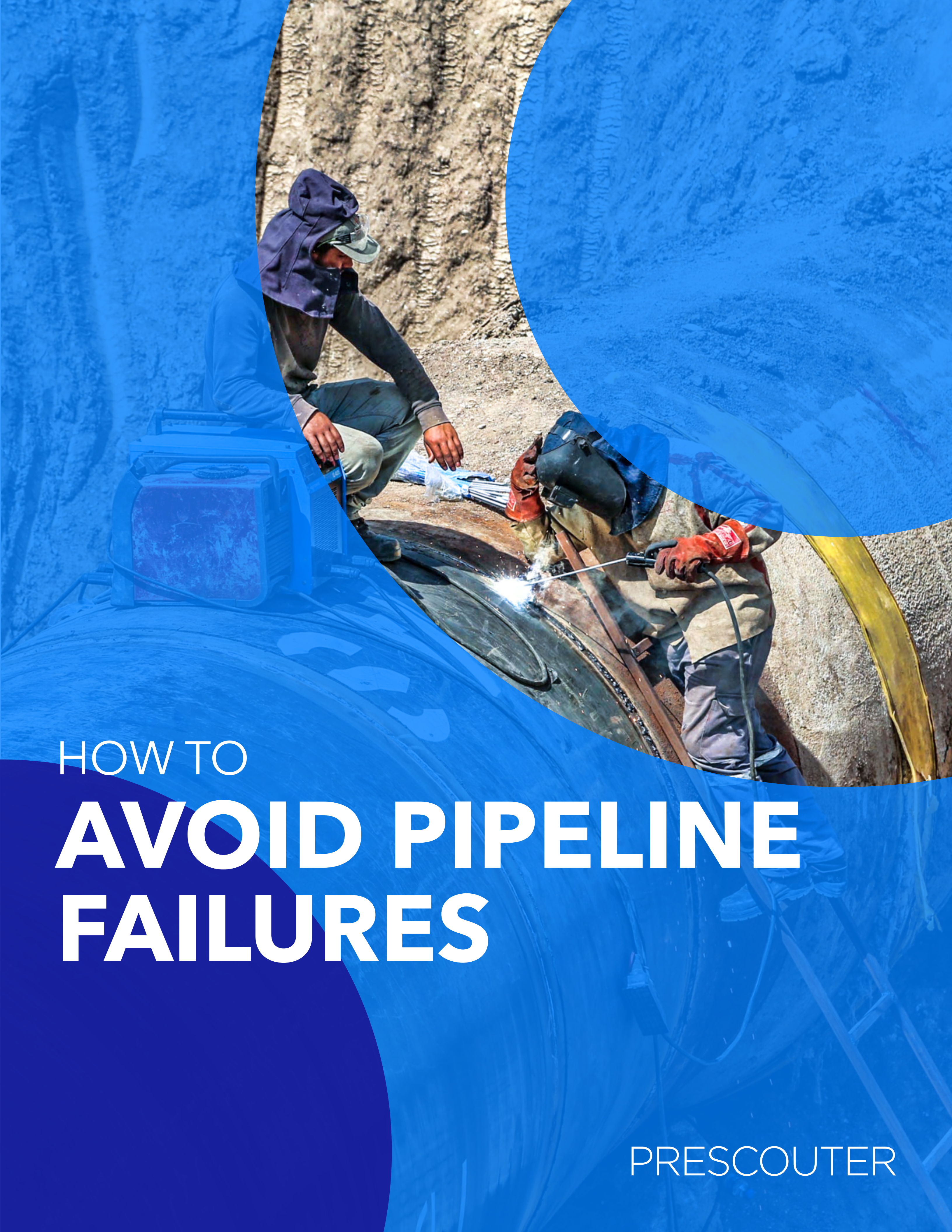

HOW TO AVOID PIPELINE FAILURES

PRESCOUTER

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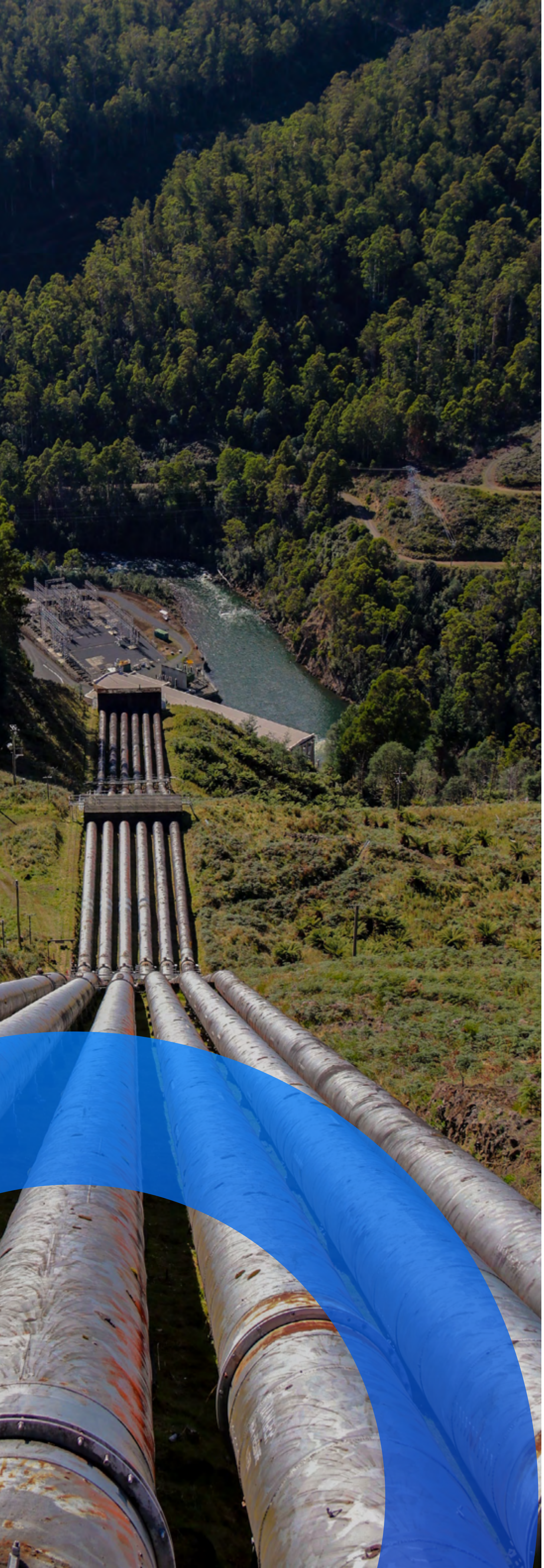
After a stint working in the industry, she joined the faculty of the Department of Civil Engineering Government Engineering College Thrissur and has experience in teaching, research, organizing training/seminars, and consultancy in hydraulics and water resources as well as in the civil engineering field in general. She has been doing research and consultancy in the field of computational hydraulics, fluid mechanics, advanced free surface flow, waterpower, bio fluid mechanics etc., giving special attention to protect the piping system against pipe burst due to the occurrence of water hammer/surge by selecting and designing appropriate surge protection devices at suitable locations.



