AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT
ADDIS ABABA UNIVRSITY

Analyze and comparison of steady state and transient pressure for DCI and HDPE pipelines using the Finite Element Method and Bentley Water Hammer software

By:

Fayera Mosisa OLjira

A Master's thesis submitted to Africa Center of Excellence for Water Management, Addis Ababa University in partial fulfillment of the requirements for The Degree of Master of Science in Water Management (Water supply and Sanitation)

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School of Graduate Studies

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Declaration

I, Candidate's Fayera Mosisa (Id No:GSR/7598/13), hereby declare that this MSc research thesis titled *"Analyze and comparison of steady state and transient pressure for DCI and HDPE pipelines using the Finite Element Method and Bentley Water Hammer software"* has been developed by me and has not been submitted to any other institution for award of any academic qualification. The content of the dissertation has not been plagiarized and where works of other researchers have been used, they have been appropriately cited.

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APPROVED BY BOARD OF EXAMINERS

This is to certify that we have read this MSc research and that in our opinion; it is fully adequate, in scope and quality, as a Master's thesis for The Degree of Master of Science in Water Management (Hydrology and Water Resources).

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ACRONYMS

AWWA	American Water Works Association
HBS	Brinell hardness
C	Hazen-Williams Roughness Coefficients
CFD	Computational Fluid Dynamics
CPVC	Chlorinated polyvinyl chloride
DCI	Ductile casted iron
Di	internal diameter
DI	Ductile iron
DLF	Dynamic load factor
E	East
ETB	Ethiopian Birr
FEM	Finite Element method
FE	Finite element
fps	Feet per second
HDPE	High Density poly ethylene
H_20	water
GPa	Giga pascal
GPS	Global positioning system
Km	kilometre
Kg/m2	kilogram per meter
L	litter
LOLP	Loss-of-load probability
m	Meter
mwc	Meter of water column
m3	cubic meter
m2	square meter
mm	millimetre
N	North
ND	Nominal diameter
MOC	Method of Characteristics
mpa	Mega Pascal
ND	Nominal diameter
Q	Discharge flow rate, m3/s

P	Pressure
Pa	Pascal
PN	Nominal pressure
PE	polyethylene
PN	Nominal pressure
PEX	Cross-Linked Polyethylene
P_{max}	Maximum pressure, Pa
P_{min}	Minimum pressure, Pa
PVC	polyvinyl chloride
UPVC	Unplasticized Polyvinyl Chloride
Psi	pounds per square inch
Rpm	Rotation per meter
SCADA	Supervisory Control and Data Acquisition
TDR	Time domain reflectometry
TWSP	Town Water Supply Project
V	Water velocity
WCM	Wave characteristics method
%	percentage
°C	degrees Celsius
°F	degree Fahrenheit

Abstract

Water hammer is a common issue in water pipelines; and cause significant damage and disruption. This study focuses on the Dire Dawa city water supply project, analyzing three transmission lines between booster pump station and service reservoirs. These lines are particularly vulnerable to water hammer, as their operation is influenced by the water levels in the two reservoirs at either end.

Most existing research focuses on either DCI or HDPE pipelines individually, lacking a comprehensive comparative analysis of their performance under steady-state and transient conditions. This gap limits the understanding of how these materials respond to different operational scenarios. The novelty of this study lies in the combined use of advanced simulation techniques (FEM and Bentley Water Hammer) to directly compare DCI and HDPE pipeline behaviours under both steady-state and transient pressure conditions, as well as hydrostatic pressure resistance, by considering detailed material properties. This integrated approach provides a more reliable understanding than previous isolated studies.

This study aims to analyze and compares the transient and steady-state pressure and structural responses of DCI and HDPE pipes. A quantitative research approach examines cause-and-effect interactions among variables. Bentley Water Hammer and FEM (Abaqus) software are used to simulate transient pressure and hydrostatic forces, respectively. Abaqus was chosen for its detailed stress analysis, crucial for safety; while Bentley Water Hammer was selected for its accuracy and user-friendly interface. Input data for the simulations are sourced from the Dire Dawa City Water and Sewerage Authority.

The study results indicate that transient pressure higher than steady-state pressure up to 127.63%. Both DCI and HDPE pipes showed the same steady-state pressure across all lines. However, HDPE pipes demonstrate advantages over DCI pipes by reducing the effects of transient pressure by up to 118.3%. Additionally, surge tanks reduce the transient pressure by 128.9% for DCI pipe and 11.7 % for HDPE pipe. When both pipes have the same nominal pressure and size, HDPE pipes experience stress levels that are 64.7% higher than those of DCI pipes.

The study finds that transient pressure exceeds steady-state pressure and is a key factor in pipe network design for setting nominal pressure. HDPE pipes demonstrate superior resistance to transient pressure compared to DCI pipes. Incorporating appropriate water hammer protection devices significantly enhances pipe performance. For the Dire Dawa city pipeline, HDPE can replace existing DCI pipes of the same nominal pressure. Further research, including laboratory models, is needed to fully understand steady-state and transient pressures in DCI and HDPE pipes.

Key Word: Water hammer, Steady state, transient, HDPE, DCI, Bentley water hammer, FEM

1. INTRODUCTION

1.1. Background

Improved and sustainable water supplies are significantly enhances a community's economic growth, and reduces poverty (Duan et al., 2014; Faouzi et al., 2021). Transmission main line investment cost is relatively high and requires cautious operation, protection and risk mitigation. One of the most significant hazards is the water hammer phenomenon (Aref M et al., 2021).

Water hammer or hydraulic transient is a pressure surge or wave instigated when flow condition, velocity or discharge suddenly changed with time. Water hammer accident causes the significant reduction and increase of water pressure in the pipeline, which seriously endangers the safety of water supply projects. The main causes of water hammer are Pump start-up/shutdown, Pump power failure, sudden Valve opening/closing, rapid change in demand in certain locations, and Change in transmission (Aly et al., 2019; Alawa L et al., 2015; Hussain, 2014).

Water hammer or hydraulic transient pressure is one of the major problems that can cause severe damage or failure to the overall piping system either due to a singular event or cumulative damage occurring over time. Water hammer has been responsible for water distribution network component failure, pipeline breakage or collapse, pipe fatigue, fracture of brittle components and piping, plastic deformation of ductile piping, and small to large leaks of piping, valves, flanges, and components, loose at connections, and intrusion of dirty water into the water distribution system. Water hammer is considered to be a threat to the public in terms of cost, health and safety (Wood et al., 2005; Leisher, 2018; Lokesh K et al., 2015).

High density polyethylene (HDPE) pipes were preferred to avoid negative pressure waves to drop to the saturated vapour pressure of the water which form a cavity in the fluid. Other strong pipes networks with high Young's modulus must employ systems to help control increase and decrease in pressure due to water hammer (Gad at el., 2014; WL Plastics manufacturer, 2022; Aly at el., 2019).

Water hammer protection devices are used to ensure the running security of piping system and electromechanical equipment. The most commonly used water hammer protection devices are air vessels, surge tanks, one-way surge tanks, Valves Pump, bypass around the pump, water hammer arrestor and air valves. Appropriate protection measures can be selected according to the characteristics of different projects. Also, joint protection schemes with multi devices were proposed for long-distance water supply systems (Miao et al., 2017; Wang et al., 2019; Shi et al., 2021).

Transient water hammer analyze is essential to verify design and operation of piping systems to define safe operation guidelines of the systems in advance (Ali, 2021; Carlsson, 2016). The most significant equation for transient flow in a pipe is Joukowsky (1898). Water hammer analyze can be done by software simulation and numerical method. Numerical analyze considers the appropriate initial and boundary conditions in which pressure and flow are variables dependent upon position and time. It used three Eulerian and two Lagrangian methods (Boulos et al, 2006). Bentley Water hammers, AFT Impulse, Computational fluid dynamics (CFD) are the popular and powerful dynamic simulation and analyze software used to calculate pressure surge transients (AFT Impulse Version 10, 2023; hammer, 2014; Aly at el., 2019). Bentley Water Hammer has chosen for its comprehensive approach to simulate the complex hydraulic behaviour of water distribution systems, leading to more accurate and reliable transient pressure simulations compared to simpler or less specialized software. The integration of GIS data, user-friendly interface, and visualization tools further enhance its practicality and usability (*Water Hammer, 2014).*

FEM (Abaqus) has ability to handle complex geometries, non-linear material behaviour, various boundary conditions, and load combination that makes it a superior method for simulating hydrostatic forces in pipelines compared to simpler analytical methods. The detailed stress and strain analysis it provides is essential for ensuring the safety and reliability of pipeline systems (*Reddy, 2006).*

Dire dawa city transmission lines were selected as case study for this study as it is subject to transient effect because of it is between two end reservoirs with high elevation difference. A quantitative research approach is used to examine and describe cause-and-effect interactions among variables. Required data were collected from the town water and sewerage authority. Bentley water hammer V8i and a FEM/abaqus software simulation were done to analyze and compare the transient and steady state pressure and structural responses for DCI and HDPE pipes.

1.2. Statement of the Problem

Water hammer/hydraulic transient pressure cause significant damage and disruption in the water supply transmission pipe lines. The hydraulic transient pressure analyze is compulsory work in water supply pipe network design in adding to steady state pressure analyze. The common question in water supply pipe network design are the hydraulic transient and steady state pressure relation, DCI and HDPE pipes transient pressure resistance capacity and their structural response against hydrostatic load.

The efficient design and operation of pipeline systems are critical for ensuring reliable fluid transport in various applications. DCI and HDP are commonly used materials for pipelines now days, each with distinct mechanical properties and behaviours under pressure. However, there is limited comprehensive research comparing the steady-state and transient pressure dynamics of these materials using advanced simulation techniques.

Existing studies often address either steady-state or transient conditions in isolation for both pipes, neglecting a holistic view of how these materials respond to different operational scenarios.

This study addressed steady state and transient pressure relation, structural response against hydrostatic load and effectiveness of surge tank in reduction of hydraulic transient pressure in HDPE and DCI pipes by using the Finite Element Method (FEM) and Bentley Water Hammer software simulation.

1.3. Research Questions

The study was under taken to answer the following questions.

- What is DCI and HDPE pipes capability in resisting the hydraulic transient pressure?
- What is the steady state and hydraulic transient pressure relation?
- What is DCI and HDPE pipes structural responses under application of hydrostatic pressure?

1.4. Objective

General objectives

The general objective of this study is to analyze and compares the transient and steady state pressure and structural responses for DCI and HDPE pipes by using Bentley water hammer and finite element method (Abaqus).

Specific objectives

The specific objectives of the studies are*:*

- To compare transient and steady state pressure for HDPE and DCI pipes.
- To analyze the DCI and HDPE pipes structural response against transient pressure/dynamic forces.
- To evaluate the use of surge tank in reduction of transient pressure for both HDPE and DCI pipes.

1.5. The Significance of the Study

This study enhances the understanding of transient pressure behaviour in DCI and HDPE pipes under both operational conditions with and without surge tanks. Through a comprehensive comparison of these pipe materials, the study will assist engineers and decision-makers in selecting the most appropriate materials for specific project during design, operation and maintenance. The integrated *use* of FEM and Bentley Water Hammer software represents a methodological advancement in hydraulic engineering simulation, offering robust and validated approach simulation techniques in hydraulic engineering. The findings explain the strengths and weaknesses of each method, guiding future research and practical applications in the field. The insights gained will have significant implications for the design, operation, and maintenance of water distribution networks. By validating simulation results with real-world data, this research aims to bridge the gap between theoretical modeling and practical application. Ultimately, this study will address existing gaps in the literature regarding comparative analyses of pipe materials, providing a valuable resource for future research in hydraulic engineering and related disciplines.

1.6. Scope of the Study

This study specifically focuses on the simulation of Ductile Cast Iron (DCI) and High-Density Polyethylene (HDPE) pipes within the context of the Dire Dawa city water supply system. The scope is limited to three transmission lines that are critical to the overall functionality of the water supply network.

To achieve the objectives of the study, two advanced software tools were employed: the Finite Element Method (FEM)/Abaqus 2011 and Bentley Water Hammer v8i, 2014 softwares. FEM was utilized for its superior capabilities in conducting detailed structural analysis, particularly in assessing the impacts of hydrostatic and transient pressures on the pipeline materials. This method allows for a comprehensive examination of the internal stresses that develop under varying pressure conditions.

Bentley Water Hammer software was employed to analyze transient pressure scenarios both with and without the incorporation of surge tank provisions. This dual approach enables a thorough investigation into how transient pressures affect pipeline integrity and performance, providing insights into the effectiveness of surge tanks in mitigating pressure fluctuations.

The study seeks to compare both steady-state and transient pressures within the pipelines, highlighting the differences in performance between DCI and HDPE materials. Specifically, it examines the ability of each material to resist transient pressures and the internal stresses induced by hydrostatic pressure. By focusing on these critical factors, the research aims to offer valuable insights for engineers and decision-makers involved in the design and management of pipeline systems.

2. Literature Review

2.1. Introduction to Water Hammer

Water hammer is a pressure wave that occurs, accidentally or intentionally, in a filled liquid pipeline when flow speed or volume changed. Water hammer, also known as hydraulic transient, is a kind of hydraulic network disruption caused by an abrupt cessation in flow (Ammer, 2014).

The description of water hammer from a physical point of view takes its starting point in Newton's second law, which expresses that force equal mass time acceleration. This means that severe water hammer occurs where large masses of fluid are given high accelerations (Larsen, 2012).

Water hammer is produced by a rapid change of velocity in pipelines; it can be caused by a sudden valve opening or closure, starting or stopping pumps, mechanical failure of a device, rapid changes in demand conditions, etc. (White, 1979). It could result in rapid changes to the pressure head which is then propagated through the pipeline in the form of a fast pressure wave that can lead to severe damage (Parmakian, 1963).

The opening of a control valve affects the hydraulic characteristics of flow and water hammer phenomenon. In addition, check valves that suddenly close create significant effects on the formation of transient (unsteady) flow in pipes (Bergant, 2006). The materials used in the pipeline also have remarkable effects on pressure values during check valve closure (Mansuri et al., 2014).

When water flows under pressure in a closed conduit (pipeline), the laws governing the changes of pressure and velocity along the pipe depend upon the conditions under which the flow occurs. If the water is considered to be incompressible and the discharge remains constant, the steady flow energy equation can be used to analyse the energetics of the flow at any given two cross-sections in the conduit. However, when the motion is unsteady, that is, when it varies rapidly from one instant to the next at any given location in the conduit. Rapid pressure changes can occur and the steady flow energy equation is no longer applicable. Such rapid fluctuations in pressure are referred to as “hydraulic transients”, commonly known as “water hammer” because of the hammering sound that often accompanies the phenomenon (Parmakian, 1963).

A water pipes system’s operating condition is almost at unsteady state. Pressures and flows change continually as pumps start and stop, demand fluctuates, and tank levels change. In addition to these normal events, unforeseen events, such as power outages and equipment malfunctions, can sharply change the operating conditions of a system. Any change in liquid flow rate, regardless of the rate or magnitude of change, requires that the liquid be accelerated or decelerated from its initial flow velocity. Deep changes in flow rate require high forces that are seen as large pressures, which caused water hammer. Entrained air or temperature changes of the water also can cause excess pressure in the water lines. Air trapped in the line will compress and will causes extra pressure on the water.

Temperature changes will actually cause the water to expand or contract, also affecting pressure. The maximum pressures experienced in a piping system are frequently the result of vapour column separation, which is caused by the formation of void packets of vapour when pressure drops so low that the liquid boils or vaporizes. Damaging pressures can occur when these cavities collapse (Parmakian, 1963).

Common system damages due to fluid transients, or water hammer, include pipe fatigue, fracture of brittle components and piping, plastic deformation of ductile piping, and small to large leaks of piping, valves, flanges, and components. The extent of water hammer damages is immense, in U.S. and Canada water main pipes more than 250,000 failures occur per year alone. The diversity of water hammer damages extends across many industries; from oil pipelines, to chemical plants. Water hammer directly caused 69.5% of water main breaks, or cracks, in U.S. and Canadian piping, i.e., fatigue failures (Leisher, 2018).

A less severe form of hammer is called surge, a slow-motion mass oscillation of water caused by internal pressure fluctuations in the system. This can be pictured as a slower “wave” of pressure building within the system. Both water hammer and surge are referred to as transient pressures. If not controlled, they both yield the same results: damage to pipes, fittings, and valves, causing leaks and shortening the life of the system. Neither the pipe nor the water will compress to absorb the shock so that the water hammer caused by the uncompressed ability of any liquid or water passing through the pipe system (Kredi, 2018).

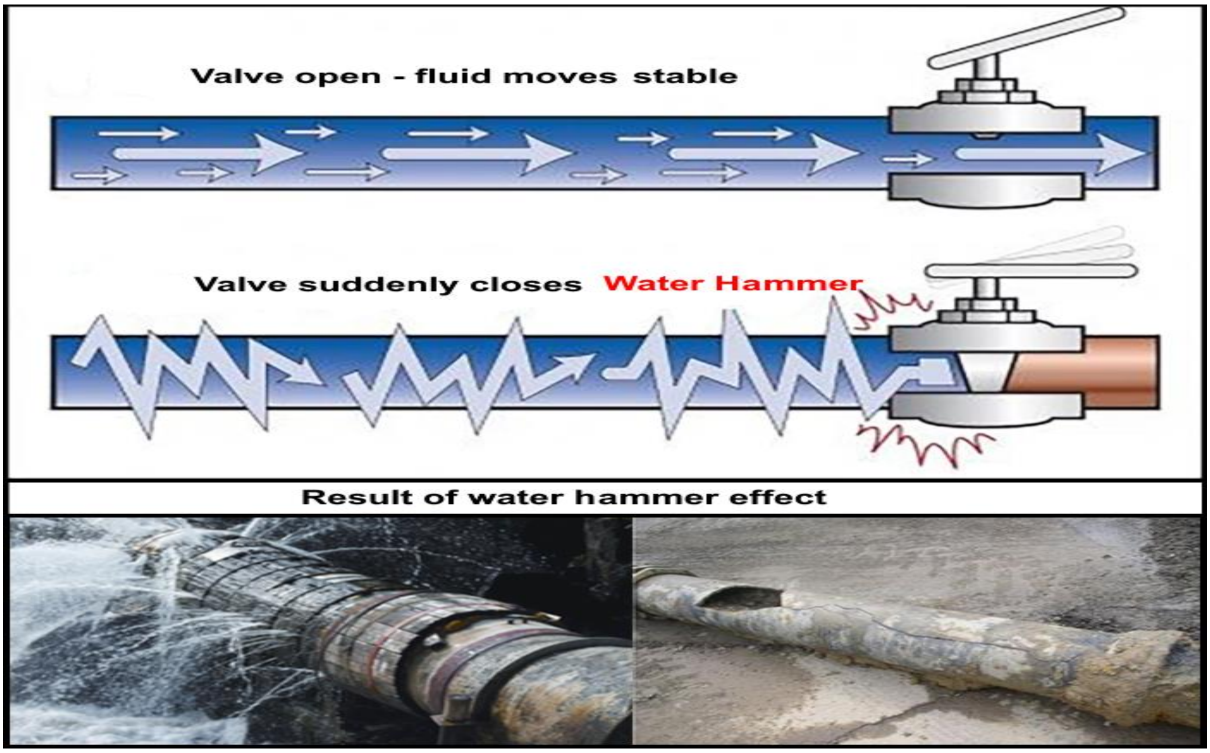


Figure 1:- Water hammer occurrence and effect (Kredi, 2018).

Reflection of water hammer

The flow propagates forwards and backwards in the pipeline after the closure of the valve. For simplicity any friction is neglected. The time it takes for the wave to move through the pipe is

$$T_o = \frac{L}{C} \ (S) \qquad (1)$$

Where L is the length of the pipeline and c is the wave celerity.

The reflection time Tf is defined as the time it takes for the pressure wave to move forward and backwards once in the pipe. This give

$$T_f = 2T_o \qquad (2)$$

Immediately after the closure of the valve a positive pressure wave starts moving against the flow direction towards the open end of the pipe. At the time $t = T_o$ the pressure has changed + ΔP everywhere in the fluid and the velocity is nil. This is an unstable situation, and the positive pressure will press the water out of the pipe by starting a wave going backwards in the pipe (towards the left in Figure 2). At the left side of the front the pressure is nil and the velocity is – *V.* Figure 2 shows how the wave propagates back and forth in the pipe.

