Risk analysis of the transient phenomena in a hydropower plant installation

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Abstract

The present work deals with risks analysis and numerical simulation of the transient phenomena in the hydraulic circuit of the SALANFE hydropower installation[1] equipped with 2 Pelton Units of 35Mw each. The main objective of this study is the scope of damage prediction originated from a water hammer or depression in a penstock using numerical investigations. In addition, the management of its impact is studied. The numerical simulations are performed with SIMSEN software developed by EPFL for a computing domain which is extended to the entire hydropower plant installation. The pressure fluctuations analyses are performed to study three emergency shutdown scenarii: (i) the new full load operating point P=2x35 MW, (ii) the partial load operating point corresponding to the injector closure in the wave reflection time (Tf=2L/a [s]), (iii) the loading of the units followed by an emergency shutdown after Tf=2L/a [s]. Based on these analyses, the appropriate solution is determined to maintain safety and optimal production. The comparison between the numerical and experimental results shows a good agreement allowing the validation of the model. The main results of this study highlight the issue that after rehabilitation of the production units and power increase from 2x30 MW to 2x35 MW, the operation mode should be modified in order to respect the security criteria. The implemented actions to reduce the risk levels are increasing the needle closure time of the turbines as well as the minimum water level of the upper reservoir in operation. This study is performed by the cooperation between Power Vision Engineering Sàrl, consulting engineers, HYDRO Exploitation SA, the service provider, and ALPIQ Suisse SA the asset manager of the SALANFE power plant installation.

Introduction

Security of hydropower plants is the most important issue determining the limits of electricity production programs. In order to guarantee the security of a hydropower plant, on behalf of ALPIQ Suisse SA, HYDRO Exploitation SA defined a proactive and systematic method to identify, evaluate and manage the operational risks.

Risk identification is the first step in risk analysis. It is critical to thoroughly list the accidental scenarii that have an impact on security. The second step is risk calculation. This step helps to estimate the occurrence probability and thus determine the risk level for each scenario. In the present work, the risk calculation is based on the numerical simulation of the identified scenario. Finally, the most appropriate solution will be proposed.

Risks are reduced if one decreases the probability of risk occurrence or severity of its effect. Four categories are used to rank the relative seriousness of a risk impact. These categories are: **I**: minor injury or a day installation unavailability, **II**: minor injury or 1 to 7 days unavailability, **III**: Injury or 1 to 4 weeks unavailability, **IV**: serious injury permanent or 1 to 3 months unavailability, **V**: serious injury permanent or 3 to 6 months unavailability, **VI**: loss of life of more than 6 months installation unavailability, see Figure 1.

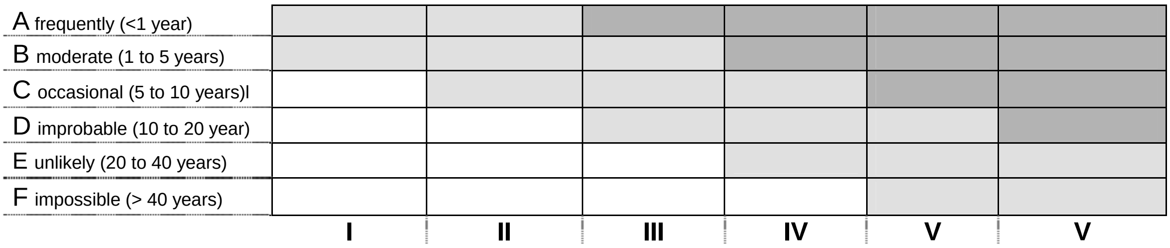


Figure 1: Risk profile table

[1] Salanfe SA : owner 100% Alpiq Suisse SA, operated by HYDRO Exploitation SA

0.1 Case Study

Risk analysis of the transient phenomena is investigated in the SALANFE hydropower plant installation, featuring:

- Salanfe dam: maximum water level Zmax=1925 masl, minimum water level Zmin=1888.5 masl;
- the intake valve "V1": butterfly valve DN 2000;
- the gallery: 643 m long with diameter between 2m and 2.92 m;
- the security valve "V2": butterfly valve DN 1400;
- the penstock: 4672 m long, diameter between 1.1 m and 1.65 m;
- Miéville powerplant: 2 Pelton units with total power of P=70 MW and flow rate of Q=5.6 m^3/s for a head between Hmax=1473.6 m and Hmin=1434.1 m.

The longitudinal profile of the SALANFE hydropower plant installation is shown in Figure 2.

