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Behaviour simulation of a main pipe depending on it's execution material, in a non-steady flowing state (water hammer)

I Popa, I D Ungureanu, S Perju and F M Martan

Hydraulic and Environmental Protection Department, Technical University of Civil Engineering, Bucharest, România

Correspondence: sergiu.ion.popa@gmail.com

Abstract. The current paper presents the optimal ways for choosing appropriate devices in order to protect the pressurized hydraulic installations in a water supply system, against water hammer phenomena. The case study done it in this research paper presents a hydraulic system formed by a main water pipe, and it's behaviour regarding the water hammer phenomena, taking into account 3 types of pipe execution materials (ductile iron, polyethylene and glass reinforced pipe). The study includes also the protection equipment's need it for each type of pipe material. Hydraulic simulation was made using a numerical calculation model, designed with a software special for non-steady flowing state in pressurized systems, called Bentley Hammer v.10i..

1. Introduction

During operation in the centralized water supply systems for the cities or economical agents, ensuring a wealthy operation of water network and a safety in operation for all technological objects inside a water supply system is the major priority for drinking water distributors.

Due to their location (out of cities, most of the time), but also taking into consideration it's key role in a water supply systems, the main adduction pipes through it's construction are large diameter pipes, with big lengths, through which the operators transport the entire amount of water need it for all consumers in a water supply.

Apparently, for the main pipes in a water supply system, the flow and pressures inside the pipe are constant, the velocity inside the pipe is constant, which is called steady flow regime, but during operation of the pipe, there could be registered some accidents, such as power failure of the pumps, or closing a valve to fast, where an unsteady flow regime is born which creates in a very short amount of time higher and lower pressures which can easily exceed the maximum values admitted by the pipe.

Looking from hydraulic point of view, in order to get a safety operation of the main pipe, starting from the designing phase of a project it is mandatory to study the scenario of unsteady flow which is well known as water hammer phenomena. The results of the calculations, reflecting the state of art and the novelty of the paper are necessary for the designers, in order to choose the best solution for protecting the pipe, but are also very important for the operators, which supervise the maintenance of the pipe in order to get a correct operation and avoid actions that could produce hydraulics shocks.

2. Technical aspects of the water hammer phenomena

Water hammer phenomena is a unsteady motion of fluid that is produced in pressurized pipes, appearing when a parameter in the flowing is rapidly changed due to an accident (power failure of pumps, closing a valve to fast, braking the pipe).[8] Unsteady flow regime usually introduce important shocks such as high and low pressures that can exceed the nominal pressure of the pipe, and produce damages such as breaking or contraction of the pipe. This shock have as a general result important damages and water losses for the water supply system.

From the physical parameters that describes motion, the most important are mean velocity related to the flow, and pressure inside pipe related to the piesometrical level. Unsteady motion has a wave characteristics; a perturbation of the boundary condition induce local changes of the pressure and flow, changes that are transmitted through waves in the entire pipe; When velocity is changed rapidly, fluid mass that is in in motion is developing forces that are acting as a pressure variations. Water is as a compressible fluid, and pipe material is elastic, the pressure variations through pipe is done as a wave, with a velocity „c" called celerity, wave which is reflected back totally or partially after it get to the end of the pipe. The main characteristic of flow wave and pressure wave is that they are associated waves, and it propagate simultaneously. The relation between this 2 waves (pressure and velocity) is given by Jukovski's equation:

$$\Delta p = \pm \rho \cdot c \cdot \Delta v \qquad [1]$$

where: Δp – pressure variation; ρ – fluid density; c – celerity; Δv – velocity variation.

The characteristic wave celerity (c) is the speed with which a disturbance moves through a fluid. Its value is approximately 1,438 m/s for water and approximately 340 m/s for air.

