# Unsteady State Analysis In Low Head Pumping Stations

**Fahri Maho, Erind Maho**

**Abstract:** Pipe failure in a rising main pipeline of a pumping station in a sensitive tourist area raised the need for a comprehensive water hammer analysis to find the causes and address protection measures. Being a low head pumping station, only a check valve has been installed to protect the system from water hammer effects. Calculations and computer modelling confirmed that immediately after an uncontrolled pump stop or power failure, the negative pressure wave starts propagating along the pipeline from the pumping station to the discharge manhole. The minimum pressure envelope intersects the rising main (pipeline), creating a vacuum on the pipeline in almost its full length. Without water hammer protection measures, the vacuum on the pipeline would be one of the main causes of the pipe failure. This study confirmed the need for water hammer analysis and consideration of protection measures even in rising mains of low head pumping stations to eliminate the consequences of such phenomenon.

**Index Terms**: low head, penstock, pipe failure, pipeline, pumping station, rising main, transient, unsteady state, wastewater, water hammer, wave velocity.

## 1 Introduction

In one of the sewerage pumping stations in the town of Ksamil, south of Albania, the rising main consisting of a 370 m long OD450 PN6 HDPE100 pipe suffered a sudden failure. The wastewater flooded above the surface and flowed along the road to the beach area, discharging into the sea. Considering the sensitivity of the area, a popular tourist spot, and the high density during the tourist season in July, the event made headlines in the local public and national media. The pumping station was under the Defect Liability Period and consisted of three installed submersible pumps (two in operation and one in standby) in the wet well, while discharge pipes and associated valves were installed in the dry chamber adjoined to the pumps pit. Additionally, a one-way valve was installed in the dry chamber for protection from water hammer. The failure of the PN6 pipe under a total gross head of 22 m (static pressure of around 2.16 bar) led to a profound investigation to determine the causes and take proper measures in other pumping stations. Whilst a detailed analysis was undertaken on numerous reasons for the pipe failure, in this paper we will focus on water hammer effects and the identification of the need for special water hammer protection measures in low head pumping stations.

## 2 Transient and Water Hammer Phenomena

During transient flow, which can be defined as the state with rapidly changed flow in hydraulic systems, velocity, pressure and other hydraulic variables change rapidly over time. Water hammer, as an example of transient flow in hydraulic systems occurs in the following cases:

1. Sudden flow stoppage (for example: valve closure, pump failure, turbine load rejection, main turbine inlet valve closure, Pelton turbine needle closure, turbine guide vanes closure, etc.)
2. Sudden flow start/start-up procedures (valve opening, pump start, turbine start - opening of guide vanes, main inlet valve, etc.)

Any sudden change in flow leads to pressure fluctuations in the system; the unsteady state of a hydraulic system generally occurs for many reasons that can be grouped as follows:

1. Uncontrolled and by accident, without control of the operation staff (e.g. pumping station failure)
2. Controlled by operation staff (e.g. pumping station pump start/stoppage, valve opening or closure)

Generally, water hammer causes pressure rise or drop in penstocks-pipelines of pumping stations/hydropower plants, rotational speed change of pump/turbine units and level/pressure variations in surge tanks. Thus, specific protective measures are generally used for protecting mechanical equipment and the pipeline from harmful water hammer effects.

If the system response is not appropriate, due to the maximum and minimum pressures not within the acceptable limits, then either the system layout or parameters have to be changed, or various control devices provided, and the system has to be analysed again. This procedure has to be repeated until a desired response is obtained. The purpose of water hammer control is to stop the kinetic energy from being converted into elastic deformation energy. This can be done by one or a combination of the following basic methods:

1. Energy storage;
2. Optimization of valve closure characteristics;
3. One-way surge and venting facilities; and
4. Optimization of the pipe system control strategy

With pressure (air) vessels and surge tanks, energy is stored as pressure energy; when a flywheel is installed, the energy stored takes the form of rotational energy. Suitable actuation schedules for the opening and closing of valves are calculated and verified by means of a surge analysis on the basis of the valve characteristic. Generally, air valves should not be used until every other solution has been ruled out. Their drawbacks are:

1. They require regular maintenance.
2. If arranged in the wrong place or mounted incorrectly, they can aggravate pressure variations instead of alleviating them.
3. Under certain circumstances, operation of the plant may be limited, as the air drawn into the system has to be removed again.
4. The handling of wastewater calls for special designs.

