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Comprehensive Approach to Surge Protection in Lift Irrigation Rising Mains: A Case Study

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Abstract:
***Background**: Lift irrigation systems are vital for agricultural productivity, often relying on extensive rising mains to transport water over varying terrains. However, these systems are highly susceptible to hydraulic transients, commonly consider as water hammer or surge, caused by sudden switches in flow velocity due to pump trips, valve closures, pump start up or power failures. Such pressure surges may be direct to catastrophic pipe bursts, equipment damage, and significant operational downtime, jeopardizing water supply and incurring substantial repair costs. This paper presents a comprehensive review of various scenarios contribute to the water hammer effect and strategies for effective surge protection in lift irrigation rising mains. This paper aims to provide engineers, designers, and system operators with a holistic framework for enhancing the reliability, longevity, and operational efficiency of lift irrigation infrastructure, ultimately contributing to sustainable water management.*
***Methodology:** To comprehensively study transient events and their implications, analysis is initiated by simulating various scenarios of transient events in the piping system. The primary goal was to thoroughly understand the intricate impact of the water hammer phenomenon. The initial step involved performing an analysis without any surge protection, specifically focusing on the critical scenario of all pumps tripping due to a power failure. This crucial preliminary analysis allowed us to precisely pinpoint locations where both maximum and minimum pressures deviated beyond acceptable operational limits. Following this foundational understanding, then proceeded to identify and determine the most effective anti-surge devices specifically tailored to mitigate these identified transients within the rising main.*
***Results**; Through rigorous transient simulations utilizing Hammer software, we established that a 55 m³ Compressed Air Vessel (with six air valves) or a 50 m³ Bladder-type Air Vessel (with six air valves) demonstrably provides the necessary capacity to effectively mitigate the severe transient pressures induced by pump trips due to power failures.*
Keywords– Hydraulic transient, protection devices, method of characteristic, Bentley hammer

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I. Introduction:

Lift irrigation schemes have become increasingly vital, particularly in regions where challenging topography prevents traditional gravity-fed irrigation using rivers and stream water. Over the past five decades, these schemes have seen massive development, significantly boosting agricultural economies by enabling water access to previously unfeasible areas. This method involves lifting water from continuing sources like rivers using powerful electric pumps and then distributing it through pipelines to adjacent fields within a designated command area. However, the very nature of these pressurized systems makes them highly susceptible to pressure transients, commonly known as water hammer or surge. These dynamic pressure fluctuations frequently arise in multiple water sources networks including lift irrigation schemes and thermal power stations—and are primarily triggered by events such as power failures, Operational sequences for pump start-up and shut-down, sudden valve closures, and check-valve slam. Inadequate transient protection can result in serious outcomes, such as water column separation and the catastrophic failure of the piping network. Therefore, transient analysis of water conveying systems is crucial for accurately predicting peak and minimum transient pressures during abnormal operations. This allows for the establishment of robust design criteria for system equipment and protective devices, thereby ensuring effective protection against system failure.

1.1. Water hammer phenomenon

The "water hammer phenomenon," also known as hydraulic shock or fluid hammer, is a critical concern in fluid conveyance systems, particularly in pressurized pipelines. It describes a sudden and often violent pressure surge or wave that propagates through a fluid when its flow is abruptly forced to stop or change direction. Imagine a column of water flowing steadily through a pipe. If a valve at the end of this pipe is suddenly closed, the moving water has significant momentum. Since liquids are largely incompressible, this momentum cannot simply vanish. Instead, the sudden stoppage causes the kinetic energy of the fluid to transform rapidly into pressure energy, creating a high- pressure shockwave that travels upstream, reflecting off closed ends and junctions, and then returning downstream. This rapid oscillation of pressure waves can be likened to a "hammering" sound within the pipes, hence the name "water hammer." The key factors contributing to water hammer are sudden valve closures, Rapid pump trips or shutdowns, Pump start-ups**,** Power failures Air within pipe line**.**

1.2. Effects of Water Hammer on the Pipe

The consequences of water hammer can range from annoying noises and vibrations to severe damage. The intense pressure spikes can easily exceed the pipe's design pressure, leading to Pipe bursts or ruptures**,** Equipment damage**,** Joint and connection leaks, Pipe deformation and support damage and cavitations.