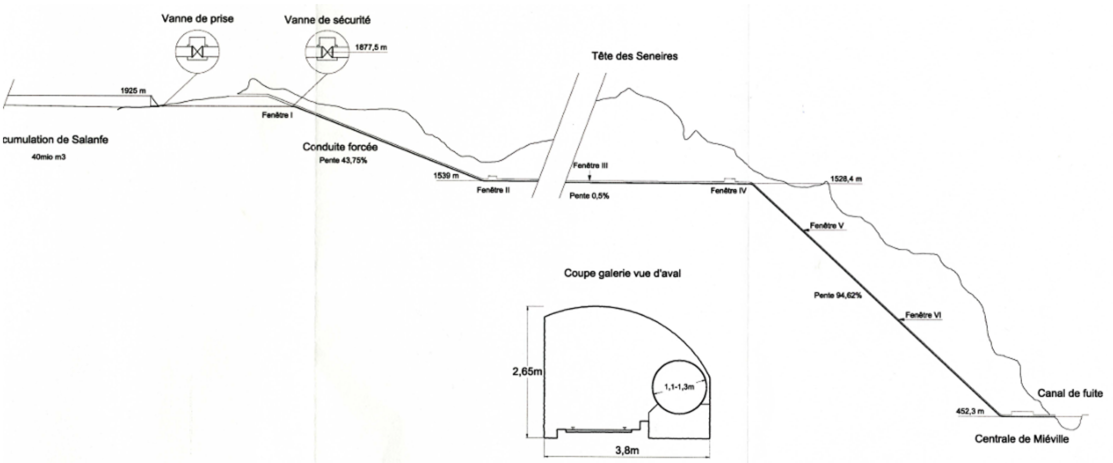


Figure 2 : Longitudinal profile of the SALANFE hydropower plant installation

0.2 Maximum and minimum pressure limits

The maximum admissible pressure along the hydraulic circuit of the SALANFE power plant installation is defined by the constructor of the penstock. The minimum pressure values are determined by considering 8 m over atmospheric pressure, Figure 3.

According to the main concept of the SALANFE power plant installation, the power units could run for a SALANFE dam water level range between Zmax=1925 masl and Zmin=1888.5 masl.

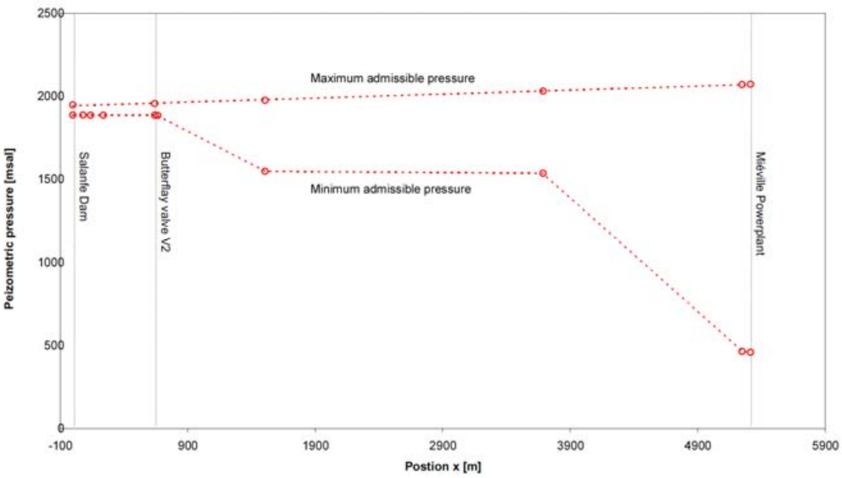


Figure 3: Maximum and minimum pressure limits along the hydraulic circuit of the SALANFE power plant installation

1. Numerical simulation

1.1 Modelling of the Hydraulic Machinery and Systems

By assuming uniform pressure and velocity distributions in the cross section and neglecting the convective terms, the one-dimensional momentum and continuity balances for an elementary pipe filled with water of length dx, cross section A and wave speed a, see Figure 4, yields to the following set of hyperbolic partial differential equations:

$$\begin{cases} \frac{\partial h}{\partial t} + \frac{a^2}{gA} \cdot \frac{\partial Q}{\partial x} = 0 \\ \frac{\partial h}{\partial x} + \frac{1}{gA} \cdot \frac{\partial Q}{\partial t} + \frac{\lambda |Q|}{2gDA^2} \cdot Q = 0 \end{cases} \tag{1}$$

The system (1) is solved using the Finite Difference Method with a 1st order center scheme discretization in space and a scheme of Lax for the discharge variable. This approach leads to a system of ordinary differential equations that can be represented as a T-shaped equivalent scheme **Error! Reference source not found.**], **Error! Reference source not found.**], **Error! Reference source not found.**] as presented in Figure 5. The RLC parameters of this equivalent scheme are given by:

$$R = \frac{\lambda \cdot |\overline{Q}| \cdot dx}{2 \cdot g \cdot D \cdot A^2} \qquad L = \frac{dx}{g \cdot A} \qquad C = \frac{g \cdot A \cdot dx}{a^2} \tag{2}$$

Where λ is the local loss coefficient. The hydraulic resistance R, the hydraulic inductance L, and the hydraulic capacitance C correspond respectively to energy losses, inertia and storage effects.

The model of a pipe of length L is made of a series of nb elements based on the equivalent scheme of Figure 4. The system of equations relative to this model is set-up using Kirchoff laws, see Figure 5. The models of the pipe, as well as the models of valve, surge tank, hydraulic turbines, etc, are implemented in the EPFL software SIMSEN developed for the simulation of the dynamic behavior of hydroelectric power plants, **Error! Reference source not found.**], **Error! Reference source not found.**]. The time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4th order procedure.

The modelling approach based on equivalent schemes of hydraulic components is extended to all the standard hydraulic components such as valve, surge tanks, air vessels, cavitation development, Francis pump-turbines, Pelton turbines, Kaplan turbines, pump, **Error! Reference source not found.**].