The water hammer phenomenon is traditionally described by one-dimensional unsteady pipe flow equations and

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equations describing boundary elements (i.e. in reservoir, valve, surge tank, pump/turbine) and constitutes the transmission of pressure waves along the pipeline resulting from a change in flow velocity. The simplified continuity and momentum equations, appropriate for most engineering applications for unsteady pipe flow, are shown in (1) and (2) [2]:

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (2)$$

where:
- H = Piezometric head (m)
- Q = Discharge ($m^3/s$)
- A = Pressure wave speed (m/s)
- D = Pipe diameter (m)
- A = Pipe area ($m^2$)
- G = Gravitational acceleration ($m/s^2$)
- f = Darcy-Weisbach friction factor
- x = Distance along the pipe (m)
- t = Time (s)

## 3 Wave Speed

Wylie and Streeter (1993) [8] showed that the equation for wave velocity a can be conveniently expressed in the general form:

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1+\frac{K}{E}\frac{D}{e}(1-\mu^2)}} \qquad (3)$$

Based on recommendations from literature for the above parameters the wave velocity can be calculated to range between 203-226 m/s, as shown in the following table.

***TABLE 1***
***Wave velocity calculation for the OD450 PN6 HDPE100 rising main pipe***

| Parameter | Units | Values |
|---|---|---|
| Internal pipe diameter D | mm | 415.6 |
| Pipe wall thickness | mm | 17.2 |
| Min. Young Modulus E | $N/m^2$ | 8.00E+08 |
| Max. Young Modulus E | $N/m^2$ | 1.00E+09 |
| Fluid bulk modulus K | $N/m^2$ | 2.19E+09 |
| Fluid density (water) ρ | $kg/m^3$ | 1,000 |
| Poisson's ratio for the pipe μ | - | 0.46 |
| Transverse contraction number | - | 0.79 |
| Min. Wave velocity | m/s | 203.0 |
| Max. Wave velocity | m/s | 226.4 |

Using the recommended values, transient calculations were performed, resulting in an average value of wave velocity of 215 m/s.

## 4 Unsteady Analysis: Pumping Station Stop or Failure

For the unsteady analysis two operation conditions were considered, for which the wave velocity is taken 215 m/s and the system is considered without water hammer protection equipment, as follows:

Case A
No. pumps in operation 1
Pumping station capacity approx. 65 l/s
Scenario Regular pump stop

Case B
No. pumps in operation 2
Pumping station capacity approx. 130 l/s
Scenario Regular pump failure

If there if a sudden power outage in the pump motor, either accidentally or deliberately, significant water hammer problems can appear. Generally, the pressure drop which follows the rapid pump stop propagates upstream from the pumping station to the end of the system (node 9, Fig. 1), with a wave velocity equal to the speed of sound through the pumped fluid. The pressure drop can lead to column separation and the consequences of cavity-closure shock which follows such an occurrence could be severe. In addition, reversal flow in the system, if not properly handled, can lead to significant overpressures in the system.

Column separations occur in both cases A and B; once separation occurs, the above calculation is no longer valid. According to the "Joukowsky equation" [5] sometimes referred to as either the "Joukowsky-Frizell" [4] or the "Allievi" equation [1], the maximum overpressure (Δp) due to a sudden change in velocity can be calculated according to (4):

$$\Delta p = a \times \Delta V/g \qquad (4)$$

where:
- a = Wave velocity (m/s)
- g = Gravitational acceleration ($m/s^2$)
- ΔV = Change in velocity (m/s)

The following table shows the calculation of overpressures due to water hammer.

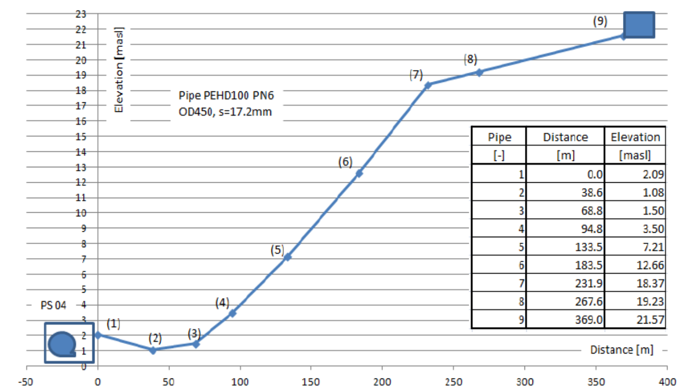
***TABLE 2***
***Calculation of wave speed in the rising main pipe***

| Parameters | Units | Case A | Case B |
|---|---|---|---|
| Max. pump flow rate | l/s | 70.0 | 130.0 |
| Internal Pipe Diameter | mm | 415.6 | 415.6 |
| Wave Speed for Transient Analysis (a) | m/s | 215.0 | 215.0 |
| Max. velocity in the pipe (V) | m/s | 0.5 | 1.0 |
| Gravitational Acceleration | m/s2 | 9.81 | 9.81 |
| Water hammer pressure increase | mWC | 11.3 | 21.0 |

For Case A, the maximum pressure at the lowest points, between nodes 2, 3 and 4 (Fig. 1) is approximately 33 mWC, which includes steady state pressure plus surge pressure.