1.3. Devices to control pressure surges in pipelines

The primary types of surge control devices used in pipe line to mitigate the damaging effects of water hammer or hydraulic transients are as follows

a) Air Vessels (Hydro pneumatic Tanks / Bladder Surge Tanks): These are sealed tanks partially filled with air (or a pre-charged bladder separating air from water) and connected to the pipeline. When a positive pressure surge occurs, water rushes into the tank, compressing the air and absorbing the excess pressure. During a negative pressure surge (down surge), the compressed air expands, pushing water back into the pipeline, preventing vacuum conditions and water column separation. It is very effective for both upsurges and down surges, provide flexible response, and can be designed for various capacities.

b) Surge Tanks (Open Surge Tanks / Stand-Pipes): These are open-to-atmosphere tanks directly connected to the pipeline. During an upsurge, water flows into the tank, allowing the pressure to dissipate. During a down surge, water flows from the tank into the pipeline, preventing low pressures. They essentially provide a free surface for the pressure wave to reflect off. It is very effective for both upsurges and down surges but only suitable where the pipeline's hydraulic grade line is relatively low (to avoid excessively tall tanks

c) Air Valves (Air Release, Vacuum Breaker, Combination Air Valves): Air Release Valves: Automatically vent accumulated air pockets from high points in the pipeline. Trapped air can exacerbate water hammer and reduce flow efficiency.

- **Air Release Valves:** Automatically vent accumulated air pockets from high points in the pipeline. Trapped air can exacerbate water hammer and reduce flow efficiency.
- **Vacuum Breaker Valves:** Allow atmospheric air to enter the pipeline when internal pressure drops below atmospheric. This prevents vacuum conditions and water column separation, which can cause severe secondary surges when the separated water columns rejoin.
- **Combination Air Valves:** Incorporate both air release and vacuum breaking functions in a single unit. These valves **r**elatively inexpensive, crucial for preventing vacuum and air-related issues and can primarily act to prevent column separation.

d) One-Way Surge Tanks (Feed Tanks): These tanks are similar to open surge tanks but are equipped with a check valve that only allows water to flow into the pipeline. Their primary purpose is to prevent initial low pressures and water column separation by providing a rapid supply of water when a down surge occurs. It is best for preventing cavitation and column separation but do not protect against high-pressure surges.

II. Mathematical Formulation:

Unsteady flows of compressible liquids within elastic pipes are described by a system of two partial differential equations: the momentum equation and the continuity equation. This model operates under several key assumptions: the liquid is considered slightly compressible, meaning its density changes minimally even with substantial pressure variations. Additionally, changes in the pipe's cross-sectional area, though finite, are assumed to be small and directly linked to pressure changes. Transient conditions in these systems are typically analyzed using the **Method of Characteristics (MOC)**.

Momentum equation: $$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Continuity equation: $$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\cdot\frac{\partial Q}{\partial x} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where, H = Total head or energy grade;
Q = Discharge through pipe;
x = distance along the conduit
t = time;
g = gravitational constant;
A = cross sectional area of the conduit
D = diameter of the conduit;
f = Darcy-Weisbach friction factor
a = celerity of a compression wave travelling through the conduit

These momentum and continuity equations form a set of non-linear, hyperbolic partial differential equations that are analytically intractable. While the coefficients of the PDEs are constant (making them quasi-linear and hyperbolic), the non-linear nature of friction losses necessitates a numerical solution. Solving these equations requires an initial condition and two boundary conditions. For complex water distribution systems, numerous additional parameters are required to address water hammer phenomena, with each system branch demanding an extra boundary condition. External boundary conditions typically involve a driving head or flow exiting the system, while internal boundary conditions account for nodal continuity, energy losses between points, and head changes across components like valves and pumps.

III. Case Study:

The Wardha Barrage project lift irrigation scheme -1 is located near village Yarandgaon, taluka Babhulgaon of Yavatmal district in Maharashtra State. This scheme proposes lifting water from Wardha barrage through pumping for irrigation of G.C.A. 7855 hectares of land. The first distribution point is situated roughly 5850 m from the lift point. An intake structure is located in the barrage wherein four Submersible centrifugal pumps (SCF) are installed to pump water through single rising main of 1040 mm diameter and 5850 m long. The total discharge of four pumps is 1.75 m^3/s and total static lift from pump sump to delivery chamber is 36.33 m whereas the total head of pump is 53.97 m. At the other end, the pipe delivers water into a delivery chamber where the flow transitions from closed conduit to an open channel. Subsequently, Water travels by gravity through a network of canals to the command area. Figure -1 below shows the rising main profile of Wardha Barrage Lift Irrigation Scheme and figure -2 depict the Steady state hydraulic grade line (HGL) along with pipeline profile.