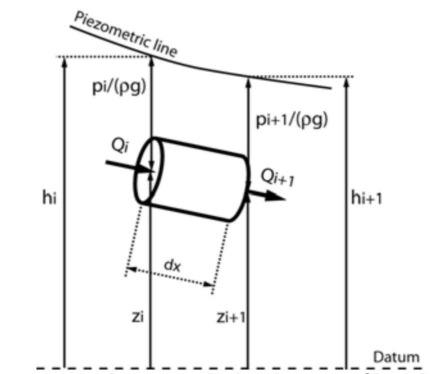


Figure 4 Elementary hydraulic pipe of length dx

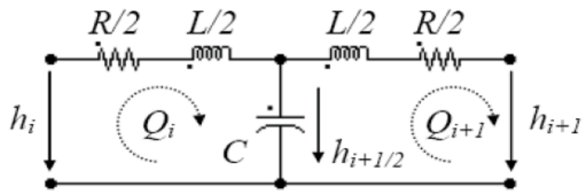


Figure 5 Equivalent circuit of an elementary pipe of length dx

Modelling of SALANFE hydropower installation

The case study is realised by SIMSEN software for a computing domain which is extended to the entire hydropower plant installation, from the dam to the tailrace. The dimensions of the pipes are based on the drawings. The head loss coefficients are adjusted in order to reproduce the measured head losses. The pressure wave speed in pipes is estimated and verified by the period of water hammer in the pipe after the butterfly valve and in the turbine penstock. For the modelling purpose, a valve has been used for the Pelton turbine injector with the corresponding characteristics, see Figure 6.

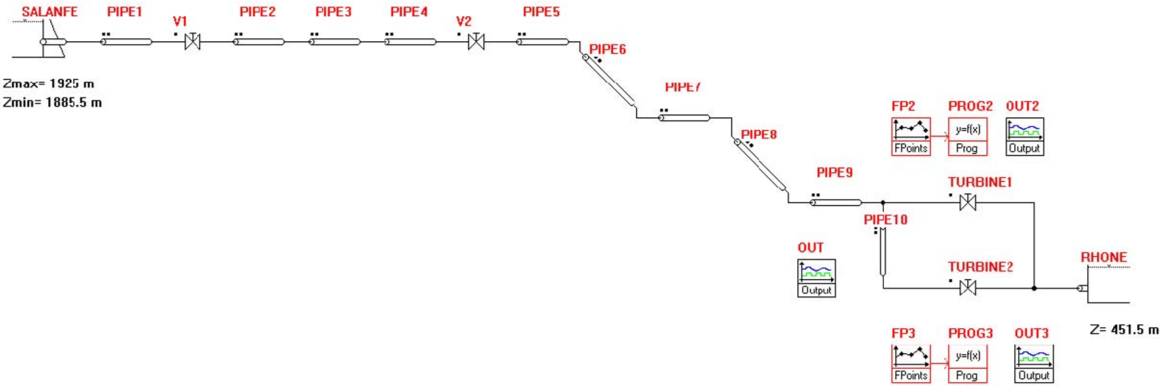


Figure 6 : Model of the SALANFE installation provided by SIMSEN software

Model validation

The pressure fluctuations resulting from the measurement and the numerical simulation during an emergency shutdown on 17th April 2004 is used for the model validation. The test condition is: power production P=2x20MW, flowrate Q= 3.2 m^3/s, injector closure time Tf=14.5 s for a needle course from 36.4% to 0%. Figure 7 illustrates the compared pressure fluctuations. It shows the consistency between the measured and the computed values for maximum amplitude, flowrate and period of water hammer. The results of the above simulation are judged good enough to predict the dynamic behavior of SALANFE hydropower installation.

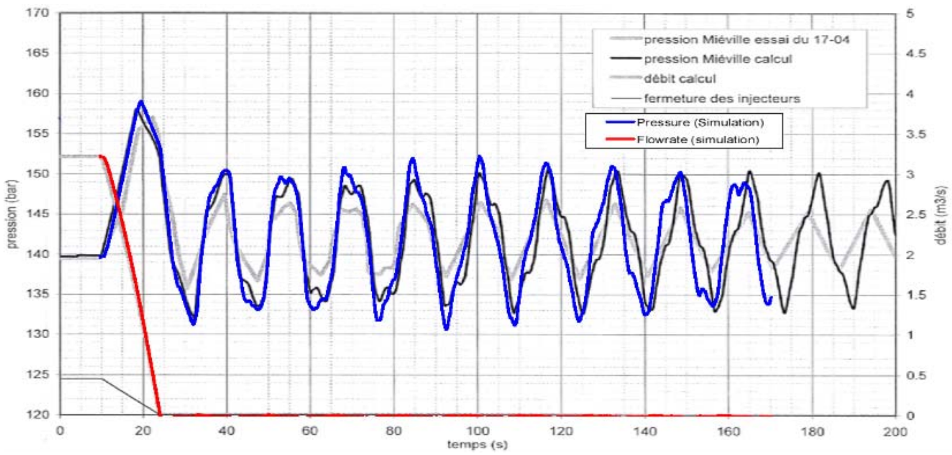


Figure 7: The comparison between the numerical results and the measurements in the penstock

2. Risk identification

2.1 Critical scenarii

In order to verify the security of the hydropower installation three critical scenarii have been studied according to the following situations.

