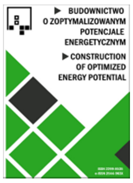
Vol. 9, No 2/2020, 39-52

DOI: 10.17512/bozpe.2020.2.05

Construction of optimized energy potential
Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X



Study into water hammer protection of a water supply duct in Movila Verde, Constanta

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Abstract: Human health and well-being are modern day challenges that are directly related to quality of drinking water supply. The study is focused on a newly conceived independent water supply system in Plopeni, which takes water from a good quality underground source, and supplies seven villages either by a series of pumping installations or by gravity. The assessment of hydraulic parameters, energy saving possibilities and the best means to protect the pipes from water hammering are the main goals of the numerical simulation during either the normal or abnormal operation of the water supply duct that carries water from the Plopeni pumping station to the neighbouring village of Movila Verde. The duct has a specific longitudinal profile that may induce unwanted and dangerous pressure variation during water hammering. The hydraulic parameters and energy consumption indicators were determined by numerical simulation in EPANET. The extreme values of pressure and the most vulnerable cross sections of the pipe during water hammering were identified by numerical simulation with a non-commercial software, named Hammer. The high-pressure values are not dangerous, but cavitation may occur. The hydraulic shock simulation was performed on different methods of protection, provided by closing procedures of the check valve, and considering that the duct is made of steel. The same simulations were considered for a HDPE-made duct of the same inner diameter. The simulation results led to the conclusion that a 60 s two-stages closing procedure proves to be the best solution to protect the steel-made duct from cavitation. In the second simulation, that of a HDPE duct with the same diameter, a 45 s two-stages closing of the check valve provides safe protection from cavitation.

Keywords: hydraulic systems, numerical simulation, fluid flow, pipelines

Please, quote this article as follows:

Constantin A., Nițescu C.Ș., Study into water hammer protection of a water supply duct in Movila Verde, Constanta, BoZPE, Vol. 9, No 2/2020, 39-52, DOI: 10.17512/bozpe.2020.2.05

Introduction

One of the today's challenges is to connect water sciences to decision makers and local communities, and this can happen through water education and research (Nidal et al., 2019). Both education and research rely more and more on numerical simulation, therefore the software industry has developed significantly during the last few decades, covering a wide range of activities. In the water field, numerical simulation allows engineers to technically assess or to foresee the operational possibilities of complex water supply systems and, furthermore, the abnormal phenomena that can occur threaten the installations.

A rich literature has been written with respect to water transients, from (Streeter, 1987) who was among the first scholars to study transients in pipes with linear elastic behaviour of the walls, to more recent researchers (Urbanowicz, 2018) who have investigated transients in viscoelastic pipes.

Regarding hydrology and water resources, numerical simulation is used to assess the state of surface or groundwater, and to identify flood protection solutions (Šoltész, 2018). Included is underwater technology, which allows divers to perform subsea tasks, which owes advances to CFD simulation (Stanciu, 2018).

Water supply is one of the key priorities of the Romanian government in the context of international with efforts aimed a more rational, safe and efficient use of water resources. Improvement of the existing water infrastructure and its development in some rural areas represents the goals of an on-going national programme. The assurance of health and well-being depends on a supply of good quality drinking water. Therefore, the engineering design, construction and exploitation of the water systems have to be at the centre of scientists' attention, as new methods and technologies are required to improve performance in this field.

International water entities consider optimization and efficiency in current practices as the main goals regarding water supply systems, as long as the replacement of all installations is not a realistic possibility (Brisbane Report, 2016).

The water infrastructure is undergoing an ample modernization and extension programme in Constanta County, Romania (RAJAC, 2017). A new configuration of the existing water supply systems must be made according to the quality of underground water sources and the extension of the inhabited area.

The study is focused on a new conceived independent water supply system, namely the Plopeni system, which takes water from an good quality underground source and supplies not only Plopeni village, but also six other villages in the near proximity. The assessment of hydraulic parameters, energy saving possibilities and the best means to protect the pipes from water hammering are the main goals of the numerical simulation during both steady or unsteady operation of the water supply duct that carries water from Plopeni pumping station (PS) to the neighbouring village of Movila Verde.