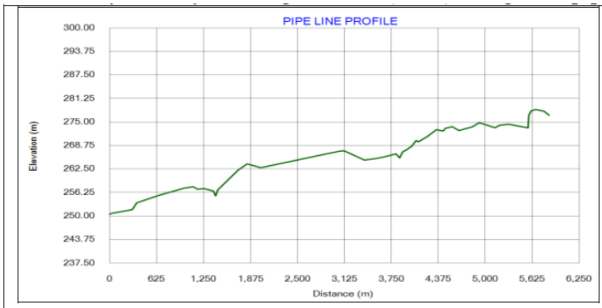

Fig. 1: Rising main profile of Wardha Barrage Lift Irrigation Scheme

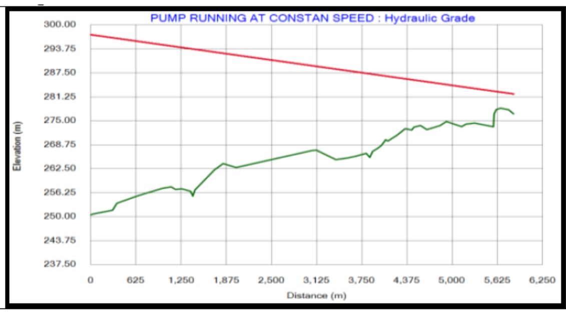

Fig. 2: Steady state hydraulic grade line (HGL) along with pipeline profile

IV. Analysis and Discussions:

Using the data provided by the project authorities, the pipeline system is simulated under various circumstances for non-protected and protected conditions. For pipelines without protection, when power failure occurs abruptly the check valves close upon that failure. Concurrently, the flow velocity rapidly reaches zero and then flows backward, negative pressure waves are prevailed downstream from the pump, and positive pressure waves are prevailed up- stream through the suction pipe. In addition, vapour pressure and column separation may occur in the discharge pipelines. The boundary condition for the analysis was the tripping of pump due to power failure with discharge pipe NRV of the closing time of 1.0 seconds. The NRV slams and is intended to close automatically immediately subsequent to the power failure. For the evaluation of transient events that is caused by pump failure, four different scenarios were taken in consideration to study the impact of phenomenon of the water hammer on the piping system. For studying transient events, four different scenarios were taken in concern to study the impact of phenomenon of the water hammer on the piping system. These scenarios are:

- Steady State Analysis

- ➢ Transient Analysis without any surge protection (Pump Start-Up, Single Pump Failure, Two Pumps Failure, Three Pumps Failure, Four Pumps Failure)
- ➢ Transient Analysis with Surge Protection of Compressed Air Vessel with Air Valves
- ➢ Transient Analysis with Surge Protection of Bladder type Air Vessel with Air Valves)

IV.1. Steady State Analysis

In a water conducting system, steady-state analysis helps determine the pressure distribution when water flows steadily through the network. Steady-state analysis is carried out to understand the system's behaviour under continuous operation with constant inputs to evaluate pressure, flow rates and other relevant quantities. These simulations use specified boundary conditions and network element set points to estimate the hydraulic state of a pipeline system operating at equilibrium. The main purpose of steady-state analysis in pipelines is to evaluate system behaviour under constant operating conditions**.** Here are some key reasons for performing steady-state analysis:

IV.2. Transient Model Analysis

The main objective of transient model analysis is:

a) Evaluate Transient Pressure Responses: Assess how the system reacts to instantaneous changes in flow conditions, focusing on both high and low transient pressures.

b) Analyze Worst-Case Scenarios: Identify the most severe conditions that could occur in the pipeline system without any surge protection.

c) Effectiveness of Surge Protection Devices: Determine how various surge protection devices can mitigate the effects of transient pressures under the worst-case conditions.

Procedures of Transient Modelling:

a) Without Surge Protection: Initial simulations were conducted to establish baseline transient pressure responses under critical operational scenarios.

b) With Surge Protection: Subsequent simulations incorporated various surge protection devices to evaluate their effectiveness in reducing transient pressures.

• **Transient Analysis without any surge protection**

The transient analysis of the irrigation pipeline system is conducted without any surge protective devices during various pump failure scenarios and a pump start-up event to highlights significant pressure variations and potential issues that necessitate surge protection. The HGL along with air/vapor volume variation graphs for critical scenarios of single pump failure, two pumps failure, three pumps failure, four pumps failure and pump start-up event are shown in figures 3,5,7,9 and 11 and the corresponding transient pressure variation graphs are depicted in figures 4,6,8,10 and 12 respectively.