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INTRODUCTION

It is highly essential to maintain the safety and reliability of high-pressure fluid pipeline systems because the fluids may be hazardous, explosive, or poisonous and failures can lead to significant economic losses, casualties, and environmental pollution. Common reasons for pipe failures include the weakness of pipe material due to corrosion (internal and external), instability in pipe alignment, damage due to natural forces (e.g., changes in temperature, drought, wind), and poor joint connections. Transient pressures, traffic load, and aging are some of the other problems that cause pipe bursts.

Considering the impact of weather conditions, as pipes age, a collection of organic material starts to form around the walls. The composition of this organic material is bacteria and secretion by the bacteria. Some factors that increase biofilm growth are rough surfaces of the pipe wall, water temperature and pH, low chlorine level in water, and low velocities of water. Over time, this material can form pits that can penetrate the wall and cause water loss, pipe breakage, and water contamination. This will weaken the strength of pipe material; and at the time of high pressure, such as during the summer, when the pumping rate is high, the pipe will break or burst. During winter, water inside the pipe expands as it gets close to freezing, and this causes an increase in pressure. When the pressure gets too high for the pipe to withstand, it ruptures.

Therefore, failures in asbestos-cement (AC) and steel pipes are known to increase during warm periods, which often coincide with high water consumption, whereas failures of cast iron pipes increase at low

Figure 1(a) Sorang Hydro Power plant accident on November 18, 2015, in Himachal Pradesh, India. It was reported that this failure occurred because of the leakage of penstock, started at an earlier date. In addition, this hydroelectric project is located in a fragile zone where slope destabilization and landslides have been blamed on rainfall fluctuations, floods, and other natural factors.

Figure 1(b) Penstock failure at Panniyar Hydroelectric project due to leakage at the joint.

temperatures. However, the effect of weather conditions on poly vinyl chloride and polyethylene pipes are not at all significant.

By collecting and analyzing the failure data, pipeline operators can find out the causes of failure events and understand the weak points in pipeline management, which are significant for pipeline risk assessment, risk mitigation, and accident prevention. Despite the impacts of weather conditions, the main trigger of pipe failures is the flow condition called "transient flow" or "hydraulic transients," the occurrence of which is unavoidable in all hydraulic systems.

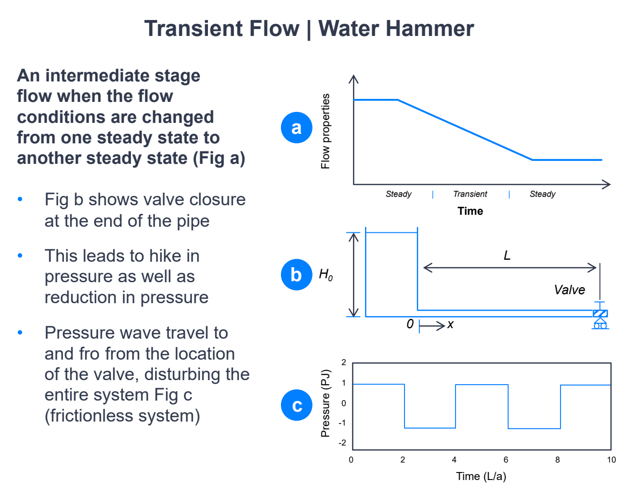
Hydraulic transients can be destructive (Fig. 1(a),(b)) by causing a catastrophic failure or a benign failure. Catastrophic failures are sudden failures such as pipe bursting/collapse, runaway pump speed, joint movement, extreme vibrations, and excessive noise. Benign failures occur over a period of time because of lining failures, pipe wall pitting, joint degradation, and repeated excessive stresses imposed upon the system. For the safe and economical design of a hydraulic system, the transient pressures should be kept within the acceptable limits.

> **The main trigger of pipe failures is the flow condition called "transient flow" or "hydraulic transients," the occurrence of which is unavoidable in all hydraulic systems.**

HYDRAULIC
TRANSIENTS

Transient flow is the intermediate-stage flow (Fig. 2), when the flow conditions are changed abruptly from one steady state to another, generally associated with a sudden change in the operating conditions used to regulate the flow. The sudden rise in pressure due to rapid flow change produces a hammering effect known as “fluid hammer.”

A typical hydraulic system consists of pumps, turbines, pipes, regulating valves, and other system components. To regulate the flow in a piping system, one has to operate flow controlling/measuring devices such as valves and flow meters. Flow operations will be gradual or sudden, depending on the requirements of the piping system. When the flow velocity changes rapidly in a hydraulic system in response to the operation of flow-control devices (for instance, a valve closure or opening, pump shutdown or trip, pump startup, or hydropower plant shutdown), pressure waves are generated from the point in the flow system where the disturbance is introduced (Fig. 3). This transient pressure wave travels from the point of generation to and fro within the system. During its travel, every point of the piping system is alternatively subjected to high and low pressure.



Transient Flow | Water Hammer

An intermediate stage flow when the flow conditions are changed from one steady state to another steady state (Fig a)

- Fig b shows valve closure at the end of the pipe
- This leads to hike in pressure as well as reduction in pressure
- Pressure wave travel to and fro from the location of the valve, disturbing the entire system Fig c (frictionless system)

Figure 2. Definition sketch of transient flow.

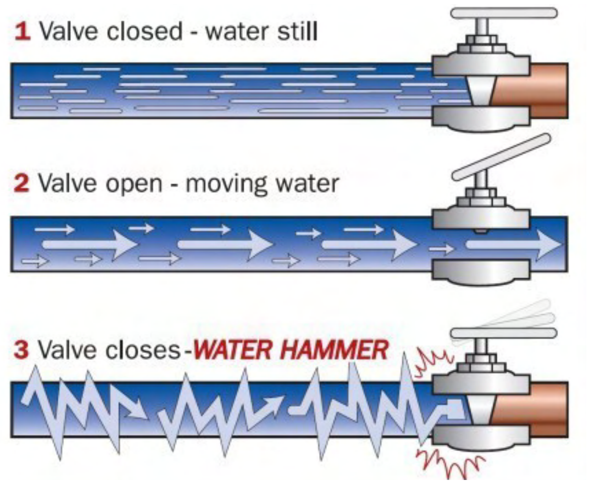


Figure 3. Occurrence of water hammer following valve closure.

Sequence of problems associated with the travel of a pressure wave

Fluid hammer:

If the high pressure generated during transient flow exceeds the safe working pressure limit of the pipe material, the pipe will burst.

Cavitation:

Gaseous cavitation: If the generated low pressure reaches saturation pressure, dissolved gases in the liquid will be released and the fluid flow becomes bubbly flow.

Vaporous cavitation: If the generated low pressure further drops from saturation pressure and becomes equal to the vapor pressure of flowing liquid, vaporization will start, resulting in vaporous cavitation (Fig. 4). Vapor bubbles will be carried away by the flowing liquid; and when the bubbly flow reaches the region of high pressure, it collapses, generating sharp high-pressure peaks that are many times higher than the transient high pressure generated earlier and are highly destructive.

Column separation:

If cavitation is prolonged (Fig. 5, 6), a vapor bubble will grow and fill the entire space, causing the liquid column to separate.

Transient Cavitation

Gaseous cavitation

Vapourous cavitation

- The formation and the growth of vapor bubbles within the liquid due to the reduction of transient pressure to the vapor pressure of liquid.

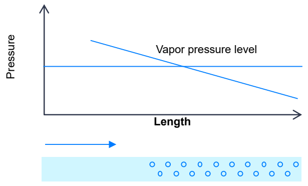


Figure 4. Schematic sketch of vaporous cavitation.

