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Protective Measures against Waterhammer in Run-of-River Hydropower Plants†

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ABSTRACT

Waterhammer is an unsteady hydraulic problem which is commonly found in the penstocks of hydropower plants, water distribution networks and pipeline systems. Due to either a malfunction of the system or inadequate operation conditions, pipeline may collapse or burst. In this paper protective measures against waterhammer problems in the penstocks of small hydropower plants are investigated. In the study, a computer program employing method of characteristics is used to solve nonlinear partial differential equations of transient flow. In a case study, waterhammer response of a run-of-river hydropower plant under instant load rejection without a protective measure and with three different protective measures are analyzed. It is observed that, by means of protective measures waterhammer pressures in the penstock are substantially diminished, and it is shown that these measures are effective and practicable.

Keywords: *Waterhammer, transient flow, run-of-river plants, penstocks, protective measures.*

1. INTRODUCTION

Energy production without problems and interruptions is crucial in small hydropower plants (SHP) in operation. Therefore, design studies of SHPs especially focus on safe and reliable operation. Steady operation of a SHP is the safest state for it as there is no change in its hydraulic variables like discharge and pressure head in the system. However, if the turbined flow changes during the hydropower generation, a disturbance will occur and cause a sudden change in the state of the system. Along the hydraulic conveyance system, namely the penstock, flow parameters start to change with time. This may cause extremely high or low pressures in the penstock and excessively high pressures may lead to great damages. Turbines, valve and several appurtenances of the penstock may be damaged. Even the penstock itself may burst or collapse. There are huge hydropower accidents caused by waterhammer that resulted in substantial damages and loss of lives in the history. Due to faulty operations of turbine valves at Bartlett Dam and Oneida Station Hydroelectric Power Plant in the USA, serious failures occurred and resulted in five lives lost [1]. Also in 1997, the penstock of Lapino SHP in Poland ruptured during the acceptance tests of its new

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governor [1]. Finally, as a result of rapid valve closure at Oigawa Hydropower Station in Japan the penstock burst and three workers lost their lives [2].

Load rejection, instant load rejection, and load acceptance cases, mechanical failures of turbine wicket gates or valves and sudden changes in the elevation of forebay may cause waterhammer in small hydropower plants. At normal operating conditions, a hydraulic turbine that is connected to a generator feeding an electricity grid has to be operated at a constant rotational speed to generate electricity at a constant frequency. Any change in frequency will result in a change in generator and turbine rotational speeds. The disturbances that change the turbine speed is monitored by the governor action which tries to keep the turbine at a synchronous speed by adjusting the wicket gates in a Francis type turbines or by a change in the position of jet deflector and closing or opening of needle valves in Pelton turbines. All of these immediate actions cause changes in turbined flow and other flow parameters and result in formation of waterhammer pressures in the penstock.

Small hydropower plants are very vulnerable to effects of waterhammer since they are generally equipped with small inertia turbines and long penstocks. Specific protective measures are generally used for protecting mechanical equipment and the penstock from harmful effects of waterhammer. Contrary to measures applied in large pipelines and hydroelectric power plants, these equipment are small and cheap. Pressure relief valves and safety membranes that are used in small hydropower plants are both safe and economic. Also, it is appropriate to use fly wheels for the safety of mechanical equipment [3].

1.1. Previous Studies

Study of hydraulic transients in closed conduits attracts many researchers because of its complexity and significance in practice. Therefore, the amount of literature on hydraulic transient concept is very impressive. Fundamental advances in hydraulic transients inspired researchers and led them to extend the literature on hydraulic transients in hydropower plants. Hovey is one of the researchers who investigated the stability of hydropower plants. He studied to provide practical information and methods for controlling transients in hydropower plants by investigating the setting of dashpot times of their governors and applied the method to Manitoba Hydropower Station. The main criterion of the method was the damping of the turbine speed critically during load changes [4]. Hagihara et al. also studied the stability of hydraulic turbine units. They adopted rigid column theory in their analytical works to calculate waterhammer effects [5].