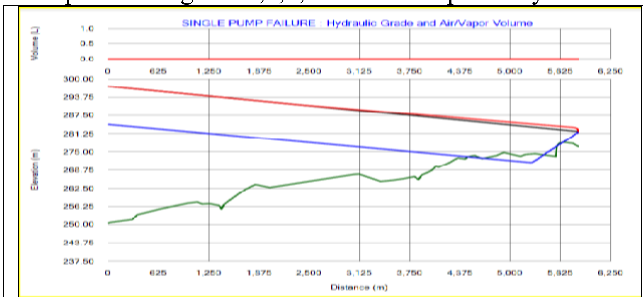

Fig.3: HGL along with Air/Vapor volume variation plot without any surge protection throughout the rising main (Single Pump Failure)

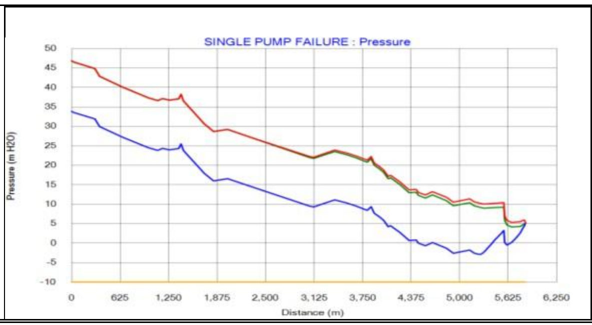

Fig. 4: Pressure variation envelope plot without any surge protection throughout the rising main (Single Pump Failure)

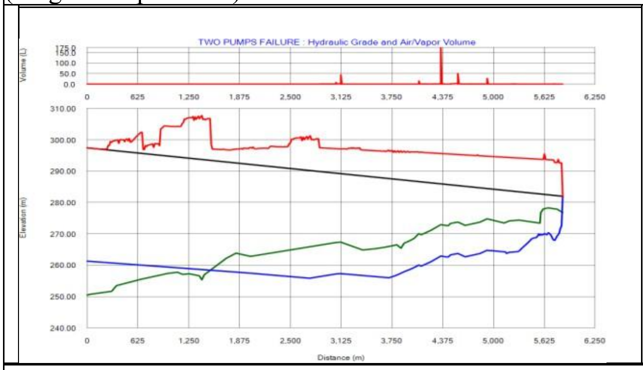

Fig.5: HGL along with Air/Vapor volume variation plot without any

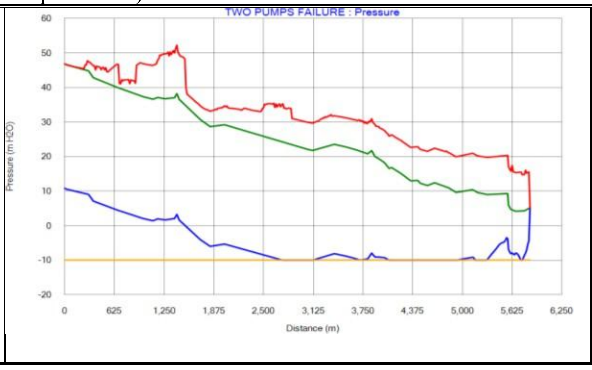

Fig.6: Pressure variation envelope plot without any surge protection

surge protection throughout the rising main (Two Pumps Failure)	throughout the rising main (Two Pumps Failure)

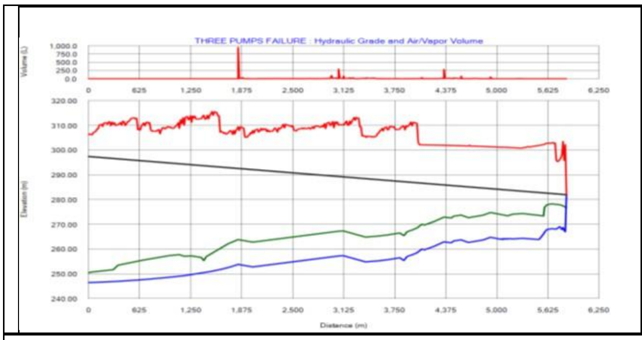

Fig.7: HGL along with Air/Vapor volume variation plot without any surge protection throughout the rising main (Three Pumps Failure)

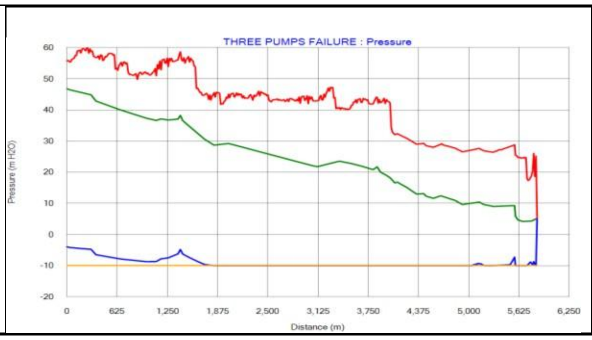

Fig. 8: Pressure variation envelope plot without any surge protection throughout the rising main (Three Pumps Failure)