Factors affecting the bubble growth

- Force acting on the bubble due to surface tension
- Ambient liquid pressure
- Vapor pressure of liquid
- Gas pressure inside the bubble
- Time pressure history to which bubble has been exposed

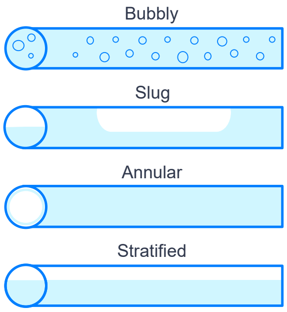


Figure 5. Factors affecting the growth of vapor bubbles.

Column Separation

The bubble formed become so large as to fill the entire cross section of the pipe and separates the conduit flow.

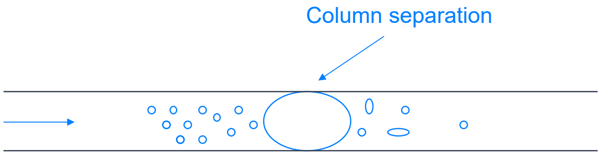


Figure 6. Schematic sketch of column separation.

Pumping Main under Column Separation

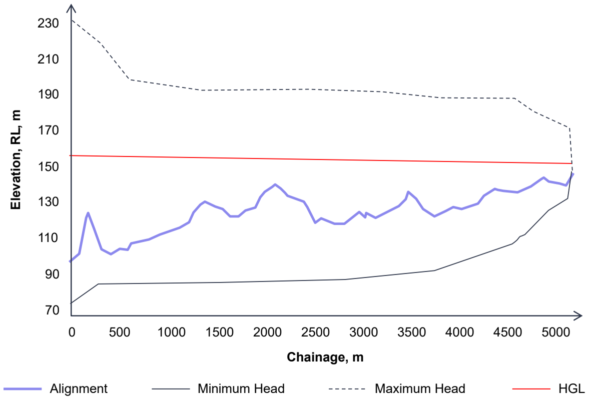
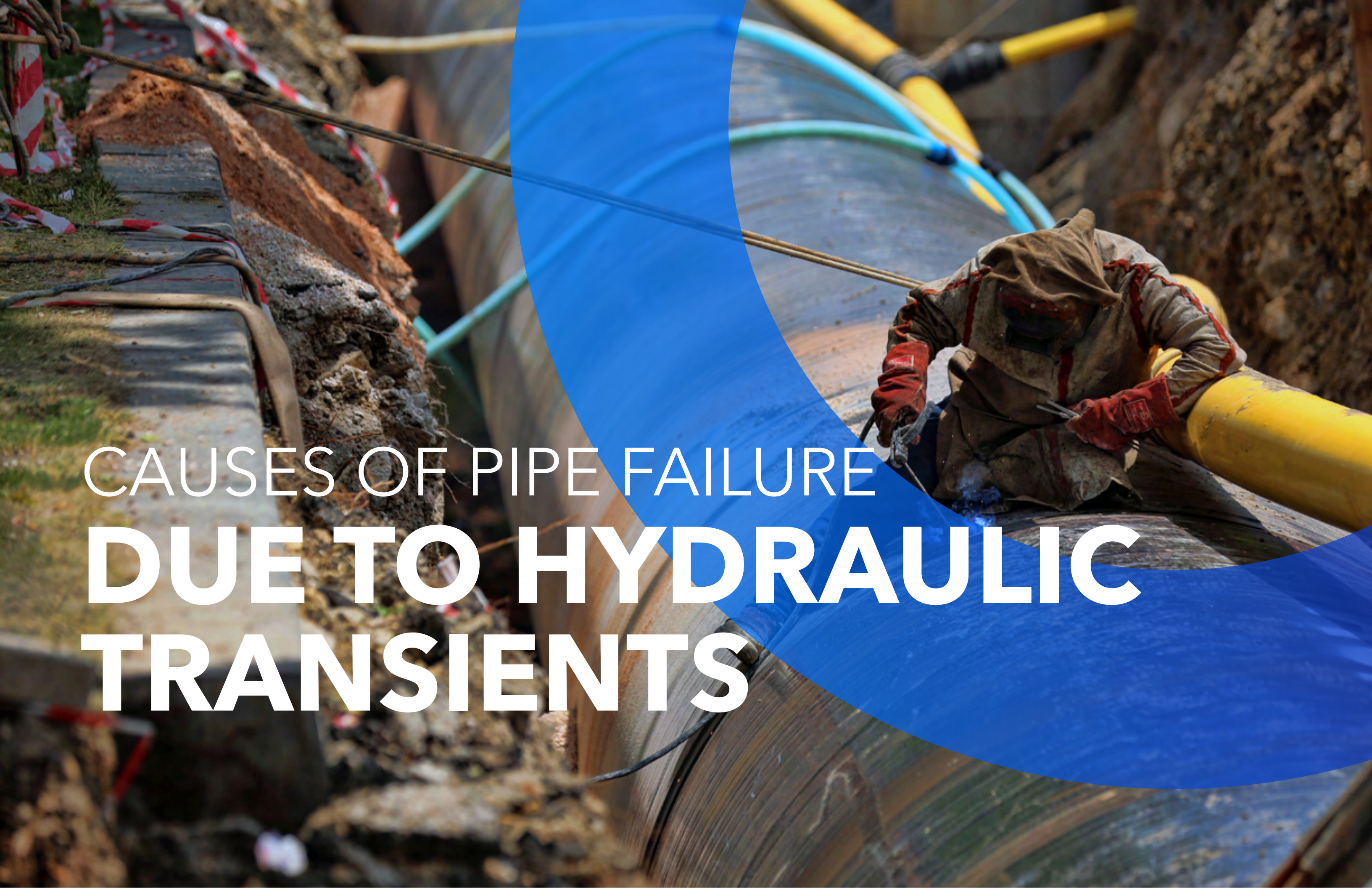


Figure 7. A typical pumping main where the chance of occurrence of cavitation is high.

> **The possibility of occurrence of cavitation, vapor collapse, column separation, and rejoining of fluid columns needs to be eliminated from all hydraulic systems. Figure 7 shows a hydraulic system (pumping main) where the probability of occurrence of cavitation and column separation are high due to pump trip because of the undulating terrain.**

Figure 7 shows maximum and minimum pressure occurring in the pumping main due to power failure. The undulating terrain promotes the chance of occurrence of cavitation and column separation followed by power failure. A large amount of energy is released as two separated columns rejoin when the pump restarts, causing an abrupt pressure surge.

Whenever a pumping main is designed, the entire hydraulic system needs to be analyzed for the transient flow condition caused by pump trip (or power failure) because it is the worst possible sudden change in the flow/ operating condition for a pumping main. Surge protection devices are selected and installed based on the maximum and minimum pressure levels following pump trip, and transient analysis is repeated again to ensure the hydraulic system is safe even in the unexpected sudden flow change. Figure 7 indicates this situation. The working of the hydraulic system is trouble-free provided that the surge protection devices are functioning properly.



CAUSES OF PIPE FAILURE DUE TO HYDRAULIC TRANSIENTS

Hydraulic transients and associated problems like vaporization, bubbly flow, cavitation, and column separation are problems that occur frequently in cross-country pipelines.