Jimenez and Chaudhry included the elasticity effects, namely the elasticity of the pipe walls and the compressibility of the water column in waterhammer effects and investigated the stability of a single hydropower station unit and they derived an analytical stability criterion [6]. Peicheng et al., as a result of tests performed on Linzhengqu Hydropower Plant, showed that pressure relief valves and safety membranes could be used in place of a surge tank in a small hydropower plant [7]. Ni et al. developed mathematical models for analyzing hydraulic transients in a hydropower plant protected by safety membranes. They analyzed a SHP with their model and compared the computed results with measured ones and found close agreement between them [8].

Ramos and Almeida presented a novel technique that parameterizes the waterhammer effects in small hydro schemes to better characterize the dynamic behavior of their turbines. Their approach considered the similarity between a turbine and a dynamic orifice. They carried out an analysis and compared laboratory and field tests results. Computer model outputs were proving that the application of the technique appears to be a powerful tool in preliminary design stages [9]. Selek et al. simulated the transient flow conditions occurred during turbine acceptance tests of Çatalan Hydropower Plant in Turkey. They solved the governing equations of unsteady flow in the penstock by the method of characteristics using various computational schemes and compared the computational results with measured ones. It is found that the variable-grid method of characteristics produces the results that agree best with experimental findings [10].

Karadzic et al. developed a novel Pelton turbine model for waterhammer analysis. They defined a boundary condition for Pelton turbine units to be used in method of characteristics. The solution method they developed describes the dynamic behavior of the rotating parts of a Pelton turbine. They proved the validity of their method by conducting experiments on Perucia SHP. They showed that the calculated and measured values of head at turbine inlet and turbine rotational speed are very close to each other [11]. Vakil and Firoozabadi studied the effects of different valve closure laws on waterhammer pressures and turbine speed. They computed the turbine speed rise and pressure increase for different turbine closure curves of a Francis turbine and validated their model by comparing their results with those obtained from a consulting company [12].

2. METHOD OF CHARACTERISTICS AND THE MATHEMATICAL MODEL

The main goal of the waterhammer analyses of a closed conduit is to determine the velocity (V) or discharge (Q) and pressure (P) or head (H) at any point at any time during a transient event. Therefore, two equations describing the transient flow are used. These equations namely, momentum and continuity equations, are generally written in terms of pressure (P) and velocity (V). Momentum and continuity equations are given in Eqs. 1 and 2, respectively.

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial P}{\partial x} + g\sin\theta + \frac{4\tau_w}{\rho D} = 0 \tag{1}$$

$$\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x} + \rho a^2\frac{\partial V}{\partial x} = 0 \tag{2}$$

In the above equations, θ is the angle the conduit makes with the horizontal, τ_w is the shear stress, D is the diameter of the pipe, *a* is the wave propagation velocity, ρ is the density of the fluid and g is the gravitational acceleration. These equations are nonlinear partial differential equations. Method of Characteristics, a worldwide accepted method, is used to solve these types of equations numerically. Above equations are transformed into four ordinary differential equations by this method. Then, these latter equations are integrated to yield finite difference equations which can be conveniently handled numerically. These equations are called characteristic C^+ and C^- equations and they are given below.

$$\frac{1}{\rho}\frac{dP}{dt} + a\frac{dV}{dt} + aF = 0 \qquad \text{if} \qquad \frac{dx}{dt} = +a \tag{3}$$

$$\frac{1}{\rho}\frac{dP}{dt} - a\frac{dV}{dt} - aF = 0 \qquad \text{if} \qquad \frac{dx}{dt} = -a \tag{4}$$

Equations 3 and 4 are only valid along their linear characteristic line. The force term F is used to represent the gravitational acceleration and wall shear stress terms of Eq. 1. Two curves shown in Figure 1 in the x-t domain having the slopes of $+1/a$ and $-1/a$ are the characteristic C^+ and C^- lines, respectively. Physically they represent the followed path of the transient disturbance. Eqs. 3 and 4 are valid on these lines and the integration of them along the C^+ and C^- lines give two compatibility equations which are given in Equations 5 and 6.

$$C^+ : H_{Pi} = C_P - BQ_{Pi} \qquad \text{and} \qquad C_P = H_{i-1} + BQ_{i-1} - RQ_{i-1}\left|Q_{i-1}\right| \tag{5}$$

$$C^- : H_{Pi} = C_M + BQ_{Pi} \qquad \text{and} \qquad C_M = H_{i+1} - BQ_{i+1} + RQ_{i+1}\left|Q_{i+1}\right| \tag{6}$$

in which

$$B = \frac{a}{gA} \quad \text{and} \quad R = \frac{f\Delta x}{2gDA^2} \tag{7}$$

where f is the friction factor in the pipe, Δx is the distance increment and A is the cross sectional area of the pipe.