To understand water hammer it is essential to realize that the wave is reflected from a closed end as well as an open end of the pipe. Reflection often plays an essential role in relation to transients in pipelines.

In theory the waves continue forever. In the real-world friction will gradually damp out the waves. The principles shown in Figure 2 will usually be valid during the first one or two reflection periods. The immediate effect of closing a valve can be found from the Joukowsky equation. Because of the reflection the pressure wave will return at the valve sometime later with the opposite sign. Consequently, the fast closure of a valve can provoke cavitation on both sides of the valve (Larsen, 2012).

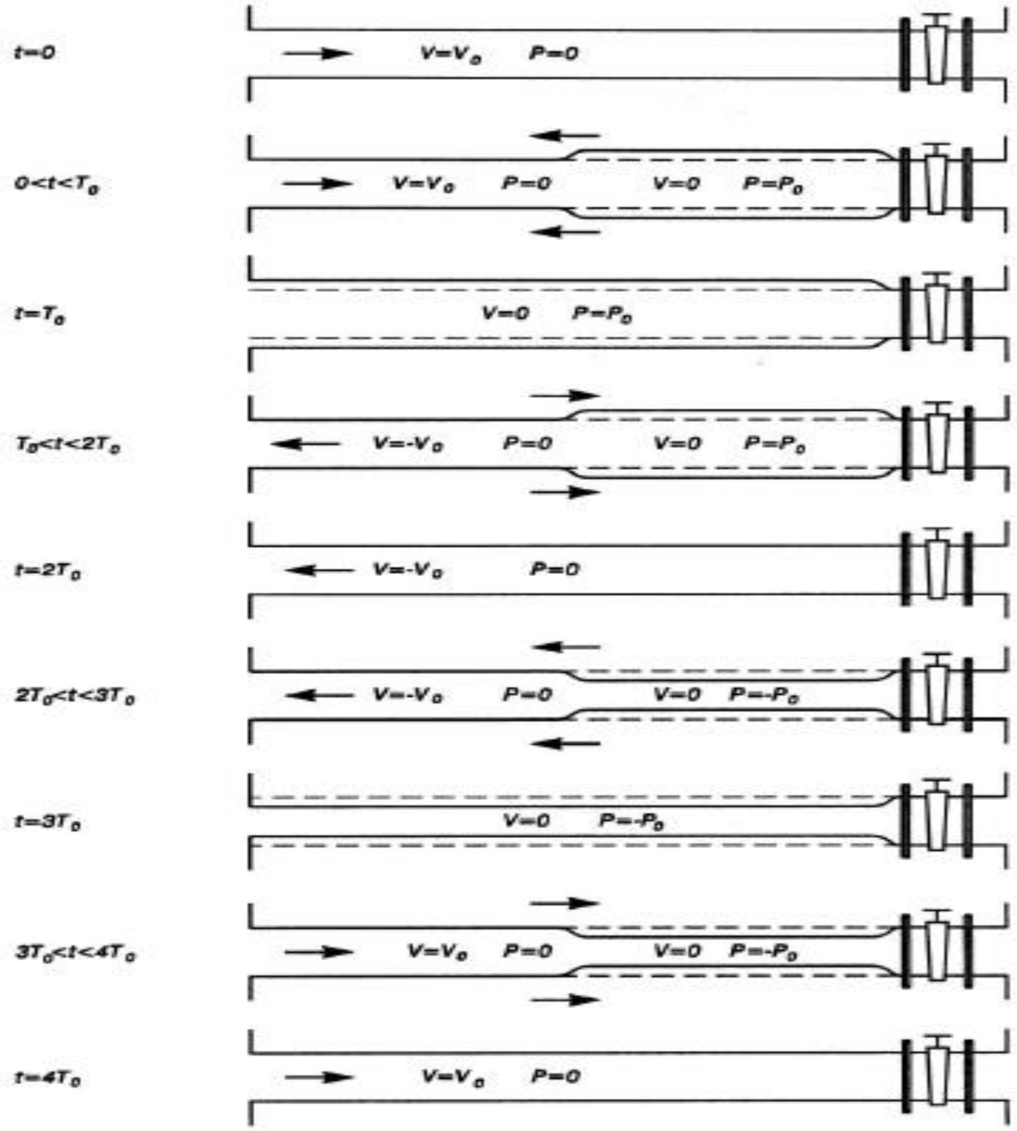


Figure 2:- Principle of water hammer reflection (Larsen, 2012).

2.2. Cause of Water Hammer

Fluid transient events are disturbances in the liquid caused during a change in operation, typically from one steady state or equilibrium condition to another (Figure 3). The principal components of the disturbances are pressure and flow changes at a point that cause propagation of pressure waves throughout the distribution system. The pressure waves travel with the velocity of sound (acoustic or sonic speed), which depends on the elasticity of the liquid and that of the pipe walls. As these waves propagate, they create transient pressure and flow conditions. Over time, damping actions and friction reduces the waves until the system stabilizes at a new steady-state. Normally, only extremely slow flow regulation can result in smooth transitions from one steady-state to another without large fluctuations in pressure or flow (Paul, 2010).

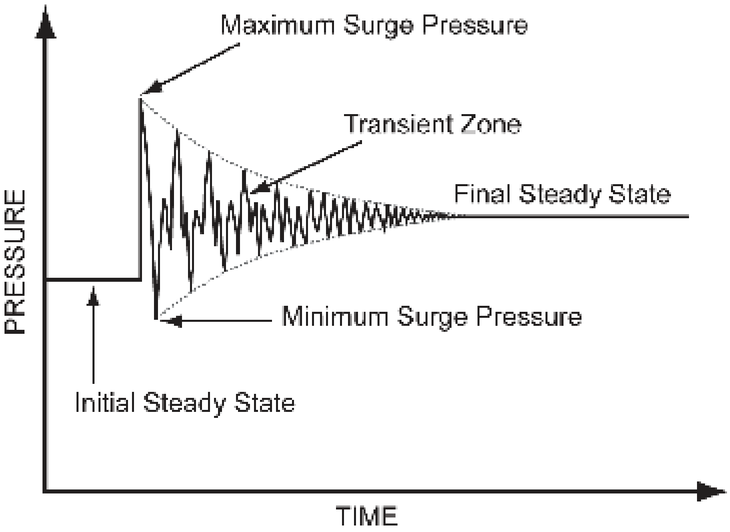


Figure 3:- Example steady state transition after a period of rapid transients (Paul, 2010).

The hammer is caused by many varies. There are four common causes that typically induce large changes in pressure in the pipe system:

1. Pump startup can induce the rapid collapse of a void space that exists downstream from a starting pump. This generates high pressures especially in the long pipes.
2. Pump power failure or cut off the electricity can create a rapid change in flow, which causes a pressure upsurge on the suction side and a pressure down surge on the discharge side. The down surge is usually the main problem. The pressure on the discharge side reaches vapour pressure, resulting in vapour column separation.

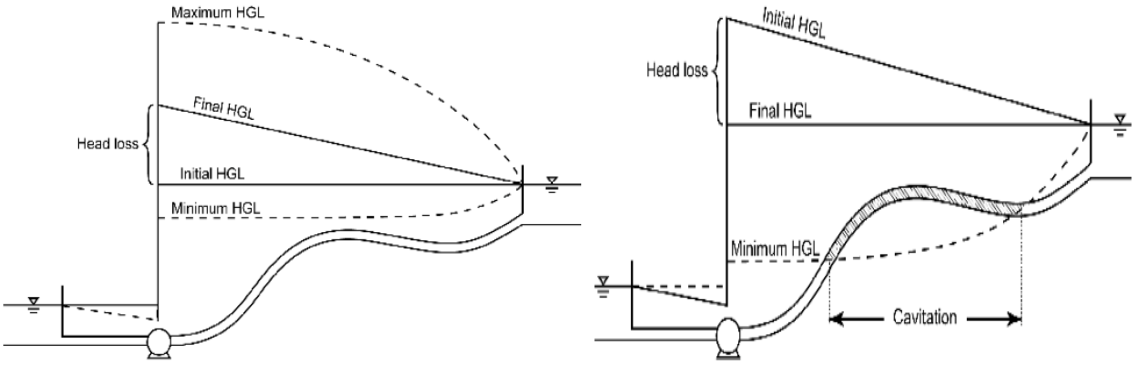


Figure 4:- a) Transient caused by pump start-up. b) Transient caused by pump shut down **(Kredi, 2018).**

3. Valve opening and closing is a principle to safe pipeline operation. Closing a valve at the downstream end of a pipeline creates a pressure wave that moves toward the reservoir. Closing a valve in less time than it takes for the pressure surge to travel to the end of the pipeline and back is called “sudden valve closure.” Sudden valve closure will change velocity quickly and can result in a pressure surge. The pressure surge resulting from a sudden valve opening is usually not as excessive.

4. Improper operation or incorporation of surge protection devices can do more harm than good things. An example is over sizing the surge relief valve or improperly selecting the vacuum breaker-air relief valve. Another example is tried to incorporate some means of preventing water hammer when it may not be a problem (Kredi, 2018).

2.3. Water Hammer/hydraulic transient pressure Analyze

2.3.1. Numerical Solutions of Transients

A transient flow solution can be obtained numerically with the appropriate initial and boundary conditions in which pressure and flow are variables dependent upon position and time. Five different numerical procedures are commonly used to approximate the solution of the governing equations. Three Eulerian methods update the hydraulic state of the system in fixed grid points as time is advanced in uniform increments. The two Lagrangian methods update the hydraulic state of the system at fixed or variable time intervals at times when a change actually occurs. Each method assumes that a steady-state hydraulic solution is available that gives initial flow and pressure distributions throughout the system.

The Eulerian methods consist of the explicit method of characteristics, explicit and implicit finite difference techniques, and finite element methods. In closed conduit applications, by far the most popular of these techniques is the method of characteristics (MOC). The method of characteristics is the most accurate in its representation of the governing equations.

All characteristics methods convert the two partial differential equations of motion and continuity into four total differential equations (that are then expressed in a finite difference form. When finite difference and finite element techniques are used, the derivatives in the governing equations are replaced with approximate difference quotients. By contrast, in the method of characteristics, only the nonlinear friction term needs to be approximated (which is typically done by a linear difference term). Explicit finite difference schemes have also significant restrictions on the maximum time step to achieve stable solutions. Although implicit methods usually overcome the stability limitations, they require a simultaneous solution for every unknown in the problem at each time step.

The main drawback of the method of characteristics is that the time step used in the solution must be common (fixed) to all pipes. In addition, the method of characteristics requires the distance step in each pipe to be a fixed multiple of the common time interval, further complicating the solution procedure.

In practice, pipes tend to have arbitrary lengths and it is seldom possible to satisfy exactly both the time interval and distance step criteria. This “discretization problem” requires the use of either interpolation procedures (that have undesirable numerical properties) or distortions of the physical problem (that introduces an error of unknown magnitude). Finally, in order to satisfy stability criteria and ensure convergence, the method of characteristics requires a small-time step. The stability criterion is developed by neglecting the nonlinear friction term and is referred to as the *Courant* condition.

The Lagrangian approach solves the transient flow problem in an event-oriented system simulation environment. In this environment, the pressure wave propagation process is driven by the distribution system activities. The Wave Characteristic Method (WCM) is an example of such an approach (Wood et al 2005a). The method tracks the movement of pressure waves as they propagate throughout the system and computes new conditions at either fixed time intervals or only at times when a change actually occurs.

The Lagrangian approach normally requires orders of magnitude fewer pressure and flow calculations, allowing very large liquid distribution systems to be solved in an expeditious manner, and has the additional advantage of using a simple physical model as the basis for its development. As such, practicing engineers can gain a better understanding of the mechanics of transient pipe flow. Finally, because the Lagrangian solution scheme is continuous in both time and space, the method is less sensitive to the structure.

Governing equations

According to a study by (Joukowski,1898), the reason for the pressure rise in the pipe was the changes in velocity and specific weight of the fluid and presented an equation for determining and calculating the velocity of the pressure surge caused by the water hammer. Equation (1) is known as the basic equation of a water hammer (Chaudry, 2014).

$$\Delta \mathrm{P} = \frac{\mathrm{a}\Delta \mathrm{V}}{\mathrm{g}} \tag{3}$$

Where a is the wave propagation velocity, g the gravitational acceleration, V change velocity, and P the pressure change. The pressure surge velocity is obtained from Eq. (4).

$$a = \sqrt{\frac{\frac{1}{\rho}}{\frac{1}{\kappa}+\frac{D}{\mathrm{twE}}}} \tag{4}$$

Where ρ is the density of the fluid, E is the modulus of elasticity of the tube, tw is the thickness of the tube wall, and K is the bulk modulus of the bulk.

Basic transient flow equations are continuity and momentum equations. Equation (5) shows the coherence for fluid based on the principles of mass survival as follows (Chaudry, 2014).

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial x} + \frac{a^2 \partial V}{\partial x} = 0 \tag{5}$$

Where a is the average wave velocity, V is the average velocity in the tube whose direction is parallel to the x − axis, and H is the height of the hydraulic gradient line. The momentum equation for a fluid can be determined by considering the forces acting on a small element or control volume, including shear stresses created by fluid motion and viscosity. Equation (6) describes the momentum equation for unstable fluid flow.

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{fV|V|}{2D} = 0 \qquad (6)$$

Where f is the Darcy–Weisbach friction factor, D is the diameter inside the tube, and V is the velocity of the fluid (Chaudry, 2014).

Maximum and minimum internal pipe pressure

Because water hammer creates the most severe forces on the pipelines, the selection of pipe material and the determination of the thickness of the pipe wall depend primarily on the stresses from the transients. In a circular pipeline with an internal pressure p a ring stress σt emerges. This stress can be expressed

$$\sigma_t = \frac{\rho\, D}{2e} \ \text{[MPa]} \qquad (7)$$

Where D is the pipe diameter and e is the thickness of the pipe wall. As long as the pressure is positive it is obvious that σt should be less than the design (permissible) strength for the pipe material. For static loads the design strengths for various materials are given in Table 2.

Table 1:- Design stress for various pipe materials. Sources; (Larsen, 2012).

Pipe material	Design stress [MPa]
Steel Ductile 0	150 – 180
Iron	200 – 250
Reinforced concrete	0
Asbestos concrete	5 –8
PVC (polyvinylchloride) 20oC	10 – 12.5
PEL (polyethylene low density) 20oC	3
PEM (polyethylene medium density) 20oC	5
PEH (polyethylene high density) 20oC	5 – 6
PP (polypropylene) 20oC	5
GRP (glass reinforced polyester)	> 100
GRE (glass reinforced epoxy)	> 100

The design stresses given in Table 2 incorporate a safety factor in the order of a magnitude of 2. If a negative pressure in the liquid occurs, resulting in a positive stress in the pipe wall, the situation is more complex. In this case there is a risk of collapse or buckling. The maximum permissible stress PE in respect to buckling is:

For a pipe restrained in the length direction

$$P_E = \frac{2}{1-\mu^2}\frac{e^3}{D^3} \quad \text{MPa} \qquad (8)$$

For an unrestrained pipe

$$P_E = \frac{2e^3}{D^3}E \quad \text{Mpa} \qquad (9)$$

Where, μ the Poisson's ratio and E is the elastic modulus (Young's modulus) of the pipe material. Because collapse or buckling in principle depends on the elastic modulus and not on the design stress of the material, it is essential to incorporate a safety factor (with a value of approximately 2) to achieve the permissible buckling stress. The equations given above are from the theory of thin-walled pipes and do not take into account the influence of soil pressure. Guidelines for the design of thick-walled pipes are found in the literature. Low pressure from water hammer caused by pump start-up and shut-down are relative short-lived and one should therefore apply the short-term elastic modulus for evaluation of collapse and buckling caused by water hammer. This stands in contrast to long-term impacts from for example external water and soil pressure. In these cases, the long-term elastic modulus should be used. Consequently, a precise evaluation of combined short- and long-term influences on plastic pipelines is difficult and uncertain. It should be emphasized that the structural design of plastic pipes also should include an estimate of the deformation of the pipe. If the cross-section of the pipe has an initial deviation from circular, this should be considered as well.

Including the safety factor gives a design buckling pressure of approximately – 50 mWc, which means that the pipe should be able to resist full vacuum (cavitation) as well as some external pressure from outside. This example only covers the strength of the pipe. In practice also the deformations should be considered. If external soil and/or water pressure is present these loads should be included as well. If the soil pressure corresponds to a soil cover of 1 m it is recommended to make a buckling analyze/consideration for pipelines with a lower strength than PN16 if a risk of full vacuum exists (Larsen, 2012).

2.4. Transient Modelling

Transient analyze of events occurring in piping systems requires many calculations and is an extremely demanding computational exercise. This is almost always carried out using transient modelling software. Having considered some of the detail of transient analyzes and protection, it is perhaps helpful to conclude with some tips or guidelines that would assist in preparing a computer simulation file. In essence, the good news is that transient modelling uses much of the same data required for steady state modelling. A steady state analyze of the initial conditions for the transient analyze is required. There are, however a number of additional considerations for developing a transient analyze model.

- The precise location of hydraulic devices (pumps, control valves, check valves, regulating valves, etc.) is required for the model.
- Transient analyze cannot accommodate exact pipe lengths so the analyze is carried out using a model with approximate pipe lengths. The length accuracy of the model (maximum difference between actual and model pipe lengths) must be sufficient to generate an accurate solution. However, increasing the accuracy will require a longer computational time.
- Cavitation must be modelled for transient analyze. If cavitation occurs at any location in the distribution system it can greatly affect the transient analyze results.
- Skeletonization guidelines are significantly different than those for steady state analyze. Dead end lines, for example, will have a very significant effect on a transient analyze while having no effect on the steady state analyze (Bong, 2007).
- A transient model should carry out calculations at all local high and low points since the pressure extremes often occur at these locations.
- It is good practice to allow a transient model to operate at steady state for a short period before the transient is initiated. This provides additional assurance that the transient model is operating correctly (Wood, 2007).

2.4.1. **Hammer v8i software**

Open flows HAMMER is used in water networks including pump or valve that can create the possibility of water hammer phenomenon. This software has an easy-to-use interface to efficiently identify, manage, and mitigate the risks associated with transients. HAMMER can identify critical points in the system that need protection and facilitate sound system design. The software focuses on the mitigating surge, not on the modeling process. It means that it can effectively develop the most appropriate strategy for controlling and limiting hydraulic transients. Also the software simulates the transient model precisely to improve the quality of the decisions and decrease the risk of approximating the behavior of protective devices and rotating equipment. Open flows HAMMER can accurately simulate the impact of a wide range of surge protection devices and rotating equipment, such as pumps and turbines. Finally, it can easily import CAD and GIS data for improved design productivity in water network modeling (HAMMER, 2014).

2.4.2. Finite Element Method (Abaqus software)

FEM are widely used to study and model various applications in different areas. FEM were originally developed to study the stress in complex aircraft structures. Now they include Computer and Industrial applications, Biomedical, Thermal and Fluid flows, Mechanical engineering discipline such as aeronautical (design of aircrafts), biomechanical etc. Automotive industries commonly use integrated

FEM in design and development of their products. The high point of FEM is its applications to any irregular geometry with various boundary conditions. Many engineering phenomena can be expressed by “governing equations” and “boundary conditions”. A FE mesh can handle any type of loading conditions such as heat flux, pressure, thermal load, gravity etc, as it can be programmed to define the reaction of structure to specific conditions. Benefits of FEM include increased accuracy, enhanced design, a faster and less expensive design process, higher quality products, increased revenue and reduced chance of field failure. But the successful application of FEM depends on the formulations, appropriate parameters and proper interpretation of the results (ABAQUS, 2011).

2.5. Pipe Material comparison for hydrostatic pressure resistance

Surge pressures in HDPE pipe are significantly lower than in DI pipe and lower than PVC pipe due to the lower value of dynamic modulus for HDPE. For example, in a typical 8” line a velocity change of 5 fps would cause a 51-psi surge in HDPE DR17 pipe, an 87 psi surge in PVC DR18 pipe, and a 262 psi surge in DI Class 350 lined pipe. Lower surge pressures often mean longer life for pumps and valves in an HDPE pipeline, as well as lower pressure class pipes. The C factor for HDPE butted fused pipe was found experimentally to be about 155. A conservative design value is 150. DI manufacturers publish an initial value of 140 for cement lined DI pipe. Many engineers assume that this value will be reduced over the life of a pipeline due to corrosion and use design values of 120 or 100. Such a reduction is not required for HDPE pipe. AWWA M-55 states that “No allowance for corrosion and therefore, no subsequent lowering of the flow capacity need be considered when using PE pipe” (Chevron Phillips Chemical Company LP, 2009).