Regular events such as the opening and closing of a valve, pump startup and shutdown, and pump trip that occur during the operation of a hydraulic system trigger hydraulic transients. Normal flow conditions are disturbed, inducing alternatively high and low pressures in the system. These pressures should be kept within the acceptable limits for the continuous and trouble-free functioning of a hydraulic system.

> **Transient analysis is essential to find the maximum and minimum pressures, and their duration, that will occur at any point for the anticipated operating conditions expected during the lifetime of the system.**

Common operating conditions generating transient flow in liquid conveying systems such as water supply schemes (pumping and gravity main), the chemical and pharmaceutical industries, hydropower plants, nuclear power plants, and long oil and gas pipelines

1 Power failure to the pumping units

2 Planned or accidental opening / closing of control valves

3 Release of entrapped air or collapse of vapor bubbles

4 Load shutdown in hydropower plants

5 Planned or accidental starting / stopping of pumps

6 Instability of pumps

7 Change in pumping rate and discharge pressure of pumping stations

8 Pipeline rupture

METHODOLOGY FOR PRESSURE SURGE PROTECTION

In general, the hydraulic transients that occur from a relatively slow change in flow rate do not affect the system adversely. But a sudden change in flow rate produces a high-magnitude pressure transient wave; and if adequate protection devices are not provided, then the generated pressure waves cause the system hydraulic components to fail or rupture (pipe burst). These pressure waves travel through the pipeline of the offending device (pump, valve, etc.), and then reverse direction. The waves move at a constant speed until they meet a boundary or barrier. The reflected and incident waves superimpose to produce a more complicated wave pattern that includes double-peaks and double-troughs.

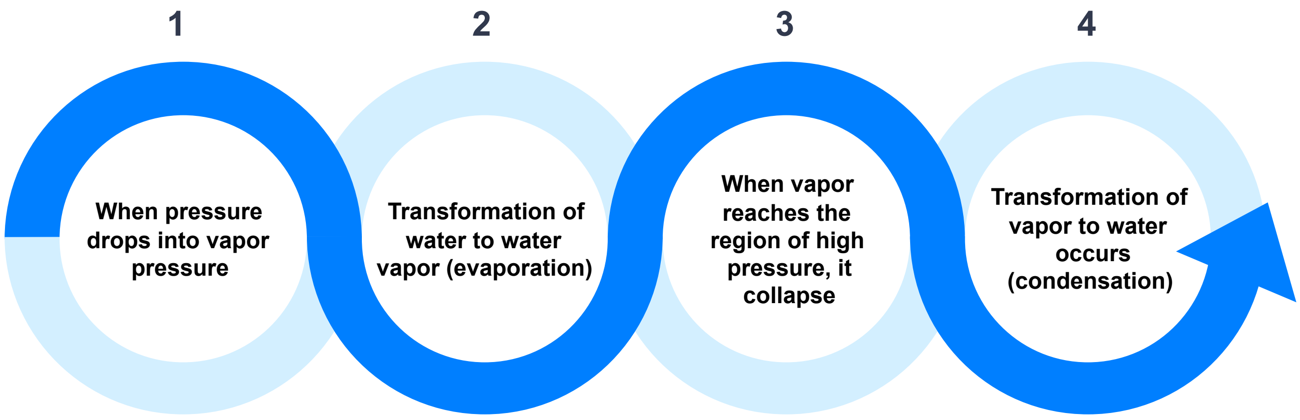
Transient flow, if not controlled, can destroy fittings, pipes, valves, instrumentation, and pumps. The consequence of improper protection from transients could be a pipe burst or equipment failure and result in damage and economic loss. The specific effects of pressure fluctuations caused by sudden flow change on piping systems depend on the type of fluid, pipe material, and operation, with pressure hikes causing pipe bursts and pressure drops causing cavitation.

Pipes that burst as a result of transients within a piping network are very common problems throughout the world. The repair work is always time consuming, and the costs of these repairs are extremely expensive. The broader consequences include inconvenience and interruption of service to customers, disruption of traffic due to road closures, fluid loss and associated costs, pump and manifold damage, and damaged pipes within the utility, to name a few.

DEFINITION

Transient cavitation: A change of phase occurs from liquid to vapor and back in a fraction of a second. This is accompanied by high-frequency pressure fluctuations. High-frequency pulses disturb the entire system, resulting in heavy noise and vibration.

Stages of cavitation:



1 **When pressure drops into vapor pressure**

2 **Transformation of water to water vapor (evaporation)**

3 **When vapor reaches the region of high pressure, it collapse**

4 **Transformation of vapor to water occurs (condensation)**

Phase change occurs	Vapor gets transported	Phase change occurs	Secondary pressure surge of high magnitude, causing surface erosion, pipe burst etc.

Cavitating flow makes problems in:

- Industrial pipe flows
- Marine propellers
- Turbo-pumps
- Fuel injectors
- Rocket propulsion systems
- Runner blades
- Hydrofoils
- Mechanical heart valves

Methodology for designing a system for safe operation:

1

Select system layout and parameters

2

Analyze system for transients caused by various possible operating conditions

3

If system performance is not acceptable, change system layout or parameters and/or provide control devices until the desired response is achieved

4

Design an overall safe, economical system

The cost of leaky pipes:

Annual costs to American households due to water and wastewater system failures was **$2 billion** in 2019. Leaking pipes lost the equivalent of **$7.6 billion** worth of treated water in 2019.

The cost of water service disruptions:

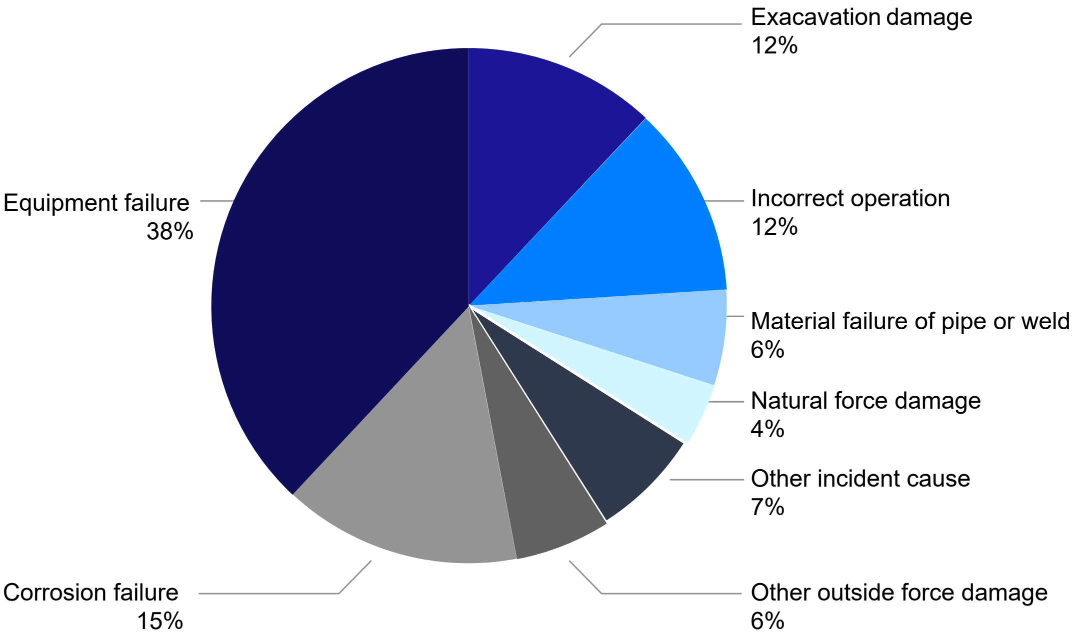
Water service disruptions resulted in **$51 billion** economic loss for 11 water-reliant industries such as education, health services, retail, construction, manufacturing and more in 2019.