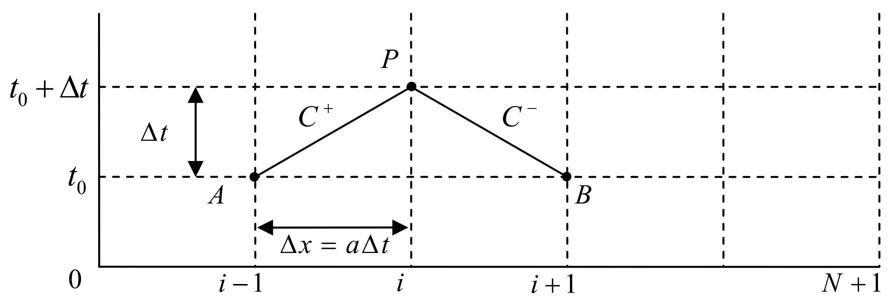

Figure 1. Characteristic lines in time-space domain

A waterhammer analysis model established by using the method of characteristics contains the equations of boundary conditions of system elements. The mathematical waterhammer model of a run-of-river plant is composed of many boundary conditions and characteristic equations. Solution of these equations requires repetitious steps and this process is very appropriate to be programmed by a computer code. To simulate the transient behavior of the SHP that is considered in the case study of the present study, the software developed by Bentley, called HAMMER, which utilizes method of characteristics for solving nonlinear partial differential equations of transient flow, is used. It allows the usage of numerous components of SHPs such as forebay, turbine, surge tank, air chamber, flywheel, pressure relief valve, and safety membranes etc. with their predefined boundary conditions and characteristic equations.

3. CASE STUDY AND ANALYSES

In the case study, waterhammer analyses of Erfelek Hydropower Plant are performed for three different scenarios. The plant is located on the Karapınar River at the Sinop province in the central Black Sea region. It is generating power with two identical Francis turbines having 6.45 MW installed capacity and been in operation since April 2010. The main penstock has a length of 1518.7 m and varying wall thickness from 8 mm to 14 mm. It consists of 19 pipe segments. The diameter of the main penstock is 1300 mm. The main pipe branches just at the upstream of the powerhouse to feed the two turbine units, and the diameter of the branching pipes is 900 mm. As built characteristics of the penstock is given in Table 1. Also, hydraulic and machinery properties of Francis turbine units are given in Table 2. There is no protective measure against waterhammer in the hydropower plant.

In the present study, waterhammer pressures are computed for three different scenarios during instant load rejection. Different protective measures are placed in each scenario and detailed information is given in Table 3 about these scenarios.

Table 1. As built penstock properties of Erfelek run-of-river plant

Segment No.	Length (m)	Wall thickness (mm)	Wave speed (m/s)	Diameter (mm)
1	34.51	8	920.36	1300
2	15.15			
3	152.99			
4	224.19			
5	136.81			
6	79.02			
7	30.13			
8	121.14			
9	57.38	10	982.63	
10	36.28			
11	31.53			
12	30.61			

Table 1. cont'd

Segment No.	Length (m)	Wall thickness (mm)	Wave speed (m/s)	Diameter (mm)
13	61.36			
14	74.05			
15	69.42	12	1031.93	
16	120.10			1300
17	6.83			
18	172.39	14	1072.07	
19	64.80			
Branch x 2	19.78	14	1160.40	900

Table 2. Basic characteristics of Francis turbine units

Type	Horizontal axis Francis
No. of identical turbine units	2
Turbine output (kW)	2 x 3225
Rated speed (rpm)	1000
Rated discharge (m^3/s)	2 x 1.83
Nominal gross head (m)	204.90
Nominal net head (m)	197.90
Moment of inertia ($kg.m^2$)	4800 (turb. + gen.)
Runner diameter (mm)	552

Table 3. Definition of scenarios considered in modeling

	Operating condition	Protective measure
Scenario A	Instant load rejection	Fly wheel
Scenario B	Instant load rejection	Pressure relief valve
Scenario C	Instant load rejection	Safety membrane