Within plastic pipe systems, such as PVC, CPVC, and PEX, the modulus of elasticity is much less than copper or steel pipe, and thus the velocity of the pressure wave is slower. This results in a lower pressure rise in plastic pipe versus metal pipe, given the same parameters. However, an equal amount of kinetic energy exists in both plastic and metal systems. The excessive energy is absorbed into the plastic piping system by the instantaneous expansion of the pipe, fittings and appurtenances within the system. Historically, water hammer damage to the pipe itself is not the main concern, because the pipe can generally handle these expansions and contractions. Rather, it is the wide variety of fitting systems for plastic pipe (i.e., solvent weld, mechanical crimp, pinch clamps, expansion fittings, both made from brass and hard plastic) that are at risk.

(Sioux Chief Manufacturing Company, 2018) studied the water hammer effect through pipeline system. The Italian engineer investigated experimentally the parameters affecting the water hammer phenomenon in PVC and steel pipes such as, pipeline diameter, pipeline length, pipeline material and the initial pressure in the pipeline. They concluded the following: Firstly, the larger diameter causes more water hammer effect compared to the small diameter. Secondly, the longer pipes produce more water hammer effect than the short pipes. Thirdly, PVC pipe reduces more water hammer effect than steel pipe, PVC (0.031 Pa), steel (0.021 Pa). Fourthly, higher pressure supply in pipe creates more water hammer effect compared with the smaller pressure supply in pipe (Aly et al, 2019).

HDPE pipes have phenomenal surge resistance. Surge pressure or “water hammer” occurs when the flow rate of fluid inside a pipe changes. This can occur when a valve opens or closes or a pump starts or stops. The amount of surge experienced inside the pipe has a direct correlation to the elastic modulus of the pipe. HDPE pipes, with its lower elastic modulus act as a giant shock absorber, resulting in very little surge pressure traveling down the water column. 2 foot per second velocity change in ductile iron pipe results in 100 psi of surge pressure. The same velocity change in HDPE pipe results in just 22 psi of surge pressure (WL Plastics manufacturer, 2022).

The ductile iron pipe resists up to 6.1 times the hydrostatic burst pressure of HDPE pipe. The burst test is the most direct measurement of a pipe material’s resistance to hydrostatic pressure. Tests were conducted in accordance with ASTM D159912 by fitting the pipe specimens with gasket, unrestrained end caps and securing them in a hydrostatic test structure to resist the end thrust. This arrangement produced stresses primarily in the circumferential direction in the walls of the pipes as internal hydrostatic pressure was applied.

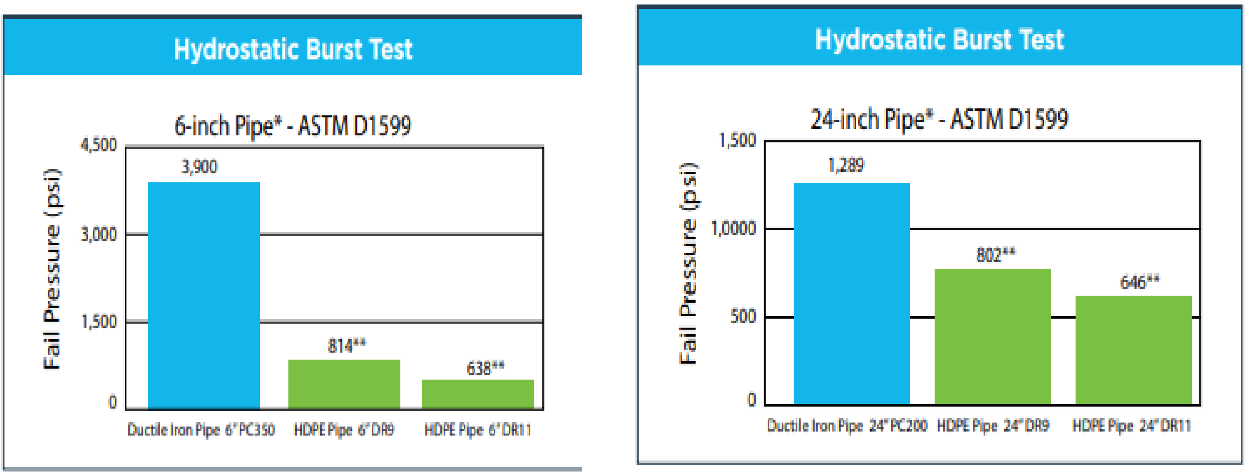


Figure 5:- Burst pressure at which HDPE and DCI pipe failed by ballooning (WL Plastics manufacturer, 2022).

Lüdecke, conducted investigation on the relation of transient pressure and steady state pressure with and without provision devices surge protection devices. For the study, Pipe length L: 2624 m, Inside diameter of Di: 605.2 mm, Steady-state flow rate: 500 l/s pump head: 287.5 m and Air vessel: Volume of air = 3.8m3, Volume of water = 6.2 m^3 were used (Lüdecke, 2006).

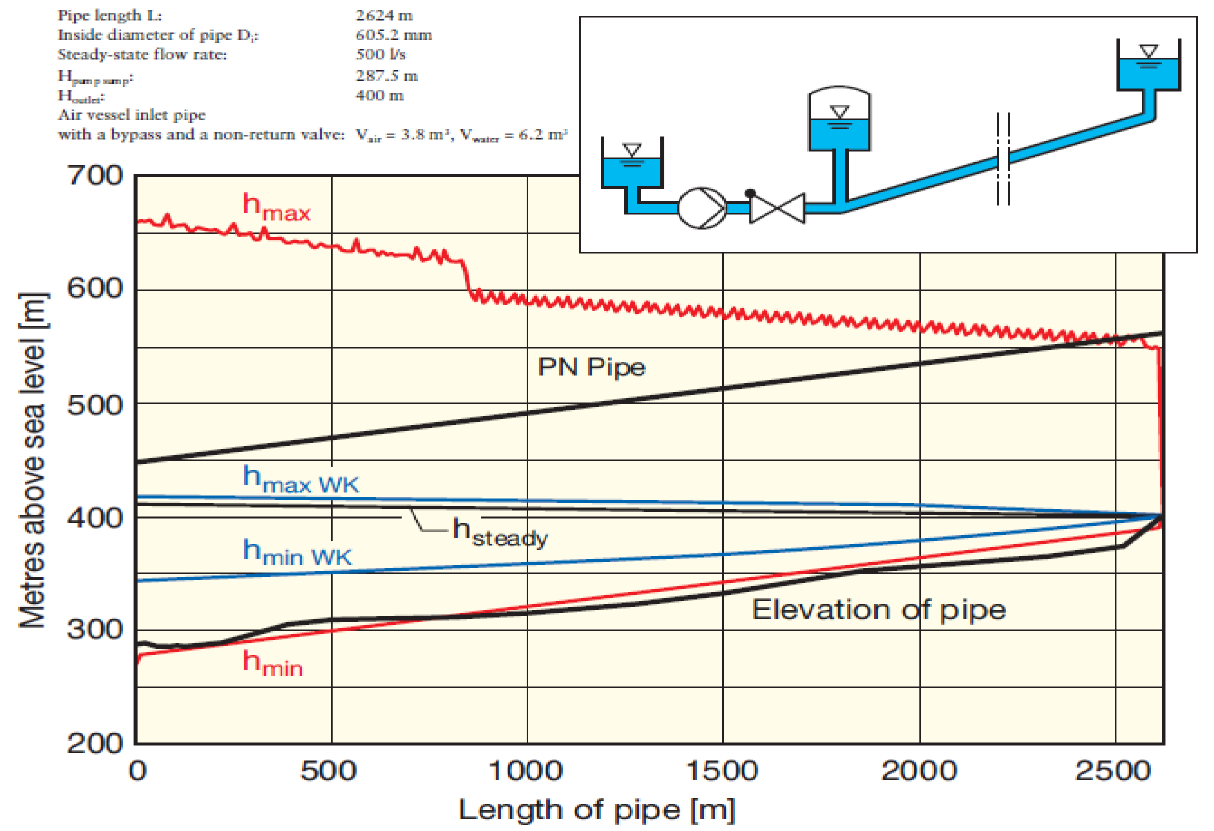


Figure 6:- Pressure head envelope of pressure transients following pump trip (Lüdecke, 2006).

From the result, maximum transient pressure higher than steady state about 195.25% and 0.96% for non-protected air vessel and Air Chamber protected air vessel respectively. Likewise, the non-protected maximum transient pressure is higher than protected maximum transient pressure 192.66%. The steady states in both scenarios were the same (Lüdecke, 2006).

(Aly at el.2019), analyze steel pipe of 1000mm diameter and 4,600 km length by using AFT. AFT impulse program transient analyses were done with two scenarios; with surge air vessel control device and without surge control. The results are presented in table below.

Table 2:- AFT impulse program transient (Aly at el.2019)

Case	P steady bar	P max bar	P min bar	Vapor Volume m^3
Protected	4.15	4.9	.05	0
Non-Protected	4.15	9.9	.9969	0

Accordingly, maximum transient pressure exceeds steady state 138.55 % and 18.07% for the case of non-protected and protected scenario simulation results respectively. Minimum transient pressure below the steady state 98.795% and 75.97 % for the case of non-protected and protected scenario simulation results respectively. Air vessel protection device reduce maximum transient pressure 102.04% and minimum transient pressure 30.02 % (Aly al et, 2019).

In addition the AWWA design standards for each pipe (ANSI/AWWA C150/A21.501 for Ductile Iron Pipe and ANSI/AWWA C9062 for HDPE pipe). The following data is drawn from several sources, including American Water Works Association (AWWA) standards, published information from pipe manufacturers and associations, and physical testing from the Ductile Iron Pipe Research Association, Structural Composites Inc. and Plastics Engineering Laboratory. The tests reported were conducted on 6-inch and 24-inch diameter Ductile Iron and HDPE pipe. The lowest Pressure Classes available for 6-inch and 24-inch diameter Ductile Iron Pipe (350 psi and 200 psi respectively) were used. DR9 (200 psi) and DR11 (160 psi) HDPE pipe were the lowest DRs available when the pipe was purchased. Higher DR HDPE pipe, which is sometimes specified, would be much weaker. This brochure presents sound engineering information that will prove that all materials are not equal (AWWA, 2010).

2.6. Methods of Controlling Transients

(Lahane, et al 2015), said that water hammer phenomenon cannot be eliminated but can be reduced by using different protection devices. They modeled pipeline using GAMBIT software and the simulation result helps the designers to have good understanding of water hammer phenomenon and work on the ways to reduce the surge.

The means of controlling pressure transients in liquid distribution systems will generally depend upon whether the initiating event results in an upsurge (e.g., a high-pressure event caused by a shutdown of a downstream pump or valve) or a down surge (e.g., a low-pressure event caused by the failure of an upstream pump or valve closure). Down surge events can lead to the undesirable occurrence of liquid-column separation (cavitation) that can result in severe pressure surges following the collapse of a vapor cavity or intrusion of contaminated liquid through a leak or other opening.

A number of surge protection devices are commonly used to control starting and stopping transients in pipe systems. No two systems are completely identical; hence the ultimate choice of surge protection devices and operating strategies usually differ. A transient analyze should be carried out to predict the effect of each individually selected device. Due to the complex nature of transient behavior, a device intended to suppress or fix a transient condition could result in a worsening of the condition if the device is not properly selected or located in the system. Designers must evaluate the relative merits and shortcomings of all the protection devices that they may select. A combination of devices may prove to be the most desirable and economical (Paul, 2010).

The surge pressure must be incorporated with the operating pressure in the design of the pipe. The recommendations and requirements regarding allowances for surge pressure are given in the American

Water Works (AWWA) standards and manuals for water supply practice, and vary depending on the type of pipe used. There are some tools to reduce the result of water hammer (AWWA, 2010).

Surge protection devices normally installed at or near the point where the disturbance is initiated such as at the pump discharge or by the closing valve (with the exception of air relief/vacuum breaking valves and feed tanks). When developing a protection strategy, it must be recognized that no two systems are hydraulically the same; hence, no general rules or universally applicable guidelines are available to eliminate pressure in liquid distribution systems. Surge protection devices and/or operating strategies must be chosen accordingly (Thorley, 1991).

1. The Valves

The valves can be an effective method of controlling transients, when properly sized and selected to perform the job for which they are intended without causing side effects. If pressure may drop at high points, an air and vacuum relief valve should be used. All downhill runs where pressure may fall very low should be protected with vacuum relief valves.

Closing the valve slowly can modify the rise in the pressure when the down surge wave resulting from the valve closing returns from the reservoir. Entrained air or temperature changes of the water can be controlled by pressure relief valves, which are set to open with excess pressure in the line and then closed when pressure drops. Relief valves are commonly used in pump stations to control pressure surges and to protect the pump station. The valves can be an effective method of controlling transients, when properly sized and selected to perform the job for which they are intended without causing side effects.

Vacuum breaker-air release valves, if properly sized and selected, can be the least expensive means of protecting a piping system. A vacuum breaker valve should be large enough to admit sufficient quantities of air during a down surge so that the pressure in the pipeline does not drop too low. However, it should not be so large that it contains an unnecessarily large volume of air, because this air will have to be vented slowly, increasing the downtime of the system (Kredi, 2018).

2. Pump

We can usually avoid the pump starting problems by increasing the flow slowly to collapse or flush out the voids gently. So, to keep pipeline velocities low a simple means of reducing hydraulic surge pressure. This not only results in lower surge pressures, but results in lower drive power and, thus, maximum operating economy (Parmakian, 1963).

3. Surge Tank

The surge can be relieved in long pipelines, with a tank of water directly connected to the pipeline called a “surge tank.” When surge is encountered, the tank will act to relieve the pressure, and can store excess liquid, giving the flow alternative storage better than that provided by expansion of the pipe wall and compression of the fluid. Surge tanks can serve for both positive and negative pressure fluctuations. These surge tanks can be used to supply fluid to the system during a down surge, to preventing or minimizing vapour separation column. Also, surge tanks may be costly surge control device (Kredi, 2018).

4. Bypass around the pump

A pipe directly from the pump sump to the main pipeline (with a non-return valve included) can fill the main pipe almost unhindered and in this way reduce water hammer. The principle is only useful in pipelines with low geometric head.

The principle may immediately seem promising but the gain is often negligible because most pumps already have a certain free opening through the pump wheel. This free opening will often be sufficient for filling the pipe (Larsen, 2012).

5. Air Chamber

Where water hammer is encountered frequently air chambers are installed in these areas, and are typically seen behind sink and tub fixtures. Shaped like thin, upside-down bottles with a small orifice connection to the pipe, they are air-filled. The air compresses to absorb the shock, protecting the supporting and piping system (Parmakian, 1963).

6. Check Valve

A check valve allows flow only in one direction and closes when flow reversal is impending. For transient control, check valves are usually installed with other devices such as a pump bypass line. Pumps are often equipped with a check valve to prevent flow reversal. Because check valves do not close instantaneously it is possible that a substantial backflow may occur before closure that can produce additional and sometimes large surges in the system. Check valve modelling includes a time delay between check valve activation and complete closure of the check valve. The check valve is often treated as a valve closing in a linear fashion that is activated by flow reversal and closes completely over the delay period. One of the great advantages of a check valve is that it can prevent pipes from draining, and keeping the pipe full of fluid tends to reduce start-up transients (Wood, 2007).

7. Avoiding the Water and Cavitation Hammers:

The best method and simple way to prevent water hammer is to close or open the valves slowly. The question whether a valve closes slowly enough can be easily calculated by the use of fluid transient software. The minimum closing time depends on the pipe length upstream the valve to the next point where pressure is fixed (i.e., vessel). At this point the high-pressure wave is reflected as a low-pressure wave. These waves may annihilate each other (Kroon, 1984).

Beside that one has to take into account that there are different valve characteristics so that pressure increase due to closing process occurs at different valve positions. In practice, 3 -10 times the minimum closing time is needed to avoid high water hammer pressure peaks. Ability is to use air vessels, surge shafts or bladder accumulators, which are installed upstream the shutoff valve. Extending the valve gear with a surge damper or a program positioned leads to the deceleration of the valve closing process. There is also another solution, which are based upon measurements and subsequent control of the valve (National Drinking Water Clearing house, 2001).

8. water hammer arrestor

A water hammer arrestor is now required where quick-closing valves are used in the water distribution system. Ideally, the flow pressure in branch lines serving fixtures should never exceed 55 psi. Pressure reducing valves should be installed to maintain proper pressure. When flow pressures are 65 to 85psi the next size water hammer arrestor should be selected. All sizing data is based on flow velocities of 10 fps or less. When long runs of piping are employed to serve a remote item of equipment, the water hammer arrestor should be located as close as possible to the point of quick closure. At this location, the water hammer arrestor will control the developed energy and prevent the shock wave from surging through the piping system.

Water hammer phenomenon occurs in closed pipes when the fluid is accelerated or decelerated very quickly, due to the rapid closure of valves or taps or as a consequence of a circulation pump stopping. The effect consists in the propagation of over- and under pressures along the pipes, which may result in noise and damage to the whole system. The water hammer arrester, when installed close to single-lever mixing taps, solenoid valves, ball valves, etc., prevents such negative effects (Mohammad, 2021).

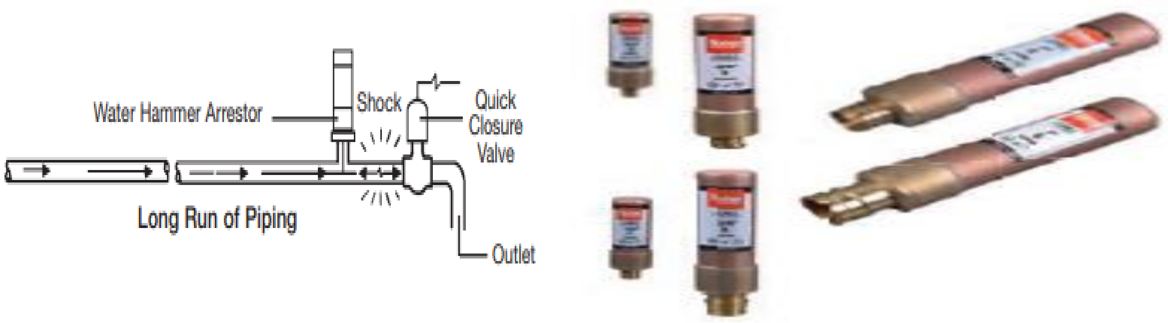


Figure 7:- Water Hammer Arrestor (Mohammad, 2021).

9. Pump Bypass Line

In low-head pumping systems that have a positive suction head, a bypass line around the pumps can be installed to allow liquid to be drawn into the discharge line following power failure and a down-surge. Bypass lines are generally short line segments equipped with a check valve (non- return valve) preventing back flow (from the pump discharge to the suction side) and installed parallel to the pump in the normal flow direction. They are activated when the pump suction head exceeds the discharge head.

They prevent high pressure buildup on the pump suction side and cavitation on the pump discharge side (Larsen, 2012).

10. Air valves

An air valve opens when the pressure in the pipe falls below zero. Air valves are efficient to avoid negative pressures in pipelines, which will reduce the high water hammer pressure peaks after reflection. Some of the most serious accidents with pipelines are coupled to the presence of accumulated air. The use of air valves necessitates specialized knowledge and considerations.

The main problem in using air valves is to get the air out of the pipeline again in a controlled manner. If the length profile has a positive slope all the way to the end of the pipe, the air will escape without problems. In pipelines with high points the air valves must be placed at the high points. Here the valves have the function first to let the air into the pipe and later to let it out again.

The design of air valves is often based on a simple rule of thumb saying that the air flow through the valve into the pipe should be equal to the steady state water flow in the pipe, and that the corresponding head loss in the air flow should be low (perhaps around 1mWc).

Letting the air out of the pipe through the valve can be critical for several reasons. First there is a risk of serious internal water hammer during the start-up of the pump after a stagnant period. The internal water hammer emerges when the air leaves the pipe through the valve and the moving water column from the pump side hit the stagnant water column on the other side of the high point. This water hammer can be more powerful than water hammer related to pump shut-down. For this reason, air valves are often designed to give a significant higher resistance to the outgoing flowing air.

Another question is whether the air valve is able to trap all the air in the pipe. The general experience is that air can only be trapped when the water is stagnant for more than a short period. A tank designed specifically to trap the air at the high point can be the only realistic way of removing the air (Larsen, 2012).