In 1848, Helmholtz demonstrated that wave celerity in a pipeline varies with the elasticity of the pipeline walls. Thirty years later, Korteweg developed an equation to determine wave celerity as a function of pipeline elasticity and liquid compressibility:

$$c := \frac{\sqrt{\frac{\varepsilon}{\rho}}}{\sqrt{1 + C_1 \cdot \frac{\varepsilon}{E} \cdot \frac{D}{e}}} \qquad [2]$$

where:

- E elasticity module of transported fluid
- ρ density of fluid
- E Young's elasticity module of pipe material
- D Inside diameter of the pipe
- e Pipe wall thickness
- C_1 coefficient depending on the pipe wall thickness and axial displacement of the pipe

For pumped main pipes, the usual accident that generates the water hammer phenomena is the rapidly and intempestive power failure at the pump engines, which cancel immediatly the momentum of the pumps rotor and stops simultaneously all the pumps inside a pumping station at that moment. When pumps are stoped suddenly, the energy that was transffered to fluid is now stopped, the flow and pumping head of the pump is zero, and the first phase of the water hammer is produced, a low pressure phase, where pressure inside the pipes are getting values smaller that in normal operating mode. The second phase of the phenomena, is caused by the wave reflection from the pumping station due to the non-return valve next to the pump, the low pressure wave are changed into high pressure waves that are transmitted back in the pipe, pressure that exceed most of the time the nominal pressure of the pipe. Wave reflection at the other terminus point of the pipe (storage tank) of this overpressure waves produce a new phase, with low pressure, but with values that are more appropiate from the normal operating mode, when compare with the first phase of the phenomena.

The wave reflection process continues until the water velocity and pressure between pumping station and storage tank are getting to zero. The evolution of pressure and flow waves can be observed and simulated only through numerical models, using software packages that are specialized in unsteady fluid motion. For this reasearch paper it was used the Bentley Hammer *v10i* software was used, specialized for the water hammer phenomena.

3. Case study. Numerical modeling of the hydraulic problem

Bentley HAMMER is an advanced numerical simulator of hydraulic transient phenomena (water hammer) in water, wastewater, industrial, and mining systems which can handle any fluid or system that a typical steady-state hydraulic model can, but it can also solve a broader range of problems, as rapidly varying or transient flow for slightly compressible, two-phase fluids (vapor and liquid) or for two-fluid systems (air and liquid), and even can make simulation of closed-conduit pressurized systems with air intake and release at discrete points. [8]

Case study presented in this paper is proposing to analyze the behaviour of a main adduction pipe using different materials that are commonly used for execution of the pipe, in a situation of a schock produced by the water hammer phenomena. Also, assumptions about solutions for protecting the pipe was made, in order to make a complete image of the problem, with direct implications in the investment cost (CAPEX) and operating cost (OPEX) of the hydraulic system.

The hydraulic system which includes the main pipe is a pressurized system, at the inlet section being designed a pumping station wich deliveres a 125 l/s flow, pumping head being established in correlation with the pipe material, and inside diameter of the pipe.

The suction tank of the pumps have the foundation at 123.50 m above the level of Black Sea, and the minimum level of water inside it is located ar 124.20 m. The hydraulic system is ended to a free surface storage tank, with a maximum water level of 233.50 m, having a geodesical height of 109,3 m. The main adduction pipe is having a total length of 12.800 m.

In the figure below is presented the piesometrical line of the hydraulic system, for the normal operating mode.