During operation of hydropower plants, if an instant load rejection case occurs, turbines have to be stopped in a short time. In such a case, it takes 11 seconds to stop turbines in Erfelek SHP. In the study, only instant load rejection case is taken into consideration since it causes the most critical pressures in the penstock. Firstly, waterhammer analysis is performed by considering the as built (without a protective measure) form of the plant. Then, with the three scenarios, analyses were performed with the protective measures to be taken against waterhammer and the results were compared. For all analyses, hydropower plant is assumed to be working in nominal discharge, head and power conditions.

3.1. Scenario A: Instant Load Rejection Case with the Effect of Flywheel

Flywheel is a mechanical surge protection device that increases the polar moment of inertia of turbine and generator couple. Especially, it helps controlling turbine speed rise during load rejection and instant load rejection cases. Two different analyses were conducted to show the effect of flywheel and its moment of inertia during waterhammer in this scenario. The as built moment of inertia of the rotating parts of the hydropower plant is 4800 kg.m^2. First, a reasonable and applicable flywheel, which increases the total rotating mass of inertia 1200 kg.m^2 is placed. Then, a fictitious, much larger GD^2 value, 7200 kg.m^2 is used for the analysis. Here, G is the weight of rotating parts and D is the radius of gyration of rotating mass. The results of the analyses are given in Figure 2 with the closure law of the turbines. According to the results, when the closure starts, pressure rises sharply at the inlet of the turbines. After reaching its maximum value, it starts to drop severely. This pressure rise is accommodated by the turbine speed rise. As it can be seen from results, thanks to the use of flywheels maximum rotational speed of the turbines reduces significantly during waterhammer. The decrease in turbine speed is 5% for the smaller flywheel and 15% for the bigger one. However, no significant changes were observed in maximum and minimum waterhammer pressures in the system.

3.2. Scenario B: Instant Load Rejection Case with the Effect of Pressure Relief Valve

Pressure (surge) relief valves are valves that are loaded by a spring or weight to open automatically when the pressure inside the penstock exceeds a prescribed pressure limit. When the valve opens, it allows the discharge of pipe flow into the atmosphere and attenuates the maximum surge pressures. In this scenario, a pressure relief valve loaded by a spring is placed 20 m away from the branch junction with a set pressure of 220 m on the main penstock. The schematic layout of the powerhouse and the pressure relief valve is given in Figure 3.

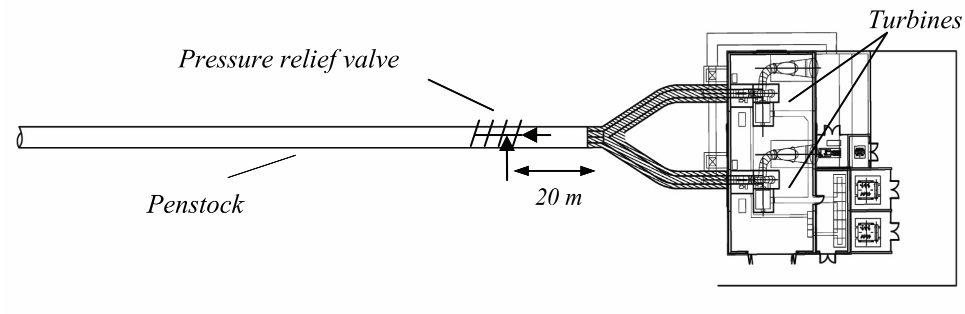

Figure 3. Plan view of the pressure relief valve and powerhouse

Pressure-time response and turbine speed rise with and without pressure relief valve protection is given in Figure 4. Just before closing of turbines, the surge relief valve is closed. When instant load rejection occurs, with the closure of the wicket gates, pressure surge develops in the penstock. Then, this pressure wave reaches the valve and after 3 seconds, the pressure on the valve exceeds 220 m and causes valve to open. The head rise in the penstock is kept at 222 m by releasing some quantity of water during 22 seconds

