WATER HAMMER ANALYSIS OF PIPELINE SYSTEM

By

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CHAPTER ١ - Introduction

١-١- Introduction

Devices such as valves, pumps and surge protection equipment exist in a pipe network. Power failure of pumps, sudden valve actions, and the operation of automatic control systems are all capable of generating high pressure waves in domestic water supply systems. These high pressures can cause pipe failures by damaging valves and fittings. Study of pressure and velocity variations under such circumstances is significant for placement of valves and other protection devices. In this study, the role of each of these devices in triggering transient conditions is studied. Analysis is performed on single and multiple pipe systems.

Transient analysis is also important to draw guidelines for future pipeline design standards. These will use true maximum loads (pressure and velocity) to select the appropriate components, rather than a notional factor of the mean operating pressure. This will lead to safer designs with less over-design, guaranteeing better system control and allowing unconventional solutions such as the omission of expensive protection devices. It will also reveal potential problems in the operation of the system at the design stage, at a much lower cost than during commissioning.

١-٢- Water Hammer Description

Liquid hammer is the destructive force, pounding noises and vibration in a piping system when liquid flowing through a pipeline is stopped abruptly. When sudden changes in flow occur, the energy associated with the flowing liquid is suddenly transformed into pressure at that location. This excess pressure is known as surge pressure and is greater with large changes in velocity.

Water hammer is usually recognized by the banging or thumpingNoise that is heard when valves are shut off. Although this is easy way to recognize the problem, water hammer doesn’t always make these telltale noises. Water hammer occurs when the flow of moving water is suddenly stopped by a closing valve. This sudden stop causes the whole column of water behind the valve to slam into the valve, and itself, like a freight train crashing into a wall. The tremendous spike of pressure that is caused, is called water hammer, and it not only acts like a tiny explosion inside pipes, it can be just as destructive.

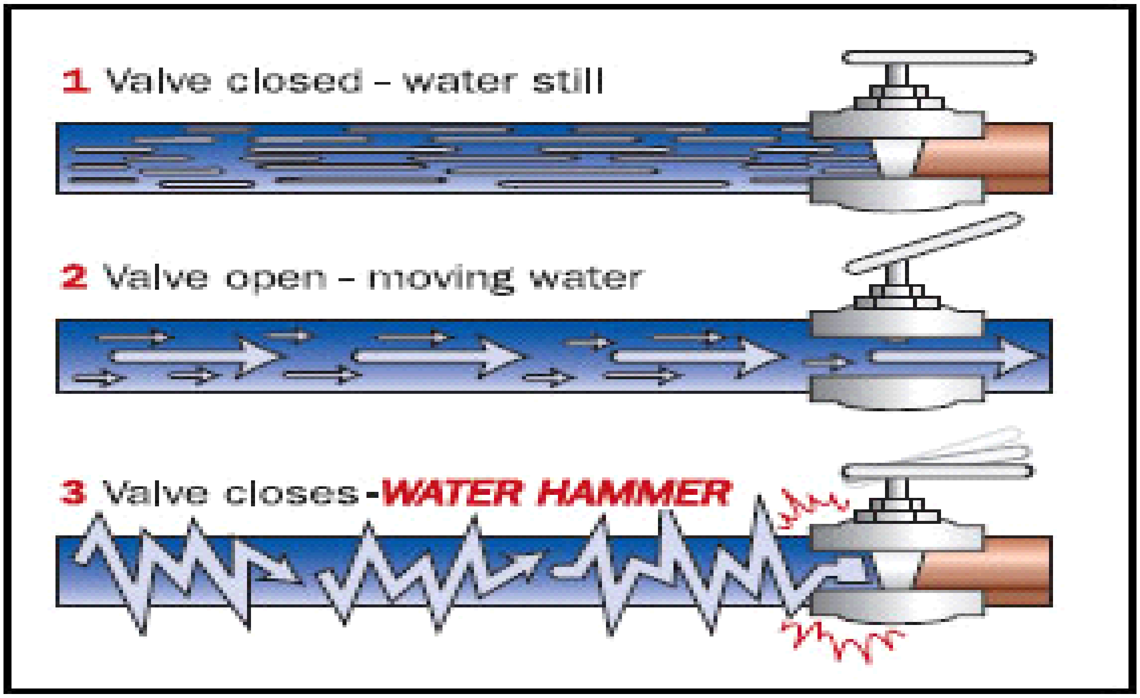


Figure ١-١ Water Hammer Description

١-٣-Causes of Transient Initiation

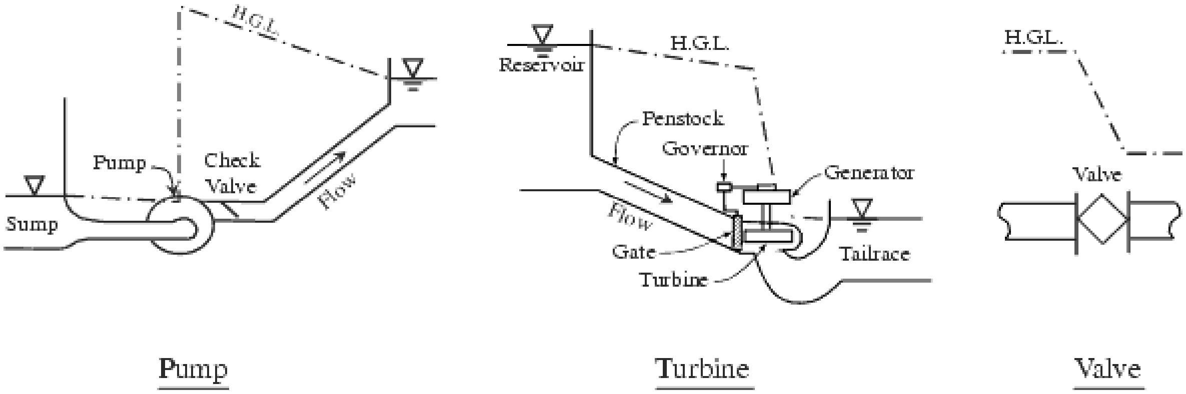
The cause of a hydraulic transient is any sudden change in the fluid itself or any sudden change at the pressurized system's boundaries, including:

- **Changes in fluid properties**—such as depressurization due to the sudden opening of a relief valve, a propagating pressure pulse, heating or cooling in cogeneration or industrial systems, mixing with solids or other liquids (may affect fluid density, specific gravity, and viscosity), formation and collapse of vapor bubbles (cavitation), and air entrainment or release from the system (at air vents and/or due to pressure waves).
- **Changes at system boundaries**—such as rapidly opening or closing a valve, pipe burst (due to high pressure) or pipe collapse (due to low pressure), pump start/shift/stop, air intake at a vacuum breaker, water intake at a valve, mass outflow at a pressure-relief valve or fire hose, breakage of a rupture disk, and hunting and/or resonance at a control valve.