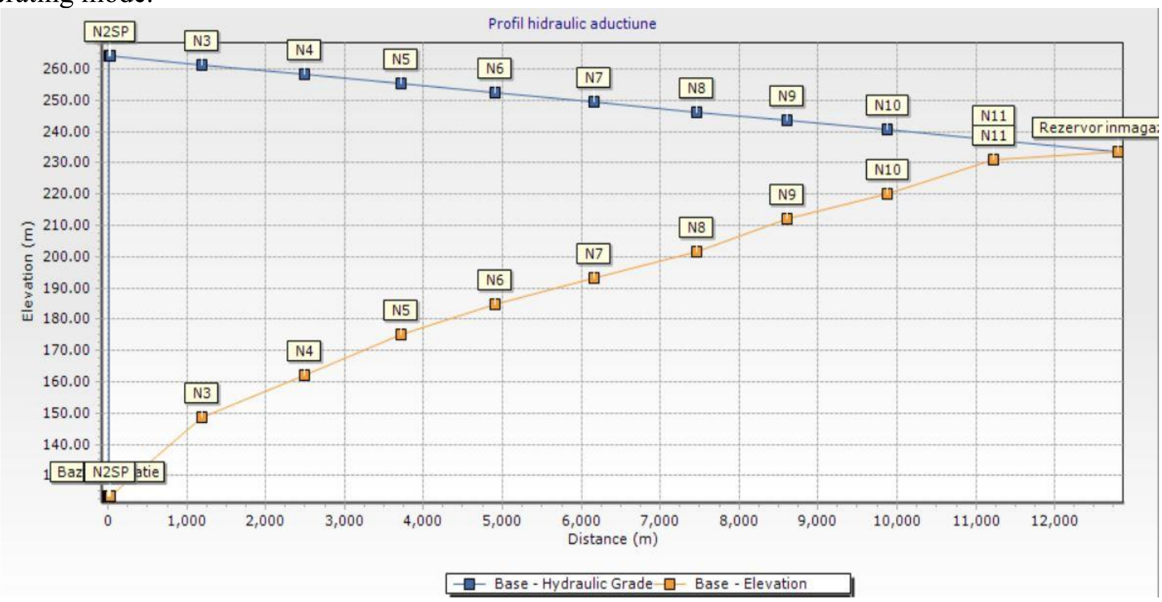

Figure 1. Piesometric line of the hydraulic system (normal operating mode)

3.1. Pipe material

As it was presented above, the analyze for the water hammer phenomena was made for 3 different types of pipe materials, as it's detailed in the following:

3.1.1. Duclile iron. With a nominal diameter DN400, pressure class C40 (it means it allows pressure inside it of maximum 40 bars, and it's the lowest pressure class for ductile iron), with the following mechanical characteristics:

- Inside diameter 400 mm
- Elastic Young's modulus 170 Gpa
- Poisson's Ration 0.28
- Wave speed (celerity) 1415 m/s
- Absolute roughness 0.12 mm

3.1.2. Glass reinforced pipes (GRP). With a nominal diameter DN400, pressure class PN16 (it means it's resistance is up to 16 bars), with the following mechanical characteristics:

- Inside diameter 403.4 mm
- Elastic Young's modulus 50 GPa
- Poisson's Ration 0.35
- Wave speed (celerity) 1150 m/s
- Absolute roughness 0.013 mm

3.1.3. High density polyethylene (PEHD). With external diameter De450 mm, pressure class PN16 (it means it's resistance is up to 16 bars), with the following mechanical characteristics:

- Inside diameter 383,2 mm
- Elastic Young's modulus 0.8 GPa
- Poisson's Ration 0.46
- Wave speed (celerity) 763 m/s
- Absolute roughness 0.01 mm

Also, in order to make the calculation right, we have to define the fluid that is transited through the main pipe, which is fresh water with the following characteristics:

- Temperature 200C
- Bulk Modulus of Elasticity 2.19 GPa
- Density 998 kg/m3

In order to simulate the water hammer phenomena, the scenario of power failure at the pumps section was done. Using technical data described above, numerical simulations was done in order to observ the behaviour of the pipe related to it's execution material, paying attention to the maximum and minimum pressure formed in the pipe during the hydraulic shock without protective equipments against it, and also making assumptions about the protective equipments and solutions that should be taken in order to safely operate the pipe.

3.2. *Results. Water hammer phenomena depending iron pipe material*

Based on the numerical simulations that has been done using software Bentley Hammer v10i, diagrams of maximum and minimum pressure inside the pipe was generated, as they are presented in the fig. 2, 3 and 4.The red line is the maximum pressures line in unsteady state of motion, blue line is the lowest pressures line for unsteady motion, and green line is the piesometric line for normal operating conditions. The reference plan (0.00) is the geodesical level of the main pipe.

