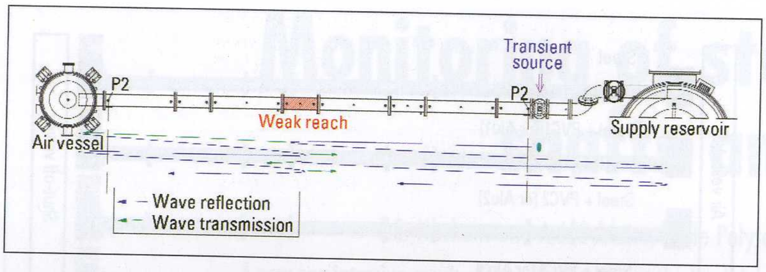


Fig. 4.Schematic plan view of the transmission-reflection waterhammer waves generated by a source (the shut-off valve) inside the test pipe.

not very well marked in case of the 'Steel+Alu' configurations. In the case of waterhammer pulses induced by the progressive stoppage of flow by the shut-off valve, no clear pressure wave front can be identified. Therefore, another approach is used to estimate the wave speed between the two pressure sensors [Hachem and Schleiss, 2011[7]].

To locate the weak reach inside the test pipe or inside the shaft, the wave reflections and transmissions are processed. As shown in Fig. 4, an incident pressure wave is divided into transmitted and reflected waves when crossing the weak reach [Wylie *et al*., 1993[8]]. Fig. 5 gives the theoretical values of the ratio between waterhammer transmission and reflection as a function of the ratio between the elasticity modulus of the weak reach and the other parts of the test pipe. PVC reaches having an E_{PVC}/E_{steel} equal to 0.014 generate reflections of up to 38 per cent of the incident wave. In the case of 'Aluminum' reaches, these reflections are around 1 per cent. This low ratio induces difficulties in detecting and capturing the reflection pressure signals in the presence of noise. In low dissipative media, a weak reach with an elasticity modulus not higher than 10 per cent relative to the other part of the structure could be located by processing the pressure reflection data. The analysis of pressure records to locate the weak reach is achieved using the Fast Fourier Transform and the Wavelets techniques [Hachem and Schleiss, 2011[9]].

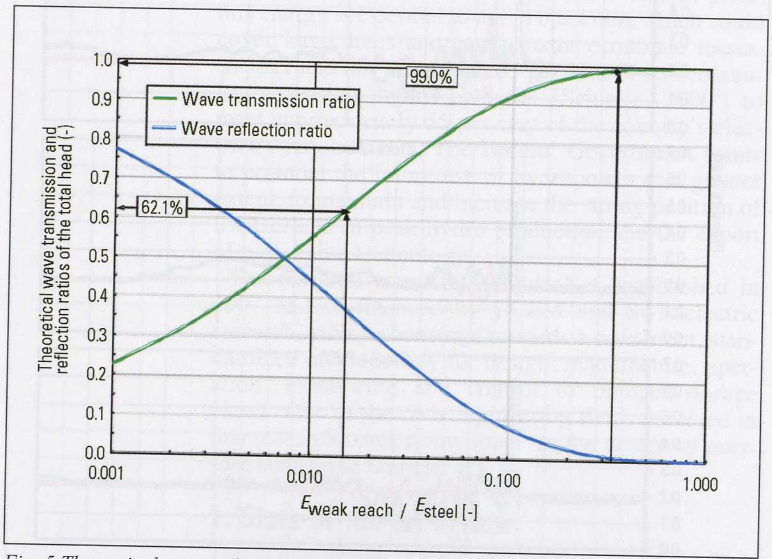
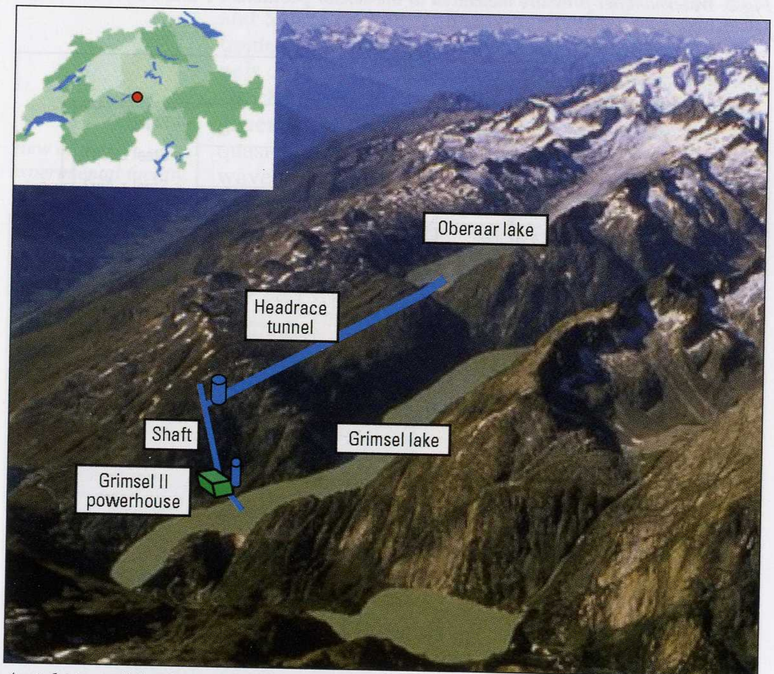