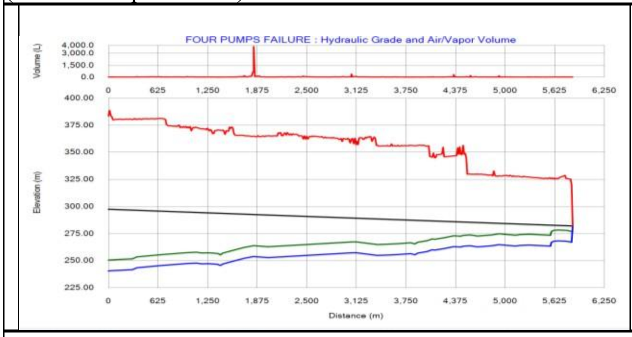

Fig.9: HGL along with Air/Vapor volume variation plot without any surge protection throughout the rising main (Four Pumps Failure

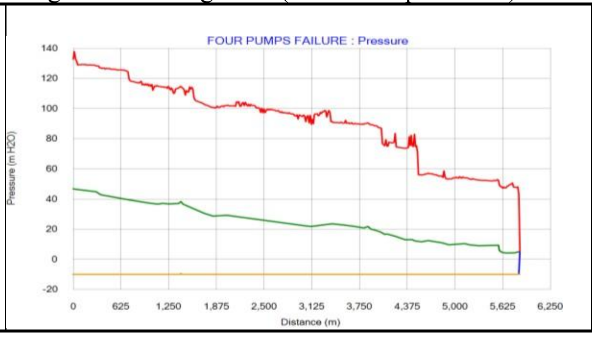

Fig.10: Pressure variation envelope plot without any surge protection throughout the rising main (Four Pumps Failure)

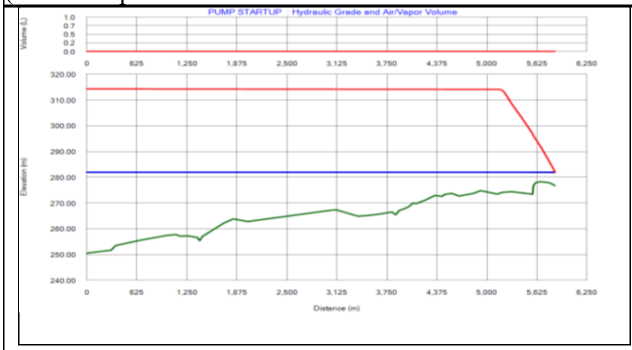

Fig.11: HGL and Air/Vapor volume plot without any surge protection throughout the rising main (Pump Start-Up)

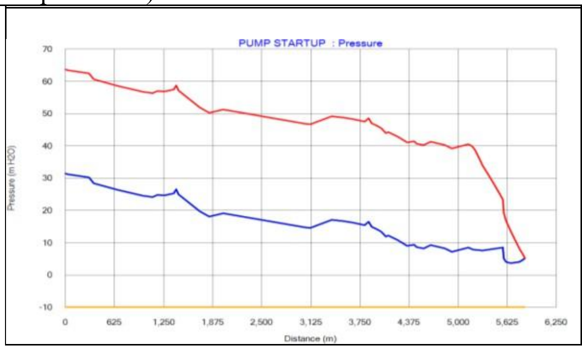

Fig.12:Pressure variation envelope plot without any surge protection throughout the rising main (Pump Start-Up)

The following are the key observations from the above graphs presented in the Table -1.

Table -1: Surge summary of different scenarios of pump failure without any surge protection

Sl. No	Description of study	HGL variation in meters of water column		Pressure variation in meters of water column		Air/Vapor volume
		Maximum	Minimum	Maximum	Minimum	
1	Single pump failure (**Three Pump Operational)**	297.45 to 282.0	284.41 to 271.38	47.0 to 5.0	-3.0 to 34.0	Nil
2	Two pumps failure (**Two Pump Operational)**	307.73 to 282.0	255.88 to 282.0	52.0 to 5.0	-10.0 to 11.0	174.5 ltrs at a chainage of 4350 m
3	Three pumps failure (**One Pump Operational)**	315.59 to 282.0	246.50 to 282	60.0 to 5.0	-10.0 to 5.0	948.5 Ltrs at chainage of 1830 m

4.	Four pumps failure (**All Pumps failure)**	388.64 to 282.0	240.46 to 282.0	138.0 to 50.0	-10.0 to 5.0	3870.0 Ltrs at a chainage of 1830 m
5	Pump Start up	314.30 to 282.0	281.86 to 282.0	64.0 to 5.0	31.0 to 4.0	Nil

Ultimately, it is found that the detailed surge analysis has been carried out during tripping of all pumps due to power failure which is the worst-case scenario than the other cases of pump failures and pump start up event. The detailed surge analysis for these circumstances is essential to find out the appropriate type and size of surge protection devices needed for the system. Implement surge protection devices such as air chambers, surge tanks, or air valves to mitigate the impact of pressure transients and protect the pipeline infrastructure. Without these devices, the system is vulnerable to hydraulic shocks, cavitation, and damage resulting from extreme pressure fluctuations.