Sudden changes such as these create a transient pressure pulse that rapidly propagates away from the disturbance, in every possible direction, and throughout the entire pressurized system. If no other transient event is triggered by the pressure wave fronts, unsteady-flow conditions continue until the transient energy is completely damped and dissipated by friction.

The majority of transients in water and wastewater systems are the result of changes at system boundaries, typically at the upstream and downstream ends of the system or at local high points. Consequently, you can reduce the risk of system damage or failure with proper **analysis** to determine the system's default dynamic response, **design** protection equipment to control transient energy, and specify **operational procedures** to avoid transients. Analysis, design, and operational procedures all benefit from computer simulations with Bentley HAMMER V٨***i*** Edition.

The three most common causes of transient initiation, or source devices, are all moving system boundaries.



Pump

Turbine

Valve

Figure ١-٢: Common Causes of Hydraulic Transients

Pumps—A pump's motor exerts a torque on a shaft that delivers energy to the pump's impeller, forcing it to rotate and add energy to the fluid as it passes from the suction to the discharge side of the pump volute. Pumps convey fluid to the downstream end of a system whose profile can be either uphill or downhill, with irregularities such as local high or low points. When the pump starts, pressure can increase rapidly. Whenever power sags or fails, the pump slows or stops and a sudden drop in pressure propagates downstream (a rise in pressure also propagates upstream in the suction system).

Turbines—Hydropower turbines are located at the downstream end of a conduit, or **penstock**, to absorb the moving water's energy and convert it to electrical current. Conceptually, a turbine is the inverse of a pump, but very few pumps or turbines can operate in both directions without damage. If the electrical load generated by a turbine is rejected, a gate must rapidly stop flow, resulting in a large increase in pressure, which propagates upstream (in the penstock).

Valves—A valve can start, change, or stop flow very suddenly. Energy conversions increase or decrease in proportion to a valve's closing or opening rate and position, or stroke. Orifices can be used to throttle flow instead of a partially open valve. Valves can also allow air into a pipeline and/or expel it, typically at local high points. Suddenly closing a flow-control valve (with piping on both sides) generates transients on both sides of the valve, as follows:

- Water initially coming towards the valve suddenly has nowhere to go. As water packs into a finite space upstream of the valve, it generates a high-pressure pulse that propagates upstream, away from the valve.
- Water initially going away from the valve cannot suddenly stop, due to its inertia and, since no flow is coming through the valve to replace it, the area downstream of the valve may "pull a vacuum," causing a low-pressure pulse to propagate downstream.

The similarity of the transient conditions caused by different source devices provides the key to transient analysis in a wide range of different systems: understand the initial state of the system and the ways in which energy and mass are added or removed from it. This is best illustrated by an example for a typical pumping system

١. A pump (upstream source device) starts up from the static HGL and accelerates flow until its input energy reaches a dynamic equilibrium with friction at the steady HGL.
٢. A power failure occurs and the pump stops supplying hydraulic energy; therefore, the HGL drops rapidly at the pump and a low-pressure pulse propagates downstream towards the reservoir. Subatmospheric pressures can occur at the high point (minimum transient head), but the reservoir maintains downstream pressure at its liquid level by accepting or supplying liquid as required, often several times during the transient event.
٣. The pressure pulse is reflected toward the pump, but it encounters a closed check valve (designed to protect the pump against high pressures) that

reflects the pulse as a high pressure toward the reservoir again (maximum transient head).

٤. Friction eventually attenuates the transient energy and the system reaches a final steady state: static HGL, in this case, since pumping has stopped and flow at the reservoir is zero.

The foregoing discussion illustrates the typical concepts to consider when analyzing hydraulic transients. Computer models are an ideal tool for tracking momentum, inertia, and friction as the transient evolves, and for correctly accounting for changes in mass and energy at boundaries. Note that transients propagate throughout the entire pressurized system.

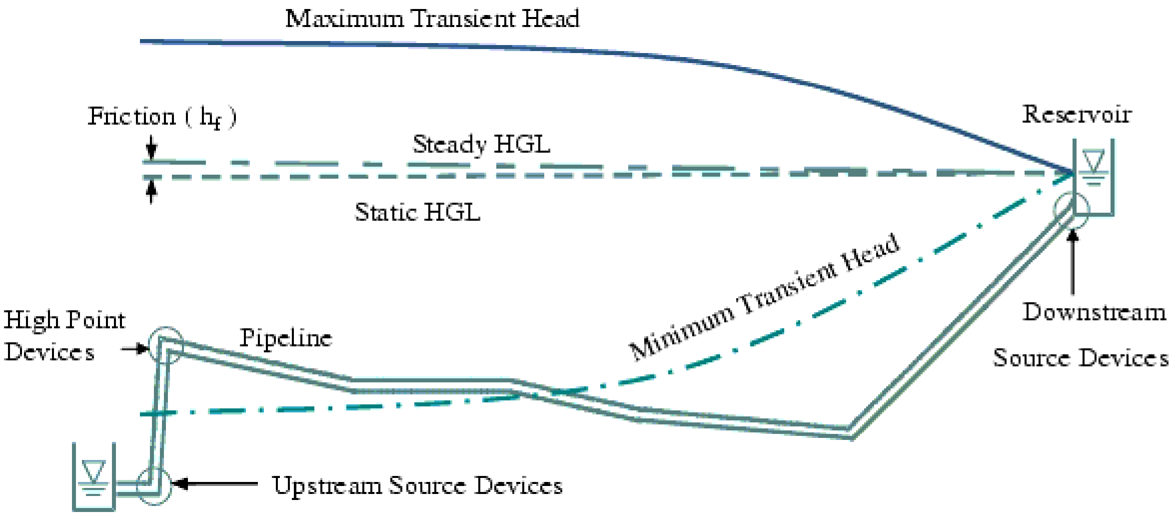


Figure ٢-٣: Typical Locations where Transient Pulses Initiate

Chapter ٢ - Water Hammer Mathematics

٢-١-The Momentum Equation

The continuity and momentum equations can be used to describe transient flow in a closed conduit. Consider a segment of a constant diameter conduit in the flow direction (x-axis) of length Δx and cross-sectional area A. For this ١-dimensional element we consider the force balance which yields the necessary momentum equation. In Figure ٢.١, the flow direction is to the right and the dashed line labeled HGL is the instantaneous hydraulic grade line. Figure ٢.١ represents the moment in time where the shock wave is propagating in the reverse direction to the flow due to a downstream disturbance.