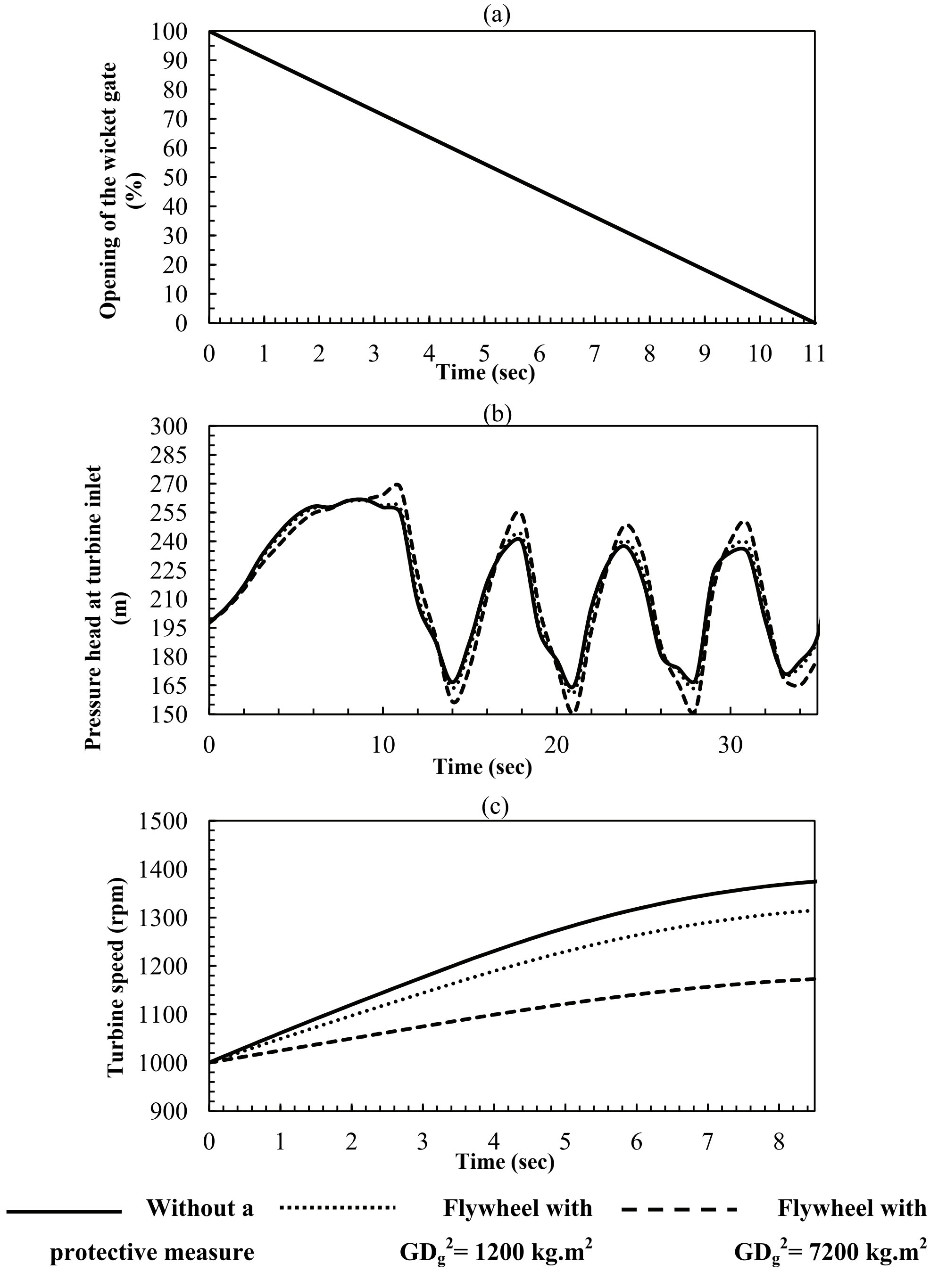

Figure 2. (a) Closure law, (b) Turbines' inlet pressure, (c) Turbines' speed rise for Scenario A

through the valve. When the transient state pressure decreases to the set pressure point, valve is closed at t=24 seconds. Then, the relieved pressure drops mildly and fluctuates until it dampens with the friction. It is clear that, this system will stabilize faster than the unprotected one. Also, besides with the maximum pressure, the minimum pressure in the penstock is kept under control with pressure relief valve. Maximum pressure rise is decreased by 15% by means of this protective measure. Moreover, maximum turbine speed is reduced by approximately 4%.