11. Air chamber

Air chambers (or air vessels) are frequently used to reduce water hammer caused by pumps and valves. They come in sizes from a few cubic centimeters to several hundred cubic meters.

The basic principle is that the compressed air in the air chamber acts as a kind of pump the first seconds after pump shut-down. The compressed air slows down the loss of velocity in the main pipe, which reduces water hammer. The disadvantage is that the pressure is kept high on the upstream side of the pump, forming a pressure gradient backwards through the pump, which will force the non-return valve to close faster and this can sometimes damage the valve.

A larger air chamber needs a compressor to keep a constant air content in the tank. Smaller air chambers can instead have the air in a closed rubber membrane. Air chambers are pressure tanks usually made of steel, and they have to comply with strict safety requirements.

Air chambers normally work fine in systems with a distinct geometric lift. For long flat length profile they do not perform well (Larsen, 2012).

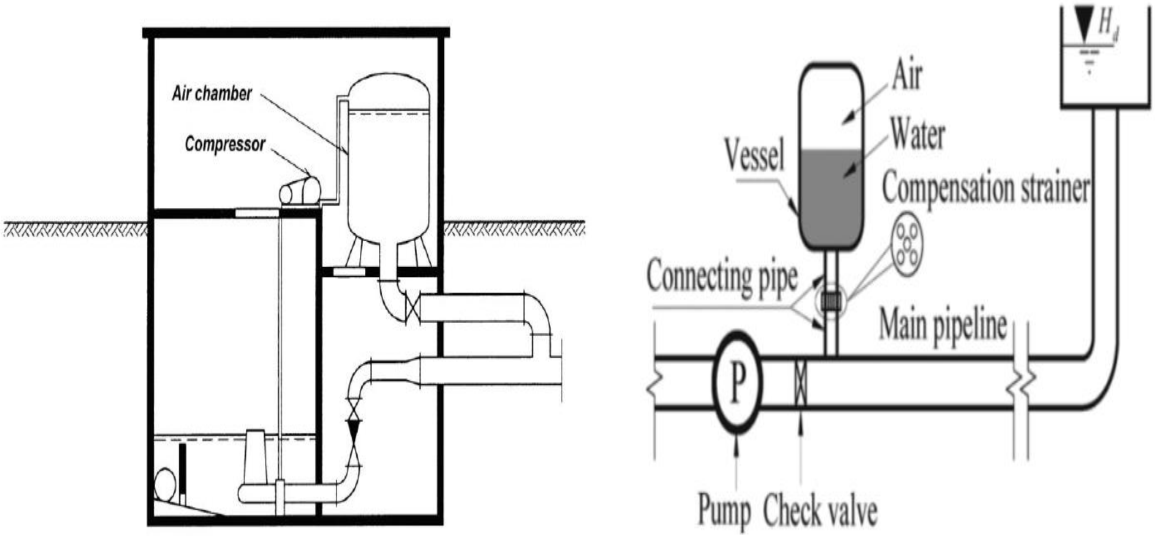


Figure 8:- Air chamber with compressor (Larsen, 2012).

12. Flywheel

It used for the water hammer especially in the case of short pipelines. The moment of inertia can be increased by installing a flywheel, which in many ways is an excellent way of reducing water hammer. However, nowadays flywheels are uncommon because they take space and are expensive. Also, the start-up procedure of the motor is more complicated when a flywheel is involved.

Recently some pump manufacturers have reinvented the use of flywheels for water hammer protection (Larsen, 2012).

13. Revolution control of pumps

Revolution (or speed) control of the pump motor is the most efficient and flexible method for reducing water hammer. The standard method is the use of a so-called ramp by which the revolution of the pump varies linearly with time (the speed is ramped-down). As the length (in time) of the ramp can usually be fully adjusted, an almost total elimination of the water hammer is possible.

It should be mentioned that a linear shut-down of the pump is not optimal from a theoretical point of view, because the pump head varies quadratic to pump speed. Thus, a shut-down ramp where the speed follows the square root of the time can reduce the necessary ramp length.

The only serious weakness of the use of speed control is the problem with power failure. For most countries statistics of the so-called LOLP (Loss-of-Load-Probability) for the power network are available (Larsen, 2012).

3. Materials and Method

3.1. Location of study area

The study was conducted in Dire Dawa city administration, which is located at 515 km east of the capital, Addis Ababa. It lies with latitude and longitude of 9˚36'N 41˚52'E and 9˚60'N 41˚86'E coordinates covering a total area of 1,288 km^2 with an elevation of 1160m amsl. Dire Dawa has an average high and low temperature of 31.8˚C and 17.9˚C respectively. The annual average precipitation is 612 mm. It bounded by the Oromia and Somali Regional state.

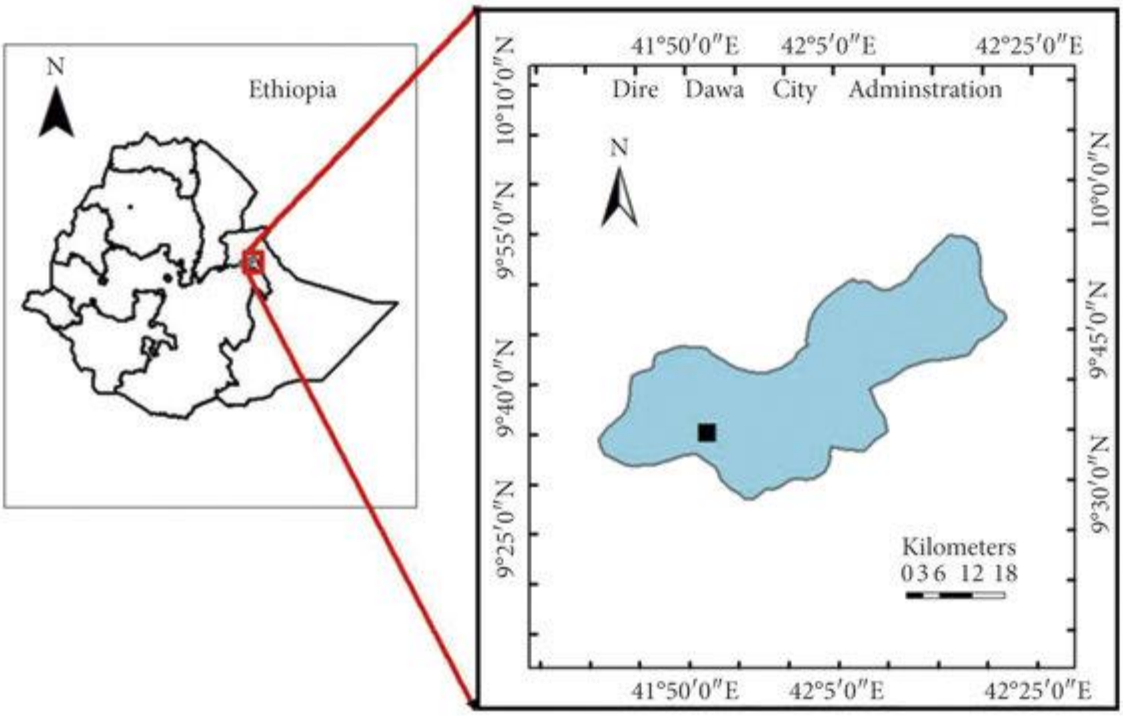


Figure 9:- Map Location of the Study Area

3.2. Data collection

The input data for Bentley water hammer V8i software model simulation were collected from Dire Dawa Water Supply and Sewerage Authority (Ms consultancy, 2015); and input data for Finite Element Method Abaqus software model simulation were collected from HDPE and DCI pipes manufactures' catalogues. A quantitative research approach is used to examine and describe cause-and-effect interactions among variables. The study has independent and dependent variables. The independent variables in this study are pipe material, pipe diameter, pipe length, water flow, pump discharge and head, surge tank and pipe junction elevation whereas the dependent variables are transient pressure, steady state pressure and pipe structural response.

The pipe material, flow condition, pump properties, the junction elevation and surge tank data were taken from Ms Consultancy 2015 water supply and sanitation project design document and projects' as built drawing which were used for Bentley water hammer software model simulation. The mechanical properties of the pipe for Abaqus software were taken from pipe manufacturer’s catalogue.

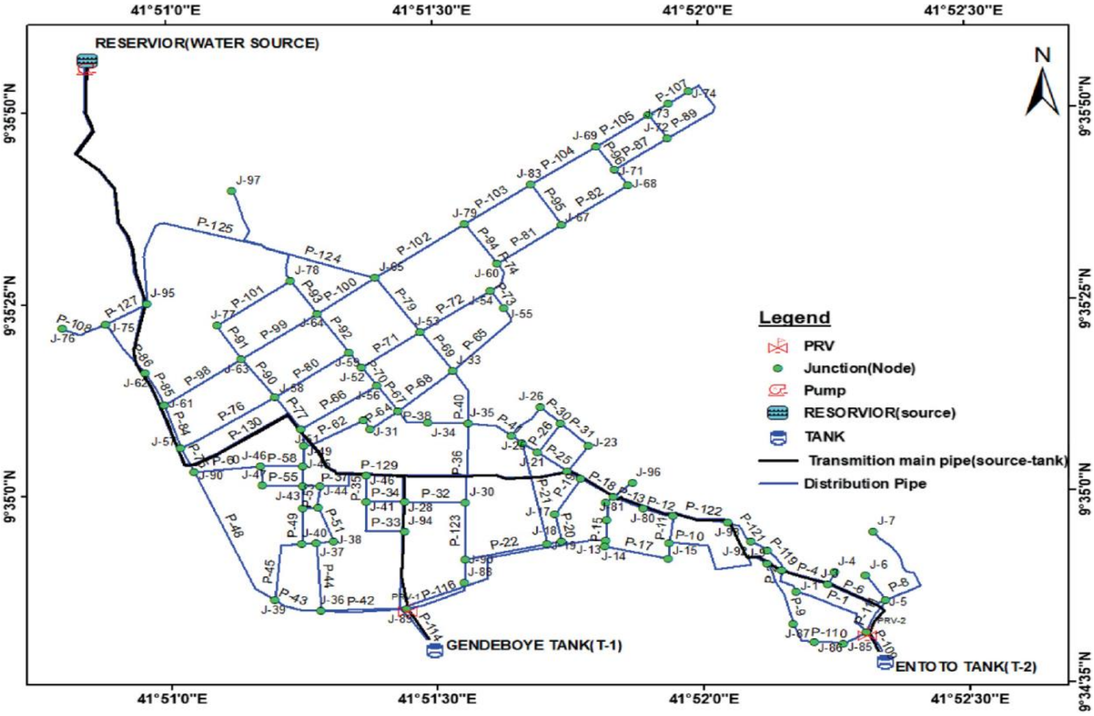


Figure 10:- Dire Dawa town Water Supply Distribution network (MS Consultancy, 2015).

The Dire Dawa city water supply project transmission main line project transport 1,041l/s clean water to sabian booster pump station. Sabian reservoirs collect the water from boren booster pumping station and existing well field. The sabian booster pumping station is transporting water to Entoto, Gende boye and kefira service reservoirs. The data collected for Bentley water hammer V8i software model simulation input were presented in table 3 and 4 while table 5 is the data used for the FEM Abaqus software model simulation.

Table 3:- Reservoirs and booster station elevation (MS Consultancy, 2015).

Reservoirs name	Reservoirs Elevation (m)	Reservoirs volume (m^3)
SABIAN booster station	1180.6	1000 and 2000
Gende Boye	1282.51	4000
Entoto	1301.9	1000
Kefira	1260.28	4000

Table 4:- Transmission lines pipe character and flow condition (MS Consultancy, 2015).

S/No	Description	Sabian to Entoto	Sabian to Gende boye	Sabian to Kefira
Pipe material properties				
1	Pipe material	DCI	DCI	DCI
2	pipe diameter (mm)	350	700	900
3	Pipe Thickness (mm)	7.7	10.8	12.6
4	Delivery pipe length (m)	4752.5	3392.9	3972
5	Flow rate (l/s)	120	480	441
Surge tank description				
1	Orientation	Horizontal surge vessel	Horizontal surge vessel	Horizontal surge vessel
2	Volume	2.5 m3	4 m3	6 m3
3	Pre-charge pressure	4 bars (g)	2.7 bars (g)	3 bars (g)
4	Flange ND	300 PN25	500 PN16	500 PN16
5	Working pressure	25 bars	16 bars	16 bars
Description of pump				
1	Brand	FLOWSERVE	FLOWSERVE	FLOWSERVE
2	Type	122 NM 6L, horizontal multistage pumps	202 NM 2L, horizontal multistage pumps	202 NM 6L, horizontal multistage pumps
3	Flow	60 l/s	147 l/s	160 l/s
4	Head	187.15 m	88.81 m	115.39 m
5	Speed of rotation	1493 rpm	1493 rpm	1493 rpm
6	Pump set inertia	1.5 kgm2	2 kgm2	2.2 kgm2

Table 5:- DCI & HDPE pipes mechanical and structural properties (International Association of Plumbing and Mechanical Officials 2020).

S/No	Description	Ductile Cast Iron Pipe	HDPE Pipe
1	Tensile Strength(Mpa)	≥420	30.5 – 33
2	Yield Strength(Mpa)	≥300	9 – 18
3	Bending Strength(Mpa)	≥590	200-360
4	Elongation (%)	≥10	9 – 18
5	Brinell Hardness(HBS)	≤230	33.0 - 66.0
6	Modulus of Elasticity (GPa)	63.0 - 172	0.700 - 1.34
7	Poisson’s Ratio	0.250 - 0.370	0.45
8	Mass density (kg/m^3)	7050	970

3.3. Method

To achieve the study's objectives, three main transmission lines of the Dire Dawa water supply scheme were used for the study; the line from the Sabian booster station to the Entoto reservoir, the line from the Sabian booster station to the Kefira reservoir, and the line from the Sabian booster station to the Gendaboye reservoir. For the analysis, Bentley Water Hammer V8i version 2014 and FEM/Abaqus version 2011 software were employed. Bentley Water Hammer V8i was used to assess both transient and steady-state pressures for DCI and HDPE pipes under two scenarios; with and without surge tank protection. FEM/Abaqus was utilized to evaluate the structural response of the pipes under dynamic loading conditions for both materials. The transient pressures generated by both pipe types were incorporated as dynamic load inputs for the FEM/Abaqus analysis. The study's analytical procedure is presented in the following flowchart.

The study method summary

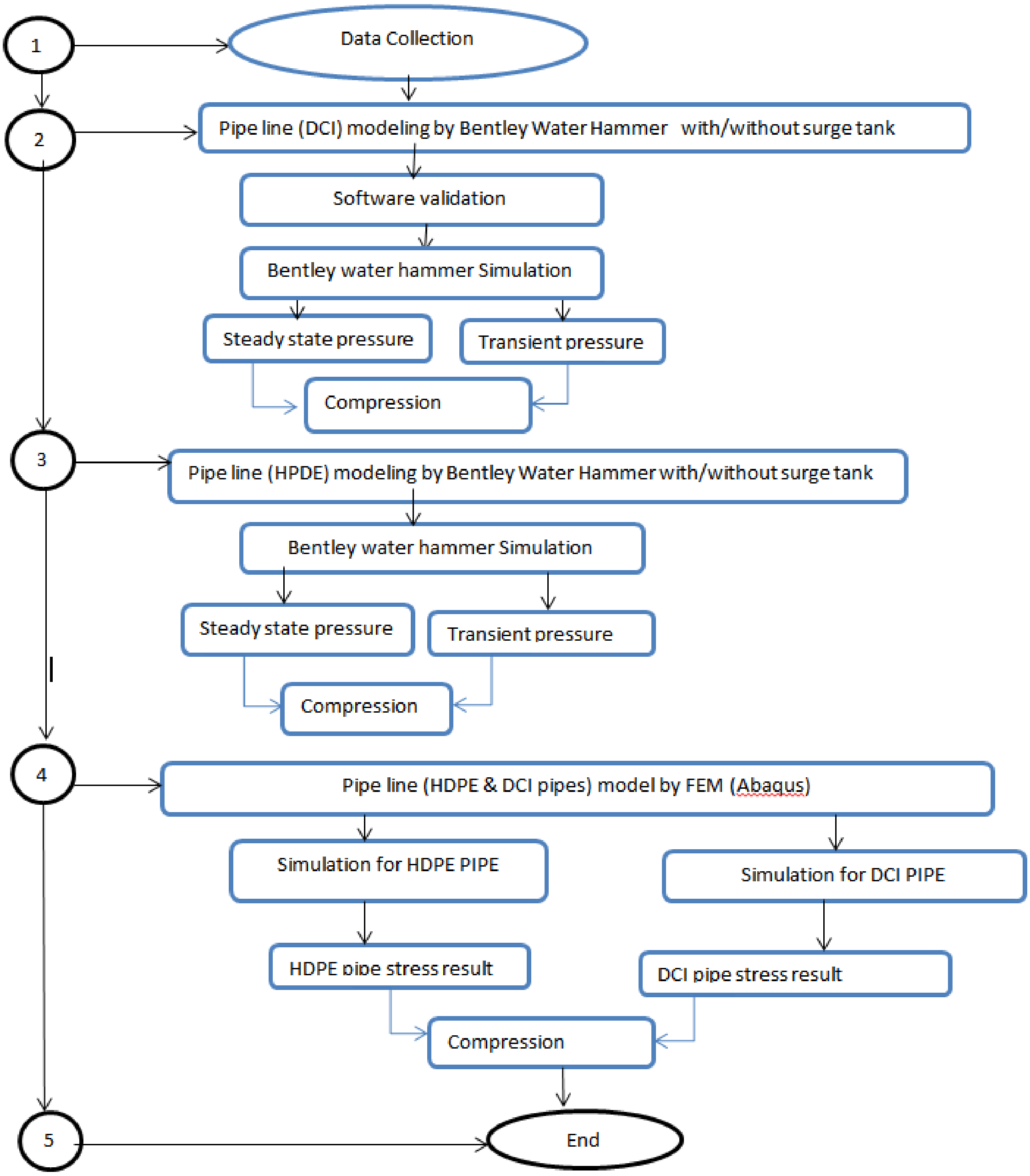


Figure 11: Analyse summary flowchart

4. Results and discussions

For this study Bentley Water Hammer V8i version 2014 and finite element method/Abaqus version 2011 software model and simulation were done. The details analyze and result discussion is presented in this chapter.

4.1. Model Validation

The calibration was done with electromechanical design which was done for DCI pipe line without surge tank. The compression of this study result and design document is presented in table 6.

The study model results were compared with the MS Consultancy (2015) and FELJAS & MASSON (2015) design report for the same pipe lines. The design was executed using CEBELMAI software, developed and commercialized by Diademe Company (Grenoble, France).

Calibration was performed based on the electromechanical design for the DCI pipeline without a surge tank. A comparison of the results from this study and the design documents is presented in Table 6

Table 6:- Bentley water hammer simulation calibration

Sabian booster station to	Description	Pipelines Results in H2O				
		study simulation	Design result	Design & simulation difference	Predicted	Predicted & simulation difference
kefira reservoir	Max. transient pressure	100.72	99.0	1.72	100.0	0.72
	Min. transient pressure	83.28	83.4	0.12	84	0.72
	Steady state pressure	3.72	3.72	0	3.5	0.22
Entoto reservoir.	Max. transient pressure	82.7	84.8	2.1	83	0.3
	Min. transient pressure	76.9	76.4	0.5	75.5	1.4
	Steady state pressure	37.1	41.5	4.4	38.5	1.4
Genda boye reservoir	Max. transient pressure	84.7	81.5	3.2	83.5	1.2
	Min. transient pressure	92.9	90.4	2.5	91.4	1.5
	Steady state pressure	19.1	19.5	0.4	19.0	0.1

According to Bahre (2021), the acceptable level of agreement between measurements and model outputs is an average difference of ±1.5 m, with a maximum of ±5.0 m. Therefore, the simulation results fall within the acceptable range of agreement.

4.1.1. Regression of the result

The regression the result was performed in the following step.

$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$……………………………………………………………………….eq

Step-1:- Residual difference, the difference between model result and predicted and was presented in the in table 6.