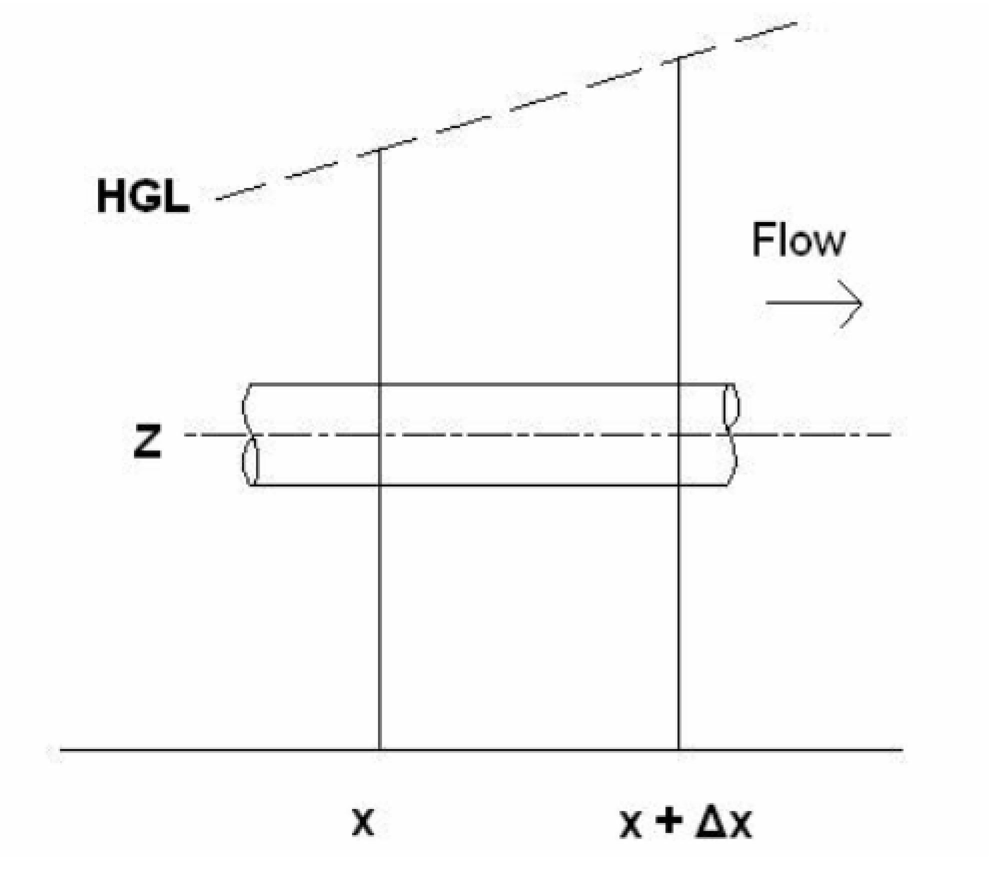


Figure 2.1 Conduit with Instantaneous HGL.

At position x, the flow is Q, and the piezometric head, pressure head plus the elevation head, is H. At the position x + Δx the flow is $Q + \frac{\partial Q}{\partial x}\,\Delta x$, and piezometric head is $H + \frac{\partial H}{\partial x}\,\Delta x$, where $\frac{\partial Q}{\partial x}$ and $\frac{\partial H}{\partial x}$ are the partial derivatives of Q and H with respect to x and are considered to increase in the positive x-direction. Figure ٢-٢ shows the forces acting on the fluid element with a free body diagram.

The angle of the conduit is unimportant for now because the H term takes into account any change in elevation of the conduit.

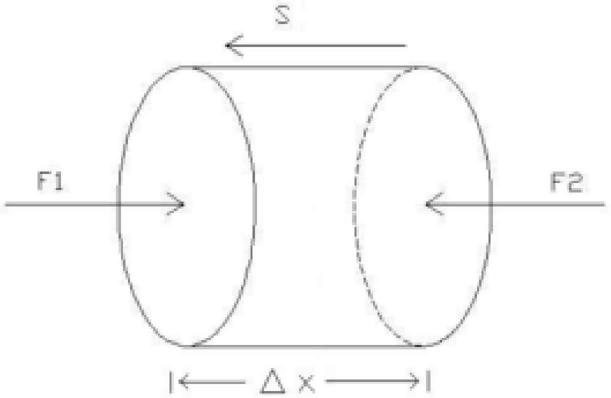


Figure 2.2 Free Body Diagram of a Fluid Element

The forces acting on the fluid element are the pressure forces, F١ and F٢, the wall shear force due to friction, S and the body force. The piezometric head $H = p/\gamma + z$ accounts for both the pressure and weight components.
Using,

F١ = $(H - z)\gamma A$
F٢ = $(H + \frac{\partial H}{\partial x}\Delta x - z)\gamma A$
A is the area on either side of the fluid element.
Appling Newton's second law of motion, we get after simplification the following form:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\frac{\partial z}{\partial x} + \frac{f|V|V}{2D} = 0$$

٢-٢-The Continuity Equation

As the water hammer pressure wave moves through a pipe, we like to account for the following: (١) Continuity of the flow (٢) the pipe wall extension and expansion due to pipe wall elasticity and compressibility of the fluid.

Hansen (١٩٦٧) has derived the most general form of the control volume equation that considers both the movement and the deformation of the control volume.

$$\frac{\partial H}{\partial t} + \frac{\partial \mathrm{Q}}{\partial x} \frac{\mathrm{c}^2}{\mathrm{gA}} = 0$$

where: c = wavespeed

٢-٣ Bentley HAMMER

Bentley HAMMER V٨*i* Edition is an advanced numerical simulator of hydraulic transient phenomena (water hammer) in water, wastewater, industrial, and mining systems. Built with busy engineers in mind, it simplifies data entry and allows you to focus on visualizing, improving, and delivering your results quickly and professionally. Bentley HAMMER V٨*i* Edition can handle any fluid or system that a typical steady-state hydraulic model like WaterCAD can, but it can also solve a broader range of problems, as shown in the table below.

Table ٢-١: Bentley HAMMER V٨i Edition Capabilities

WaterCAD	**Bentley HAMMER V٨*i* Edition***
Steady or gradually varying turbulent flow	Rapidly varying or transient flow
Incompressible, Newtonian, single-phase fluids	Slightly compressible, two-phase fluids (vapor and liquid) and two-fluid systems (air and liquid)
Full pipes	Closed-conduit pressurized systems with air intake and release at discrete points

With Bentley HAMMER V٨*i* Edition, you can analyze drinking water systems, sewage forcemains, fire protection systems, well pumps, and raw-water transmission lines. You can change the specific gravity of the fluid to model oil or slurries, for example. Bentley HAMMER V٨*i* Edition assumes that changes in other fluid properties, such as temperature, are negligible. It does not currently model fluids with significant thermal variations, such as can occur in cogeneration or industrial systems.

The Bentley HAMMER V٨*i* Edition algorithms will grow and evolve to keep pace with the state of the practice in water distribution and wastewater collection modeling. Because the mathematical solution methods are continually extended, this manual deals primarily with the fundamental principles underlying these algorithms and focuses less on the details of their implementation.