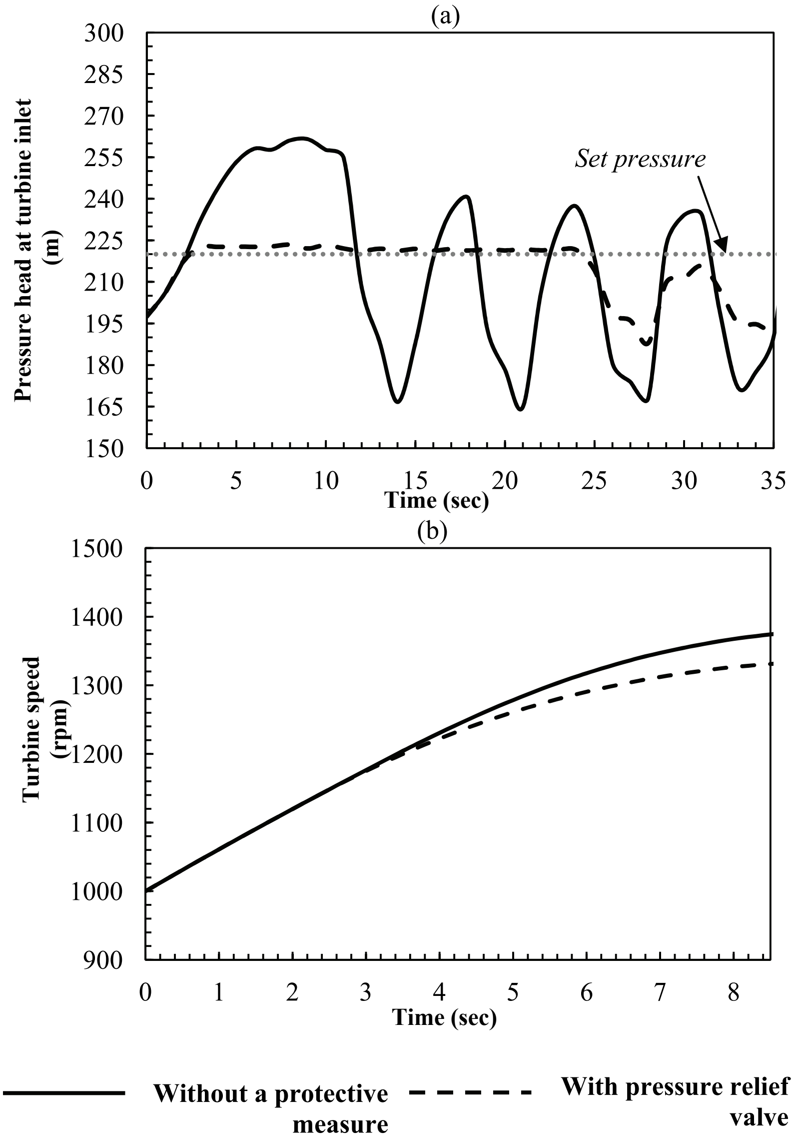

Figure 4. (a) Turbines' inlet pressure; (b) Turbines' speed rise for Scenario B

3.3. Scenario C: Instant Load Rejection Case with the Effect of Safety Membranes

This protective measure, also called rupture disk, is made of a material that is weaker than the penstock's material. Usually aluminum is used for the membrane in steel penstocks. These controlled weak points are designed to rupture in sequence when the pressure on the membranes rises above their set point. If the waterhammer pressure in the penstock rises over the design pressure, the safety membrane bursts and surge pressure is eliminated by discharging some quantity of water through the orifice of the membrane. Safety membranes which can be used as an alternative to the pressure relief valve are placed on the penstock of Erfelek SHP with 10 m of intervals, starting from the branching junction. According to the preliminary studies, it is determined to install three membranes with 300 mm of diameter. To keep the pressure rise under a certain level in the penstock, the first and second membranes rupture pressure is set up to 220 m, and the third one's set pressure is selected as 230 m. Schematic illustration of installed safety membranes are presented in Figure 5. These controlled weak points are designed to rupture in sequence when the pressure on the membranes rises above their set point. First one, nearest to the turbines, is designed to rupture first. When the discharge through it is inadequate to relief the pressure rise, the second one and subsequently the third one will rupture.