Step-2:- calculating the square sum of residual difference (SS_{res} =8.8)

Step-3:- calculating the mean study simulation result (mean =64.57)

Step-4:- calculating the total Squares /the sum of the squares of the difference between the observed values and their mean/ SS_{tot} =9870.3

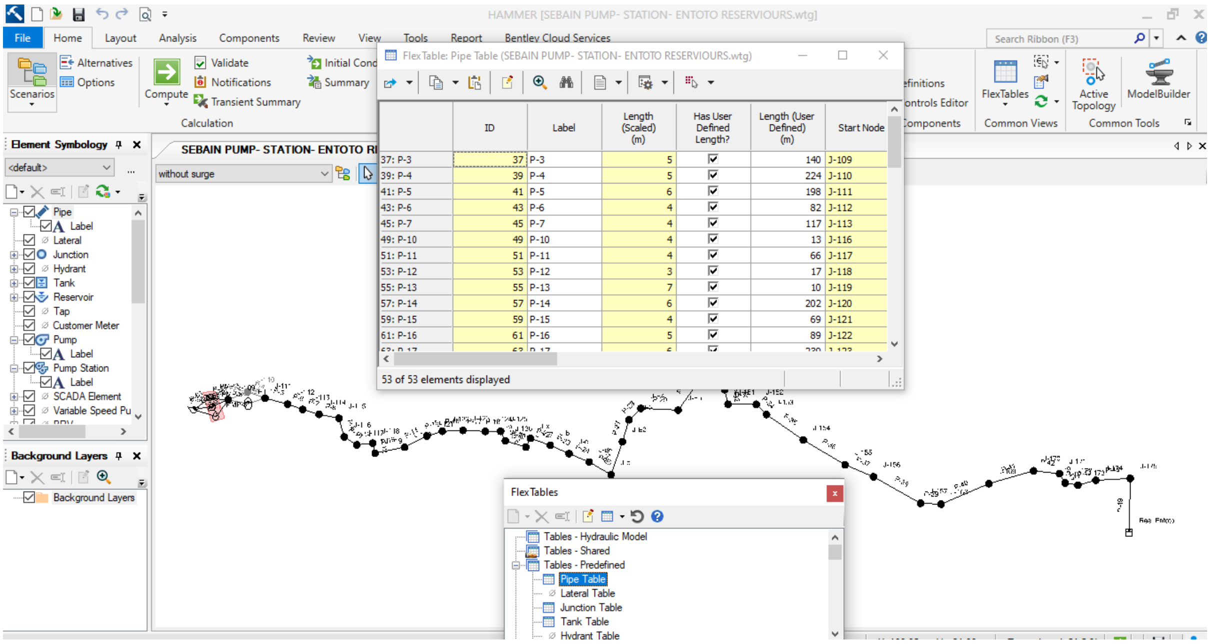
Step-5:- Calculating the regression square (R^2), which resulted in 0.995, indicates that 99.5% of the variance in the study's simulation results can be explained by the Bentley Water Hammer simulation, suggesting an excellent fit.

4.2. Bentley Water Hammer

Bentley Water Hammer V8i software model and simulation were includes building network, setting scenario and alternatives, wave speed calculation and analyze, which are done in sequential way.

4.2.1. Building a Network

The Network building was done by connecting nodes, pumping stations, pipes, and services reservoirs on the Bentley water hammer V8i software working space. Figure 12 shows network built for the sabian to Entoto service reservoir the transmission main pipe.



FlexTable: Pipe Table (SEBAIN PUMP- STATION- ENTOTO RESERVIOURS.wtg)

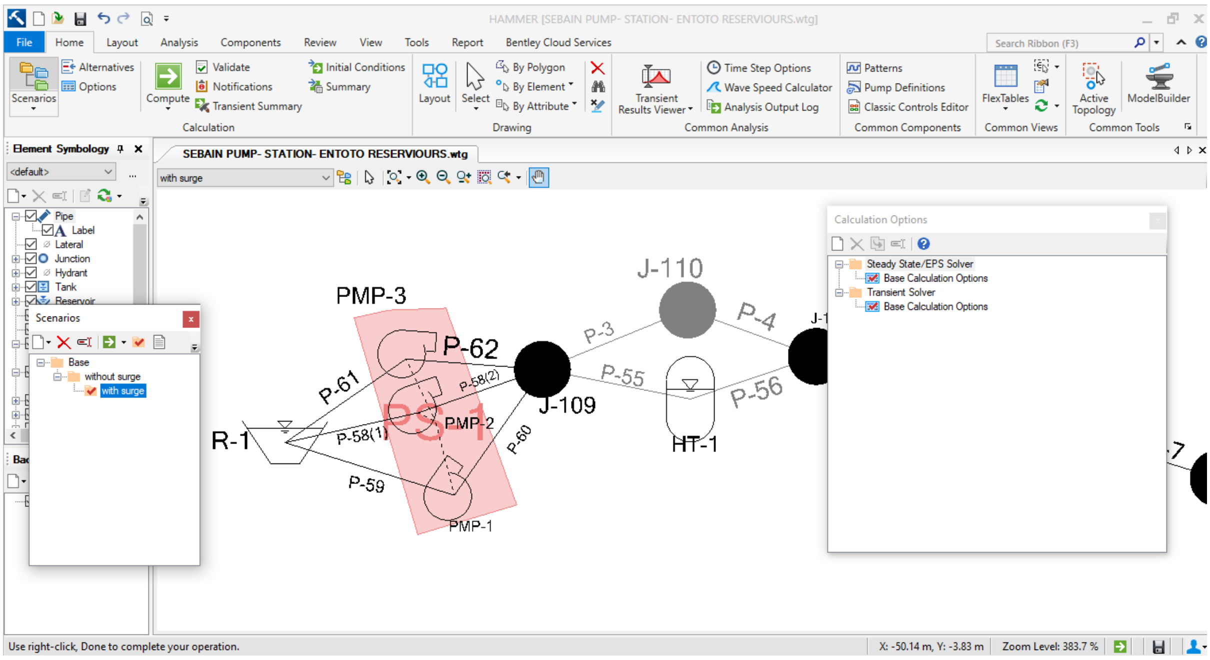
	ID	Label	Length (Scaled) (m)	Has User Defined Length?	Length (User Defined) (m)	Start Node
37: P-3	37	P-3	5	☑	140	J-109
39: P-4	39	P-4	5	☑	224	J-110
41: P-5	41	P-5	6	☑	198	J-111
43: P-6	43	P-6	4	☑	82	J-112
45: P-7	45	P-7	4	☑	117	J-113
49: P-10	49	P-10	4	☑	13	J-116
51: P-11	51	P-11	4	☑	66	J-117
53: P-12	53	P-12	3	☑	17	J-118
55: P-13	55	P-13	7	☑	10	J-119
57: P-14	57	P-14	6	☑	202	J-120
59: P-15	59	P-15	4	☑	69	J-121
61: P-16	61	P-16	5	☑	89	J-122

53 of 53 elements displayed

Figure 12:- Sabian booster station to Entoto reservoir transmission main pipe network builds

4.2.2. Scenario and Alternatives Management

For this study two scenarios were built. The first scenario is with surge tank protection near to pump station and the second scenario is without surge tank protection. Accordingly two simulations were done for both DCI and HPDE, which were totally four simulations.



HAMMER [SEBAIN PUMP- STATION- ENTOTO RESERVIOURS.wtg]

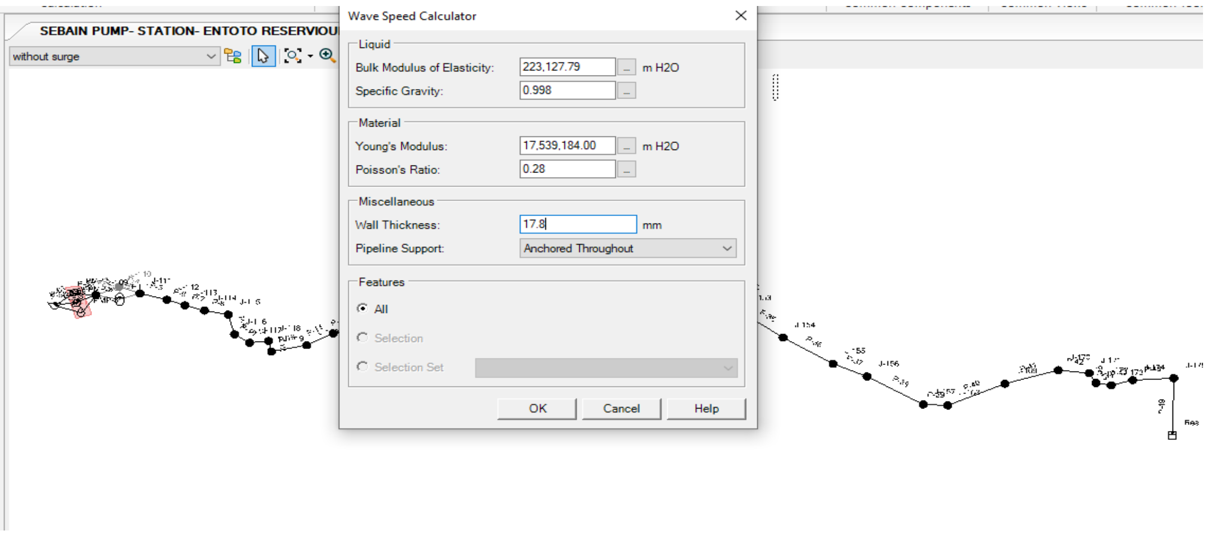
Use right-click, Done to complete your operation.

X: -50.14 m, Y: -3.83 m Zoom Level: 383.7 %

Figure 13:- Sabian booster station to Entoto reservoir transmission main pipe Scenario

4.2.3. Wave Speed Calculator

The wave speed calculation is necessary parameter for transient pressure analyze. It is done automatically by software after entering required data. The mechanical pipe properties like bulk modulus of elasticity and young's modulus from material were selected from Liquid Engineering Libraries as shown on figure 14. Other parameters like pipe thickness dimension and temperature were filled manually. Figure 14 shows the Wave Speed Calculator for the sabian to Entoto service reservoir the transmission main pipe.



Bulk Modulus of Elasticity: 223,127.79 m H2O

Specific Gravity: 0.998

Young's Modulus: 17,539,184.00 m H2O

Poisson's Ratio: 0.28

Wall Thickness: 17.8 mm

Pipeline Support: Anchored Throughout

● All

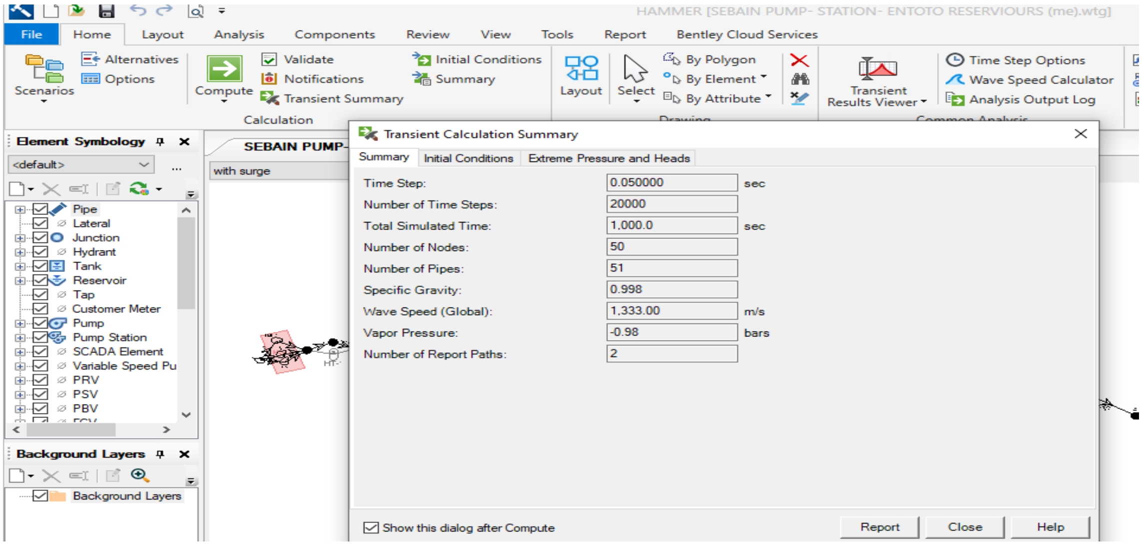
○ Selection

○ Selection Set

Figure 14:- Sabian booster station to Entoto reservoir transmission pipe wave speed calculation.

4.2.4. Analyzing the Model

Once network building and required data entered, software analyze continues. In Bentley water hammer V8i software analyzes, the validation and computation of the model are two steps done. Validation is computed to perform a short run that detects errors before a (much longer) full run. Computation is done to run the model, go to analyze and then compute to run the model.



Time Step: 0.050000 sec

Number of Time Steps: 20000

Total Simulated Time: 1,000.0 sec

Number of Nodes: 50

Number of Pipes: 51

Specific Gravity: 0.998

Wave Speed (Global): 1,333.00 m/s

Vapor Pressure: -0.98 bars

Number of Report Paths: 2

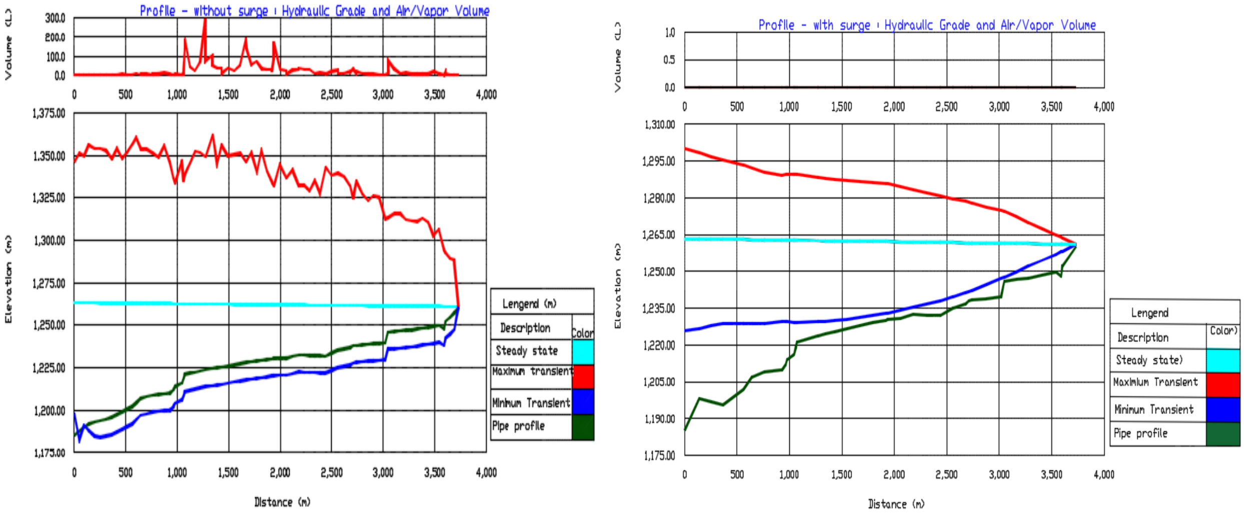
☑ Show this dialog after Compute

Figure 15:- Sabian booster station to Entoto reservoir analysing the model.

4.3. The Bentley water hammer v8i Transmission line Simulation for DCI pipe

The Bentley water hammer simulations for DCI in three transmissions main were done with two scenarios. First scenario model and simulation was done without surge tank protection. The result shows the steady state pressure in transmission main line were ranges between 3.72 and 37.1 m H2O above static head which is same to the study document value done by water Gems software. The maximum transient pressure result ranges is between 82.7 and 100.72 m H2O and the minimum or negative transient pressure ranges between 76.9 and 83.28 m H2O above static head.

The second scenario model and simulation was done with surge tank protection. The result shows the steady state pressure value were the same in both cases as it considers the same parameters in both cases. The Maximum transient pressure ranges between 20.6 and 49.1 m H2O and the minimum or negative transient pressure ranges between 34.28 and 55.9 m H2O above static head.



a. DCI pipe without surge tank

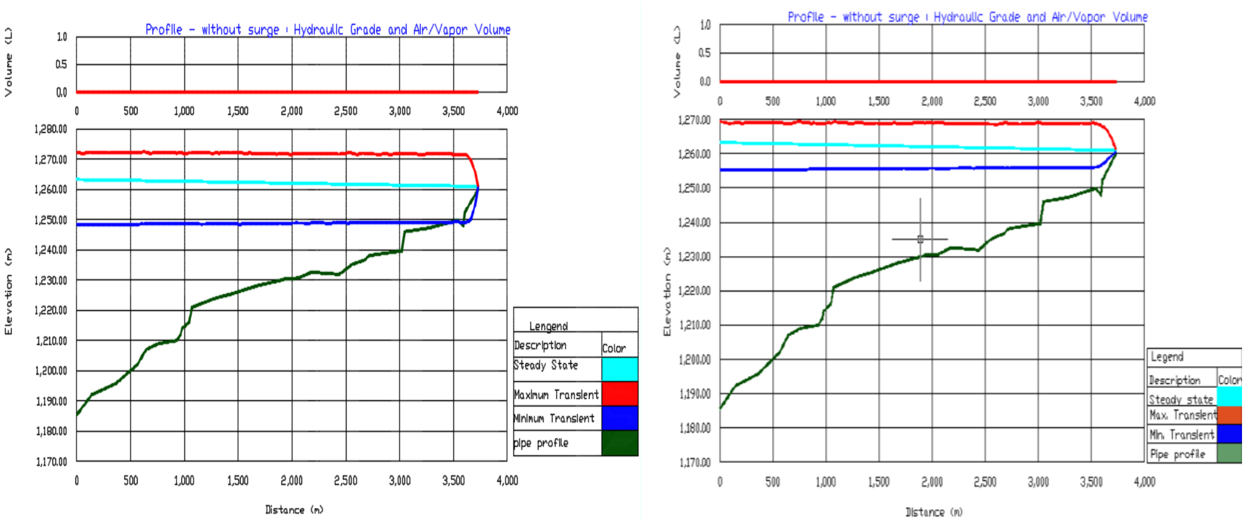
b. DCI pipe with surge tank

Figure 16:- Sabian Booster to Kefira Reservoir Transmission line Bentley water hammers Simulation result.

4.4. The Bentley water hammer v8i Transmission line Simulation with HDPE pipe

The Bentley water hammer simulations for HDPE pipe in three transmissions main were done by two scenarios. First scenario model and simulation was done without surge tank protection. The result shows the steady state pressure in transmission main line were ranges between 3.72 and 37.1 m H2O above static head, which is same with study document value done by water Gems software by MS consultancy study. The maximum transient pressure range is between 12.52 and 39.7 m H2O above static head and the minimum or negative transient pressure range is between 5.9 and 30.6m H2O above static head.

The second scenario model and simulation was done with surge tank protection. The result shows the steady state pressure, maximum transient and negative transient pressure result is same with the first scenario.

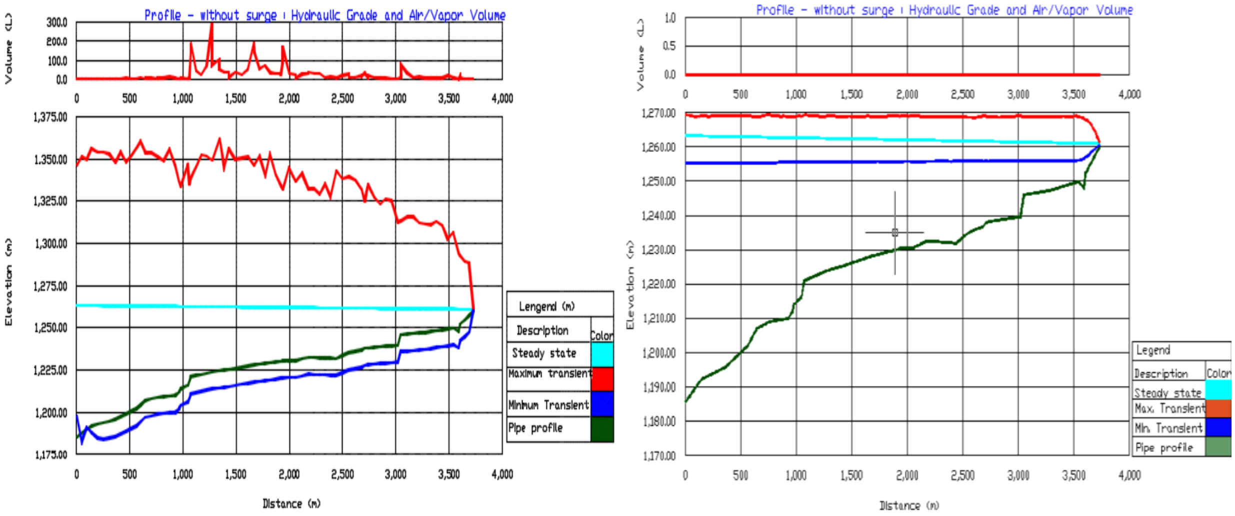


a. Kefira HDPE line without surge tank b. Kefira HDPE line with surge tank

Figure 17:- Bentley water hammers Simulation (HDPE) result with and without surge tank.