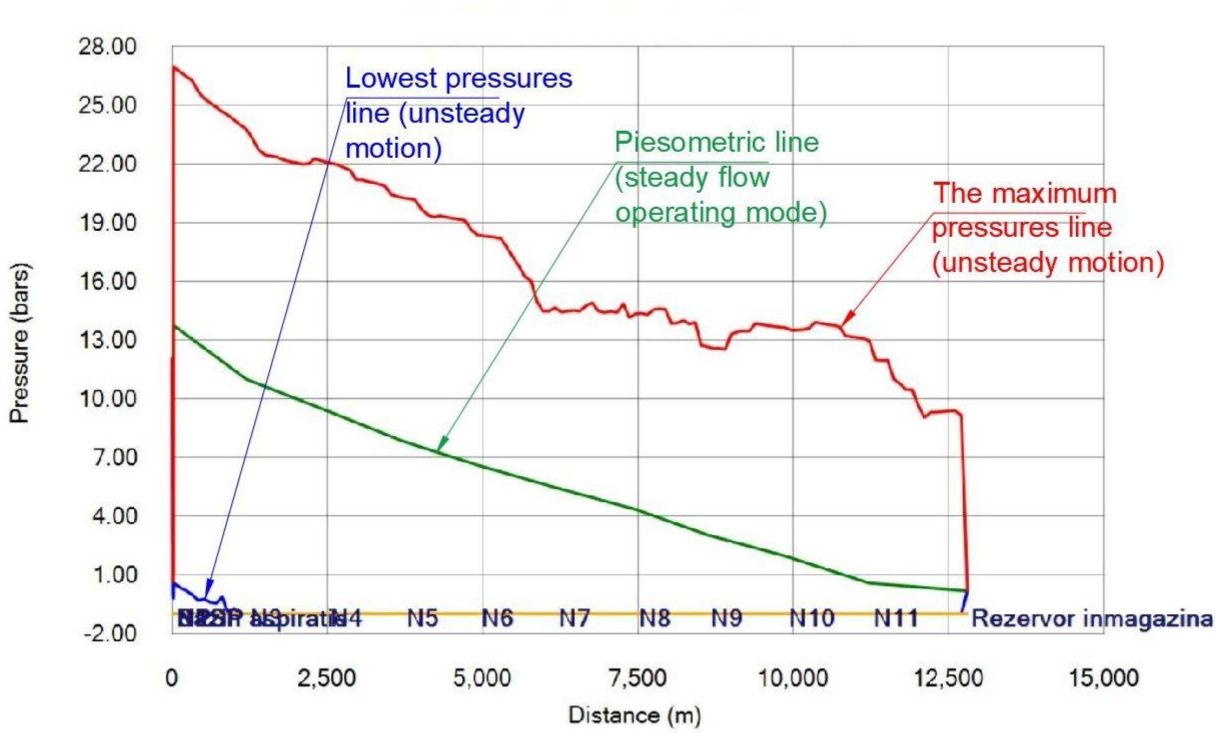

Figure 2. Water hammer phenomena for the ductile iron pipe

As it can be observed, for the ductile iron pipe the maximum pressure line (red line) takes values from 27 bars in the inlet section of the pipe, decreasing along the pipe length up to the values of 10 bar in the outlet section. As it was mentioned before, the minimum production line of ductile iron is C40, which allows pressure inside the pipe up to 40 bars. In this case, if the fittings along the pipe (elbows, tee, valves, dismantling joints, etc) are dimensioned properly, taking into consideration the maximum pressure inside the hydraulic system on each point from the longitudinal profile, and establish the maximum operating pressure according to the water hammer phenomane, it should be no problems during exploatation. No instalations of protection against the phenomena should be installed.