The cost of pipe corrosion:

Corrosion can be a major cause of water main breaks, with **75%** of all utilities in the US and Canada reporting corrosive soil conditions in 2018. Corrosion is estimated to cost the US drinking water and sewer system sector **$79.6 billion** annually – **75%** of the annual cost of corrosion in the utilities category.

Causes of Pipeline Incidents in 2020.

Source: PHMSA, analyzed by FracTracker Alliance. Data downloaded 3/4/2021. (USA)



SURGE PROTECTION VS. FAILURE

The magnitude of the transient pressures depends on various factors, including the time and type of closure of the valve, pump characteristics, pipe characteristics, and presence of other components such as surge protection devices. Changing the operating conditions of the hydraulic system, type of pipe, pipe material, and pipe thickness modify the transient condition within the system. Protection devices to be selected for the hydraulic system are based on the transient analysis.

> **Protection devices that are poorly designed or misplaced are another potential source of trouble in hydraulic systems. The protection devices need to be designed and placed with caution to protect the hydraulic system from operating troubles and failure. Transient analysis is to be repeated again with the selected protection devices until the hydraulic system is found to be safe.**

Table 1. Primary attributes and design variables of key surge protection devices (Boulos et al., 2005)

Protection Device	Primary Attributes	Decision Variables
Check valve	• Limits flow to one direction • Permits selective connections • Prevents/limits line draining	• Size and location • Specific valve configuration • Antishock (dampening) characteristics
Pump bypass line	• Permits direct connection and flow around a pump • Can limit up-and-down surge	• Size and location • Exact points connected • Check-valve properties
Open surge tank	• Permits inflow/outflow to external storage • May require water circulation • Can limit up-and-down surge	• Size and location • Connection properties • Tank configuration • Overflow level
Closed surge tank (air chamber)	• As pressure changes, water is exchanged so the volume of pressurized air expands or contracts	• Location • Volume (total/water/air) • Configuration/geometry • Orifice/connector losses
Feed tank (one-way tank)	• Permits inflow into the line from an external source • Requires filling	• Size and location • Connection properties • Tank configuration
Surge anticipation valve	• Permits discharge to a drain • Has both high- and low-pressure pilots to initiate action • May accentuate downsurge	• Size and location • High- and low-pressure set points • Opening/closing times
Combination air-release and vacuum-breaking valve	• When pressure falls, its large orifice admits air • Controlled release of pressurized air through an orifice	• Location • Small and large orifice sizes • Specific valve configuration
Pressure-relief valve	• Opens to discharge fluids at a pre-set pressure value • Generally opens quickly and closes slowly	• Size and location • High-pressure set point • Opening/closing times

Mitigation measures

Mitigation measures such as a change in the type of pipe, pipe material, pipe alignment, or operating conditions and providing surge protection devices can be incorporated to ensure safety and economy in the hydraulic system.

- ✓ **Starting and stopping pumps:** During normal operations, pumps should be started one at a time, perhaps against a slowly opening pump-control valve, and perhaps using reduced-voltage startup. Likewise, stop pumps one at a time, perhaps using pump-control valves to slow line velocities before tripping the pump. Always open and close valves slowly.

- ✓ **Flywheels** can be added to some installations to increase the moment of inertia. Flywheels act as a source of supplemental kinetic energy that can be used to bring the system slowly to rest following power failure, thus avoiding excessively positive or negative pressures. However, pump manufacturers advise against using this method, as it reduces the efficiency of the pump.

- ✓ **A combination of air admission and release valves,** carefully sized and spaced, can be used to prevent unacceptable negative pressures. These must be carefully designed to avoid sharp pressure spikes that result when the last bit of air is expelled and a rapidly moving column of water is suddenly brought to rest.

- ✓ **Surge-relief or surge-anticipator valves** can be used in some circumstances to "shave off" high-pressure spikes. However, they do little or nothing to prevent unacceptably low pressures and the resulting column separation.

- ✓ **Surge tanks** (open to atmosphere) are effective sources of potential energy that can be adopted to minimize transient pressures. They are effective in preventing downsurges, typically caused by pump shutdown, as well as upsurges, which are caused by reverse flow or pump startup. A problem with surge tanks is that they must be as high as the hydraulic gradient, plus upsurge at that point, and these heights are usually prohibitive.

- ✓ **Surge chambers** (pressurized air vessels) require water level controls and an air compressor. This form of surge protection is frequently the most expensive surge control alternative, and space must be provided for tanks, which can be large. Also, in cold climates, tanks must be enclosed to prevent freezing. However, in general, surge chambers provide the greatest level of surge protection against both excessively positive and negative transient pressures.

- ✓ In conjunction with surge chambers, adding strategically located air valves to lift the hydraulic grade line over high points in a pipeline profile can sometimes significantly reduce the surge chamber size.

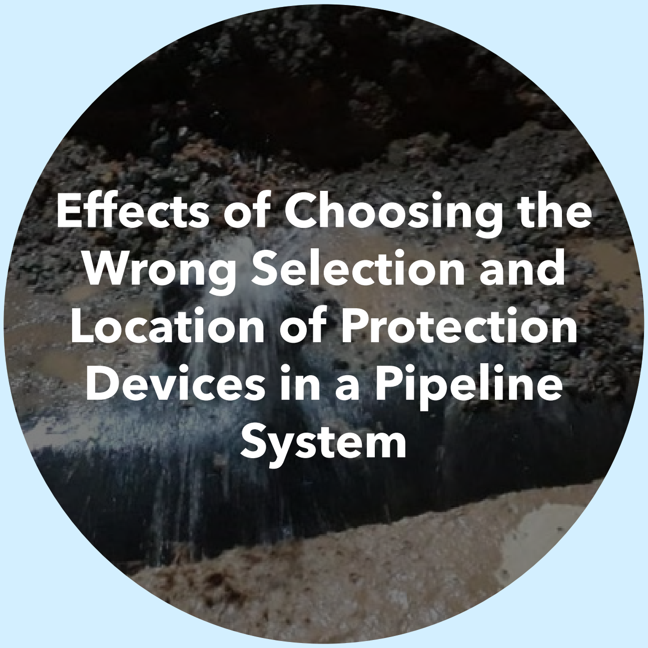
- ✓ **A pressure snubber** is a device for slowing the rate of change of system flow. Installation of a properly sized snubber can safeguard from the water hammer damage by minimizing the water hammer pressure pulse and bringing the pressure rise within safe limits.

CASE STUDIES

How transient analysis prevents the hydraulic system from experiencing pipe failure and economic losses and aids in achieving a trouble-free operating system is exemplified in the following case studies.

How Transient Analysis Prevents Hydraulic System Pipe Failure

1



Effects of Choosing the Wrong Selection and Location of Protection Devices in a Pipeline System

2

CASE STUDY 1

How Transient Analysis Prevents Hydraulic System Pipe Failure

A pumping main was discharging water 5 km away from the pump intake. Transient analysis due to pump trip was conducted and found extensive occurrence of low pressure along the pipe alignment, starting from the pumping station.