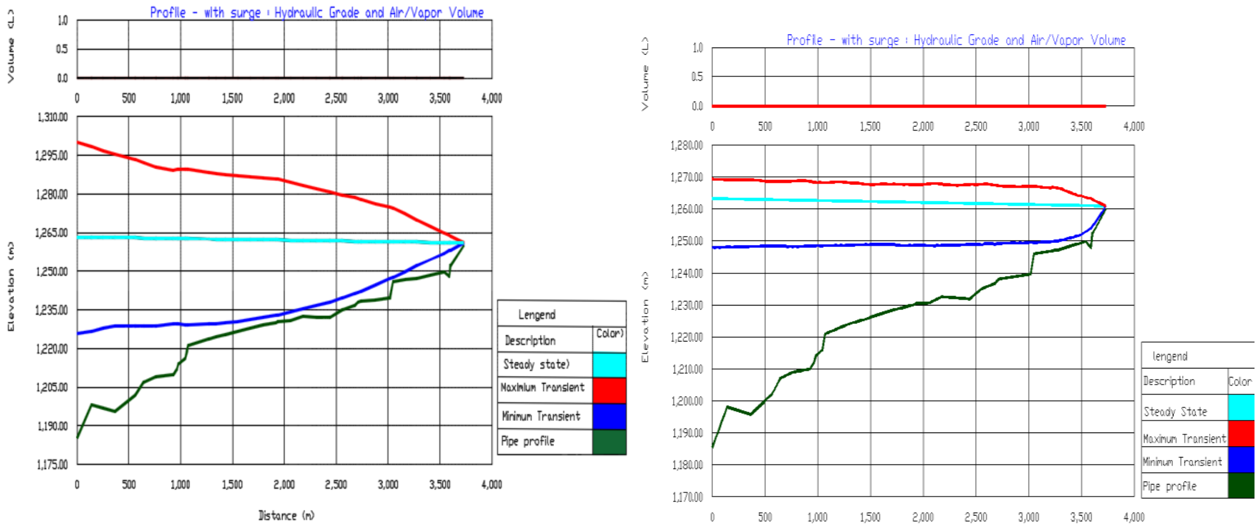
4.5. The Bentley water hammer v8i Simulation result Compression for HDPE and DCI pipes

HDPE and DCI pipes transient and steady state pressure compression were done for the analyze result without surge tank protection. Accordingly, the analyze result shows HDPE pipe reduces the maximum transient pressure with range of 104 % and minimum transient pressure up to 118.3%. The HDPE pipe hydraulic transient pressure resistance is higher than DCI pipe due to its lower value of dynamic modulus. While steady state pressure for both DCI and HDPE pipe is almost the same since it is less dependent to the pipe material properties.



a. DCI pipe without surge tank b. HDPE pipe without surge tank

Figure 18:- Sabian Booster to Kefira Reservoir Transmission line Bentley water hammers Simulation result.



a. DCI pipe with surge tank b. HDPE pipe with surge tank

Figure 19:- Sabian Booster to Kefira Reservoir Transmission line Bentley water hammers Simulation result.

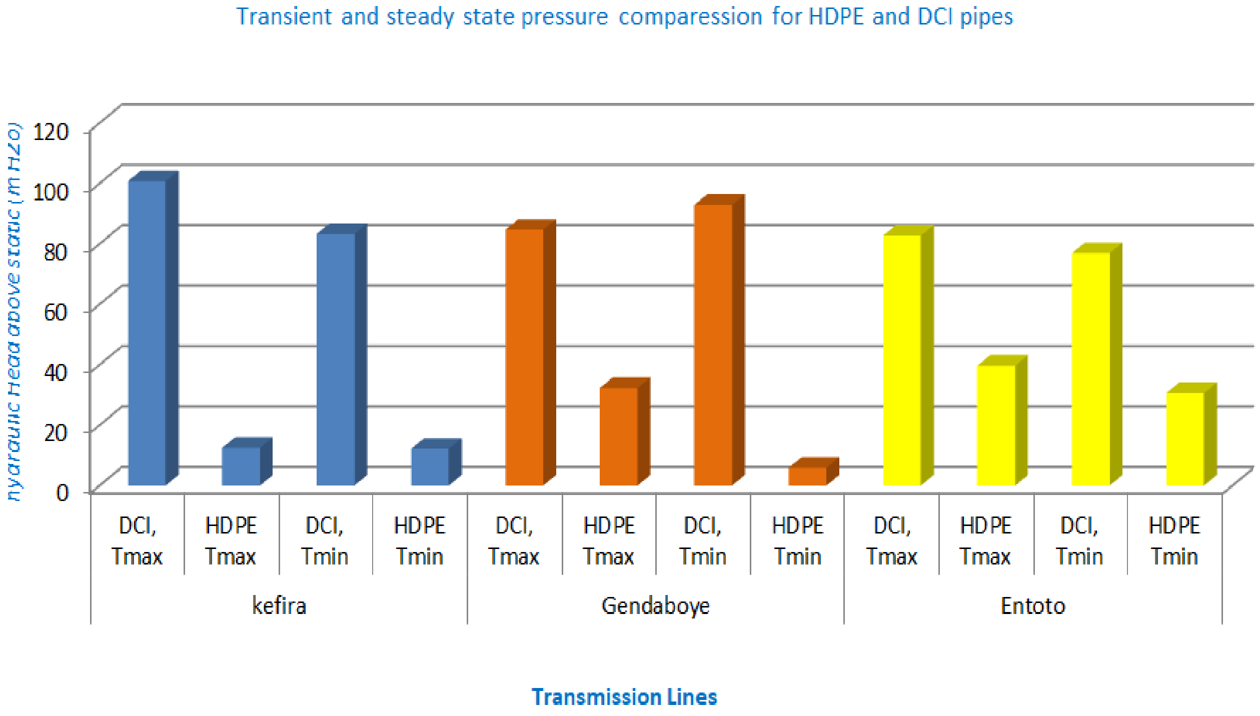
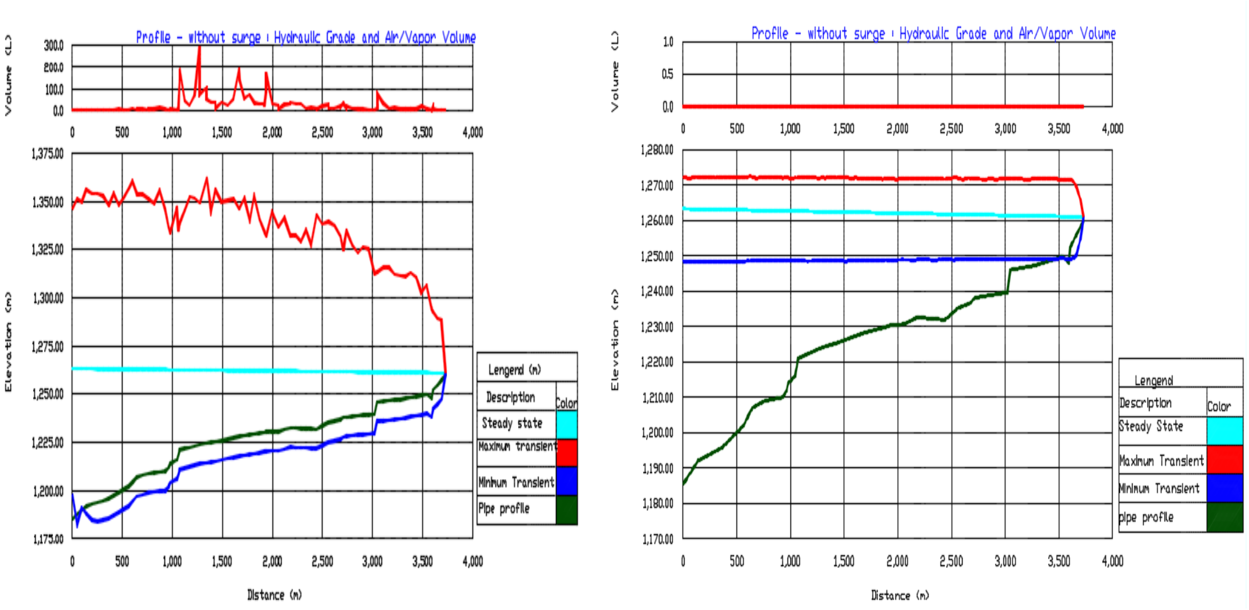


Figure 20:- Compression of HDPE and DCI pipes for transient and steady state pressure. Sources; (own sources)

According to the study conducted by Chevron Phillips Chemical Company LP, 2009, hydraulic transient pressure in HDPE pipe is about 413.7 % lower than DCI pipe; and the study result by WL Plastics manufacturer, 2022 shows HDPE pipe transient lower than DCI by 354.54 %. This due to HDPE has lower value of dynamic modulus and due its higher shock absorption

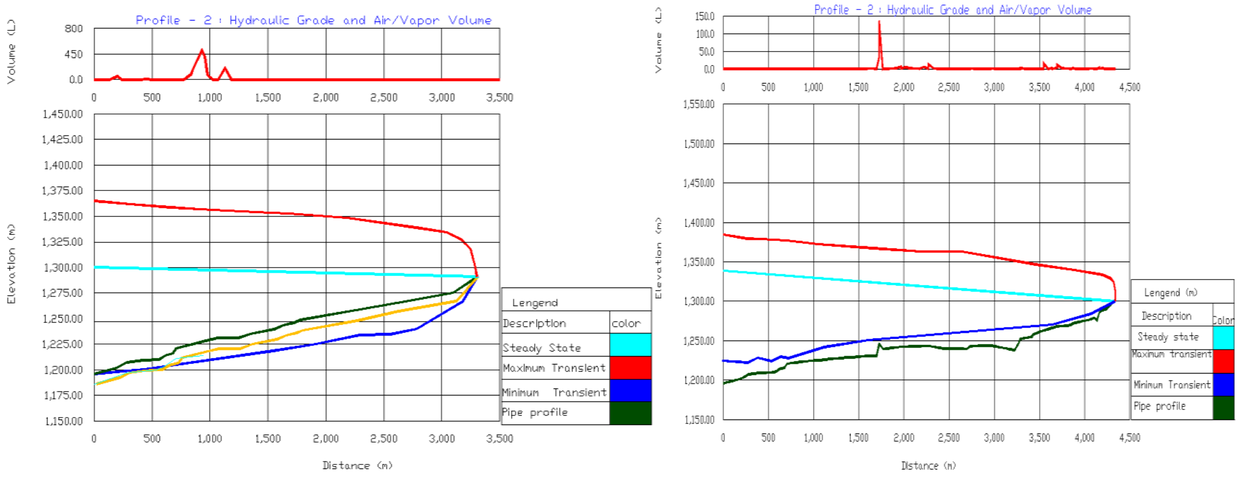
4.5. Compression of steady state and transient pressure

Compression of steady state and transient pressure were done for both DCI and HDPE pipes on the analyze results without provision of surge tank protection. The result shows, the DCI pipe maximum transient pressure exceed steady state pressure up to 127.63 %, and minimum transient below steady state pressure up to 114.4%. The HDPE pipe maximum transients exceed steady state pressure up to 11.57% and minimum transient exceed steady state pressure up to 44.13 %. The compression show that transient pressure is much higher than transient pressure and also the DCI pipe transient pressure is much higher than steady state pressure compare to HDPE pipe.



a. DCI pipe without surge tank b. HDPE pipe without surge tank

Figure 21:- Sabian Booster to Kefira Reservoir line Bentley water hammers Simulation result



a. Genda boye DCI pipe without surge tank b. DCI pipe without surge tank Entoto

Figure 22:- Bentley water hammer Simulation result.

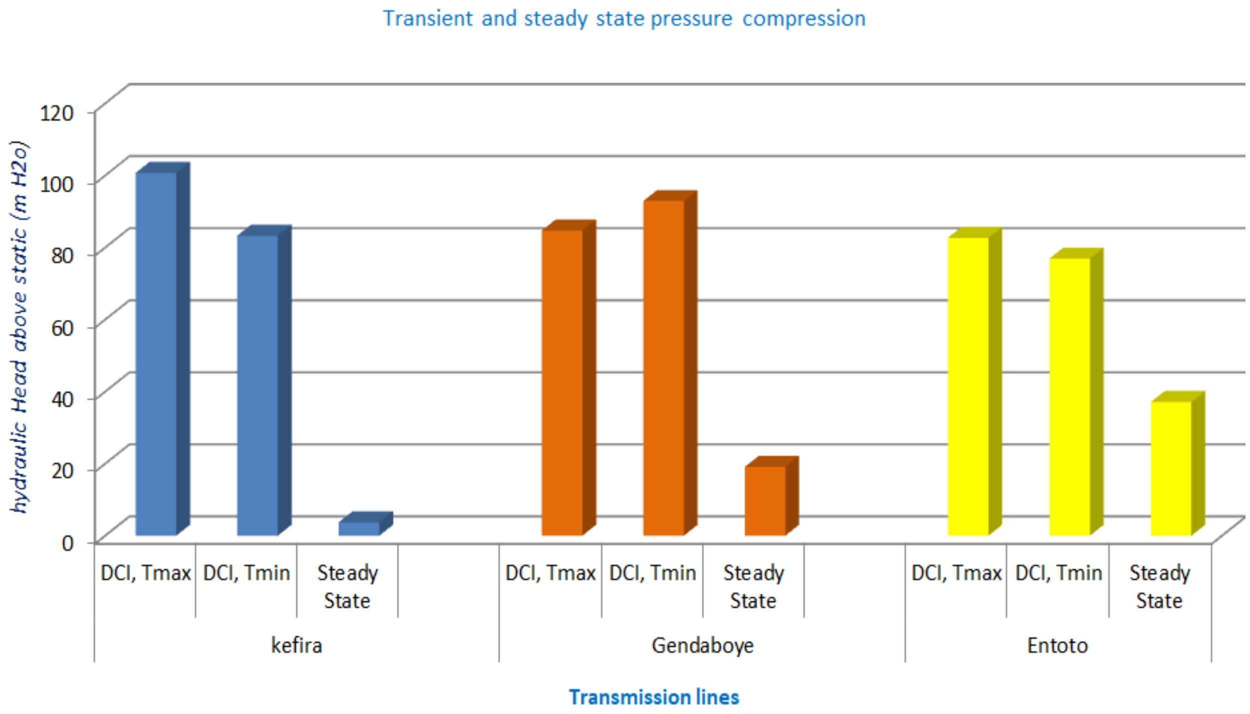
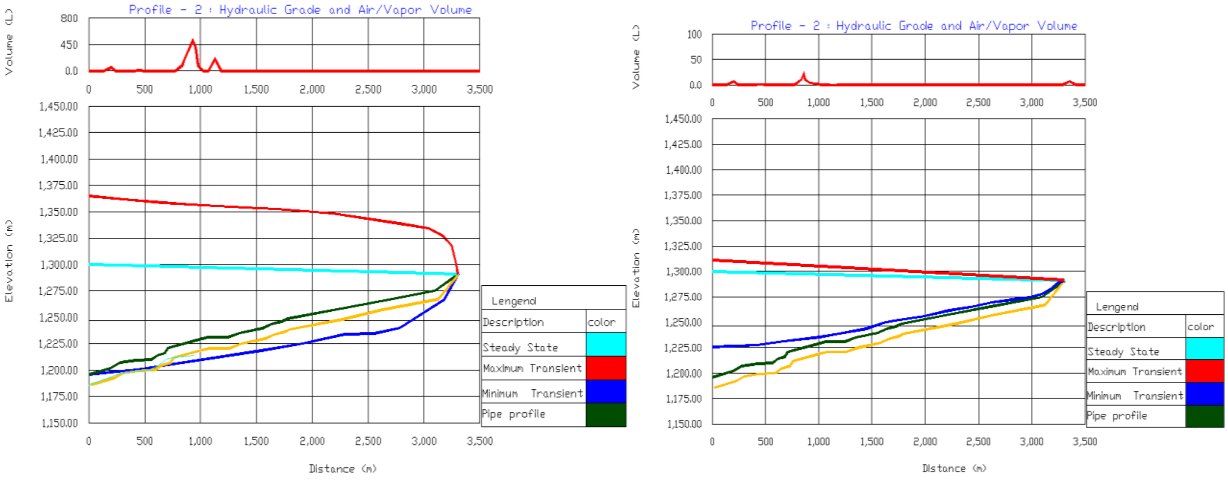


Figure 23:- Compression of steady state and transient pressure.

(Aly at el.2019) conducted analysis steel pipe of 1000mm diameter and 4,600 km length by using AFT. The result shows maximum transient pressure exceeds steady state 138.55 %. (Lüdecke 2006) study on the relation of transient pressure and steady state pressure with and without provision devices surge protection devices. Maximum transient pressure is higher than steady state by 199.19% and Minimum transient pressure is lower than steady state by 108.5%.

4.6. Use of surge tank in reduction of steady state and transient pressure

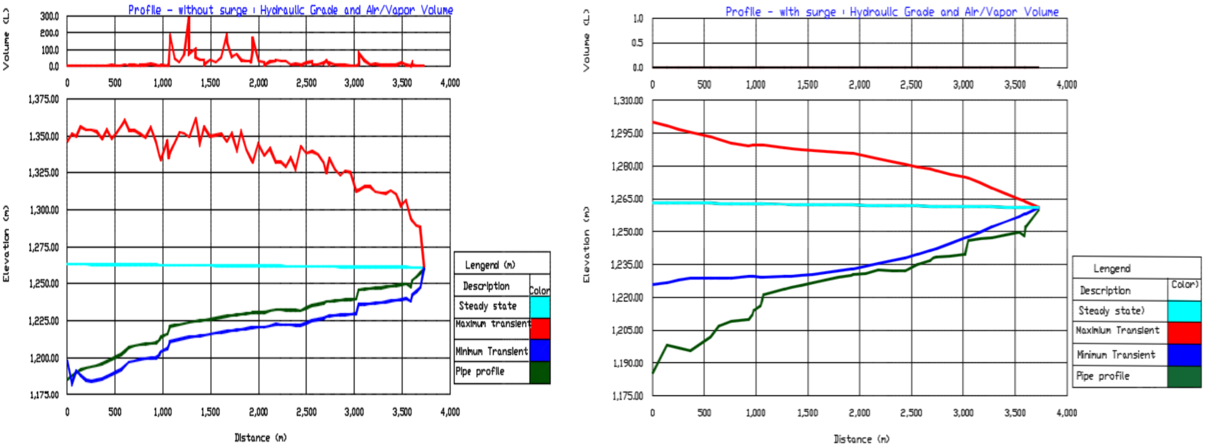
To examine surge tank effectiveness in reduction of pressure, Bentley water hammer simulation were done for both DCI and HDPE pipes with two scenarios with and without provision of surge tank. The simulation result shows, the surge tank reduce the maximum transient pressure up to 56.47% and minimum transient pressure up to 128.9 % for DCI pipe. The surge tank reduces the maximum transient pressure up to 10.4% and minimum transient pressure up to 11.7 % HDPE pipe. The provision of a surge tank has no impact on the steady-state pressure for both DCI and HDPE pipes.



a. DCI pipe without surge tank

b. DCI pipe with surge tank

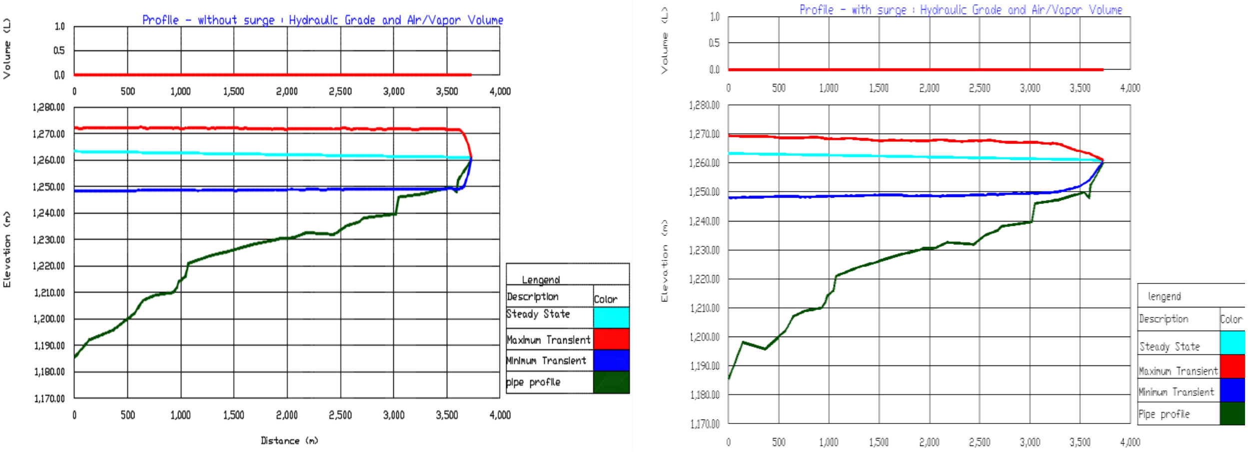
Figure 24:- Sabian booster to Genda boye reservoir line Bentley water hammer simulation result.



a. DCI pipe without surge tank

b. DCI pipe with surge tank

Figure 25:- Sabian booster to Kefira Reservoir line Bentley water hammer simulation result.



a. HDPE pipe without surge tank

b. HDPE pipe with surge tank

Figure 26:- Sabian booster to Kefira Reservoir line Bentley water hammer simulation result.