- **Scenario 1:** emergency shutdown at full load operating point P=2x35 MW at the maximum and the minimum dam water level;
- **Scenario 2:** emergency shutdown at partial load corresponding to the injector closure in the penstock reflection time ($T_f = 2L/a$) at the maximum and the minimum dam water level;
- **Scenario 3:** loading of the units followed by an emergency shutdown after, Tf=2L/a=7.8 s, at the maximum and the minimum dam water level.

3. Risk evaluation

3.1 Scenario 1: emergency shutdown at full load operating point P=2x35 MW

The pressure amplitude caused by water hammer is a function of flow rate and at the full load operating point the flow rate is maximal. That is why scenario 1 is considered as a critical case.

In the case of emergency shutdown at full load operating points, P=2x35 MW, the pressure fluctuations resulting from the numerical simulations is presented in Figure 8-i. These values are taken at the upstream of the Pelton turbines. In the initial configuration, the injector closure time of the Pelton turbines is 73 s for 100% of the needle courses.

The maximum and the minimum pressure values along the hydraulic circuit are presented in Figure 8-ii. The blue and the black curves show the piezometric lines respectively at the water levels Z=1925 masl and Z=1888.5 masl in the SALANFE dam. Regarding the last results, the minimum pressure in the security valve "V2" is about -2 m below that the atmospheric pressure, see Figure 8-iii. However, the maximum pressure does not exceeds the admissible pressure limits.

The occurrence probability of the emergency shutdown at full load operating point could be high, because most of the time the units could be run at the best efficiency point or full load operating point where the power production is gainful.

3.2 Scenario 2: emergency shutdown at partial load (injector closure in the wave reflection time)

The closure of an injector, in the wave reflection time ($T_f = 2L/a$) create a direct water hammer in the hydraulic circuit. The amplitude of the pressure fluctuation is determined by the wave speed and flow velocity ($\Delta H = aC/g$).

The second accidental scenario is the emergency shutdown at part load operating point corresponds to the injector closure in the wave reflection time, Tf=2L/a=7.8 s. This situation is studied for the dam water levels of Z=1925 masl and Z=1888.5masl. The numerical simulation results are presented in Figure 9. Figure 9-i illustrates the pressure fluctuation during the first 100 seconds after the emergency shutdown where flow rate decreases to zero after 7.8 s.

The maximum pressure caused by the second scenario at the end of the penstock is 60 m over than the case of emergency shut down at full operating point. Figure 9-ii shows that the maximum pressure along the hydraulic circuit does not exceed the maximum pressure limits for all SALANFE dam water level. However, at the low water level, Z=1888.5 m, scenario 2 leads to a minimum pressure at which the security valve "V2" experiences -7.8 m below the atmospheric pressure.

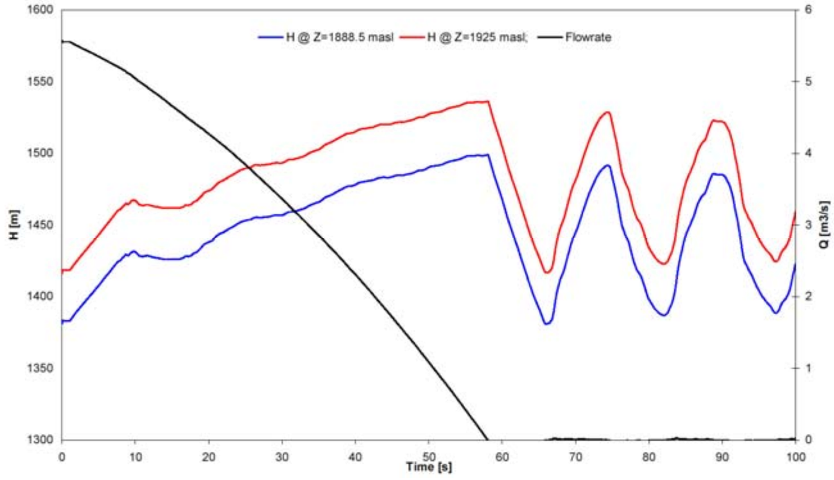
The occurrence probability of the emergency shutdown in the wave reflection period is medium because turbine experiences this condition at each loading.

3.3 Scenario 3: loading of the units followed by an emergency shutdown after Tf=2L/a=7.8 seconds.

The case of the loading followed by an emergency shutdown after Tf=2L/a is another critical case. The loading from zero needle opening creates a pressure fall, which is followed by a pressure rise after an half of water hammer period. Suddenly, if an emergency shutdown occurs, the superposition of the pressure waves created by the loading and the emergency shutdown generates the substantial pressure amplitude.

Figure 10-i indicates the maximum pressure after two periods of the pressure fluctuations after emergency shutdown. Comparing the maximum pressure in the penstock obtained in scenario 3, H_{max}=1610.2mWC with the case1, H_{max}=1534.4 mWC or case 2, H_{max}=1581.1 mWC, highlights this issue that scenario 3 is the worst case. It is the same issue in section valve V2. At the minimum water level, the minimum pressure falls to -9.2 m of the atmospheric pressure see Figure 10-iii.