1. The Plopeni water supply system

The independent water supply system Plopeni is located in the Southern Constanta County, Romania. It takes water from the Plopeni underground source and conveys it to Plopeni village and six other villages in the vicinity: Movila Verde, Independența, Fântâna Mare, Dumbrăveni, Furnica and Tufani as can be seen in Figure 1. The old underground sources, previously used by these settlements, no longer meet the quality requirements for drinkable water. Moreover, some of the old pipelines of the distribution system, made of steel, must be replaced by HDPE pipes.

Fig. 1. Rural region supplied by the water system Plopeni [Google maps]

The most important villages in the system are Independenta, with 1285 inhabitants, and Plopeni, with a population of about 1188, the other villages are inhabited by smaller numbers of people, between 700 and 400 population.

High-quality drinkable water is taken from the Plopeni source and pumped to the Plopeni reservoir. A new proposed well in the source will add a flow rate of 10.83 l/s to the existing 16.67 l/s. The pumping station at Plopeni takes water from the reservoir and supplies it to Plopeni village and to the water mains that supplies Movila Verde reservoirs. A second pumping station, Movila Verde, supplies the Independența reservoir, from which a subsequent pumping station, named Independența, supplies water to the reservoirs of the other four villages. Dumbrăveni, Fântâna Mare, Furnica and Tufani are all supplied by gravitational flow. The pumping stations parameters are given in Table 1.

Table 1. Pumping stations in Plopeni water supply system (*own study*)

No	Pumping station		Head [m]	Discharge [l/s]	Power [kW]
1	Plopeni source	Existing well	82	16.67	19
		New well	130	10.83	22
2	Plopeni		69	14.38	13.89
3	Movila Mare		28	11.6	4.55
4	Independența		63	6.41	5.65

The water system covers a wide area, so the total length of the mains is 33.064 km. The pipelines are steel, or HDPE made, and the diameter varies in the range De 200/125/90 mm, according to the flow rate. Specific for this system is the rapid change of elevation along the mains. Water is conveyed by a series of four pumping stations from the wells to the Independenta reservoir. This reservoir is placed at an elevation of 153 m, but the highest elevation downstream is of 180 m. Nevertheless, it allows gravitation water flow to the downstream villages.

The discharge ducts of these pumping stations are each around 6 km long, and have a longitudinal profile characterized by rapid changes of slope. These changes in elevation lead to variable pressure along the duct, during normal operation. Moreover, the rapid manoeuvring of the valves or accidental power failure may provoke unwanted hydraulic shock and consequently critical damage to the installation.

Therefore, the numerical simulation helps the designers to properly size the system, and to determine the field of pressure, in all the nodes of the hydraulic system, at any moment of each possible operation scenario. By numerical simulation it is possible to identify the most vulnerable cross-sections of the pipes during a potential hydraulic shock and to choose the most efficient protective devices.

A thorough investigation of the water flow through the system was performed during the engineering design phase for the whole system. Focus was on the mains that conveys water from the Plopeni PS to the Movila Verde reservoir. The discharge requested by the downstream villages is 14.38 l/s according to (SR 1343-1/ 2006) and the pumping head is 69 mwc.

The longitudinal profile of this duct, with a diameter of 200 mm, is represented in Figure 2. The length of the duct is 6088 m.

The duct has a specific profile, with rapid changes of slope following the terrain profile, therefore a thorough investigation into peak pressure values during transit should be performed.

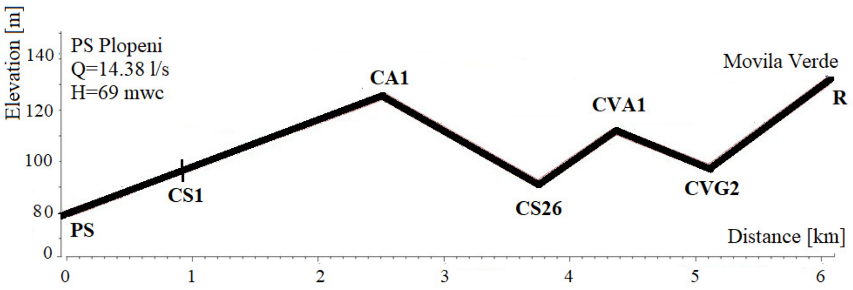


Fig. 2. Longitudinal profile of the water supply duct Plopeni-Movila Verde (*own study*)

2. Numerical simulation

2.1. Steady state operation. EPANET numerical simulation

EPANET is a free software developed by U.S. Environmental Protection Agency (EPA). It is conceived as a hydraulic analysis tool running under Windows, and provides an integrated environment for editing networks, and running hydraulic and water quality simulations (Rossman, 2000).