This appendix introduces the principles of hydraulic transients in piping systems, reviews current analytical approaches and engineering practices, discusses the potential sources and impacts of water hammer, and presents a proven approach to help you select and size surge-control equipment. Several transient simulations are integrated into the discussion to provide context.

Chapter ٣ - Water Hammer Analysis

٣-١ STEADY STATE ANALYSIS

The starting point of the line is considered as being the Low Lift station and the end point reservoir. The design is carried out for a line section of ٢٨٧٠.٣٤ m long. The pump capacity is ٣٢٠٠ m٣/h against a total head of ١٢٨.٢٥ m.

The pipeline topography along the selected route is listed below

Table ٢-٢: Topographical data

PVI	Station	Elevation
١	٠+٠٠	٤٢١.٩٢٩
٢	٠+٨٢.٧٦	٤٢٢.٥٠٩
٣	١+١٩.٩٦	٤٢٦.٠٢١
٤	٢+٦٨.٢٦	٤٢٤.٧٦٧
٥	٣+٢٢.٦٤	٤٢٠.٢٧٨
٦	٤+٦٩.٦١	٤٢٤.٦١٩
٧	٦+٥٣.٤٣	٤٢٣.٢٣١
٨	٦+٦٨.٣٤	٤٢٣.٩٢٩
٩	٨+٠٠	٤٢٣.٥٥٥
١٠	٩+٠٠	٤٢٣.٥٥٥
١١	٩+٥٥.٣٨	٤٢٢.٦
١٢	٩+٨٥.٢٠	٤٢٣.٨١٣
١٣	١١+٠٠	٤٣٠
١٤	١١+٥٠	٤٣٣.٦٩٢
١٥	١٣+٢٥.٨٥	٤٥٥.٥٥١
١٦	١٣+٣٩.٥٥	٤٥٤.٢٩٨
١٧	١٦+٥٠	٤٨٦.٢٣٥
١٨	١٧+٢٧.٥٢	٤٨٤.٥٢٤
١٩	٢٠+٠٠	٤٩٥.٩٥
٢٠	٢١+٠٠	٤٩٧.٧٨١

٢١	٢٢+٠٠	٤٩٧.٧٨١
٢٢	٢٢+٥٠	٤٩٨.٥٦٢
٢٣	٢٤+٦٥.٦٣	٥١٢.٩٢٣
٢٤	٢٧+٨٩.٣١	٥٣٠
٢٥	٢٨+٠٠	٥٢٨.٤٥١
٢٦	٢٨+١٧.٢٥	٥٣٠
٢٧	٢٨+٢٦.٥٥	٥٣١.٠٨٦
٢٨	٢٨+٧٠.٣٤	٥٢٨.٧٢٨

In the design of the water supply system, pipeline head losses are considered as major losses and additional minor losses are due to the bending elements. Pipe material is chosen to be X-٤٢ which from point of longer life time and durability is advantageous.

Table ٢-٣:Pipe(٩٠٠ mm dia., X-٤٢) and flow data

L(m)	٢٨٧٠.٣٤
D (mm)	٩٠٠
Fs	٠.٧٥
Sy (MPa)	٢٩٠
Density (kg/m^{٣})	١٠٠٠
g(m/s^{٢})	٩.٨١
Hpump (m)	١٢٨.٢٥
Q (m^{٣}/h)	٣٢٠٠

The steady state calculation was first executed for the pipeline system in order to define the initial condition for the surge analysis. Fig(٣-١) shows the hydraulic grade line for steady state case.

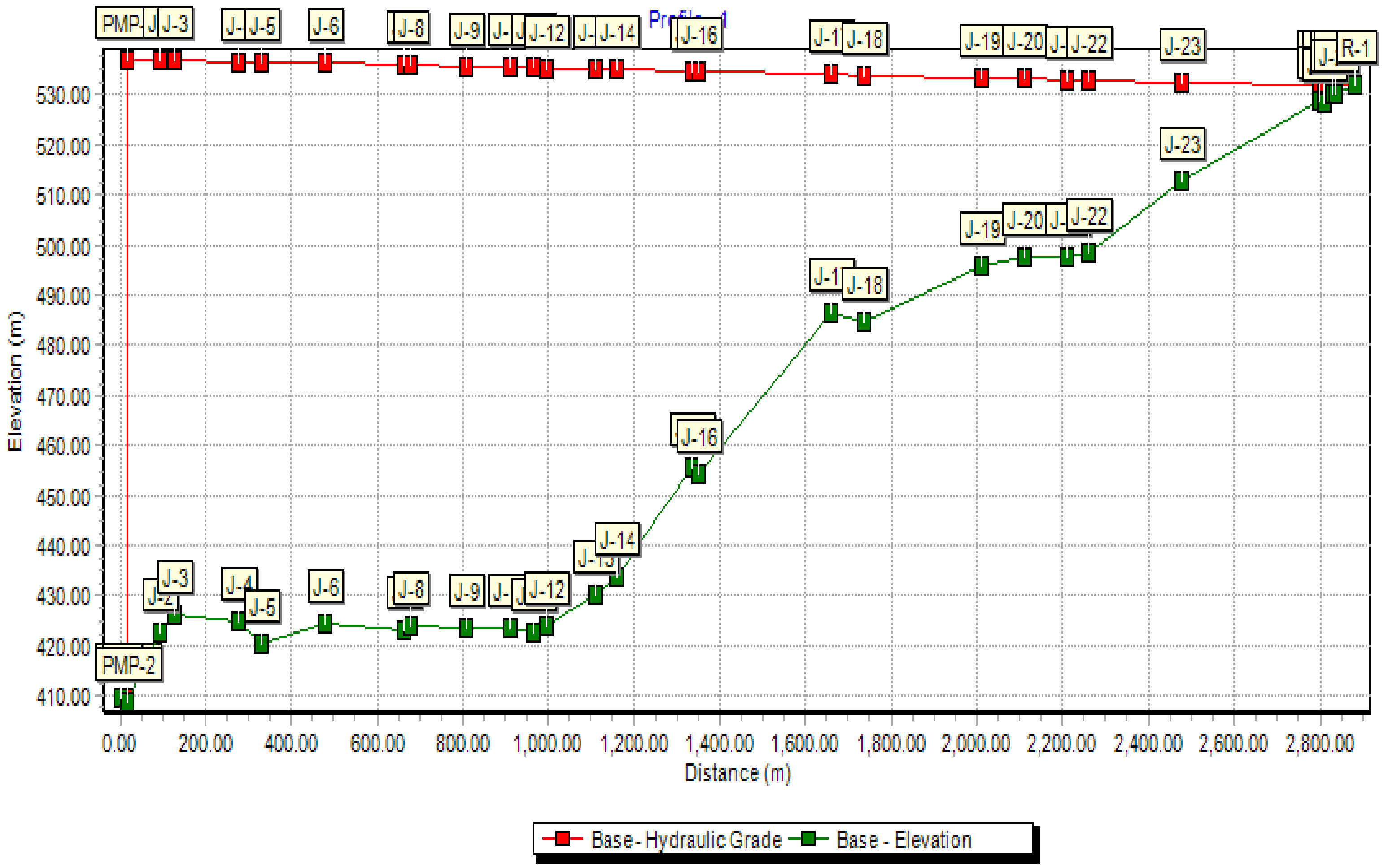


Figure ٣-١ Steady state Head Profil

٣-٢-TRANSIENT ANALYSIS

The most servere water hammer conditions are caused by a sudden pumps trip or power failure to the pump/motor sets. At the outset runs are carried out without any control devices installed on the pipeline in order to determine the nature and extent of the transient.