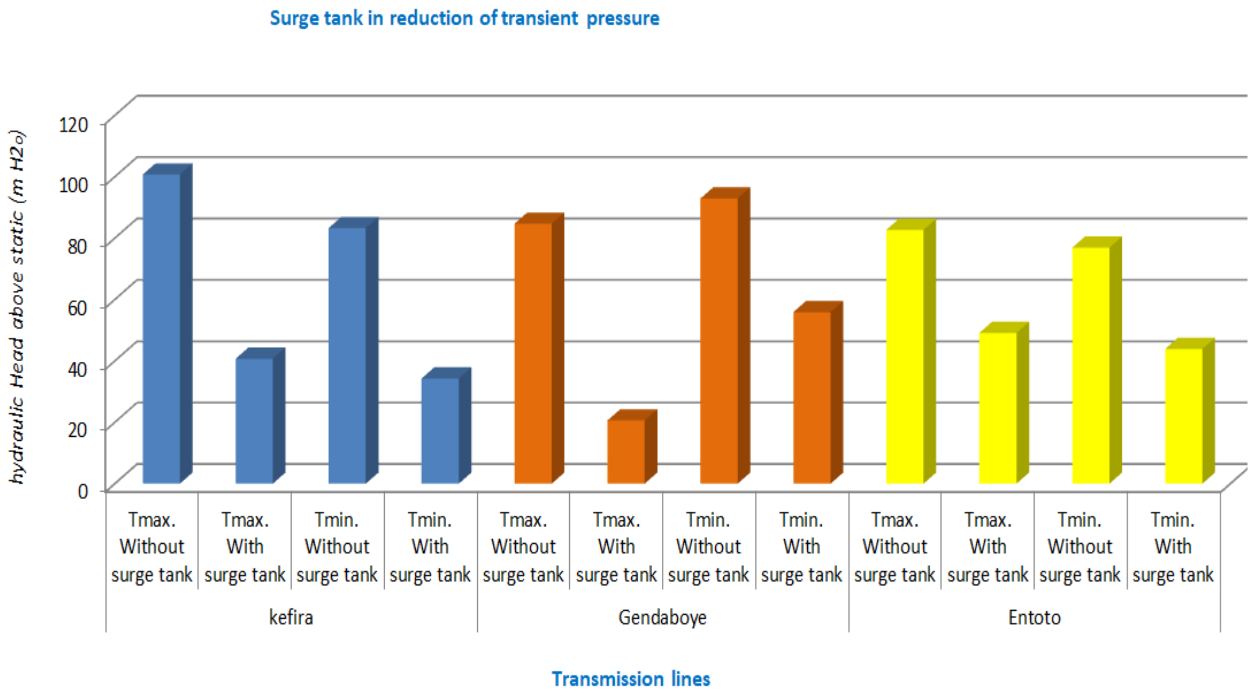


Figure 27: - Surge Tank Transient Pressure Reduction for DCI pipe.

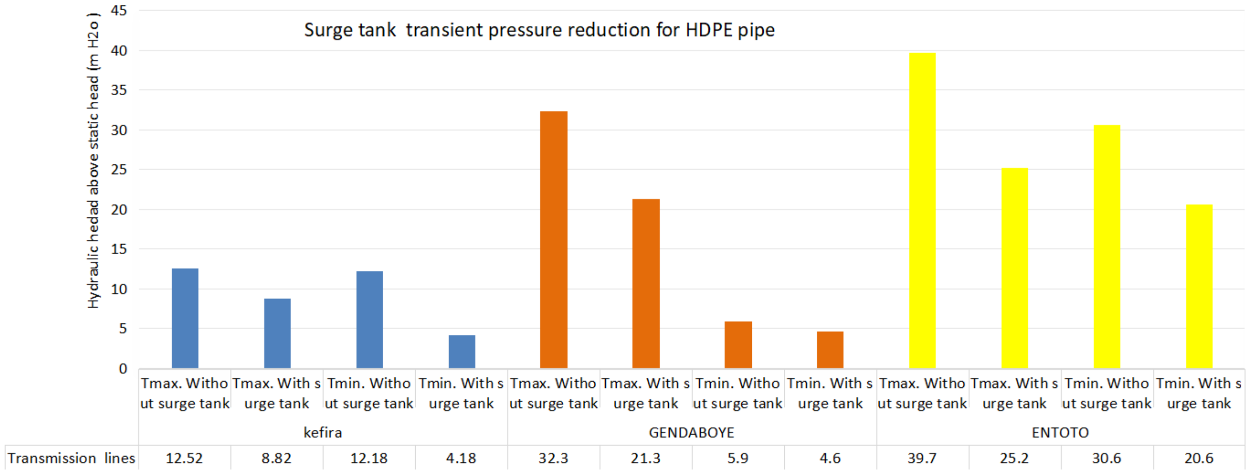


Figure 28: - Surge Tank Transient Pressure Reduction for HDPE pipe.

(Kredi, 2018) study shows surge tank serve to protect both positive and negative pressure of transmissions pipe system. It can be used to supply fluid to the system during a down surge, to preventing or minimizing vapour separation column. According to Lüdecke (2006), air vessel devices reduce the maximum transient by 183.14% and the minimum transient by 102.04%. Aly et al. (2019) found that air vessel protection reduces the maximum transient by 140.38%.

4.8. Water supply and sanitation transient pressure Design result

Dire dawa Water supply and sanitation electromechanical design document part comprises transient design for all transmission pipe lines. The calculation was performed with CEBELMAI software developed and commercialized by Diademe Company (Grenoble, France).

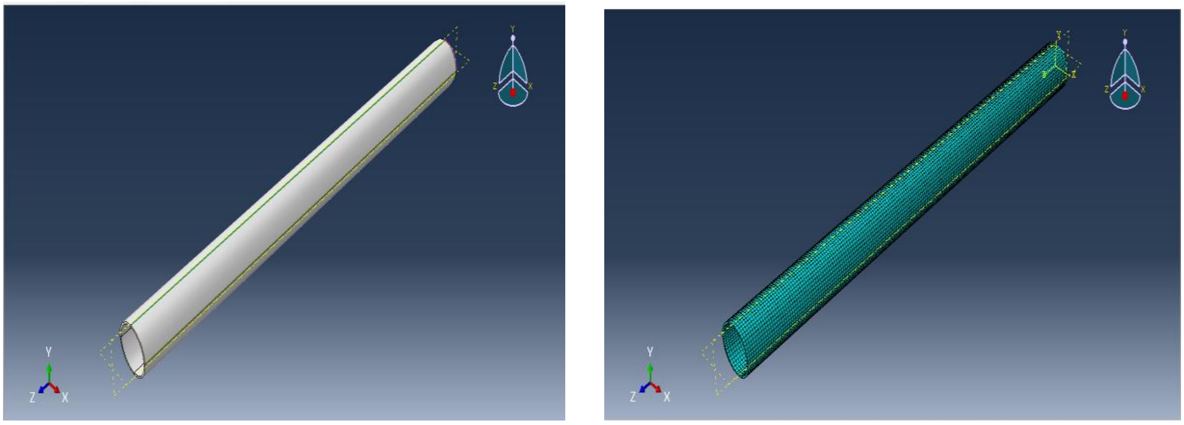
Table 7:- Design document study transmission main transient pressure EBELMAI software (MS consultancy, 2015)

S.No	Pipe line	Steady state head m H2O	Maximum Transient m H2O		Minimum Transient m H2O		%. Transient higher than steady state		% of Surge tank reduces Transient	
			Without surge	With surge	Without surge	With surge	Max.	Min.	Max.	Min.
1	Borena to Goro	1241	1300	1241	1118	1170	47.9	100	48	73.2
2	Borena to Sabian	1200	1225	1206	1125	1160	30.5	91.5	21.5	87.5
3	Tome to Police meret	1210	1256	1218	1185	1220	58	102.7	58	39.4
4	Legehare to upper kefira	1290	1332	1290	1185	1235	40	100	40	90.9

The result shows, Transient pressure can be higher than steady state pressure up 102.7 %, and surge tank can reduce both transient up to 90.9 %.

4.9. Finite Element Method/ Abaqus Software

The ABAQUS (2011) simulation was conducted through a systematic approach comprising three essential steps: modeling the pipe, pre-processing, and solution.

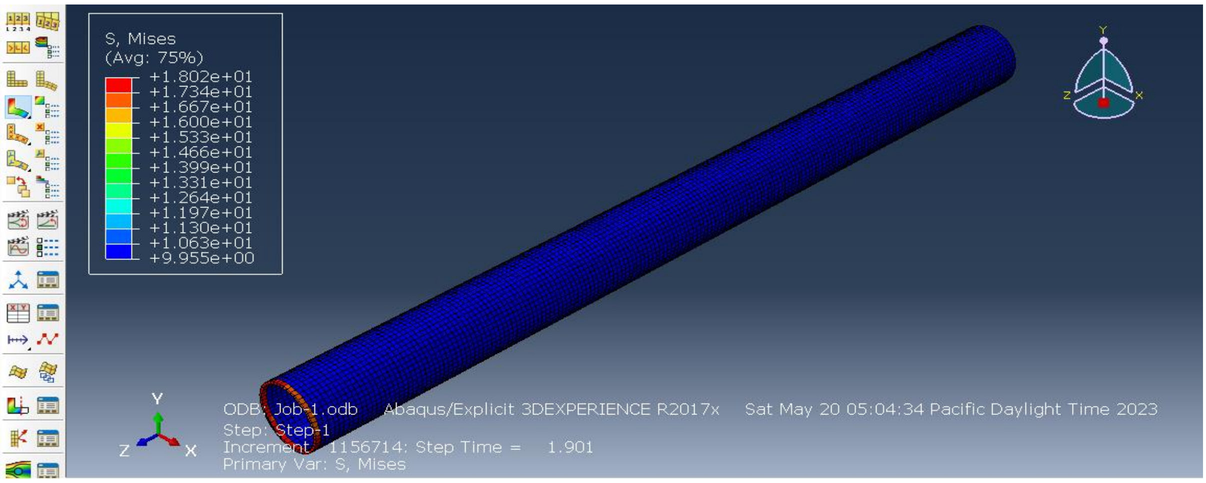


a. part

b. mesh

Figure 29:-Abaqus finite element model

The solution step includes job creation, Submitting, Running, and Results.



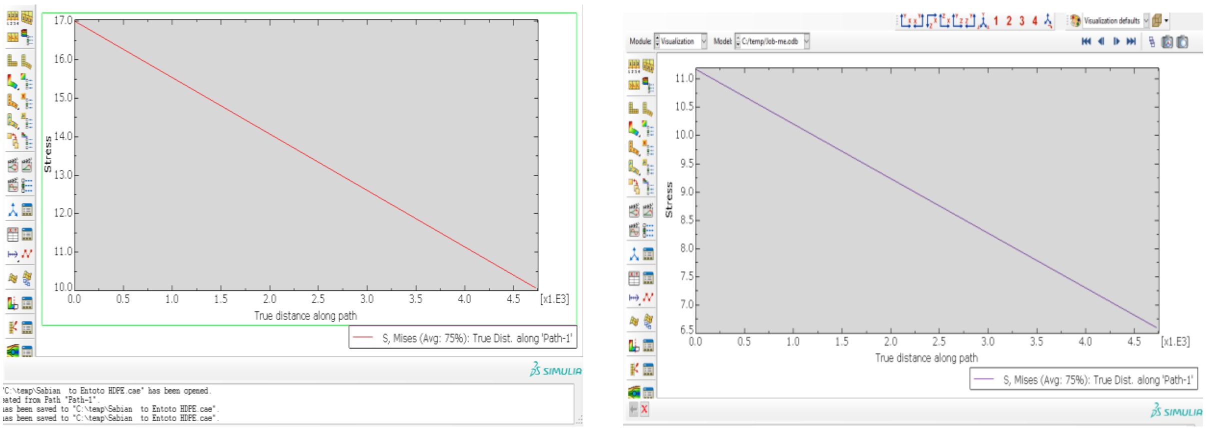
```
S, Mises
(Avg: 75%)
 +1.802e+01
 +1.734e+01
 +1.667e+01
 +1.600e+01
 +1.533e+01
 +1.466e+01
 +1.399e+01
 +1.331e+01
 +1.264e+01
 +1.197e+01
 +1.130e+01
 +1.063e+01
 +9.955e+00
```

```
ODB: Job-1.odb    Abaqus/Explicit 3DEXPERIENCE R2017x    Sat May 20 05:04:34 Pacific Daylight Time 2023
Step: Step-1
Increment  1156714: Step Time =    1.901
Primary Var: S, Mises
```

Figure 30:- Abaqus analyze result of pipe model

4.8.1. Abaqus simulation for DCI and HDPE pipes result compression

The finite element method/Abaqus software model simulations were done for 150mm and 350 mm ND diameter for both HDPE and DCI pipes. For both pipes the same nominal pressure and hydrostatic dynamic load were used to compare the result. Figure 26 and 27 shows the DCI pipe hydrostatic Burst pressure resistance strength is up to 1.65 or 64.7% higher than HDPE pipe. DCI pipe has higher yield strength than HDPE and its structural resistance pressure is also higher than HDPE pipe. Also the result shows large diameter is more stressed than the smaller diameter where applied load and pipe nominal pressure is the same.

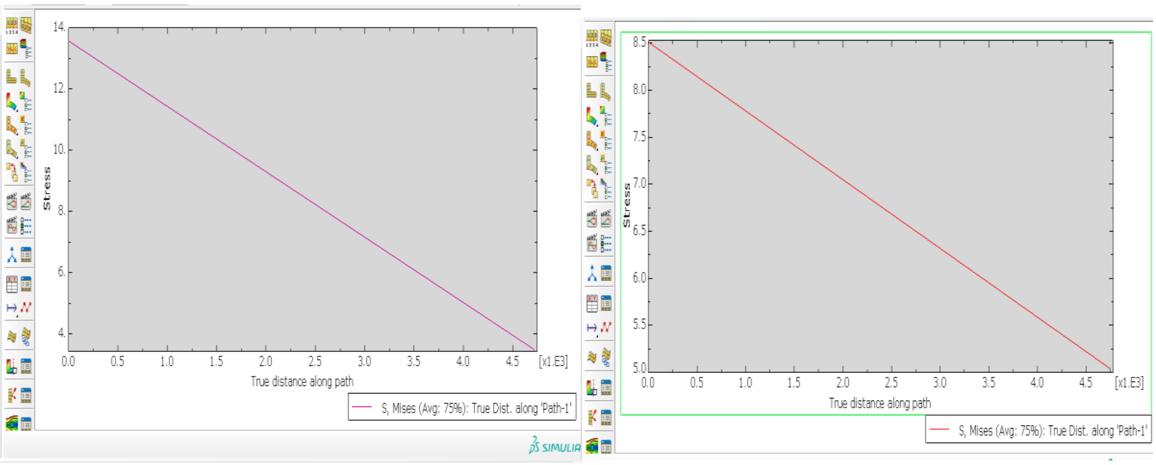


```
'C:\temp\Sabian  to Entoto HDPE.cae" has been opened.
eated from Path "Path-1".
ias been saved to "C:\temp\Sabian  to Entoto HDPE.cae".
ias been saved to "C:\temp\Sabian  to Entoto HDPE.cae".
```

a. 315 mm dia HDPE internal stress

b. 315 mm dia DCI internal stress

Figure 31:- Abaqus simulation internal pipe stress result. Sources; (own sources)



a. 150 mm dia HDPE internal stress

b. 150 mm dia DCI internal stress

Figure 32:- :- Abaqus simulation internal pipe stress result. Sources; (own sources)

Lüdecke (2006) performed burst tests on DCI and HDPE pipes as per ASTM D1599-12 standards. The results showed that DCI pipes had a hydrostatic burst pressure that was 6.1 times greater than that of HDPE pipes.

5. Conclusions and recommendations

5.1. Conclusions

In this study, primarily hydraulic modelling of transmission lines was performed using Bentley water hammer V8i version 2014 and finite element method (Abaqus 2011). Two scenarios model with and without surge tank provision were done by Bentley water hammer V8i, 2014 for three pipe lines for DCI and HDPE pipes. Finite element method /Abaqus software simulation were done for DCI and HDPE pipes of 315 and 150 mm diameter.

The Bentley water hammer V8i result shows, maximum transient pressure is higher than steady state for DCI pipe up to 127 %. Surge tank reduce the transient pressure up to 128.9 % for DCI pipe and up to 11.7 % for HDPE pipe. HDPE pipe reduce the surge effect in the system than DCI pipe up 118.3%. The finite element method/Abaqus analyze result shows, the HDPE pipe is 64.7 % higher stressed than DCI pipe where both pipes have the same diameter.

Therefore, the study results reveals that; transient pressure is higher than steady state and determinant for fixing the pipe nominal pressure; HDPE pipe have phenomenal higher surge resistance than DCI pipe; surge tank have vital important in reduction of transient pressure or surge and HDPE pipe is highly stressed than DCI pipes under application of the same dynamic load.

For Dire dawa water supply transmission lines, HDPE pipe of the same PN and nominal diameter with existing DCI pipe can be replaced whenever required as it reduce the effect of transient pressure in addition to its availability locally by less price.

5.2. Recommendations

In the design of water supply scheme pipe networks, it is essential to analyze both steady-state and hydraulic transient pressures. This analysis provides the critical pressure information necessary for designers to select the appropriate pipes nominal pressure.

HDPE (High-Density Polyethylene) pipe is feasible to use for both transmission and distribution networks due to their significant advantages in reducing the effects of transient pressures. HDPE pipes are known for their flexibility and resistance to pressure fluctuations, making them suitable for various applications.

For pipe lines exposed to high stress or rock, DCI (Ductile Cast Iron) pipe is more recommendable than flexible pipe. DCI pipes offer excellent stress resistance, making them ideal for environments where pressure levels may be elevated.

Furthermore, this study inspires future researchers to expand the analysis of hydraulic transient pressures and steady-state pressures with number of additional water supply pipe lines. Future investigations should include comparative studies of DCI and HDPE pipe performance under hydraulic transient conditions using different simulation methods and laboratory experiments. This current study is limited to three transmission lines within a single project, and broader analysis could yield valuable insights for improved design practices.