For Case B, where two pumps are in operation with a capacity of around 130 l/s, the maximum pressure at the lowest points (between nodes 2, 3 and 4 in Fig. 1) is approximately 43 mWC, which includes steady state pressure plus surge pressure.

However, for similar low head pumping stations, the overpressure is not as serious when compared to the vacuum created along the rising main pipe due to pump failure. Both operation conditions A and B were computationally modelled, using the pumping station and rising main system given in the following figure.




| Pipe | Distance | Elevation |
|---|---|---|
| [-] | [m] | [masl] |
| 1 | 0.0 | 2.09 |
| 2 | 38.6 | 1.08 |
| 3 | 68.8 | 1.50 |
| 4 | 94.8 | 3.50 |
| 5 | 133.5 | 7.21 |
| 6 | 183.5 | 12.66 |
| 7 | 231.9 | 18.37 |
| 8 | 267.6 | 19.23 |
| 9 | 369.0 | 21.57 |

***Fig. 1**. Pumping station system geometry.*

The following diagrams resulting from the simulations show wave propagation along the rising main pipe for different time steps.

Case A: One pump in operation (capacity approx. 70 l/s), regular stop
The following diagram shows wave propagation along the rising main pipe after pump failure. After one second, the pipe section from node 6 to node 9 is under vacuum conditions (negative pressure).

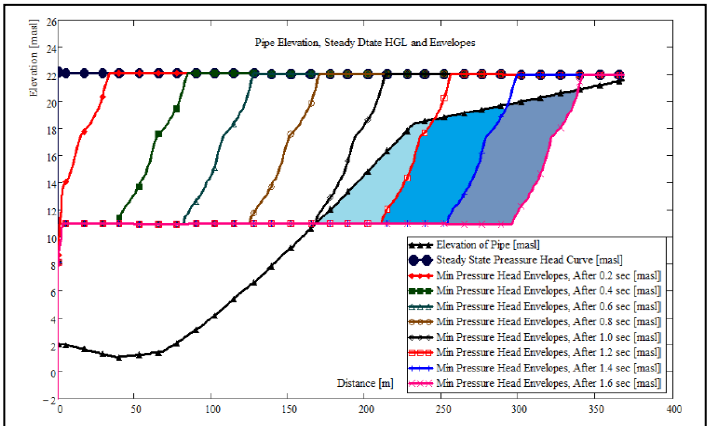
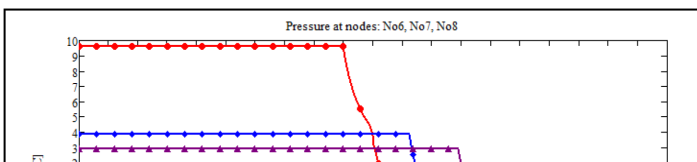



***Fig. 2**. Wave propagation along the rising main pipe for different time steps (case A).*

The following diagram shows the pressure at nodes 6, 7 and 8 during the first two seconds.




Case B: Two pumps in operation (capacity approx. 130 l/s), power failure
The following diagram shows wave propagation along the rising main pipe after pump failure. After approximately 1.7 seconds almost the whole the pipeline is under vacuum conditions (negative pressure).