Determination of appropriate surge control strategies, the recommendation for the suppression of peak pressures and the elimination of column separation are then addresses.

The analysis revolves over the adequate water hammer control being required whether to mitigate the pressure rise or to prevent negative pressures and vapour pockets from developing at apexes or over the entire pipeline.

Multiple verification runs were carried out with various control devices recommended to limit extent of the transients simulating failure of the pumps.

RUN ١: **WATER PIPE WITHOUT ANY PROTECTION**

No water hammer preventing devices has been taken. All input values are given in the appendix.

HAMMER Program has been run and surge calculated.

Fig(٣-٢) shows the profile of maximum and minimum heads, Some of the important results of this run:

There is minus ٩٧.٩ KPa (١ bar) pressures and cavitations at pipe ٩٠٠ mm. Max pressure in ٩٠٠ mm is ٤,٠٠٩.٩ KPa (٤٠ bar).

So water hammer preventing devices should be taken to prevent minus pressures and to decrease max pressures during surge.

Other pressures and heads can be seen in result sheets as attachment in the folders.

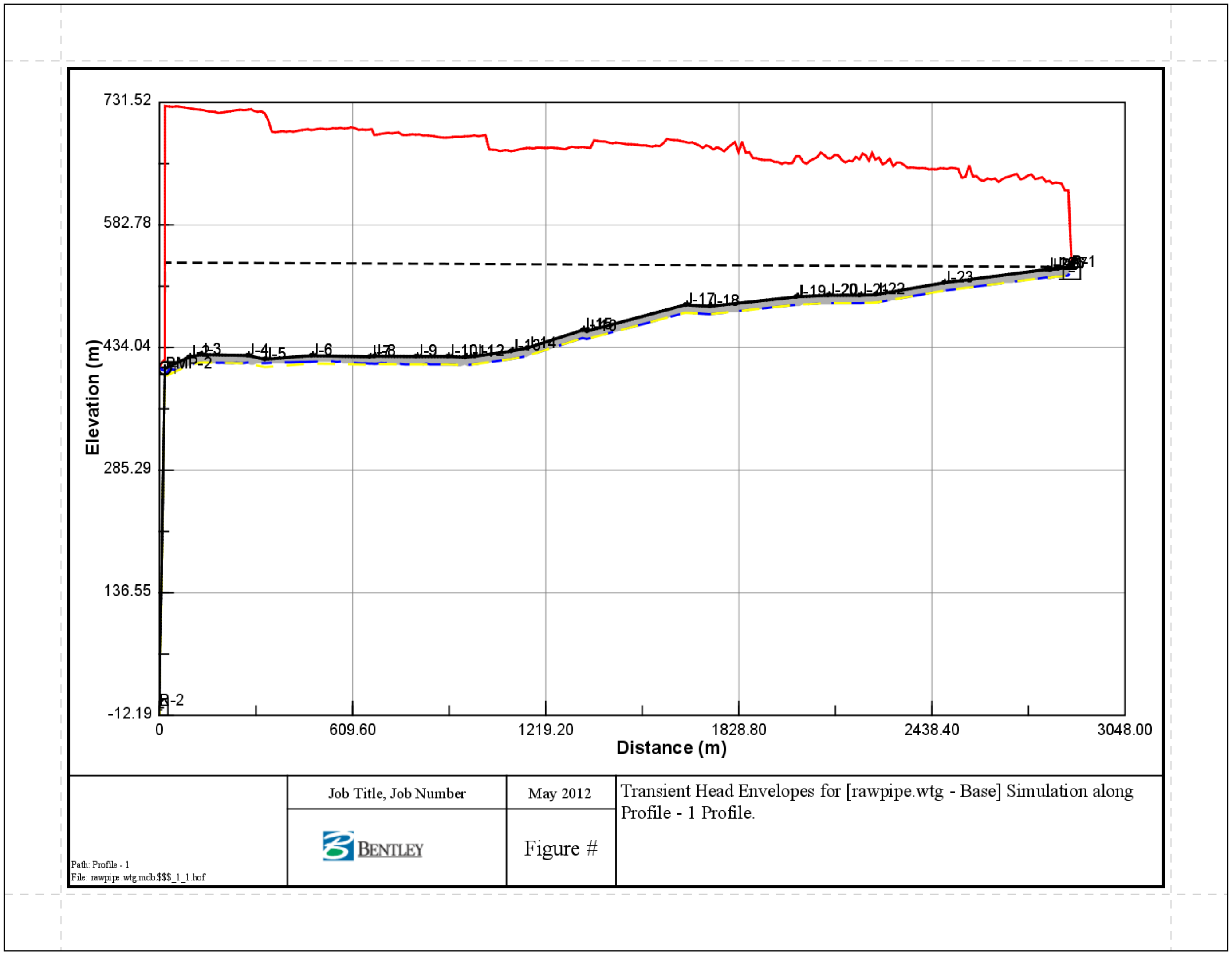


Figure ٣-٢ Water Hammer Analysis Head Profile (without Protection)

RUN ٢: **WATER PIPE WITH PROTECTION**

Same inputs as previous run with following changes:

one ٣٠ m٣ bypassed air vessel. ٢٠٠ mm air vent valves has been put at various peaks shown in the profile.

Some of the important results of this run is that there are no cavitations at pipes ٩٠٠ mm. There is only some negative pressures at the end of ٩٠٠ mm pipe for very short period, which is tolerable. So measures are very effective. This can also be seen if head and pressure graphs in steel pipes with and with no measure are compared. These head and pressure the appendix.