The maximum pressure caused in the system was within the working pressure of the pipes, hence the system was safe from upsurge. But the minimum pressure caused in the system was well below cavitation pressure, making the system unsafe. Extensive occurrence of cavitation was observed from the location of the pump in the system without any surge protection devices (Fig. 8). This necessitated that the system be protected from transient pressures.

Analysis showed that although the minimum pressure level rose up due to the addition of air valves at the peaks, the system was free from downsurge and safe (Fig. 9). The reliability of the air valves should have been checked with care to avoid further complicating the system behavior.

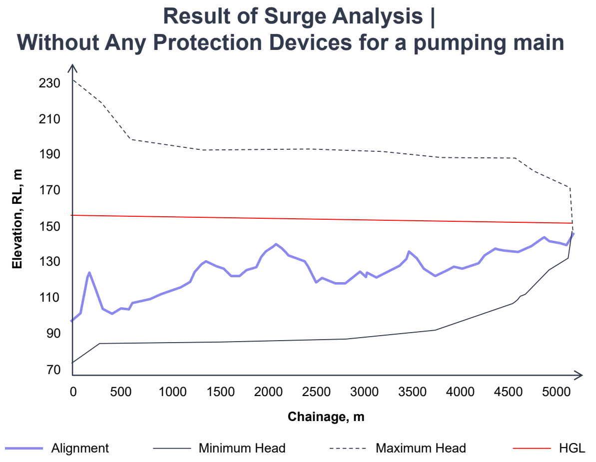


Figure 8. Maximum and minimum pressure head along the pipe alignment without surge protection.

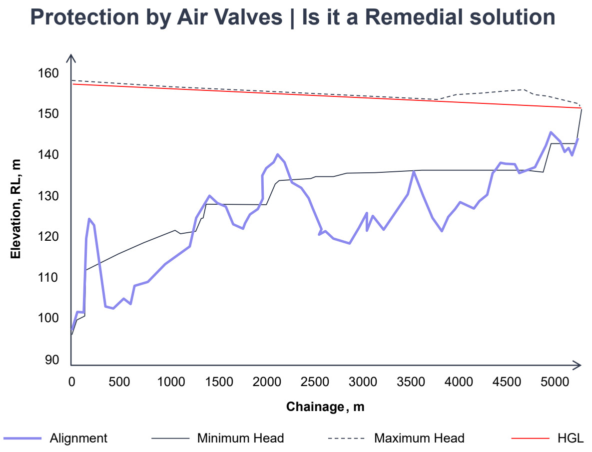


Figure 9. Maximum and minimum pressure head along the pipe alignment with surge protection by air valves at the summits of the terrain.

CASE STUDY 2

Effects of Choosing the Wrong Selection and Location of Protection Devices in a Pipeline System

This case study highlights the necessity of undergoing transient analysis to detect the wrong selection and location of protection devices for a hydraulic system and how one can make the system safe, economical, and trouble free.

The pumping main consists of two vertical turbine pumps that pump water to a water treatment plant 19.3 km away through a series of high-density polyethylene (HDPE) and mild steel pipes. The project was executed in the year 2017, and more than 50 pipe bursts occurred within 3.5 years of its launch.

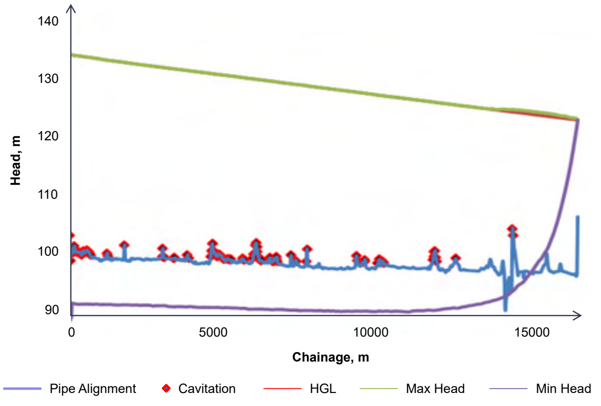


Figure 10. Pressure variation along the pipe without protection (Arunab, 2021).

System components

Pump

The intake of the pumping system is from a 10 m diameter intake well situated in the river. The free water level of the intake well is at -10.73 m. Three 240 hp vertical turbine pumps are connected in parallel, out of which one is a standby. The combined discharge of the pumps is 62 MLD. However, the pumping was reduced to 31 MLD due to frequent bursting of the pipes. The speed of the pump is 1475 rpm, efficiency was 60%, and the rated pump head is 38 m. Other relevant data are collected from specifications of hydraulic components.

Pipeline

The pipeline is a combination of both viscoelastic pipes consisting of HDPE and rigid pipes of mild steel, with a total length of 19.3 kms. A combination of PN6 PE100 HDPE pipes with a nominal diameter of 1000 mm and an individual pipe length of 12 m and mild steel pipes with a nominal diameter of 900 mm and 8 mm thickness are used in the system. The HDPE pipes are connected by fusion joints. The HDPE pipes under water are connected using sleeves. The longitudinal alignment of the pipe is as shown in Figure 10.

Transient analysis

TA non-return valve is present just downstream of the pump. Fifty-two air valves of 200 mm diameter, three sluice valves, two zero-velocity valves, and a scour valve are present in the existing pumping main, whose locations are marked in the survey details. The diameter of the zero-velocity valves is the same as that of the pipe.

A raw water pumping main should be analyzed under various scenarios causing transient flow that are possible in the system, such as pump startup, pump shutdown, and pump trip conditions. In this case study, the system was analyzed for the worst situation, i.e., pump trip. Analysis was carried out for the following situations:

1. No surge protection devices, in order to check the intensity of pressure surges
2. All the protection devices as present in the field, in order to identify the performance of each device

Initially, the hydraulic system was analyzed without any surge protection devices. Transient analysis was carried out during the simultaneous trip of both the pumps, the most severe transient flow condition that occurs for this particular system. Figure 10 shows the points along the pipeline where the pressure was below cavitation pressure.

The maximum pressure caused in the system was within the working pressure of the pipes. Hence, the system was safe from upsurge and no surge protection was needed to resist upsurge. However, the analysis shows that downsurge was prevailing near the pumping station (Fig 10). The minimum pressure caused in the system was well below cavitation pressure, making it unsafe.

The severity of pressure head fluctuations at a specific point can be understood by analyzing the pressure head vs. time curve at that point (at the pump, which is generally the location of transient flow). The transient flow in this particular system was initiated by the simultaneous trip of both the pumps, causing severe head fluctuations at the pump. The analysis shows that the pressure head at the pump dropped toward vapor pressure and needed protection against downsurge.

To rectify the problem and prevent pipe burst, transient analysis was repeated with the existing installed surge protection devices. The analysis shows that the system was safe (theoretically, for the combination of 52 air valves and 2 zero-velocity valves) as shown in Figure 11. However, the system continues to experience frequent pipe bursts, as previously mentioned.

Although the system appears to consist of the usual configuration of pumping mains, to solve the problem, checking the feasibility of the selection of protection devices and their locations is recommended.