Also, from the figure above, it can be observed that the minimum pressures line are not getting lower than the geodesical level of the pipe, which proves that the air valves that was dimensioned in the highest points of the pipe are enough for avoiding pressures lower than the atmospheric pressure, which can put the pipe in danger of contraction.

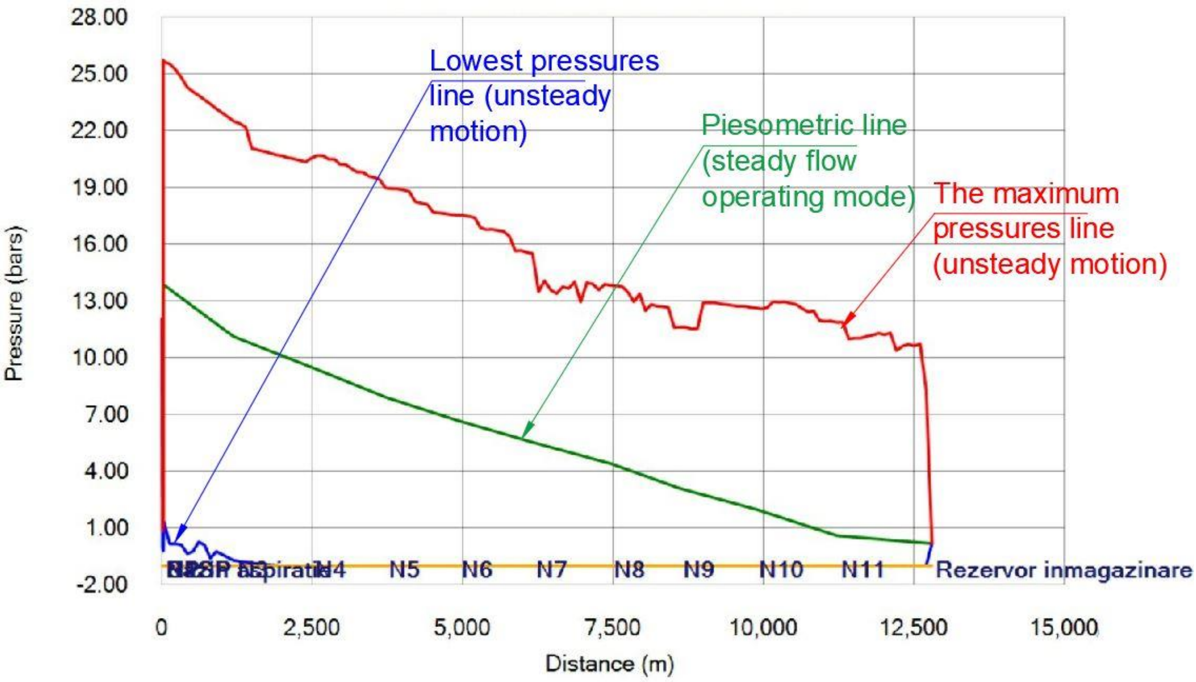

Figure 3. Water hammer phenomena for the GRP pipe

For the GRP pipe, taking into consideration it's different mechanical characteristics when compare with ductile iron, the maximum pressure line (red line) decrease in values and it has a maximum of 25.50 bars in the inlet section of the pipe. Due to smaller roughness, the pressures are increased in the outlet section of the pipe up to 13 bars.

However, if we talk about pipe resistance, the initial data was that the maximum pressure in exploatation of this pipe can not be higher than 16 bars, which are clearly excedees in the first 6.000 m of the pipe. Also, for the rest of the pipe, the maximum pressure are not impresively decreased, which will stress the pipe up to it's limit in operation.

For this case, there are 2 options of solving the problem: first is to dimension properly the first 6000 m of the pipe, taking into consideration the maximum pressure from the water hammer phenomena for pipe and fittings. The second option is to dimension an instalation that will protect the pipe against water hammer phenomena. Instalations that can protect the hydrauic systems can be release valves combined with air inlet valves, or hydropneumatic tanks. For this case, the hydropneumatic tank was taken into consideration in order to protect the pipe.