The hydraulic modelling capabilities of this computer programme enable the researchers to better understand water flow through distribution systems, and therefore improve it from a hydraulic and energetic point of view. It also makes it possible to assess alternative management strategies. Nevertheless, simulation is a rapid and reliable means of analysis, but it has to be performed by specialists with solid knowledge in the field. Otherwise, there is a real risk of misusing the results.

EPANET considers two main concepts for the physical parts of a hydraulic system: junctions and links. The nodes, reservoirs and tanks are considered junctions, while the pipes, pumps and valves are considered links. There is no distributed demand along the pipe, but all the water demand is concentrated in junctions. The steady or quasi-steady (slowly variable according to a demand pattern) operation of a hydraulic system can be investigated, during a chosen period. Apart from hydraulic analysis, the water quality can be investigated in different scenarios (Rossman, 2000).

As the demand flow rate is imposed in the the junctions, EPANET software calculates the required pressure and head values. The results can be gathered as fields of data or as time series regarding pressure, velocity, flow, pollutant concentration etc. The software uses equations that are specific for steady state flow. The water demand variation in time is a slow one, so the use of steady state flow equations is appropriate.

Figure 3 presents the EPANET map of the Plopeni water system. The model has 604 junctions, 604 pipes, and 7 tanks. The reservoir models the Plopeni underground source.

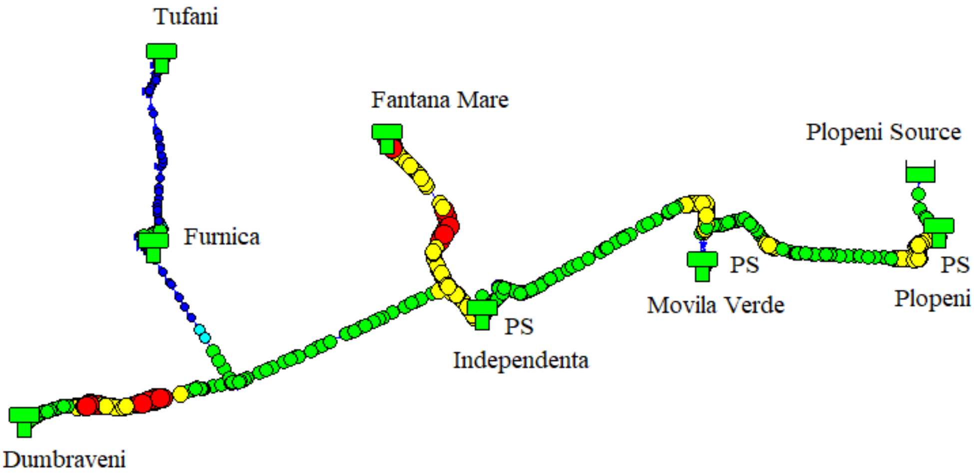
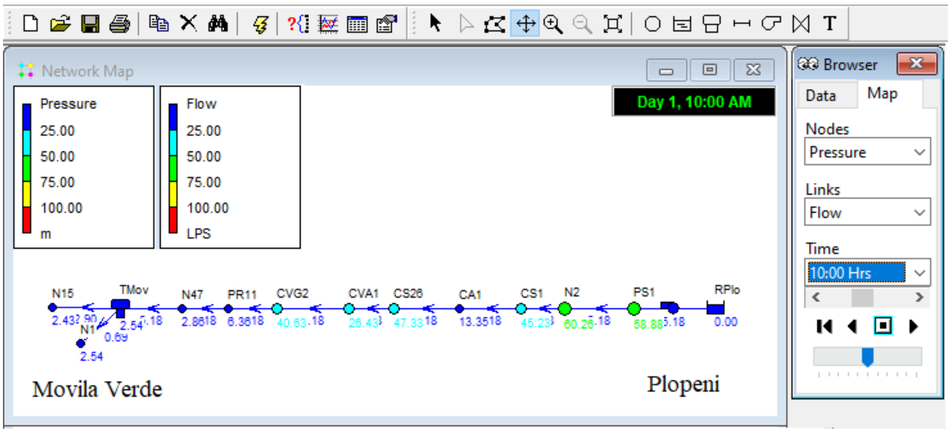