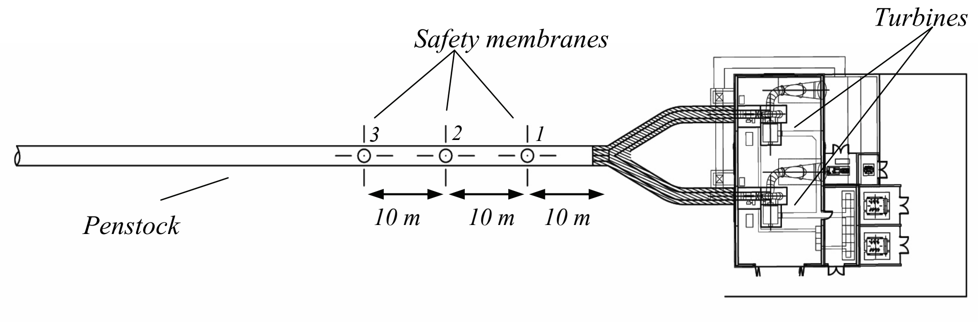

Figure 5. Plan view of the safety membranes and powerhouse

Figure 6 (a) and (b) shows transient pressure heads at turbines' inlets and turbine speed rise, respectively. Determined set pressures (220 m and 230 m) are labeled as "Set pressure 1" and "Set pressure 2" on the figure. By the initiation of the wicket gate closure, waterhammer pressure in the penstock rises to the set pressure of the membranes in 2 seconds and causes the first safety membrane to rupture. After releasing some quantity of water, the pressure drops; however, after the reflection of the pressure wave from upstream and downstream it rises again and causes the second membrane to explode. Similarly, if the released quantity of water from the second membrane is insufficient to suppress the pressure rise, the third membrane ruptures which results in significant decrease in pressure. After every relief of the transient pressure from the membranes, it drops instantaneously since the safety membranes are free and uncontrolled openings. It is possible to conclude that considerable amount of pressure is dampened thanks to the safety membranes. Maximum pressure and maximum turbine speed rises are decreased by 14% and 5%, respectively by means of this protective equipment.