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Annex 1:- Study Transmission main lines ground profile

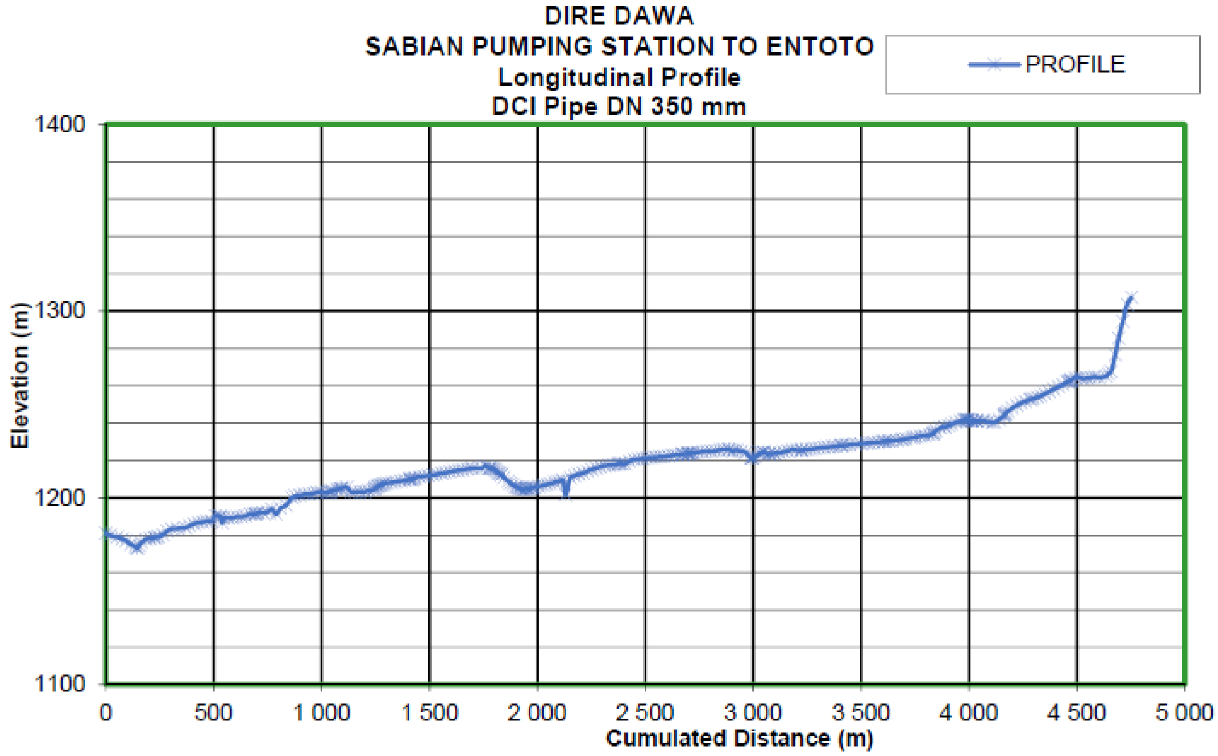


Figure 33:- Sabian booster pump station to Entoto reservoir Longitudinal Profile

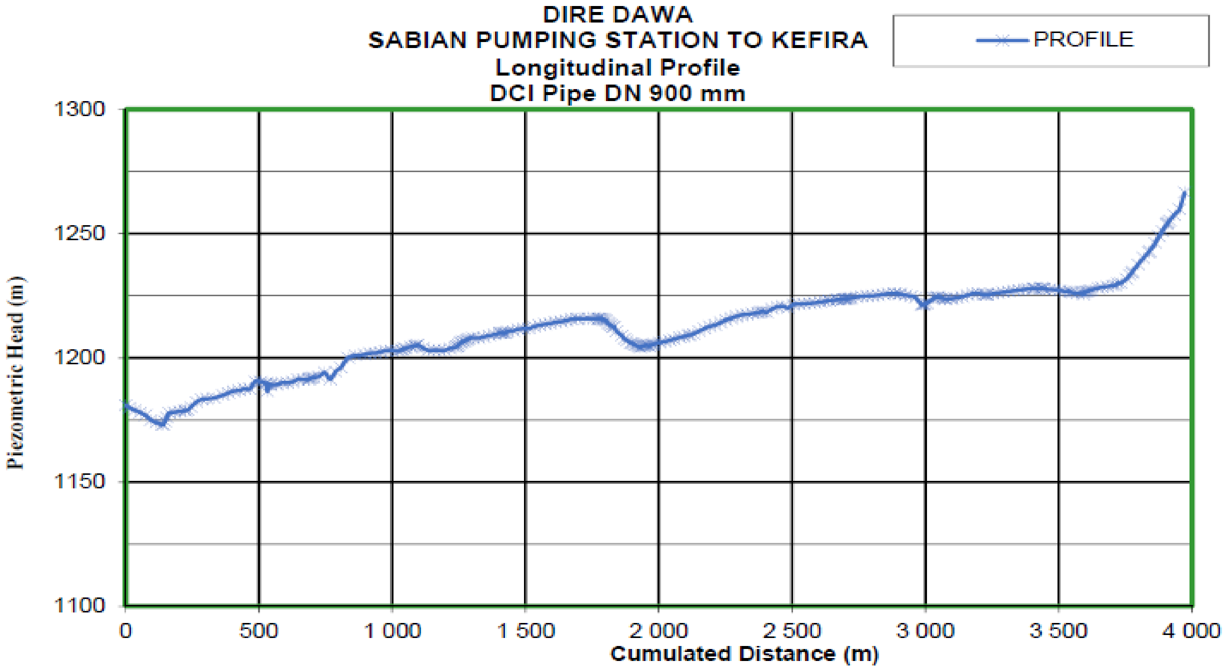
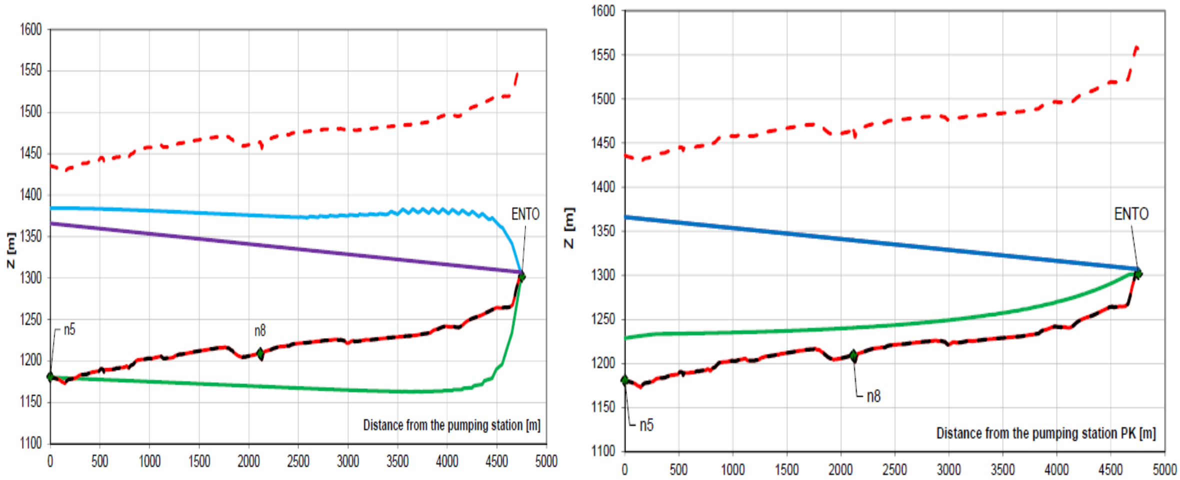


Figure 34:- Sabian booster pump station to Kefira reservoir Longitudinal Profile

Annex 2:- Design Document Transient pressure

CEBELMAIL software steady state and transient pressure simulation result from the electromechanical design document.

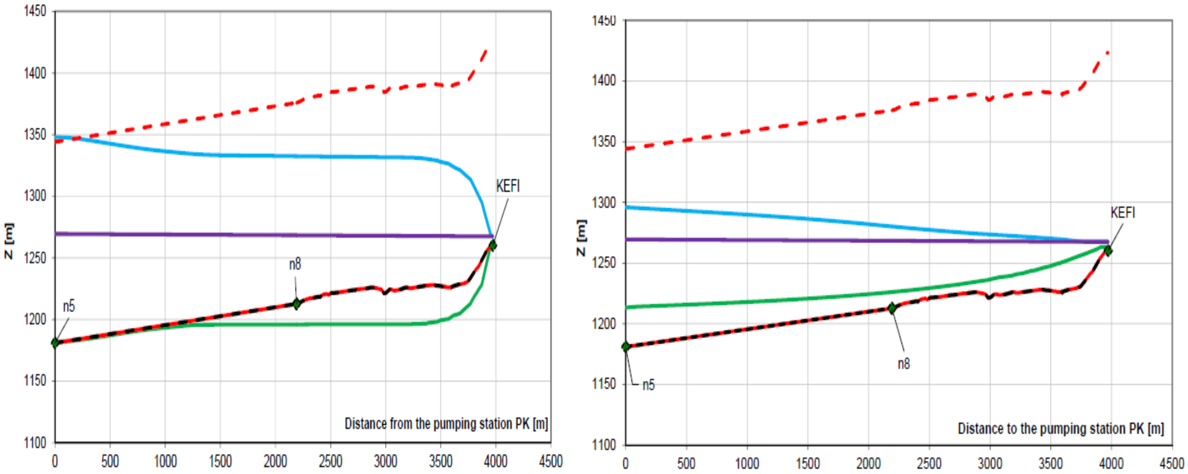
a. Sabian Booster station to Entoto Reservoir pipe delivery by CEBELMAIL a software



a. without surge tank b. with surge tank

Figure 35:- Transient pressure for DCI pipe along sabain to Entoto transmission main

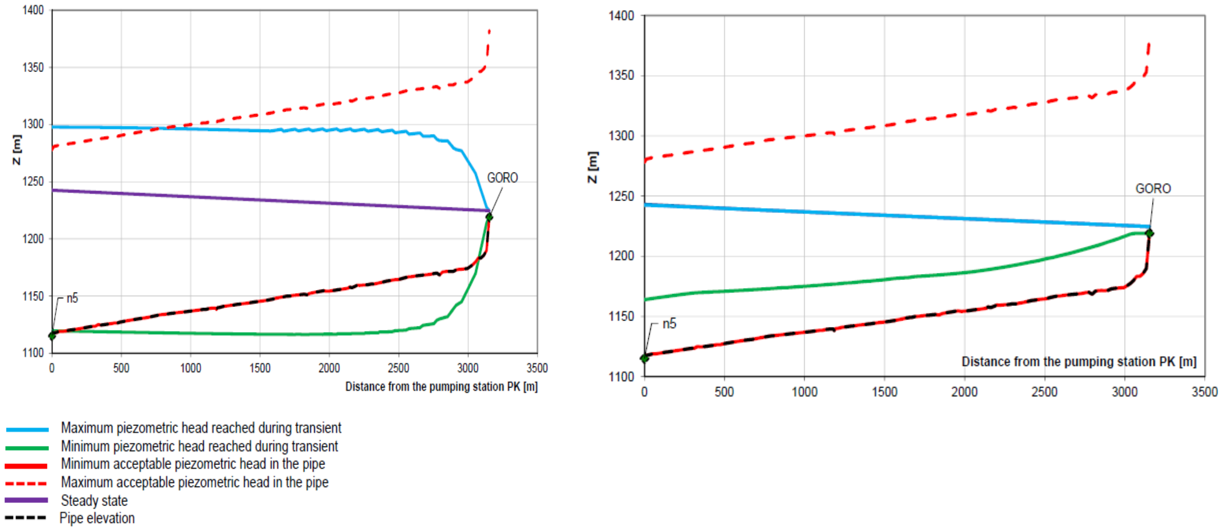
b. Sabian Booster station to Kefira Reservoir pipe delivery Water hammer result



a. without surge tank b. with surge tank

Figure 36:- Transient pressure for DCI pipe along sabain to Entoto transmission main

c. Boren to Goro Reservoir pipe delivery Water hammer result by CEBELMAILa software

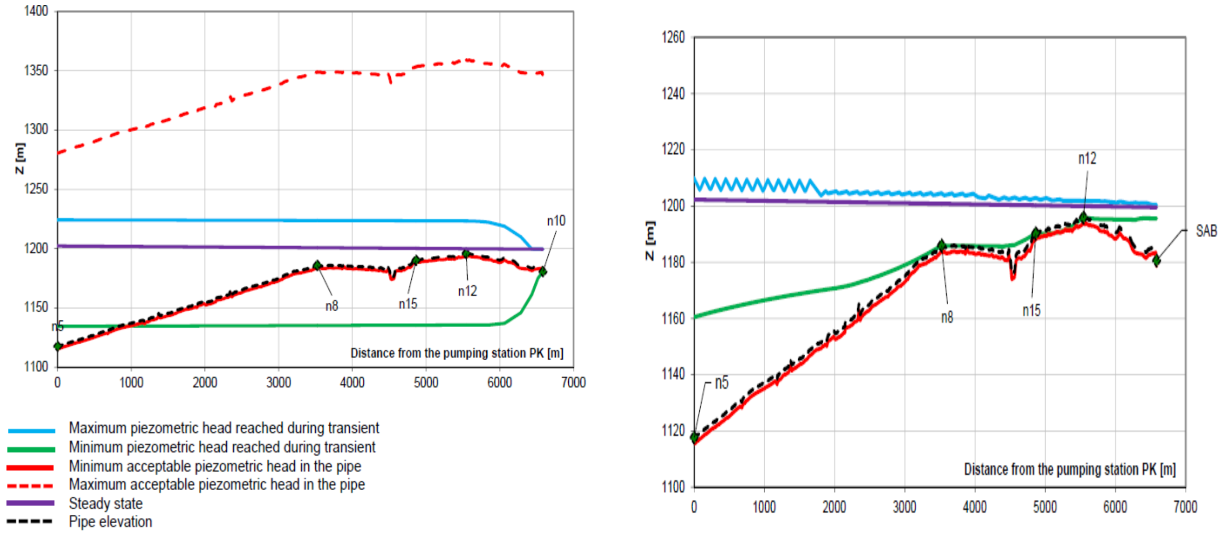


a. without surge tank

b. with surge tank

Figure 37:- Transient pressure for DCI pipe along sabain to Goro transmission main

d. Boren to Sabian booster pump station pipe delivery Water hammer result by CEBELMAILa software

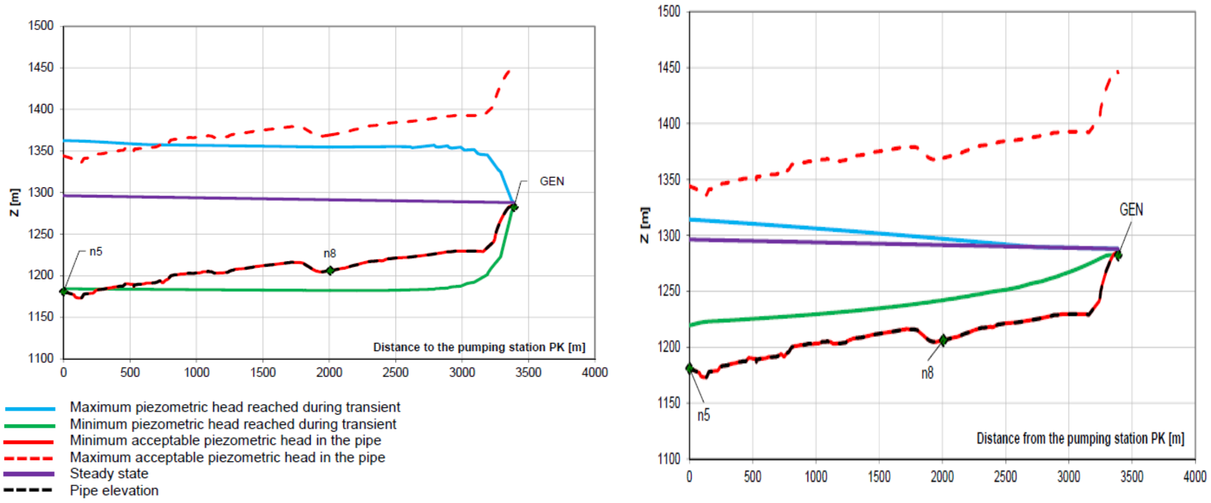


a. without surge tank

b. with surge tank

Figure 38:- Transient pressure for DCI pipe along sabain to Goro transmission main

e. Sabian booster station to Gendaboye Reservoir pipe delivery Water hammer result by CEBELMAILa software

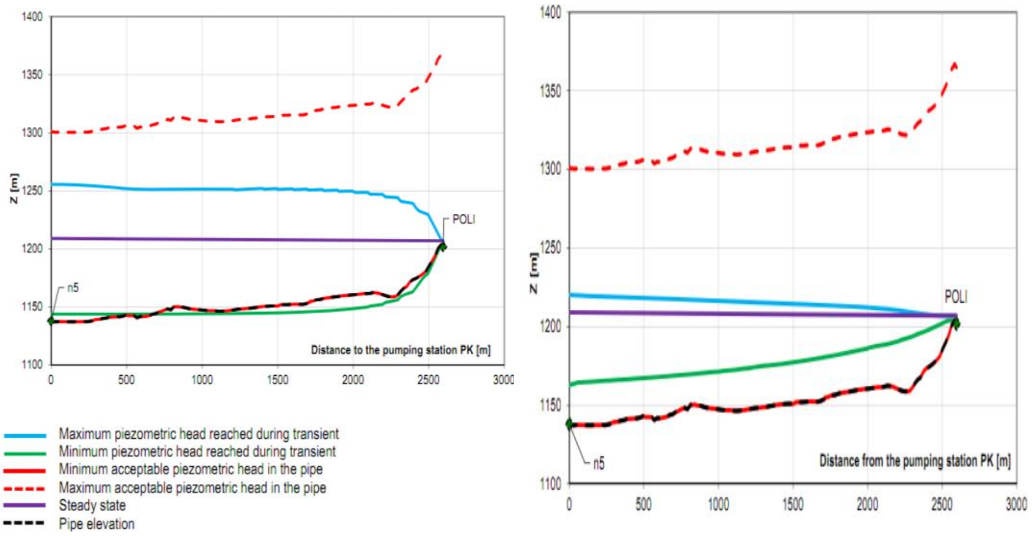


a. without surge tank

b. with surge tank

Figure 39:- Transient pressure for DCI pipe along sabain to Gendaboye transmission main

f. Tome to Police Meret Pipe Reservoir pipe delivery Water hammer result by CEBELMAILa software

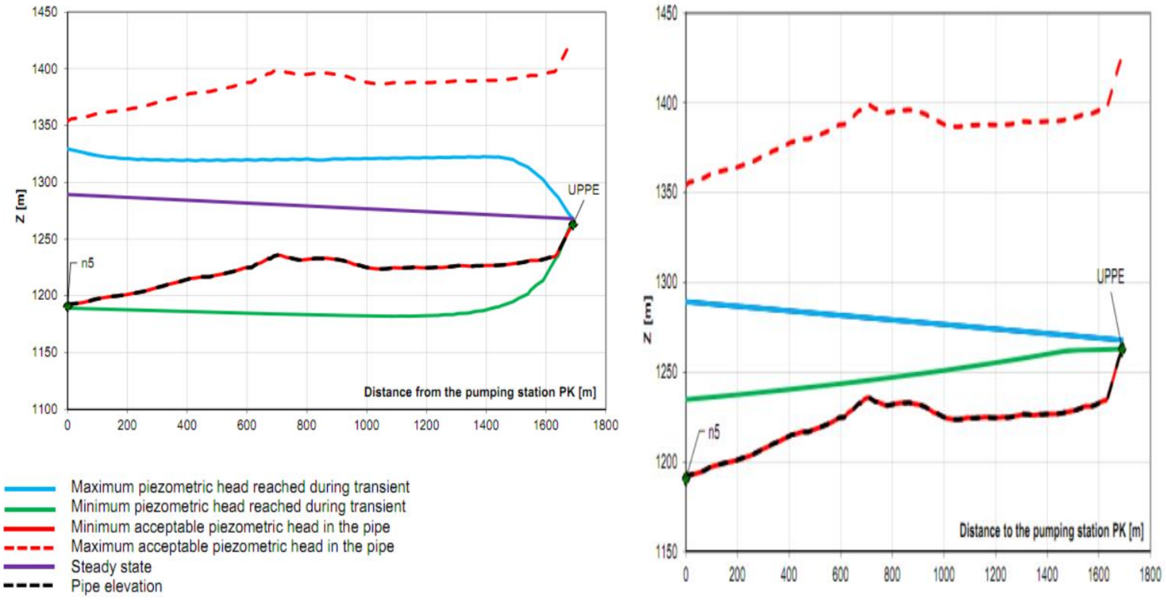


a. without surge tank

b. with surge tank

Figure 40:- Transient pressure for DCI pipe along Tome to Police Meret transmission main

g. **Legehare pumping station to upper kefira transmission main pi**pe Reservoir pipe delivery Water hammer result by CEBELMAILa software



a. Without surge tank

b. with surge tank

Figure 41:- Transient pressure for DCI pipe along Legehare pumping station to upper kefira transmission main