Fig. 3. Plopeni water supply system (EPANET map)

The study only concentrates on part of the system, namely the main Plopeni-Movila Verde, which can be seen modelled in EPANET in Figure 4.

In Figure 4, the pump PS1 stands for the pumping station Plopeni. The reservoir RPlo has a volume of 250 m^3 and it is fed by the source. The reservoir head is 81 m, and it is considered to have a constant water level.


Day 1, 10:00 AM

Nodes: Pressure

Links: Flow

Time: 10:00 Hrs

Fig. 4. Water supply duct Plopeni-Movila Mare (*own study*)

The numeric simulation in EPANET referred to the following scenarios:

a. The pumps PS1 have constant speed;

b. The pumps PS1 have variable speed.

In both cases, the pump operation is controlled by the water level in the tank TMov. The water demand pattern was implemented according to the standard water demand for the rural area (NP 133-2013). This demand pattern was imposed at the end nodes N1 and N15. The demand in node N1 models the water demand in Movila Verde village and the demand in node N15 stands for the flow rate requested by the downstream villages.

In both scenarios, the pumps operate as long as the water level in the tank TMov remains below 2 m. This dependency is modelled by a script written in the *Controls* data input window. In the second scenario, the pumps speed also varies by means of a script in *Controls*. The pumps speed values during 24 hours, in accordance with the water demand variation, were determined with the affinity law, which statues the proportionality between rotational speed and the discharge (Constantin, 2011).

2.2. Unsteady operation. HAMMER numerical simulation

Once the regime operation hydraulic parameters were determined with EPANET, the investigation into hydraulic shock and its extreme pressure values was developed by numerical simulation, using specialized software. The governing equations used in water hammer research and their limitations are important for interpreting the results of the numerical models, and for obtaining reliable data from a simulation (Ghidaoui, 2005). Therefore, a good understanding of the mathematical model and the assumptions the software uses are important. The software used in this study, for the simulation of the system's operation during water hammering, is a non-commercial specialised software, named *Hammer*.

The mathematical model comprises of the equation of mass conservation (1) and the equation of motion (2).

Water is assumed to be a one-phase barotropic and compressible fluid, that flows in one direction (along *x* axis)

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial x} = 0 \tag{1}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial p}{\partial x} + \rho g + \frac{4\tau_o}{D} = 0 \tag{2}$$

where:

x – length [m],

t – time [s],

ρ – water density [Kg/m^3],

v – water velocity [m/s],

D – pipe's diameter [m],

p – pressure [N/m^2],

τ_0 – share stress [N/m^2],

g – gravity [m/s^2].

After successive transformations, the partial differential equations (1) and (2) turn into four total differential equations, (3) and (4), knowing that $v \ll c$:

$$\frac{dx}{dt} = \pm c \tag{3}$$

$$\pm \frac{g}{c}\frac{dH}{dt} + \frac{dv}{dt} + \frac{\lambda}{2D} v|v| = 0 \tag{4}$$

where:

c – celerity [m/s],

H – hydraulic head [m],

λ – Darcy friction coefficient [–].

The equations are linearised and solved by the method of characteristics; detailed mathematical considerations are found in (Popescu, 1987).

The software counts on the same Darcy-Weisbach formula for the head losses as in the steady flow (Popescu, 1987). The celerity in a water pipeline depends both on water compressibility and pipe wall distensibility (Lighthill, 2007; Streeter, 1987). A steel made pipe, as the mains that supplies Movila Verde, has a low distensibility of the wall, therefore celerity in water has high values, around 1000-1200 m/s. The distensibility of the HDPE pipe's wall decreases the celerity in water significantly. The formula proposed by (Carmona-Paredes et al., 2019) for a pipe made of viscoelastic material is:

$$c = 1423.6 \cdot \left(\frac{D_{ext}}{e}\right)^{-0.502} \tag{5}$$

where:

D_{ext} – pipe's external diameter [mm],

e – wall thickness [mm].