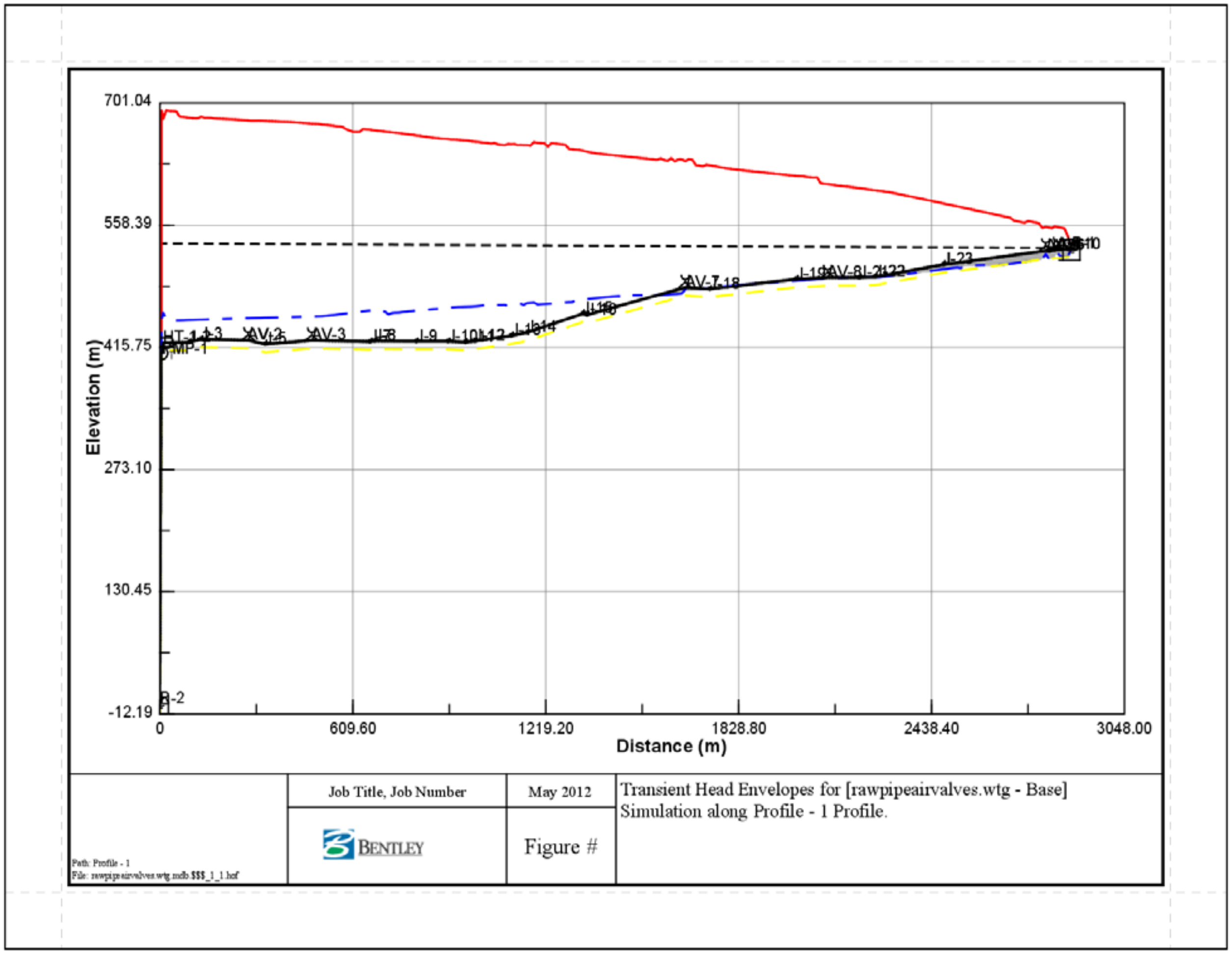
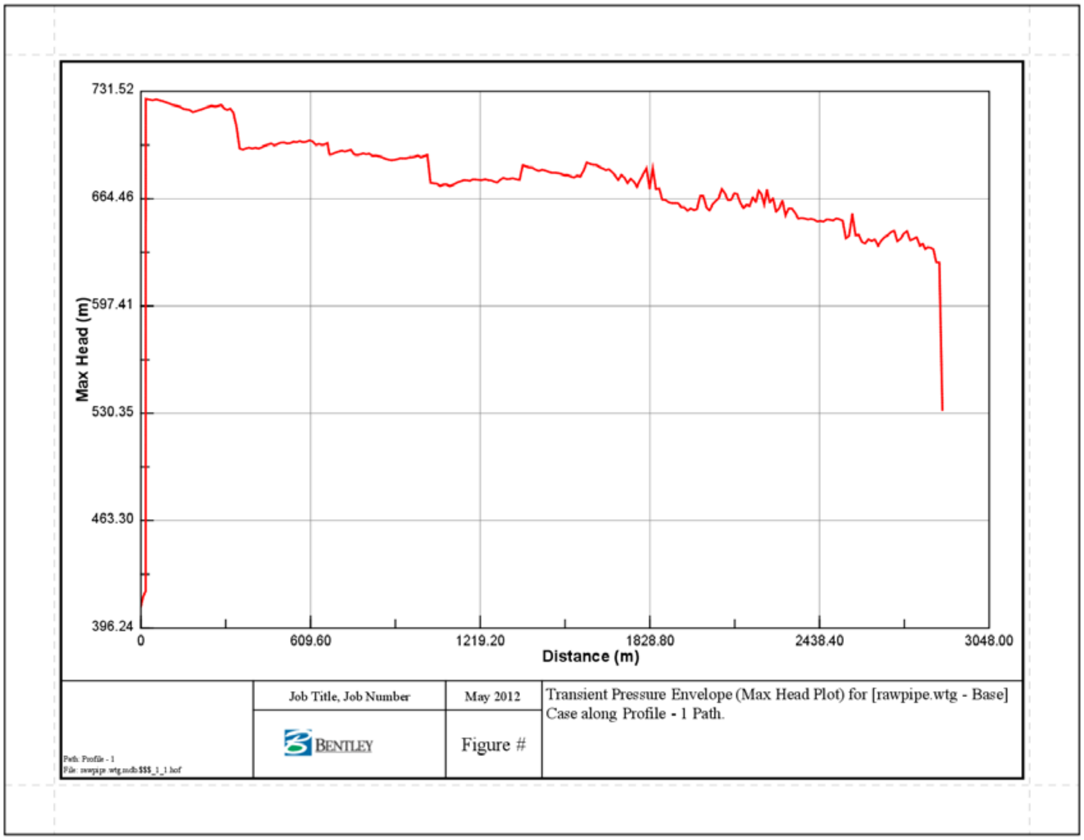


Figure ٣-٣ Water Hammer Analysis Head Profile (with Protection)