The occurrence probability of scenario 3 is low. For this case, three conditions are necessary. Firstly, the SALANFE dam should be at minimum water level, secondly, both production units should start loading simultaneously from zero opening and finally an emergency shutdown should occur exactly after two periods of pressure wave reflection time. However, the risk level is very high, and thus the last mentioned risk should be addressed with appropriate caution.



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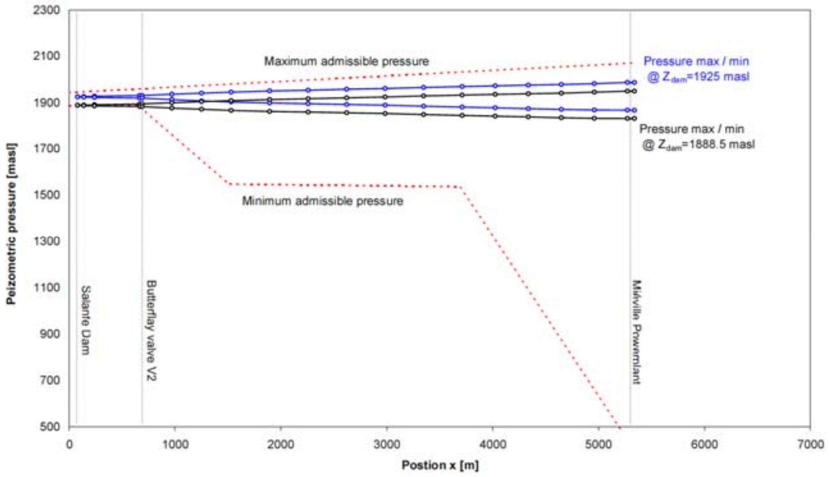

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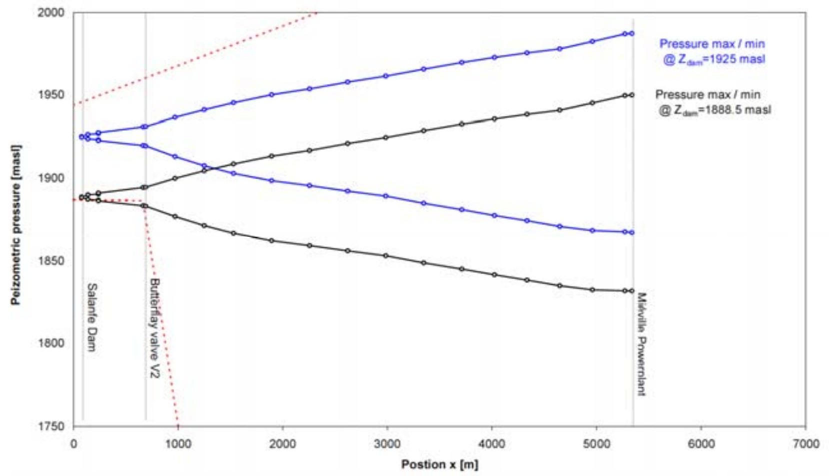
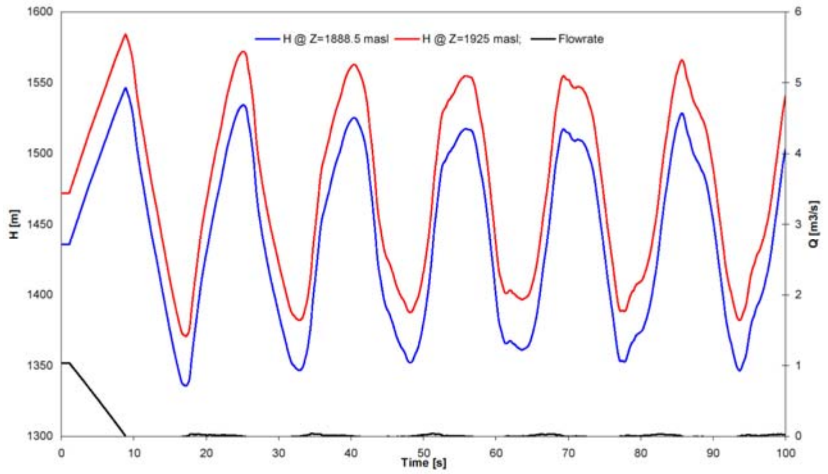


iii)

Figure 8 : Scenario1- Results of the numerical simulations for the of emergency shutdown at full load operating point, P=2x35 MW: i) Pressure fluctuations in the penstock upstream of the turbines, ii) Piezometric lines for the minimum and the maximum values for the longitudinal hydraulic profile, iii) highlighted piezometric lines for the minimum and the maximum values for the longitudinal hydraulic profile.