Fig. 5.Theoretical ratios of wave transmission and reflection as a function of the ratio of the elasticity modulus of the weak reach and the other stretches of the test pipe.



Aerial view of the Grimsel II site with the upper and lower reservoir of the pumped-storage scheme.

3. Prototype measurements

3.1 Description of the site

The Grimsel II pumped-storage plant is in the Canton of Bern, in the central part of Switzerland, at an elevation of 1760 m (see photo below left). It has been in operation since 1982. The plant is owned by Kraftwerke Oberhasli AG (KWO) and has an underground powerhouse, equipped with four reversible Francis pump-turbine units with a total capacity of 350 MW. A 4 km-long headrace tunnel with an internal diameter of 6.8 m connects the Oberaar Lake (the upper reservoir) to the vertical 123 m-high surge tank, which is 16 m in diameter. This surge tank is followed by the security butterfly valve and then a steel-lined shaft, with an internal diameter of 3.8 m and a length of 650 m. The upstream end of the shaft is connected to a 170 m-long inclined tunnel which is the extension of the shaft excavation. It functions as an inclined surge tank. The steel-lined shaft has a slope of 100 per cent and conveys water from el. 2213 to the powerhouse. On the low pressure side, downstream from the pump-turbine units, a third vertical surge tank, 155 m high with a diameter of 8 m, is connected laterally to the 300 m-long steel-lined tailrace tunnel which connects the powerhouse to Lake Grimsel (the lower reservoir). Fig. 6 is a schematic 3D view of this water conveyance system, including the shaft, the surge

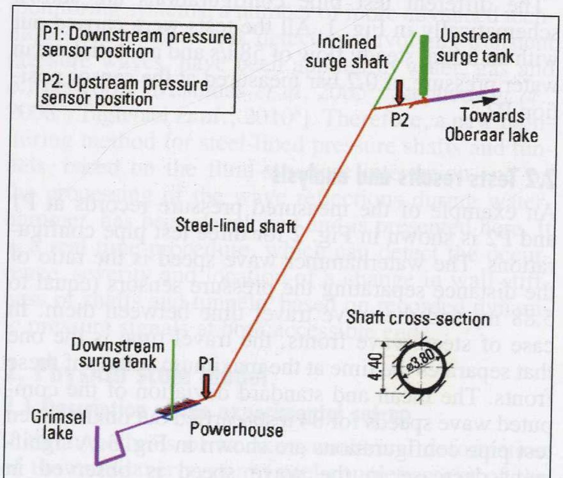


Fig. 6. Schematic 3D view of the Grimsel II waterway system with the two positions of the data acquisition systems and a cross-section of the steel-lined shaft.

tanks and the powerhouse. The two positions of the pressure sensors, P1 and P2, and the lateral cross-section of the steel-lined shaft, are also shown.

3.2 In-situ measurements

The two data acquisition systems at P1 and P2 are actually in the test phase. Each system contains one high resolution pressure sensor, an acquisition card and a PC. They are synchronized through a fibreoptic connection, and they can be accessed on-line from the Laboratoire de Constructions Hydrauliques (LCH) in Lausanne.

The first preliminary data are very promising, and the ongoing work will consolidate the stability of the two acquisition systems. The wave speed estimation procedure will be validated during start-up and shut-down of the pumps and turbines, with a special focus on wave dissipation and dispersion intensities. The localization procedure of weak reaches will be implemented with the aim of detecting the location of some potential geological and geotechnical weak zones of the rock mass surrounding the steel liner. The estimated locations will be compared with the real ones, which can be obtained from the existing as-built drawings of the shaft.