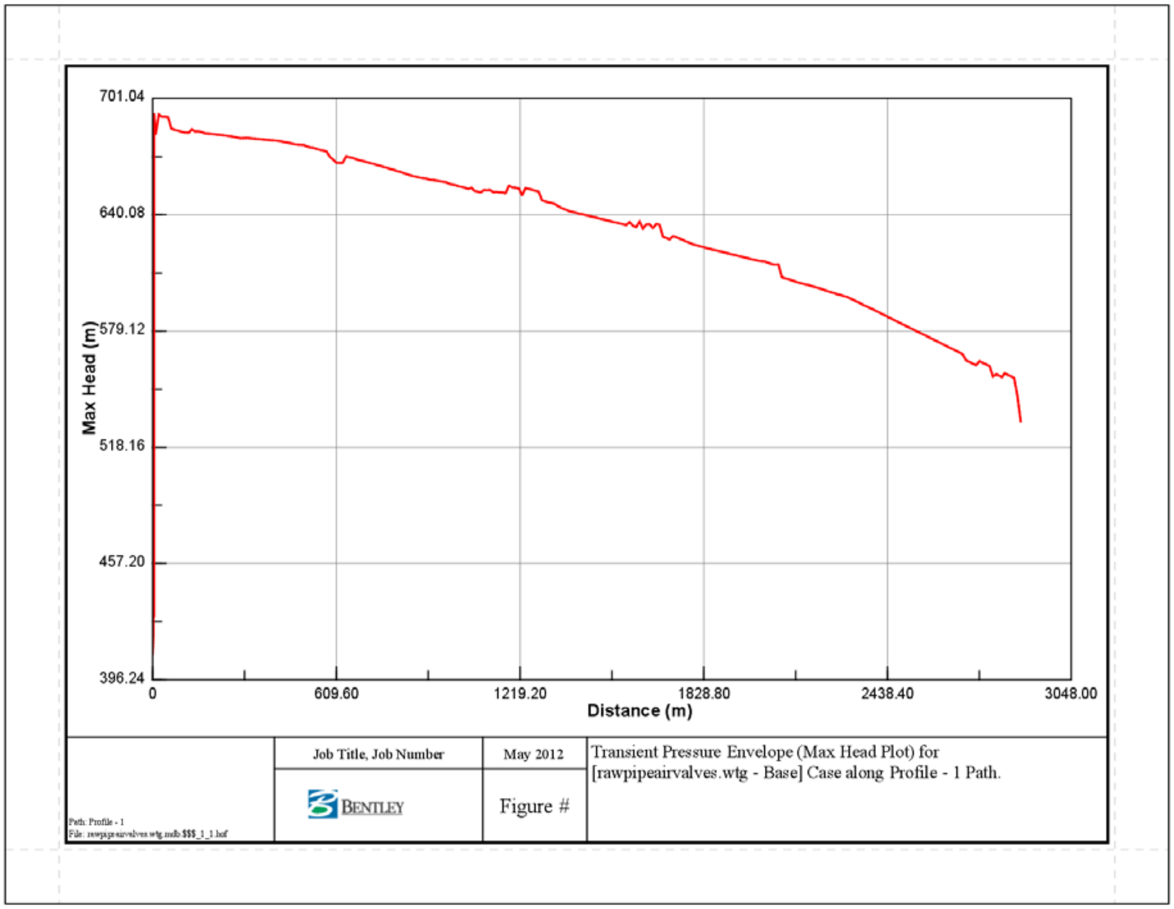
٣-٣- RESULTS ANALYSIS

From the figure shown below it is clear the advantage of protection of the pipeline against water hammer will affect the following parameters:-

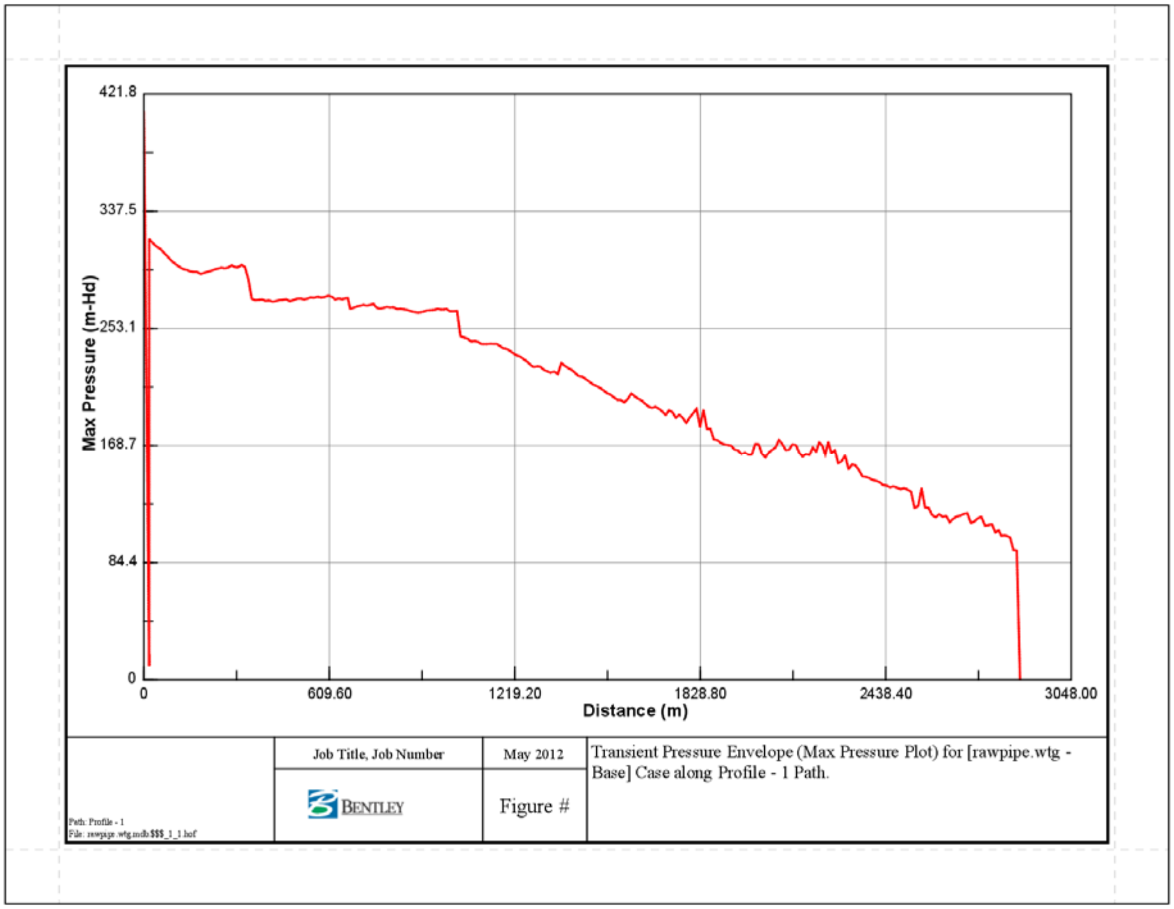
١- Decrease the maximum head of water .
٢- Decrease the maximum pressure of water
٣- Increase the minimum head of water ,that causes the decrease of cavitations
٤- Increase the minimum pressure of water.
٥- Decrease the maximum volume of air by passing the air from the valve.