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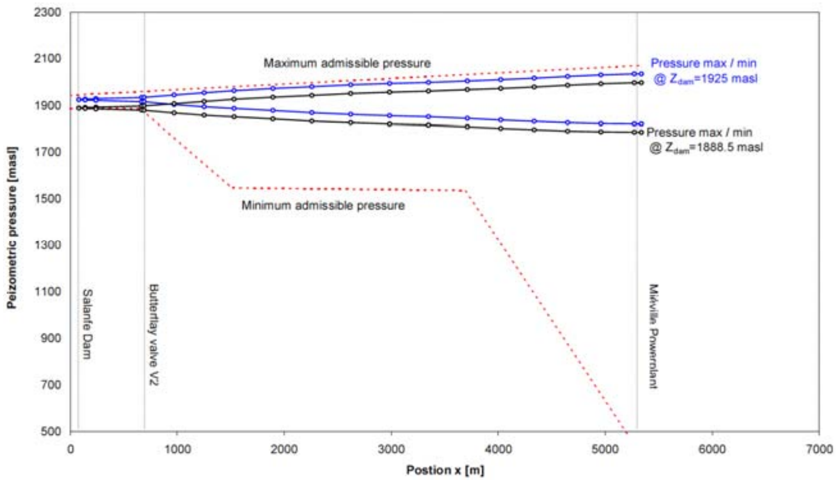

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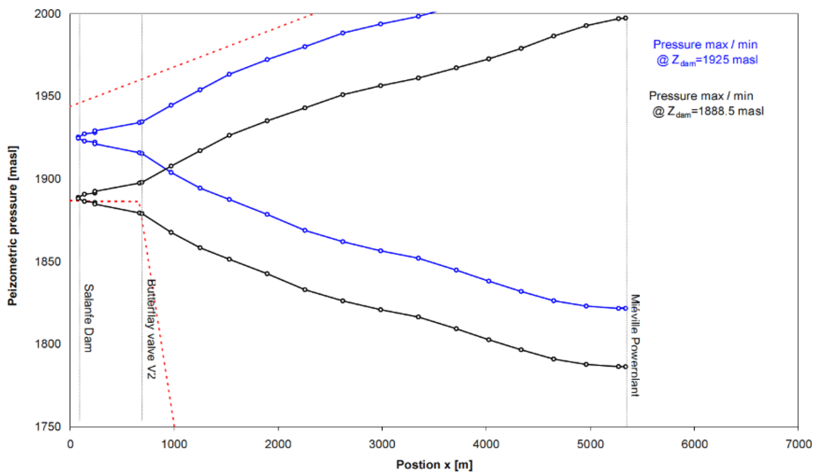
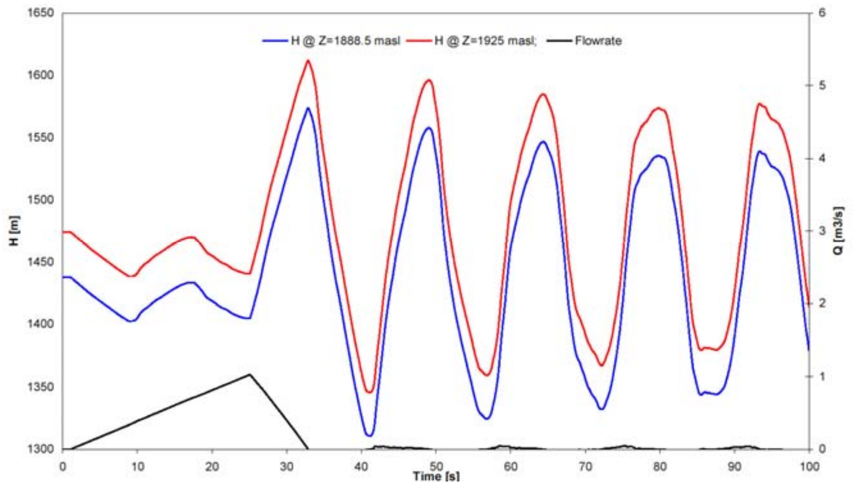


iii)

Figure 9 : Scenario2- Results of the numerical simulations for emergency shutdown in the period of wave reflection Tf=2L/a=7.8 s : i) Pressure fluctuations in the penstock upstream of the turbines, ii) Piezometric lines for the minimum and the maximum values for the longitudinal hydraulic profile, iii) highlighted piezometric lines for the minimum and the maximum values for the longitudinal hydraulic profile.



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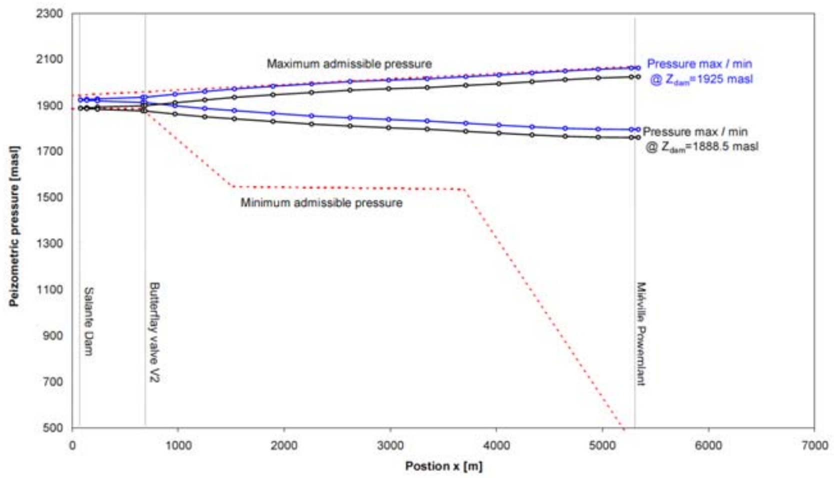