For a HDPE pipe with the diameter of 200 mm and the wall thickness of 11.2 mm, the celerity obtained by relationship (5) is 334 m/s. The method of characteristics permits a relatively easy implementation of various boundary conditions.

The pressure and flow changes during the water hammer phenomenon form pressure waves, and respective flow waves along the pipe. These disturbances are associated to each other, as they generate and propagate simultaneously. When such a wave, called the incident wave, meets a point where the geometric characteristics of the pipe change suddenly, a reflection and refraction phenomenon occurs (Fig. 5). When the incident wave encounters a very large tank or reservoir, the wave resistance is equal to 0, and reflection takes place with the change of the wave sign, that leads to an attenuation of the disturbance. When the incident wave encounters a closed end of the pipe, the resistance wave tends to infinity, and the reflection occurs without any change in the wave sign, therefore the disturbance enhances.

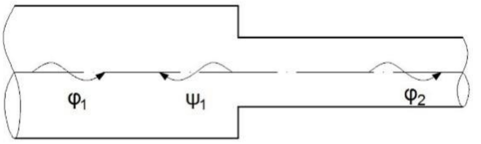


Fig. 5. Incident wave φ_1 separates into refracted wave, φ_2, and reflected wave, ψ_1, at a sudden change in diameter of the pipe (*own drawing*)

Consequently, thorough attention has to be paid to the implementation of the boundary conditions.

The discharge duct of the Plopeni PS was divided into ten sections by 11 calculation nodes. The boundary conditions were chosen according to the characteristics of the pumps, check valves, reservoirs and other devices that are mounted on the discharge duct.

The simulation was conducted under the assumption the steel made duct has no protection means. The extreme values of pressure and the most vulnerable cross sections of the pipe were identified. Subsequently, the hydraulic shock simulation was performed with different methods of protection, provided by a special closing regulation of the check valve. The same simulation was performed HDPE-made duct, in order to compare the extreme pressure values.

3. Results. Discussion of the acquired results

3.1. Results of the quasi-steady flow simulation

The numerical simulation in EPANET gave a picture of the system's operation in a quasi-steady regime. Firstly, the simulation of the water flow through the mains of Plopeni-Movila Verde was made in the case of constant speed pumps in PS1. A pump continuously discharged a flow rate of 14.38 l/s at a constant head of 69 m. Pressure variation along the duct is due to the change in elevation and, obviously, to the head loss. The results regarding the pressure field along the duct showed a minimum pressure of 16.3 mwc in node CA1, where the elevation has a peak value of 125.63 m at the axis of the duct. The energy consumption in this case is 0.39 kWh/m^3, for an overall efficiency of the pump of 60%.

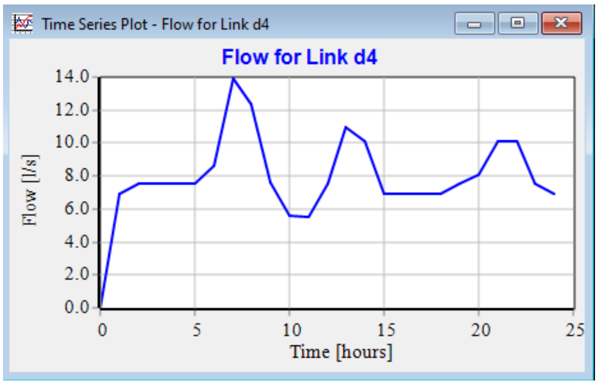


Fig. 6. Discharge time series at the pump PS1, in the case of variable speed (*own study*)

The second simulation was of a variable speed pump in PS1. The pumped flow rate follows the variation of the water demand. As the pumping installation has a high static head, of 54 m, the pump's speed may be varied in a narrow range.
The minimal pressure in node CA1 decreases at 15 mwc, as the graph in Figure 7 shows.