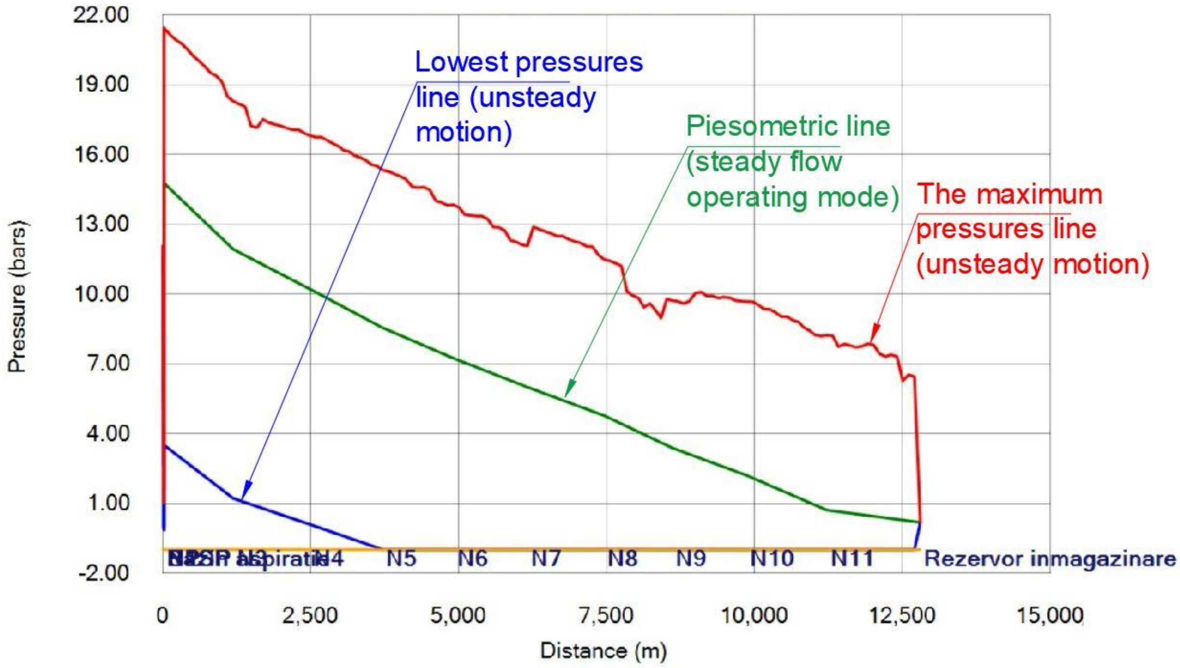

Figure. 4. Water hammer phenomena for the PEHD pipe

For the PEHD pipe, the celerity, in direct correlation with Young's modulus is the lowest, which lead to the conclusion shown in the chart above that the water hammer phenomena is acting in less violent that the other 2 cases presented above. The maximum pressure inside the pipe is not higher than 21 bars in the inlet section, and it's decreased up to 7 bars in the outlet section. The maximum nominal pressure of the pipe (PN16) is exceeded in the first 3.000 m of the pipe, and it can be replaced easely with the next pressure class (PN20) in almost entire part that is having problems.

Also, lowest pressure line is not decreasing under the geodesical level of the pipe, so it will not be problems with low pressures during exploatation.

However, the pipe can not be changed (e.g. is already installed), protection equipments can be installed in order to protect the pipe, which are further investigated.

3.3. *Protection equipment for the case analyzed*

As it has been shown above, for the ductile iron pipe there are no additional equipments necessary in order to protect the pipe against water hammer phenomena. Sizing the fittings properly according with the maximum pressures from the water hammer is sufficient.