• **Transient Analysis with Surge protection of rising main with compressed Air Vessel of 55 m^3 Capacity and air valves of 6 Nos.**

With the above configuration, further the analysis was carried out with compressed air vessel of 55 m^3 along with the air valves of -6 Nos. The variation of HGL and Pressure from the transient analysis is plotted in figures 13 and 14 respectively. Also, the variation of gas pressure and gas volume inside the air vessel are shown in figures 15 and 16 respectively.

Finally, after thorough analysis, it has been determined that incorporating a 55 m³ capacity compressed air vessel at a chainage of 10 meters, combined with the installation of six kinetic air valves of size 100 mm at strategic apex points along the rising main, will adequately address and mitigate transient pressures resulting from pump trips due to power failures. Also, sufficient reserve volume of water is available after the down surge event. This configuration has been shown to effectively stabilize pressure fluctuations and protect the system from potential damage associated with sudden changes in pressure.

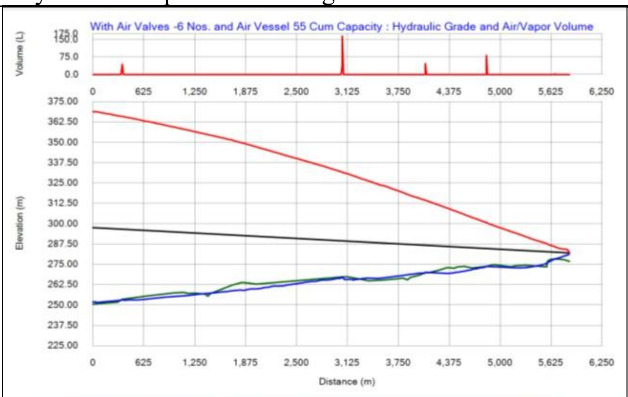

Fig. 13: HGL variation and Air/Vapor volume plot with a surge protection of air vessel of 55 m^3 capacity and air valves -6 Nos. throughout the rising main

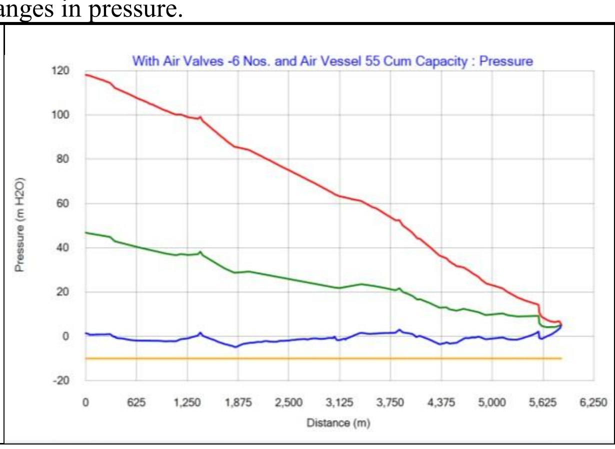

Fig. 14: Pressure variation envelope plot with a surge protection of 55 m^3 capacity air vessel and air valve-6 Nos. throughout the rising main