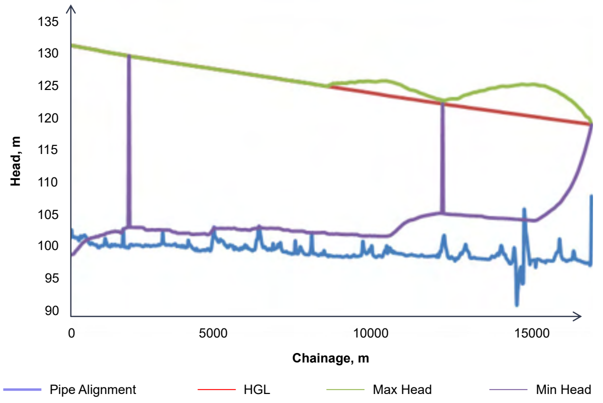


Figure 11. Pressure head along the pipe alignment with surge protection devices (52 AVs and 2 zero-velocity valves) (Arunab, 2021)

Critical observations for the selection of surge protection devices for this hydraulic system

1. Upsurge is not a problem. Maximum upsurge coincides with the hydraulic gradient line even without any surge protection devices and is within the limits of the working pressure of the pipe material (Fig. 10 and 11). Hence, zero-velocity valves (mainly suitable for upsurge) are not necessary.
2. Placing 52 air valves at various locations of the pipe alignment (including summits) was unable to solve the problem of cavitation nearer the pump (Fig. 11).
3. The pressure variation near the pump (Fig 11) shows that the pressure fluctuations are comparatively less and the system is safe from cavitation. However, the existing hydraulic system is still experiencing frequent pipe burst (Fig. 12).

From the analysis, it is evident that the system is experiencing problems due to downsurge pressures. However, the upsurge pressure is below the working pressure of the pipes. In general, zero-velocity valves are provided to protect the hydraulic system from upsurge. However, such a protection device is unsuitable in this particular hydraulic system.

This case study also considers the feasibility of the number of air valves and their locations. Ramezani et al. (2015) reports that the number, location, type, and inflow and outflow diameter of air valves used can significantly affect the primary and secondary transient pressures within a hydraulic system. Hence, transient analysis should be repeated, identifying the key positions and removing the air valves from the system one by one. The main locations for air valves are high elevation areas and knees. Based on this, analysis was repeated with 8 air valves.

Figure 12(a). Burst pipe at a low pressure region of the pumping main.

Figure 12(a). Burst pipe at a low pressure region of the pumping main.

The analysis shows that the system protected with 8 air valve devices is not safe. Several regions in the pipeline near the pump are under cavitation pressure. On comparing the transient analysis of the system protected by 52 air valves to the system protected by 8 air valves, it was found that the performance of the system for both situations are similar. The comparison shows that the remaining 44 air valves present in the existing hydraulic system are absolutely unnecessary. The analysis needed to be continued to understand the number and location of air valves or other surge protection devices required to make the system safe. Transient analysis was repeated, and final analysis showed that the hydraulic system with 2 air valves at two different locations was able to limit the downsurge, as shown in Figure 13. The analysis shows that the system protected with the above combination of surge protection devices is safe from transient pressures.

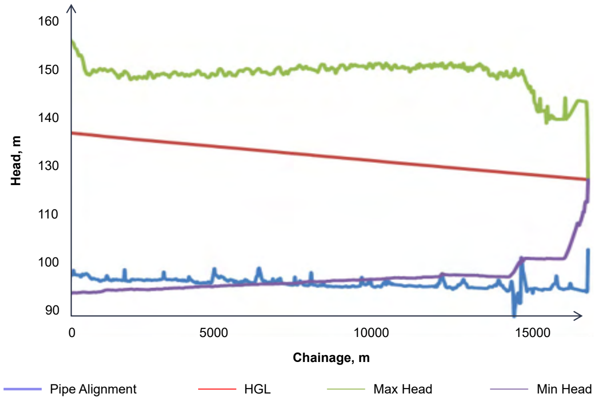


Figure 13. Pressure variation along pipe alignment with surge protection devices (2 air valves) (Arunab, 2021).

The highest pressure occurring in the system is 51.28 m of water column, which is within the working pressure of the pipes. Hence, the system is safe from upsurge pressure. The lowest pressure occurring in the system is -6.5 m of water column, which is higher than -7.3 m, hence the system is safe from cavitation also. Additionally, pressure fluctuations at the pump are within safe limits.

Economic loss due to improper selection of surge protection devices

The transient pressures occurring in a system directly affect the overall cost of a hydraulic system. The pipe type, pipe material, grade of pipe, type of surge protection device, and its size and location can be scientifically fixed after the transient analysis of the proposed system at the design stage. Pipes and surge protection devices hold a major share of the total project cost.

Scientifically selecting these will ensure an economic and safe hydraulic system. Randomly selecting pipe and surge protection devices without proper knowledge of the behavior of the hydraulic system during transient flow will lead to operational troubles in the system and may lead to failure of the system.

This not only disrupts the intended purpose of the system but also increases the cost encountered for the repair and replacement of the damaged components. For a project like a raw water pumping main, failure or operational trouble leads to social problems also. The cost details of the surge protection devices mentioned in this study are provided in Table 2. The total cost of the surge protection devices used in the case study and the cost of those used in an optimized hydraulic system are provided in Table 3. The total cost savings for the surge protection devices in an optimized system are USD $14,000.

Table 2. Price details of surge protection devices

Surge protection device	Specification	Price (USD)
Air valve	200 mm	$147
Zero velocity valve	1000 mm	$3,333

Table 3. Total cost of surge protection devices.

System	Surge protection devices	Total cost (USD)
System in case study	52 air valves and 2 zero-velocity valves	$14,293
Optimized system	2 air valves	$293

Case Study 2 Conclusions

The raw water pumping main in Case Study 2 consists of a non-return valve, 52 air valves, and 2 zero-velocity valves for protection from hydraulic transients. From the transient analysis conducted, it is evident that a comparable degree of protection can be achieved by providing just 2 air valves at key locations.

The hydraulic analysis of this particular system indicates that installing air valves at unsuitable locations invites extreme transient pressures within the system. The zero-velocity valve is a costly device that reduces the working head and causes economic losses. Unnecessarily providing protection devices leads to economic losses, complex behavior of the system, and operational problems. These complexities are likely to be the cause of frequent bursts in the pipeline, as shown in Figure 14.

Figure 14. Pipe burst due to malfunctioning of surge protection devices.

The pipes bursting in Figure 14, as well those in Figure 12, occur because of the low pressure (negative pressure wave). This type of failure occurs in a water supply scheme when a pump restarts and is working with full pressure after a power failure. This type of problem also will occur when the air valves are not working properly, as when they allow air entry following pump trip to prevent the occurrence of vacuum at summit but are unable to expel air as per design at the time of pressure rise when the pump restarts.

KEY TAKEAWAYS
FOR A SAFE AND ECONOMICAL HYDRAULIC SYSTEM

The general criteria adopted for a safe and economical hydraulic system are:

- Transient analysis should be carried out for large hydraulic systems to understand the complex behavior of the system under various operating conditions that are likely to occur multiple times during its life cycle. This can reduce the overall cost of the project and ensure safe, trouble-free working of the hydraulic system.

- The profile of the ground operational conditions of the hydraulic system and the type of pipe used are the major influencing factors of the behavior of the hydraulic system. Changes implemented to these should be a primary concern in ensuring the safety and economy of the hydraulic system.

- The effects of a surge protection device in a particular system need to be studied thoroughly in designing the device to check its suitability for that system and determine its location.