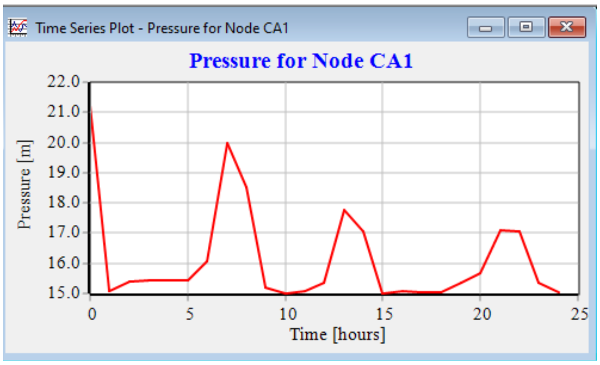


Fig. 7. Pressure variation in node CA1, in the case of variable speed (*own study*)

The delivered flow rate varies during a day, and its maximal value is recorded at 07:00 am, according to the demand pattern (Fig. 6). The energy consumption in this case is 0.21 kWh/m^3, which means an important energy saving.

In the third simulation in EPANET, pump operation controlled by the water level in the tank TMov (see Fig. 4) was considered. It is a simple strategy that brings a little more energy saving, as the pump is closed between midnight and 05:00 am, while the water demand is low. Energy consumption in this case is 0.20 kWh/m^3, for the same efficiency of the pump.

3.2. Results of the transient flow simulation

The simulation of the transient movement in the duct was conducted for the most harmful case, when transients are generated by an electric power failure.

The simulation considered two cases:

- the existing steel made duct, of 200 mm in diameter;
- a HDPE duct with the same inner diameter, to possibly replace the existing one.

Figure 8 presents the pressure variation in the three most representative calculus nodes: node PS1, right after the pump, node CA1, where the elevation has a maximal point, node CS26 – the lowest point, and the reservoir R (see Fig. 2). The duct is steel made, consequently the celerity is high. A value of 1200 m/s was obtained for celerity, according to the elastic modulus of water and steel, respectively, and the geometry of the duct.

The results showed no dangerous maximal pressure values. The highest-pressure value is of 87 mwc in the cross-section close to the pump, which doesn't require special protection.

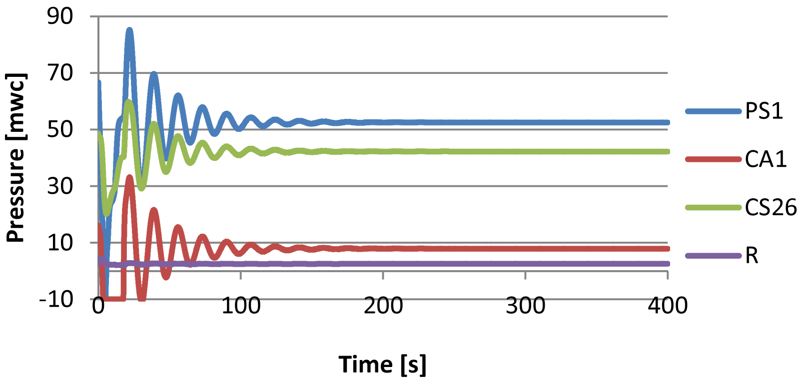


Fig. 8. Pressure variation during hydraulic shock. Unprotected steel duct (*own study*)

The real threat is cavitation. This dangerous phenomenon occurs when the pressure is lower than –5 mwc, cavitation appears in the node PS1 for about a second, at the first oscillation of the pressure, and also in the node CA1, where it lasts for about 15 s at the first oscillation and for another 4.5 s at the second oscillation, during the hydraulic shock provoked by an accidental pump stoppage.

Consequently, an investigation was conducted into which means of protection may keep pressure values in a non-harmful range. Taken into consideration were three means of protection which refer to the way the check valve closes:

1. Linear closing law, in 15 s;
2. Two stages closing law, in 45 seconds;
3. Two stages closing law, in 60 seconds.

The results regarding pressure in the nodes mentioned above are graphically represented in Figures 9-11. Each figure shows pressure variation in a comparative manner, which means the results were plotted in either the three protection cases or the unprotected duct case on the same axis, for each node.