For the GRP pipe, where the pressure are higher than the pipe can take, there are 2 solutions that was disscused in the upper section: first is the resizing of the pipe and fittings pressure class (which can be expensive, due to the fact that the total pipe and fittings that have to be resized is 6000 m, with pressures up to 26 bars), or to dimension protection equipments such as release valve or hydropneumatic tanks. For the case of dimensioning protection equipments, it was taken into consideration as a solution for protection a hydroneumatic tanks. According to calculations, in order to maintain the pressure up to the nominal pressure of the pipe (PN16) a 2500 liters hydropneumatic tank was necessary. The results of the simulation is shown below:

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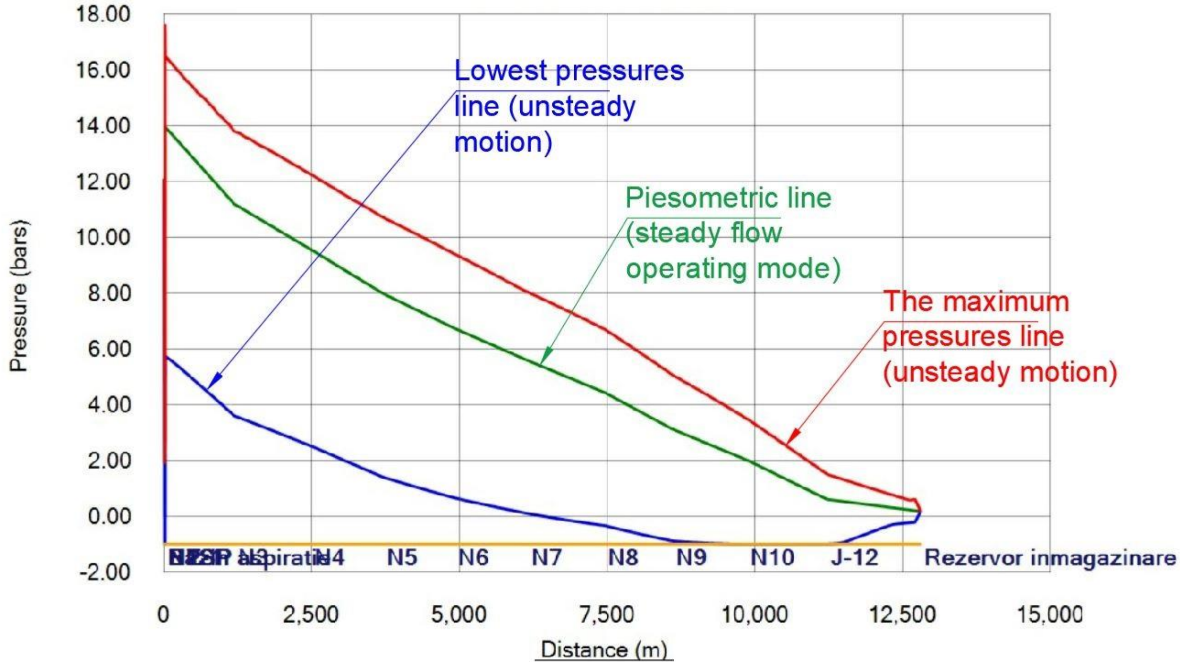

Figure 5. Water hammer phenomena for the GRP pipe, with a 2500 l hydropneumatic tank added

For PEHD case, where maximum pressure are not very dangerous, the most simple thing to do is to rediomension the pipe and fitting properly in the first 3000 m. However, if a protection equipment is necessary, it can be installed very easily an hydropneumatic tank. According to calculations, for this case an hydropneumatic tank with a volume of 100 l is sufficient in order to keep pressure in the pressure class of the pipe. The results are shown below:

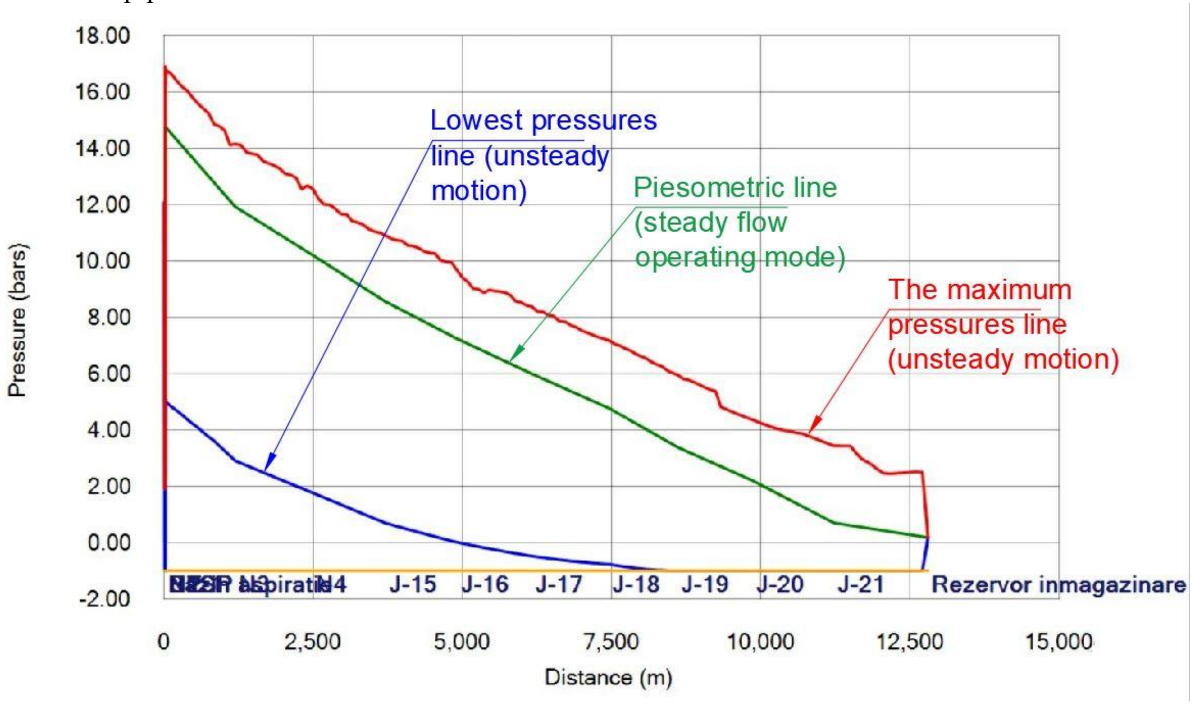

Figure 6. Water hammer phenomena for the PEHD pipe, with 100 l hydropneumatic tank added

4. Conclusions

In order to establish what is the best execution material for pipes, correlated with water hammer phenomena, 3 types of materials was analyzed (ductile iron, GRP and PEHD) , in a case study presented above.

Pipes that are made from ductile iron have the minimum pressure class C40 (which resist up to 40 bars), so the maximum pressures that can occur from the water hammer (for this case scenario) can not put in danger our hydraulic system, if the fittings are dimensioned at a properly pressure class. No additional investments are need it in order to protect the hidraulic system. However, the ductile iron is the most expensive material from the list, so we can not say that allways this is the best solution, related to the CAPEX calculation.

For the GRP pipe, which is the cheapest material from our list, the investment costs for protection against water hammer will be increased. As it is shown above, we can eather resize the pressure class of the pipe for almost half of the main pipe with higher pressure class up to PN25, or we can install a hydropneumatic tanks with a minimum volume of 2500 liters, both solution being expensive.

For the PEHD pipe, which is a more flexible and elastic pipe, the water hammer phenomena is not so violent, presenting lower pressure when compare to the others. For this case, it is necesary to resize the pipe for almost 3000 m, with the next pressure class, or to install a small hydropneumatic tank with a volume of 100 l. Both are cheap solutions, but are oversized by the pipe cost.

In conclusion , we can say that the proper solution can be chosen only when we compare the total investment cost for the pipe, fittings, and also for the protection equipments against water hammer phenomena. It is unproperly to choose the material of a pipe without making an evaluation of the overpressure from the unsteady motion, in order to be aware of all additional equipments an installations need it.

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