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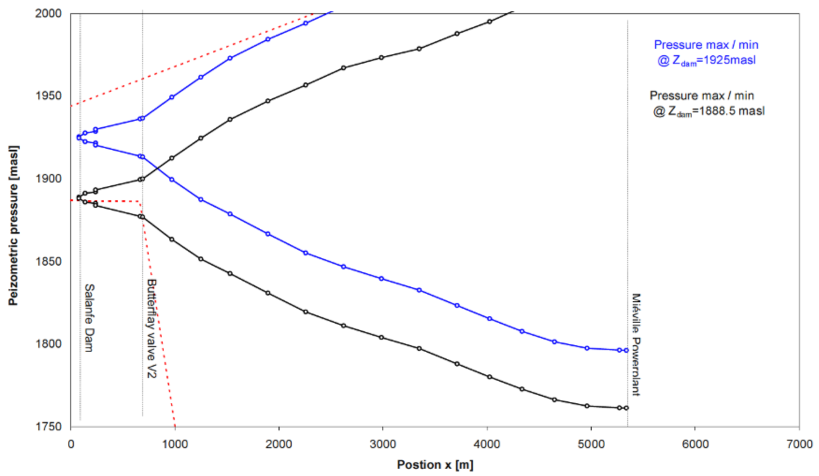

iii)

Figure 10 : Scenario3- Results of the numerical simulations for loading of the units followed by emergency shutdown in the wave reflection period: i) Pressure fluctuations in the penstock upstream of the turbines, ii) Piezometric lines for the minimum and the maximum values for the longitudinal hydraulic profile, iii) highlighted piezometric lines for the minimum and the maximum values for the longitudinal hydraulic profile.

4. Risk management

Risk management consists of the definition of cost, planning and implementation of actions to reduce risk level. The results of the studied critical scenarii are presented in a risk estimation table, see Figure 11. Accordingly, the three scenarii are located in the level zone risks (grey zone). Thereby, risk reduction actions should primarily be proposed and implemented to reduce the high level risks.

The actions for risk reduction might be:

- optimization of the needle closure time (decrease the impact level);
- modification of the minimum water level in the SALANFE dam (decrease the impact level);
- modification of the turbine start up configuration (decrease the risk probability).

To reduce the probability of the risk occurrence in scenario 3, a situational start up of the turbines should be avoided. In this case, firstly, one of the units starts-up and takes the load at minimum power set point. After 2 minutes the second unit starts-up. This delay is defined in order to damp on the pressure fluctuations in the penstock induced by the loading of the first unit. Thus, scenario 3 is transformed into scenario 2, where the emergency shutdown occurs from the quasi stable conditions. Thus the second scenario could become the worst case.

In order to manage the risk of direct water hammer, scenario 2, we have the possibility to increase the needle closure time as well as the minimum water level in the SALANFE dam. Increasing the needle closure time leads us to decrease the pressure amplitude of a water hammer. The results of the numerical simulation at the partial operating load, for a needle closure time equal to TF=105 s for the total needle course are presented in Figure 12 and Figure 13. Accordingly, the minimum pressure in the section of the security valve increases of 8 mWC from Z=1879 masl to Z=1883 masl at the section of security valve "V2". However, it is not enough to respect the security factor, Z_{min}=1887 masl.

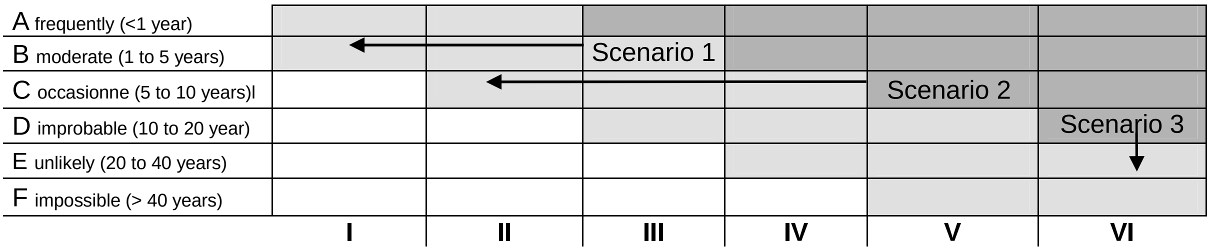

Figure 11: Risk profile table for the three scenarii before and after the risk manageemnt

Thereby, it is necessary to increase the closing time of the injectors or to modify the minimum water level in the SALANFE dam, see Figure 14 . The risks of the all three scenarii could be managed by:

- avoiding the simultaneous start-up and loading of the turbine;:
- avoiding the unit operations at the water level in the SALANFE dam below1892 masl;
- increasing the injector closure time to 105 seconds from 100% to 0% of the needle course.

5. Conclusion

This paper presents the risk analysis related to the transient phenomena in the SALANFE power plant installation. Firstly, the three critical emergency shutdown scenarii are identified. In the next step the case study is modelled by SIMSEN software. The model is compared and validated by the measurement results. The results of the numerical simulation highlights this issue that after rehabilitation of the production units the operation mode should be modified in order to respect the security criteria. These modifications might be the following points:

- it is necessary to avoid any simultaneous loading of the turbines;
- the injector closure time should be increased to 105 seconds for the total course of needles;
- the power production with 2 units should be limited to a minimum water level in the SALANFE dam equal to 1892 masl.