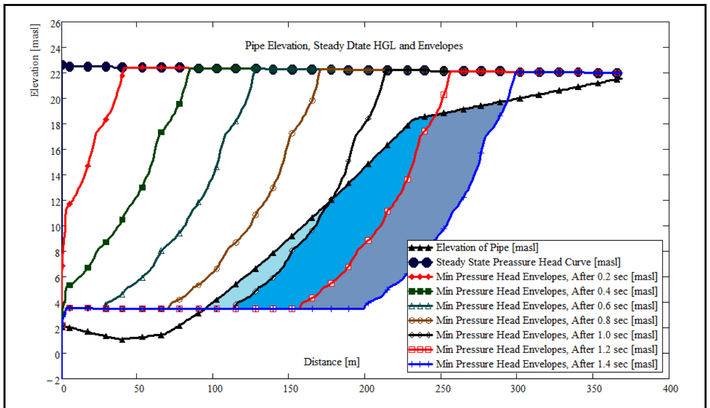



***Fig. 4**. Wave propagation along the rising main pipe for different time steps (case B)*

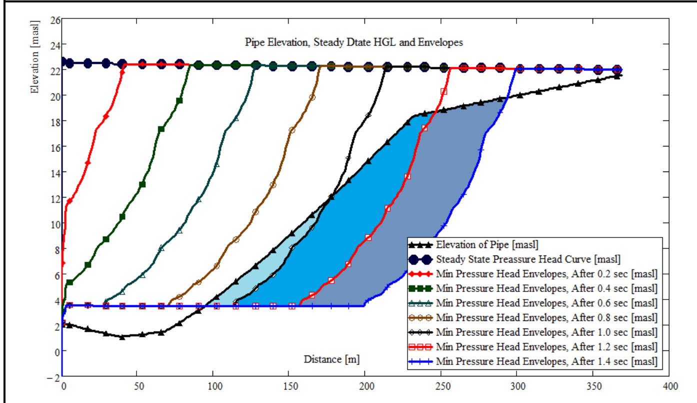



***Fig. 5**. Pressure in pipe section between nodes 6-8 during the first two seconds (case B)*

From the above unsteady analysis during the sudden pump stop or power failure, it is confirmed that the pressure drops upstream of the pumps and negative pressure wave starts propagating along the pipeline from the pumping station (node 1) to the end of the system (node 9) with the wave speed. It is not advisable that the minimum pressure line (envelope of negative pressure), intersects with the profile of a pipeline, otherwise negative pressure will occur in the pipeline as it happened in this case.The load arising from the negative pressure must be added to the dead and live load to check for pipe deflection, critical buckling pressure, wall crushing performance and bending stress-strain (where necessary). There is no available information regarding the minimum allowable vacuum which pipes can be exposed. However, attempts were made to calculate this based on the allowable pipe material characteristics provided by the HDPE pipes producers. The estimated critical external collapse pressure is given against the time under continuous external pressure loading. With respect to the safety side of the calculation, a maximum allowed negative pressure (vacuum) of 1.34 mWC is adopted for the purpose of water hammer calculation, although a higher value of negative pressure (vacuum), up to 4.85 m, is acceptable for a short time period (up to 1-minute duration). For durations less than 1 minute, we do not have data, though it is expected that the allowable negative pressure would be higher. There are other factors which can cause the pipe break of the rising main of the pumping stations such as:

1. Material failure;
2. Installation practice;
3. System design; and
4. Environmental conditions.

However, in this paper we focused on the effects of the negative pressure in low head pumping stations and the need to address this phenomenon during the design of pumping station installations.

## 5 Conclusions

From the above analysis on the pipe failure in the rising main of a low head pumping station, we can conclude the following:

1. A detailed water hammer analysis should be undertaken for low head pumping stations and rising mains, not only for positive but also negative overpressures.
2. The calculation result indicates that water hammer occurred in both normal and in uncontrolled (power failure) stop in pumping stations.
3. Negative pressures caused by water hammer should be carefully addressed in low head pumping stations.
4. Water hammer analysis for pumping stations and rising mains should be comprehensive and consider all potential causes.
5. Water hammer protection measures should be considered to avoid all potential consequences.

## References

[1] L. Allievi, Teoria del colpo d'ariete. (Theory of water-hammer.) Atti del Collegio degli Ingegneri ed Architetti Italiani, Milan, Italy (in Italian). (French translation by D. Gaden, 1921, Paris: Dunod; English translation by E.E. Halmos, 1925, Rome: Riccardo Garroni, 1913.

[2] M. H. Chaudhry, Applied Hydraulic Transients, Second ed, New York: Van Nostrand Reinhold Co, 1987.

[3] J. Duc, "Negative pressure phenomena in pump pipelines," in ASME International Symposium on Water Hammer in Pumped Storage Projects, Chicago, 1965.

[4] J. Frizell, "Pressures resulting from changes of velocity of water in pipes," ASCE, vol. 39, no. 819, pp. 1-18, 1898.

[5] N. Joukowsky, "Über den hydraulischen Stoss in Wasserleitungsröhren. (On the hydraulic hammer in water supply pipes)," Memoires de l'Academie Imperiale des Sciences de St.- Petersbourg, Series 8, vol. 9, no. 5, 1900.

[6] J. Zaruba, Water hammer in pipe-line systems, 1993.

[7] A. Simpson, "Large water hammer pressure due to column separation in sloping pipes," Ph.D. Thesis, Dept. of Civil Engineering, the University of Michigan, Ann Arbor,, Michigan, 1986.

[8] E. Wylie and V. Streeter, Fluid transients, New York, NY, USA: McGraw-Hill International Book Co., 1978.

[9] E. Wylie and V. Streeter, Fluid Transients in Systems, New Jersey: Prentice-Hall, Englewood Cliffs, 1993.

[10] E. Wylie and V. Streeter, Fluid Transients (Republished with minor corrections by , Michigan, 1983), New York, (1978), McGraw-Hill.