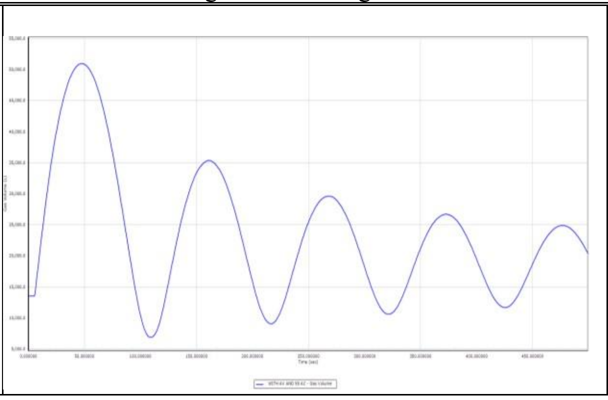

Fig. 15: Variation of Gas volume inside the air vessel

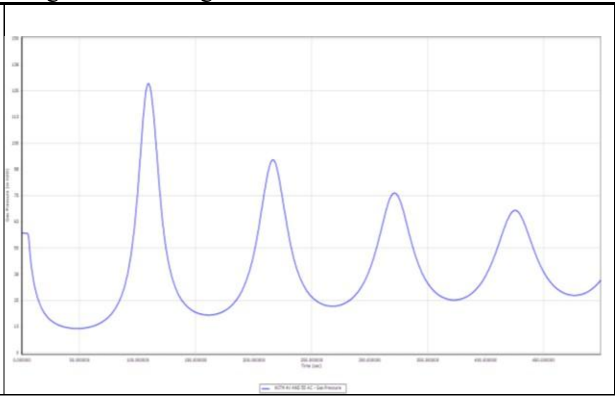

Fig. 16: Variation of Gas Pressure inside the air vessel

- **Transient Analysis with Surge protection of Bladder type Surge vessel throughout the Rising Main with Air Valves**

Incorporating a compressed air vessel as a surge protection system can add complexity to the overall system, but it can also offer significant benefits in managing pressure fluctuations and reducing the risk of damage. This air vessel might require additional components like pressure regulators, compressor to maintain pressure, pump to maintain water level, valves, and monitoring equipment etc. To manage the reserve volume of water and prevent air entrapment during down surge event, the size of the vessel is critical. A larger vessel can provide more reserve volume, reducing the risk of air being entrapped. However, this must be balanced against cost and space constraints.

To overcome the above draw backs, further analysis has been carried out using bladder type air vessel. The primary component of a bladder-type surge vessel is the flexible bladder or diaphragm, typically made of rubber or synthetic materials. This bladder separates the air chamber from the water chamber within the vessel, offering several advantages over traditional surge vessels. The variation of HGL and Pressure are shown in figures 17 and 18 respectively. Also, the variation of gas volume and gas pressure in the bladder vessel are shown in figures 19 and 20 respectively.

Finally, after thorough analysis, it has been determined that incorporating a 50 m³ capacity of bladder type surge vessel at a chainage of 10 meters, combined with the installation of six kinetic air valves of size 100 mm at strategic apex points along the rising main, will adequately address and mitigate transient pressures resulting from pump trips due to power failures. Also, sufficient reserve volume of water is available after the down surge event. This configuration has been shown to effectively stabilize pressure fluctuations and protect the system from potential damage associated with sudden changes in pressure.

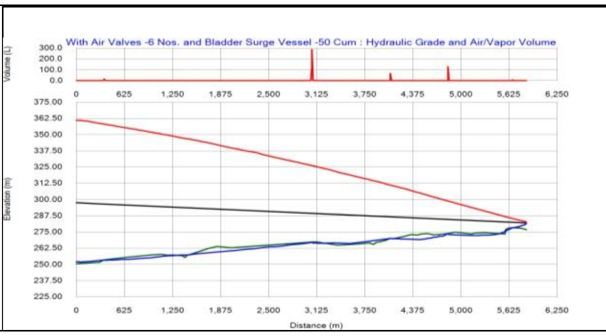

Fig. 17: HGL variation envelope and Air/Vapor volume plot with a bladder surge vessel of 50 m³ and air valves -6 Nos. throughout the rising main

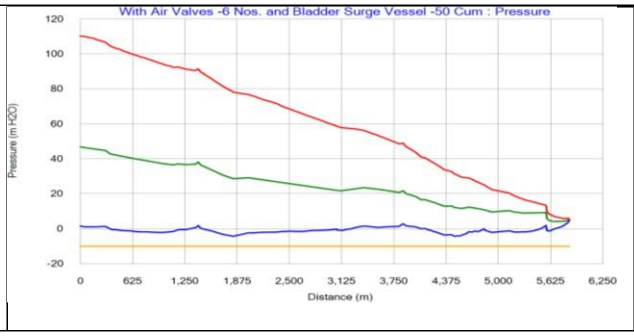

Fig. 18: Pressure variation envelope plot with bladder surge vessel 55 m³ capacity and air valves -6 Nos. throughout the rising main