The risk reduction actions have been already considered in the operating modes of the SALANFE installation.

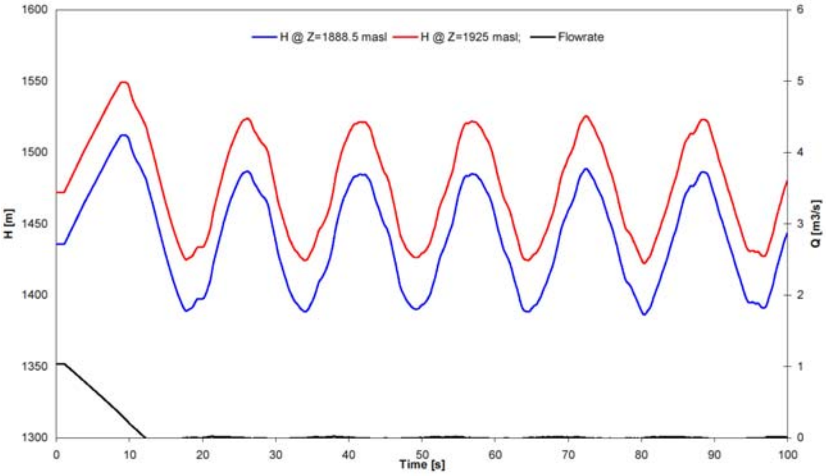

Figure 12: Scenario2- emergency shutdown in the period of the wave reflection Tf=7.8 s- pressure fluctuations in the penstock at upstream of the turbines at water levels Z=1925 masl and Z=1888.5 masl.

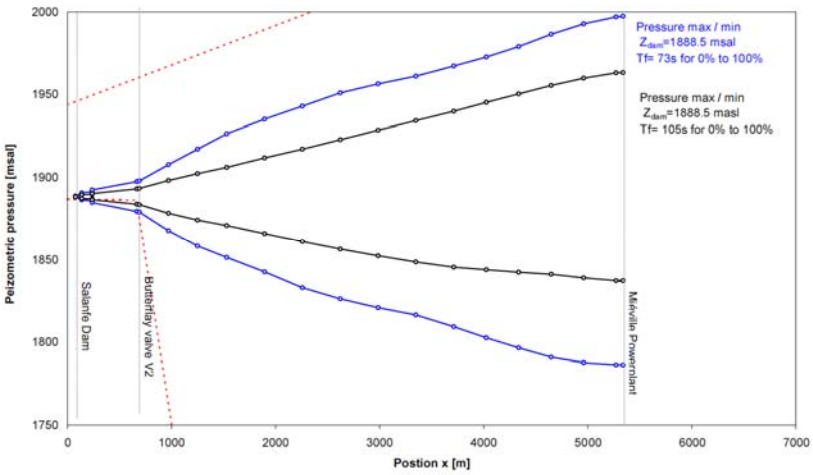

Figure 13: Scenario2- emergency shutdown in the period of the wave reflection tf=7.8 s- the comparison between the Piezometric lines for two injector closure times before rehabilitation,, Tf=73 s (blue curve), and after rehabilitation, Tf=105 s (black curve) at the water level Z=1888.5 masl.

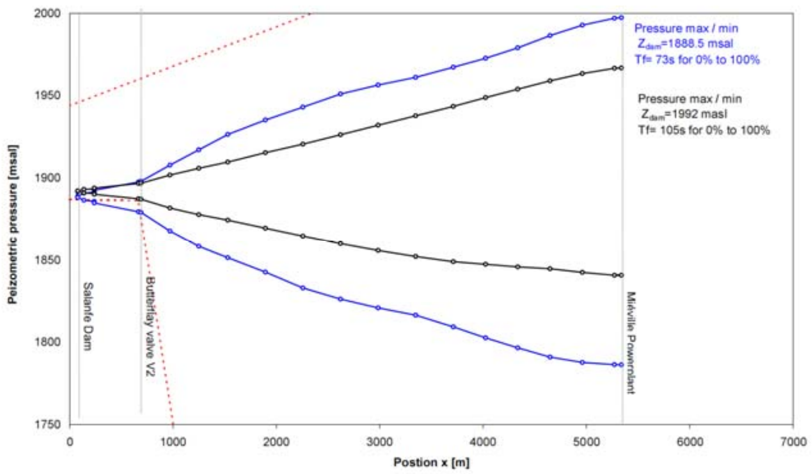

Figure 14: Scenario2- emergency shutdown in the period of the wave reflection tf=7.8 s- the comparison between the Piezometric lines for two injector closure times before rehabilitation, Tf=73 s (blue curve)at the water level Z=1888.5 masl and after rehabilitation, Tf=105 s (black curve) at the water level Z=1892 masl

Nomenclature

H	piezometric head	[mWC]
Z	Water level	[masl]
C	flow velocity	[m/s]
Q	flowrate	[m^3/s]
a	wave speed	[m/s]
L	hydraulic circuit length	[m]
Tf	injector closure time	[s]

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