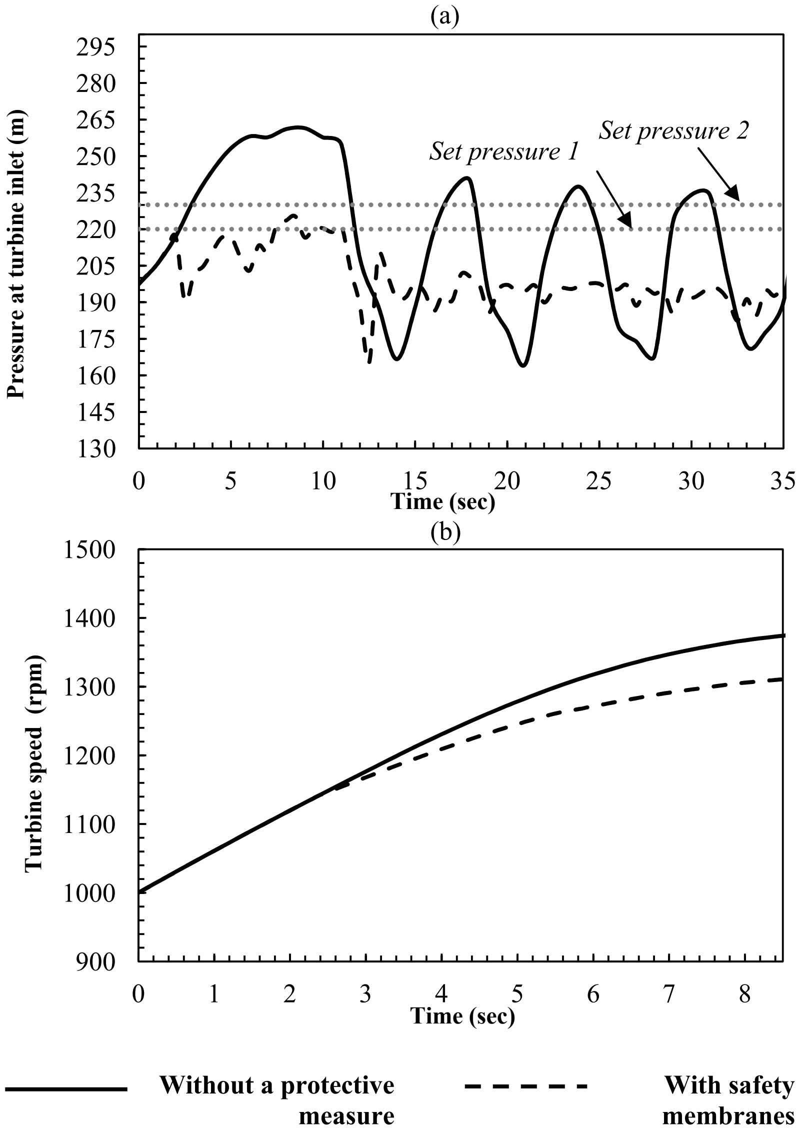

Figure 6. (a) Turbines' inlet pressure; (b) Turbines' speed rise for Scenario C

4. COMPARISON OF ANALYSES RESULTS

Table 4 is introduced to present the effects of three protective measures and the advantages and/or disadvantages of them. In this table, waterhammer analyses results of the as built (without a protective measure) form and the protected forms are compared. The maximum pressure rises at the turbines' inlets during the instant load rejection and their increase ratios over the nominal states are given for envisaged protective measures. Also, the maximum turbine speeds and their increase ratios are provided.

Table 4. Comparison of the effects of protective measures on maximum pressure head and turbine speed

	Maximum pressure head (m)	Increase over nominal pressure head (%)	Maximum turbine speed (rpm)	Increase over nominal turbine speed (%)
Without a protective measure	261.5	32.1	1376.4	37.6
Flywheel with GD_g^2=1200 kg.m^2	261.1	32.0	1316.9	31.7
Flywheel with GD_g^2=7200 kg.m^2	268.1	35.5	1174.3	17.4
Pressure relief valve	223.5	12.9	1332.7	33.3
Safety membranes	225.2	13.8	1312.8	31.3

5. CONCLUSIONS

The number of run-of-river hydropower plants in Turkey is increasing rapidly and waterhammer phenomenon is a major problem that has to be considered in those plants. In the study, analyses of protective measures against waterhammer in run-of-river plants are presented. In determining protective measures, it is seen that they are specific to SHPs, reliable, easy to operate, economic and cheap in maintenance. Waterhammer analyses of a hydropower plant in operation are performed for three different protective measures in three scenarios.

Conclusions obtained from these analyses are given below.

- Flywheels can significantly reduce the speed rise of turbines during transient states in run-of-river hydropower plants. However, this measure does not decrease the waterhammer pressures in the penstock. It helps protecting mechanical equipment in the plant. By means of this tool, as well as ensuring safe operation, maintenance and repair costs can be reduced and even lifetime of the equipment can be extended.
- Pressure relief valves are very effective in reducing waterhammer pressures in the penstock. Results showed that they might be preferred as a standalone protective measure. However, their effect on turbine speed rise is small compared to flywheels.

- Safety membranes also play a major role in reducing the maximum surge pressures occurred during waterhammer. They have little effects on reducing the turbine speed like valves and they can be used as a standalone protective measure in run-of-river hydropower plants.
- The use of surge tank and air chamber in run-of-river hydropower plants might be expensive; therefore, both pressure relief valve and safety membrane can be preferred instead of them.

Symbols

A : Cross-sectional area of the pipe, (m^2)

a : Wave propagation velocity through the fluid, (m/s)

B : Pipeline characteristic impedance

C^+ : Positive characteristics line

C^- : Negative characteristics line

D : Diameter of the pipe, (m)

f : Darcy Weisbah friction factor

F : A force term including gravitational acceleration and wall shear stress

g : Gravitational acceleration, (m/s^2)

H : Piezometric head in the pipe, (m)

P : Pressure, (N/m^2)

Q : Discharge, (m^3/s)

R : Pipeline resistance coefficient

V : Velocity, (m/s)

θ : Angle the conduit makes with the horizontal

ρ : Density of the fluid, (kg/m^3)

τ_w : Wall shear stress, (N/m^2)

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