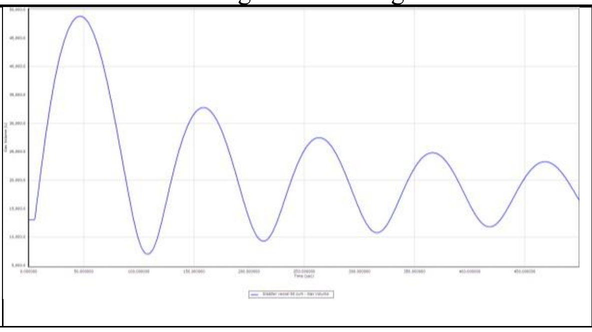

Fig. 19: Gas Volume variation inside the 50 m³ bladder surge vessel

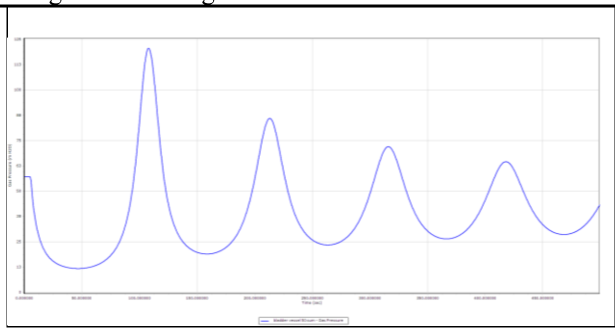

Fig. 20: Gas Pressure variation inside the 50 m³ capacity bladdder surge vessel

V. RECOMMENDATIONS:

Based on multiple transient modelling simulations, the study recommends the following options for surge protection:

Option 1: A compressed air vessel with a capacity of 55 m³, paired with six double-acting kinetic air valves of 100 mm in size. The pressure variation at the starting of chainage i.e., Ch. 0.0 m with surge protection of 55 m³ capacity compressed air vessel and without any surge protection is shown in figure 21.

Option 2: A bladder-type surge vessel with a capacity of 50 m³, also coupled with six double-acting kinetic air valves of 100 mm in size. The pressure variation at the starting of chainage i.e., Ch. 0.0 m with surge protection

of 50 m³ capacity bladder type air vessel and without any surge protection is shown in figure 22.
Among these options, compressed air vessels are often preferred in high-pressure, high-capacity, or rugged environments due to their durability, maintenance requirements, and overall longevity. However, the best choice depends on the specific needs and constraints of application and the overall cost of the project. The surge analysis summary is presented in Table -2.

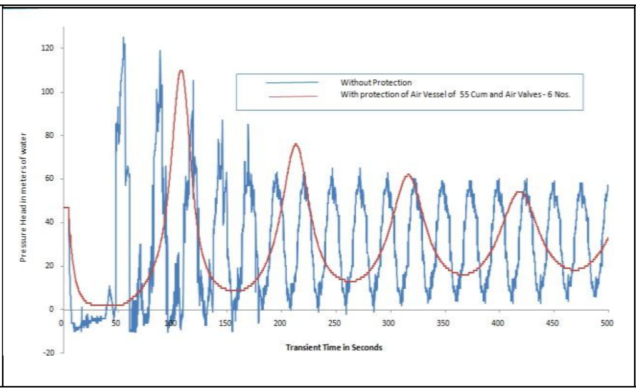

Fig. 21: Pressure variation without and with protection of 50 m^3 capacity compressed air vessel

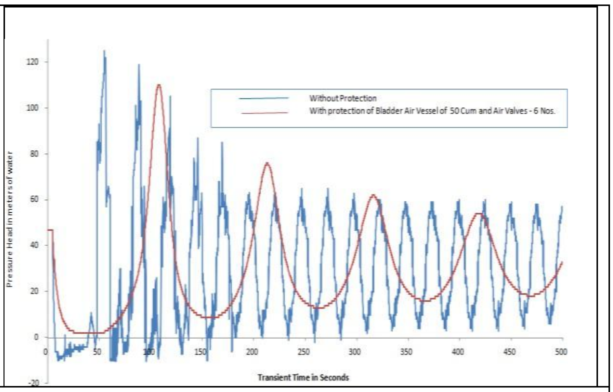

Fig.22: Pressure variation without and with protection of 50 m^3 capacity Bladder surge vessel

Table - 2
Surge Summary Report

	Description of case study	Maximum Pressure variation along rising main in meters of water column		Minimum Pressure variation along rising main in meters of water column		Limitting value of pressures in meters of water column	
		Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
	Transient analysis without any surge protection						
1	Tripping all pumps due to power failure	138.0	5.0	Well below the vapor pressure head of -10.0 meters of water column		165.0	- 9.5
Transient analysis with surge protection							
2.	Transient analysis with surge protection of Compressed air vessel of 55 Cum and air valves of 100 mm – 6 Nos. (Option 1)	118.0	5.0	- 5.0	5.0	165.0	- 9.5
3.	Transient analysis with surge protection of Bladder type surge vessel of 50 Cum and air valves of 150 mm – 6 Nos. (Option 2)	110.0	5.0	- 4.0	5.0	165.0	- 9.5
9.0	Final conclusion	Both are recommended but choosing an option based on cost analysis					

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