Imposing a 15 s linear closing law of the check valve, cavitation doesn't occur in the node PS1 any longer. But in the node CA1 cavitation occurs and lasts for a shorter time, for about 8 s during the first oscillation (Fig. 9).

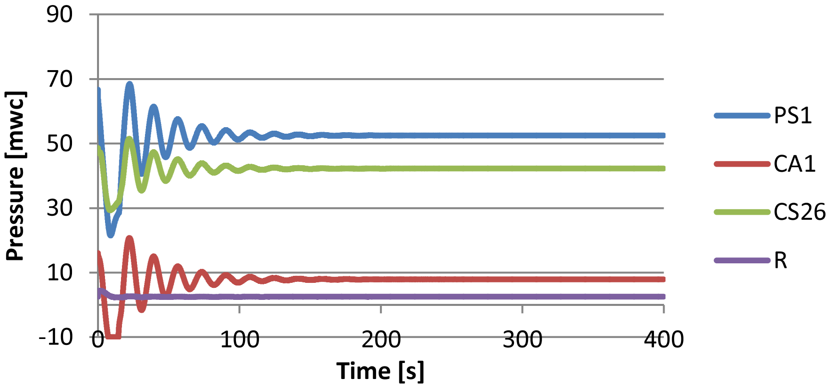


Fig. 9. Pressure variation during hydraulic shock, in the case of 15 s linear closing low of the check valve on the steel duct (*own study*)

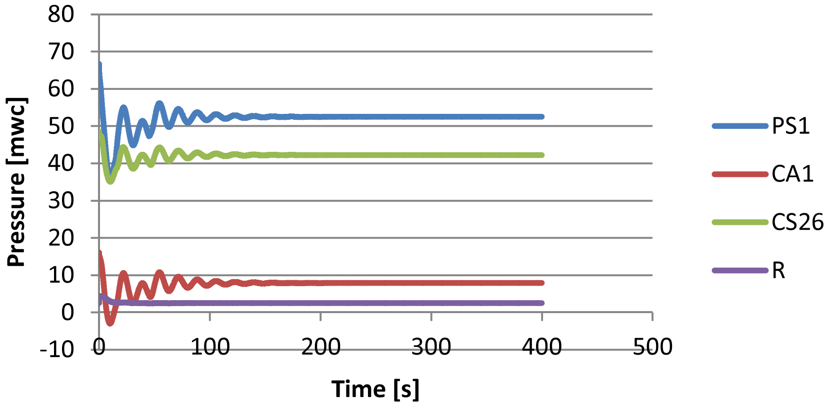


Fig. 10. Pressure variation during hydraulic shock, in the case of 45 s two-stages closing low of the check valve on the steel duct (*own study*)

A better solution seems to be when a 45 s two-stages closing law is used. Meaning that when stopping the pump, the valve disc, during the first stage, closes quickly 75% under the action of the self-weight and a spring, preventing water to flow backwards with a dangerous flow rate, and in the second stage it closes slowly and completely. The pressure variation is shown in Figure 10. This time, cavitation doesn't occur along the entire duct. Minimal pressure takes positive values in all nodes, except for the node CA1, where the minimal pressure reaches the value of –5 mwc.

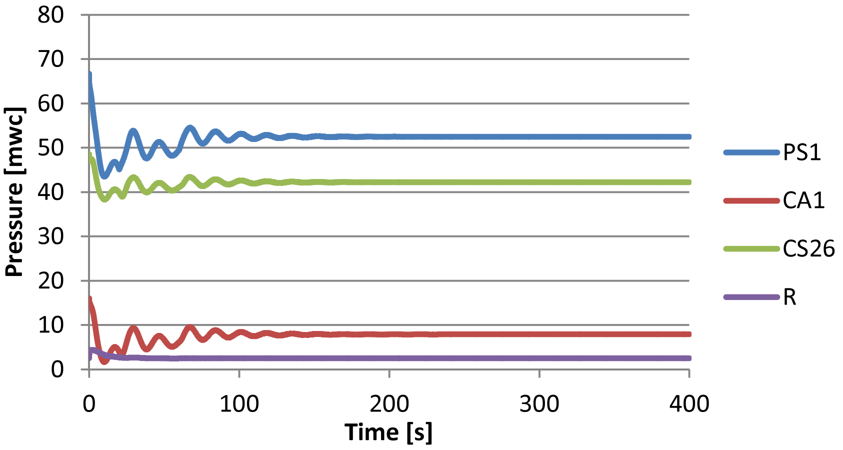


Fig. 11. Pressure variation during hydraulic shock, in the case of 60 s two-stages closing low of the check valve on he steel duct (*own study*)

A similar case, with a 60 s two-stages closing law proves to be the best solution to protect the steel made duct from cavitation. In this case, positive minimal pressure values are recorded along the duct, as seen in Figure 11.