4. Conclusion

The method described here has so far been validated by a series of experimental tests carried out on a physical scale facility. The assessment of in-situ pressure data measured at the shaft of a pumped-storage plant are now in progress to test and extend the monitoring method to real scale structures. ◊

Acknowledgment

The study described here is part of the research project HydroNet (modern methodologies for the design, manufacturing and operation of pumped-storage plants) funded by the Swiss Competence Center Energy and Mobility, CCEM-CH (www.ccem.ch), Swisselectric research (www.swisselectric-research.ch) and the Swiss Office for Energy. Kraftwerke Oberhasli AG (KWO) supported the installation and the operation of prototype measurements (see: www.grimselstrom.ch).

References

1. **Schleiss, A.J.**, "The importance of hydraulic schemes for sustainable development in the 21st Century", *Hydropower & Dams*; Vol. 7, Issue 3, 2000.
2. **Hachem, F.E. and Schleiss, A.J.**, "The design of steel-lined pressure tunnels and shafts", *Hydropower & Dams*; Vol. 16, Issue 3, 2009.
3. **Hachem, F.E. and Schleiss, A.J.**, "A review of wave celerity in frictionless and axisymmetrical steel-lined pressure tunnels", *Journal of Fluids and Structures*, Vol. 27, 2011.
4. **Misiunas, D., Vitkovsky, J., Olsson, G., Simpson, A., and Lambert, M.**, "Pipeline break detection using pressure transient monitoring", *Journal of Water Resources Planning and Management*, Vol. 131, No. 4, 2005.
5. **Stephens, M.L., Simpson, A.R., and Lambert, M.F.**, "Internal wall condition assessment for water pipelines using inverse transient analysis", *Proceedings*, 10th Annual Symposium on Water Distribution Systems Analysis, ASCE, Kruger National Park, South Africa; 2008.
6. **Taghvaei, M., Beck, S.B.M., and Boxall, J.B.**, "Leak detection in pipes using induced water hammer pulses and cepstrum analysis", *International Journal of COMADEM*, Vol. 13, No. 1; 2010.
7. **Hachem, F.E. and Schleiss, A.J.**, "Physical tests for estimating the waterhammer wave speed in pipes and tunnels with local weak wall stiffness", *Proceedings*, 2011 World Environmental & Water Resources Congress (EWRI), Palm Springs, California, USA; May 2011.
8. **Wylie, E.B., Suo, L., and Streeter, V.L.**, "Fluid Transients in Systems", facsimile edition, Prentice Hall, Englewood Cliffs, NJ, USA; 1993
9. **Hachem, F.E. and Schleiss, A.J.**, "Detection of local wall stiffness drop in steel-lined pressure tunnels and shafts of hydroelectric power plants using steep pressure wave excitation and wavelet decomposition", *Journal of Hydraulic Engineering*, under review (second round); 2011.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Prof Dr Anton J. Schleiss graduated in Civil Engineering from the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland, in 1978. After joining the Laboratory of Hydraulic, Hydrology and Glaciology at ETH as a Research Associate and Senior Assistant, in 1986 he obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design. After that he worked for 11 years for Electrowatt Engineering Ltd in Zurich, and was involved in the design of many hydro projects around the world as an expert on hydraulic engineering and underground waterways. Until 1996 he was Head of the Hydraulic Structures Section in the Hydropower Department at Electrowatt. In 1997 he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) in the Civil Engineering Department of the Swiss Federal Institute of Technology Lausanne (EPFL). The LCH activities comprise education, research and services in the field of both fundamental and applied hydraulics, and the design of hydraulic structures and schemes. The research studies and expertise involve both numerical and physical modelling, and focus on the interaction between water, sediment-rock, air and hydraulic structures, as well as associated environmental issues. From 1999 to 2009 he was Director of the Master of Advanced Studies (MAS) in Water Resources Management and Hydraulic Engineering held in Lausanne in collaboration with ETH Zurich and the universities of Innsbruck (Austria), Munich (Germany), Grenoble (France) and Liège (Belgium). Prof Schleiss is also involved as an international expert on several dam and hydropower plant projects in various parts of the world as well as flood protection projects mainly in Switzerland. From 1998 to 2009 he was Chairman of the Swiss Committee on Flood Protection (KOHS). Since April 2006 he has been Director of the Civil Engineering Programme of EPFL and Chairman of the Swiss Committee on Dams (SwissCOLD). In 2006 he obtained the ASCE Karl Emil Hilgard Hydraulic Prize and the J. C. Stevens Award.

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