- Unnecessarily providing protection devices leads to complexities that are likely to be the cause of frequent bursts in the pipeline.

- A complete transient analysis of a hydraulic system can be done with a small fraction of the resources (time, data, money) required for the entire project, can reduce the overall cost of the project and provide a safe hydraulic system, which ensures trouble-free working of the hydraulic system.

- A thorough study of the behavior of a hydraulic system during transient flow helps water resource managers, engineers and designers to plan, design and develop a safe and economic hydraulic system.

NEW
TECHNOLOGY SOLUTIONS

Any method that can proactively act to moderate factors such pressure and changes in the flow rate can make the system safe in real time. Until recently, electromechanical controls have been utilized. The advent of new technologies like the Internet of Things (IoT), machine learning (ML), and deep learning (DL) have revolutionized the control system for water supply to a great extent.

The IoT is a system of interrelated sensing devices with unique identifiers so that each system can be directly connected to a network and be able to transfer data over the network without requiring human-to-human or human-to-computer interaction. IoT devices share the data they collect through an IoT gateway or other edge device where the data is either sent to cloud servers before analysing or is analyzed locally. Sometimes these devices interact with other related devices and act on the information they get from one another. These devices do most of the work without human intervention, although people can interact with the devices; for instance, to set them up, give them instructions, or access the data and even link to remote stations such as hydropower plants, cross country oil piping systems, and nuclear power plants. These systems can be effectively used for managing the system in real time. A few examples are provided here.

IoT and ML/DL for efficient control of water supply system over undulating terrain

A network of pipes for water supply is spread over an undulating terrain with many valves. An undulating terrain makes the actual pressure inside the pipe vary drastically because of elevation change and varying demand from different portions. If proper balancing has not been carried out by controlling the valves in real time, connections in certain high-elevation areas will be deprived of supply due to inadequate pressure. If the system is equipped with IoT-enabled pressure sensors, this data can be received in real time to a processing center. Partial closing of valves that supply water to low lying areas can bring back the pressure in high-elevation areas and avoid such interruption. The partial shutting of the valve can be carried out by employing either a system using a rule-based approach or a system based on ML/DL. Machine learning and deep learning systems try to achieve the capability of the human brain in making decisions, of course in a limited manner, by using the concept of learning from examples.

IoT and ML/DL for efficient control of water hammer

IoT and ML/DL can also be used for controlling the water hammer in a piping system. The data regarding pressure fluctuations at salient points corresponding to the change in flow rate can be detected by IoT sensors in real time and can be transferred to the processing center. using the concept of learning from examples.

The processing center can take corrective measures in real time. For example, at the onset of pressure rise, the bypass valves can be operated before the surge reaches critical locations. Also, the system can send instructions to the surge protection devices so they are actuated to control the surge. As previously mentioned, the control system can be either rule-based or ML/DL-based. Thus, a sustainable trouble-free hydraulic system can be established without human intervention. Importantly, transient analysis should be conducted in the same system initially to generate the data that will be used to train the ML/DL-based control system for better response. Many commercial software platforms are available for conducting transient analysis in a piping system.

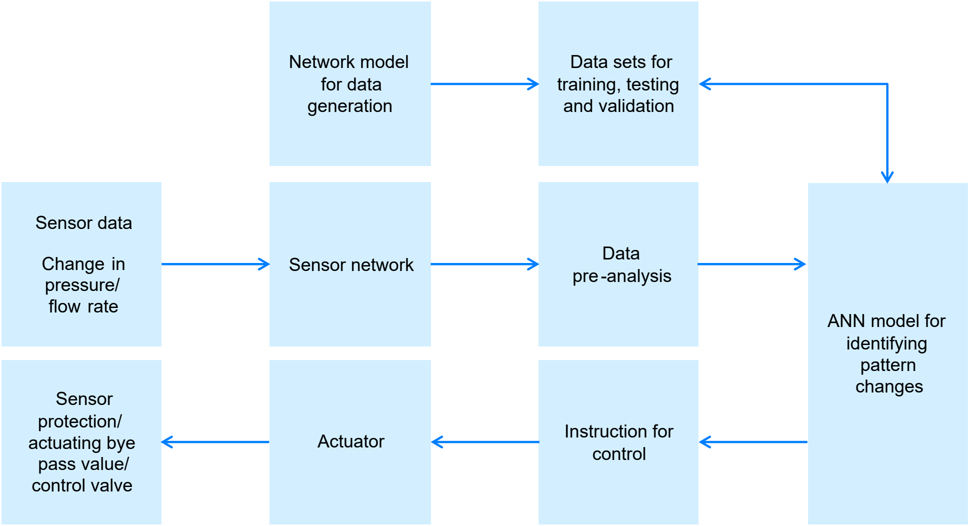


Figure 15. IoT and ML/DL-based architecture.

IoT and DL for detecting leaks in a supply system

Leaks in a piping system can change the pressure at salient points. The change in pattern of pressure at these points can be utilized for detecting the pressure variation. IoT can record the pressure and transfer the data in real time to a data processing center. The advent of ML/DL has opened an avenue for detecting the pattern changes, and this technique can be used for identifying the presence and location of leaks from the change in pattern of pressure at salient points. Figure 15 depicts IoT and ML/DL-based architecture.

Belsito et al. (1998) and Barradass et al. (2009) detected the location and size of the leaks in a pipeline by using an artificial neural network (ANN) (a deep learning structure). Bohorquez et al. (2020) presented an innovative transient-based technique that used ANN to identify topological elements such as junctions in water pipeline networks and the characteristics of leaks. In this technique, the pressure head data of consequent transient events are required for the training and testing of the ANN and are obtained from numerical models of transient flow.

USE CASES

xylem
Let's Solve Water

Xylem announced on **September 22, 2021,** that their AI-driven predictive modeling services helped the City of Raleigh Public Utilities Department (Raleigh Water) get a clearer picture of its 2,340 miles of aging pipeline system. Xylem's sensors and advanced risk analytics combined with Esri's location intelligence software enabled Raleigh Water to more accurately and quickly identify potential trouble spots. Xylem reported that "deciding which water mains to replace took 75% less time than in the past, while also reducing unnecessary capital costs and water loss from pipe failures."

EMERSON.

Colombia's 484-mile-long Centro Oriente natural gas pipeline is a complex system traversing diverse, often rugged terrain at the base of the Andes Mountains. To ensure high-integrity information gathering and transmission, the operator deployed **Emerson's Remote Automation** Solutions, including the OpenEnterprise SCADA package for data acquisition, continuous monitoring, and control capabilities.

senet
the *sensible* network company

In 2018, Western Municipal Water District in Riverside County, California, implemented **Neptune's Advanced Metering Infrastructure** with network design and deployment services provided by Senet. Powered by **Senet's** cloud-based network management system, the system provides for long-range connectivity, maximizing network performance. Benefits include cost savings, optimized service delivery, and a reduction in water loss from 12% to less than 3.5%.

AFT
Applied Flow Technology

The British engineering consultancy company Hatch used **AFT Impulse** software to perform a transient analysis on a complex water injection system located offshore Brazil in order to resolve an overpressure safety issue caused by subsea valve operations. The Hatch engineer was able to effectively model adjustments to significantly improve runtime, and the recommended valve closure combinations successfully resolved the surge issue.

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