As mentioned above, we have conducted the simulation of the hydraulic shock in a HDPE duct with the same diameter, to possibly replace the existing steel-made duct. The celerity calculated by Hammer is 337 m/s, a value that fits very well with the one determined by the relationship (5).

The pressure variation is presented in Figure 12 only for node CA1, the most likely to have negative minimal pressure. In the case that the duct has no protection from the hydraulic shock, minimal pressure in node CA1 reaches –5 mwc only at the first oscillation, so the danger of cavitation is very much unlikely.

When a 15 s linear closing law is imposed, the minimal pressure value rises a bit, but the difference is insignificant. The 45 s two-stages closing law of the check valve provides a very safe protection from cavitation. In this case, minimal pressure along the duct is positive, as presented in Figure 12.

Either way, a couple of air valves is recommended to be mounted in node CA1, as additional protection.

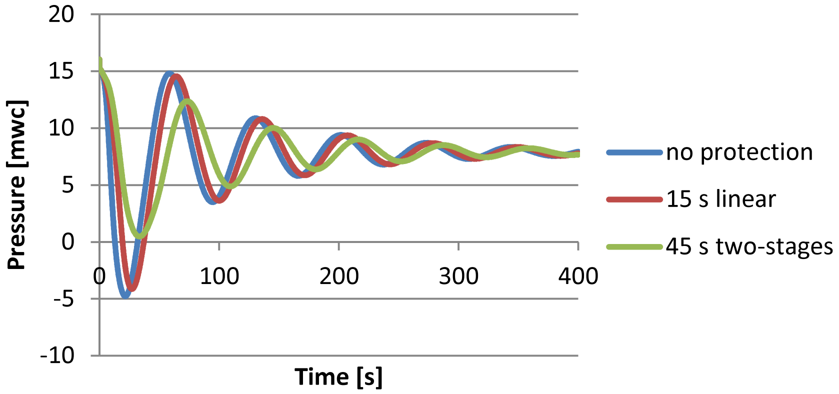


Fig. 12. Pressure variation during hydraulic shock in HDPE duct, in node CA1 (*own study*)

Conclusions

The study of the water flow through the duct that supplies the Movila Verde village showed that the hydraulic parameters may be easily determined by numerical simulation and processed as field values or time series.

EPANET is a very useful simulation tool, that can simulate the operation of the hydraulic system in different scenarios and assess the electric energy consumed for a unit volume of pumped water. The use of a variable speed pump, instead of a constant speed one and the correlation of the pump's operation time with the water level in the discharge tank of the studied water system can cut off almost half of the consumed energy.

It is also a good method to determine the regime hydraulic parameters (velocity and pressure) as a starting base for the transient water movement simulation.

The numerical simulation of the transients in the Movila Verde water supply duct allowed a rapid identification of the most vulnerable cross sections of the duct and showed that the real danger during possible hydraulic shock is cavitation, due to the longitudinal profile of the duct. The Hammer programme leads to reliable results in single ducts or branched water systems.

Taking into account the high pumping head, we recommend the steel-made duct, protected both by a 60 s two-stage closing law of the check valve and a pair of air valves in the node with the most rapid slope change.

The HDPE pipe is also a good technical alternative, if the duct is protected by a shorter closing law of the check valve, of only 45 s. With this protection, the minimal pressure values stay positive along the duct, even in the most dangerous case of water hammering provoked by a pump stoppage.

The study will be continued with investigations on pressure variation in Movila Verde water supply duct in other different scenarios that can lead to water hammering. The same analysis will be conducted for the other branches of the water supply system.

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