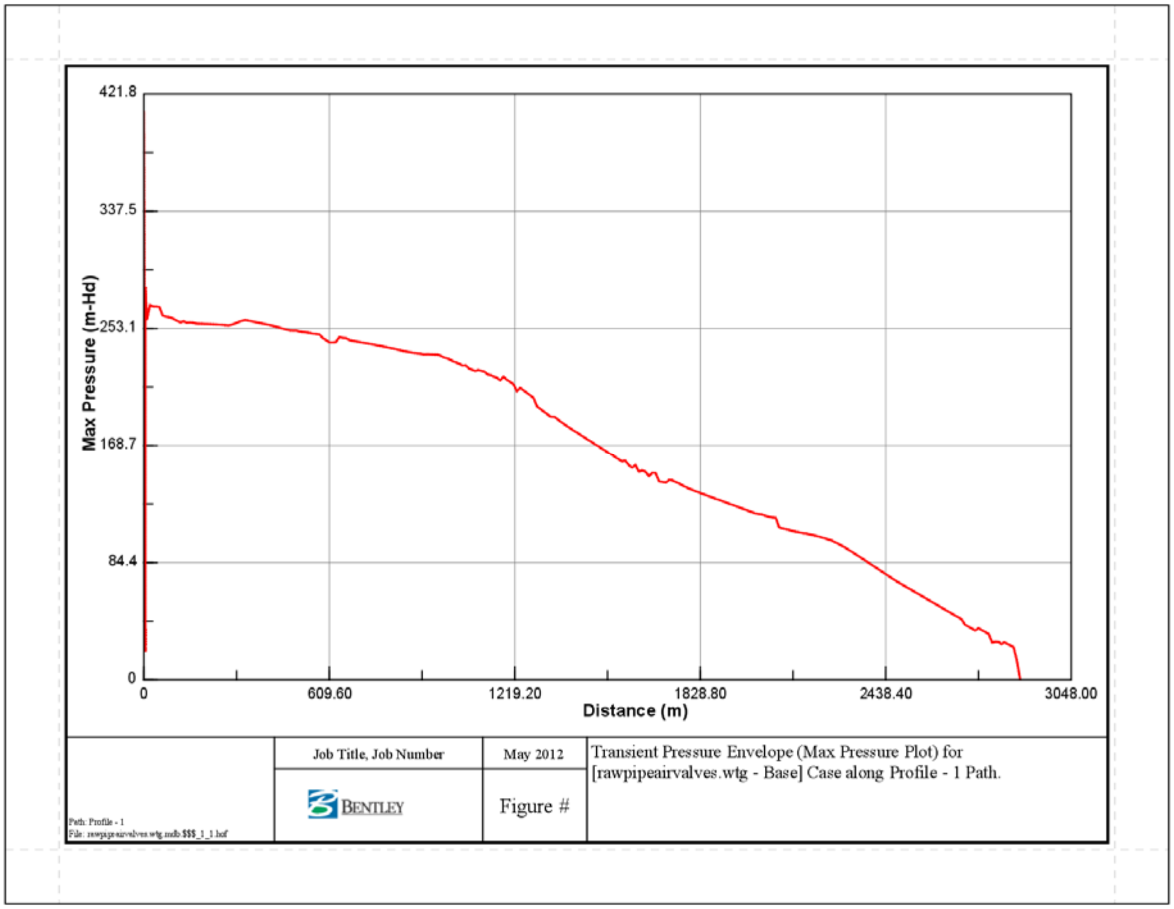
Fig(٣-٣-a) Max head plot without valve



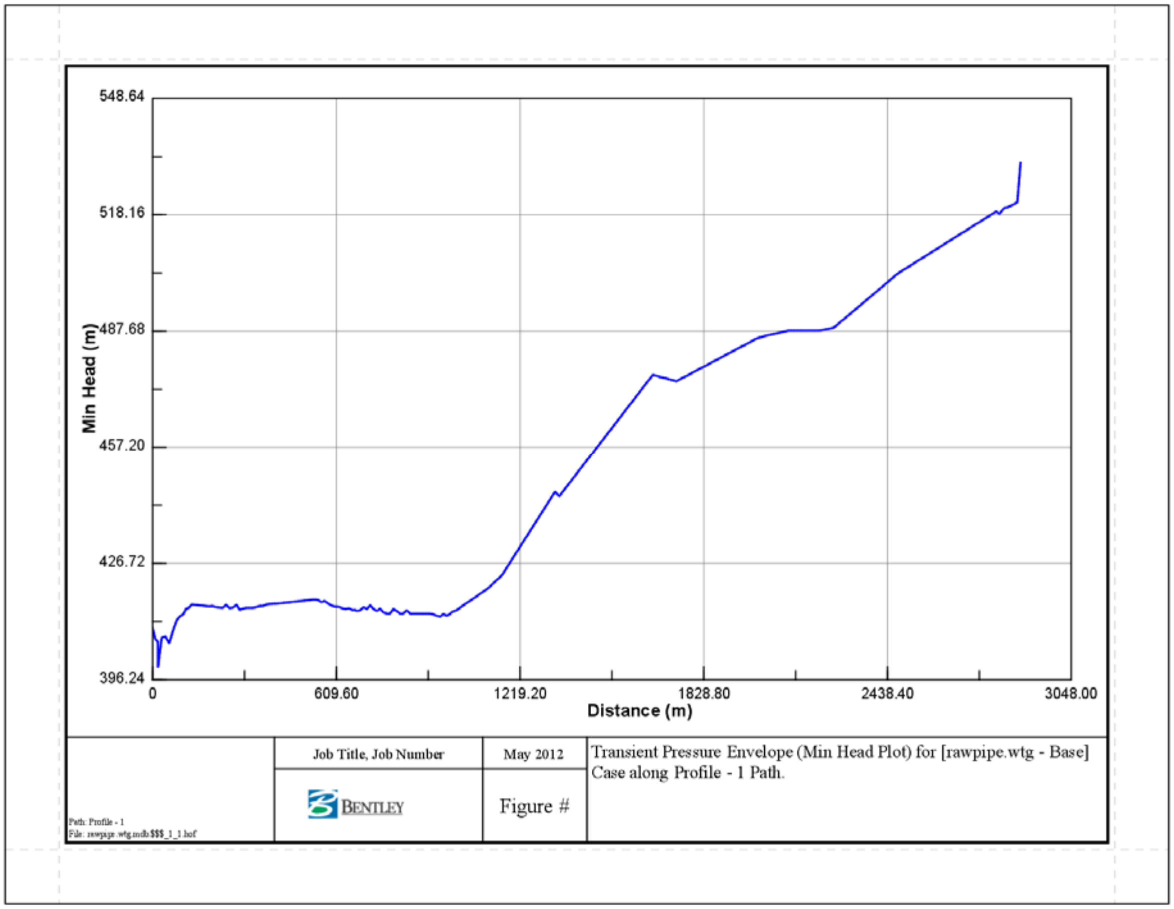
Fig(٣-٣-b) Max head with valve



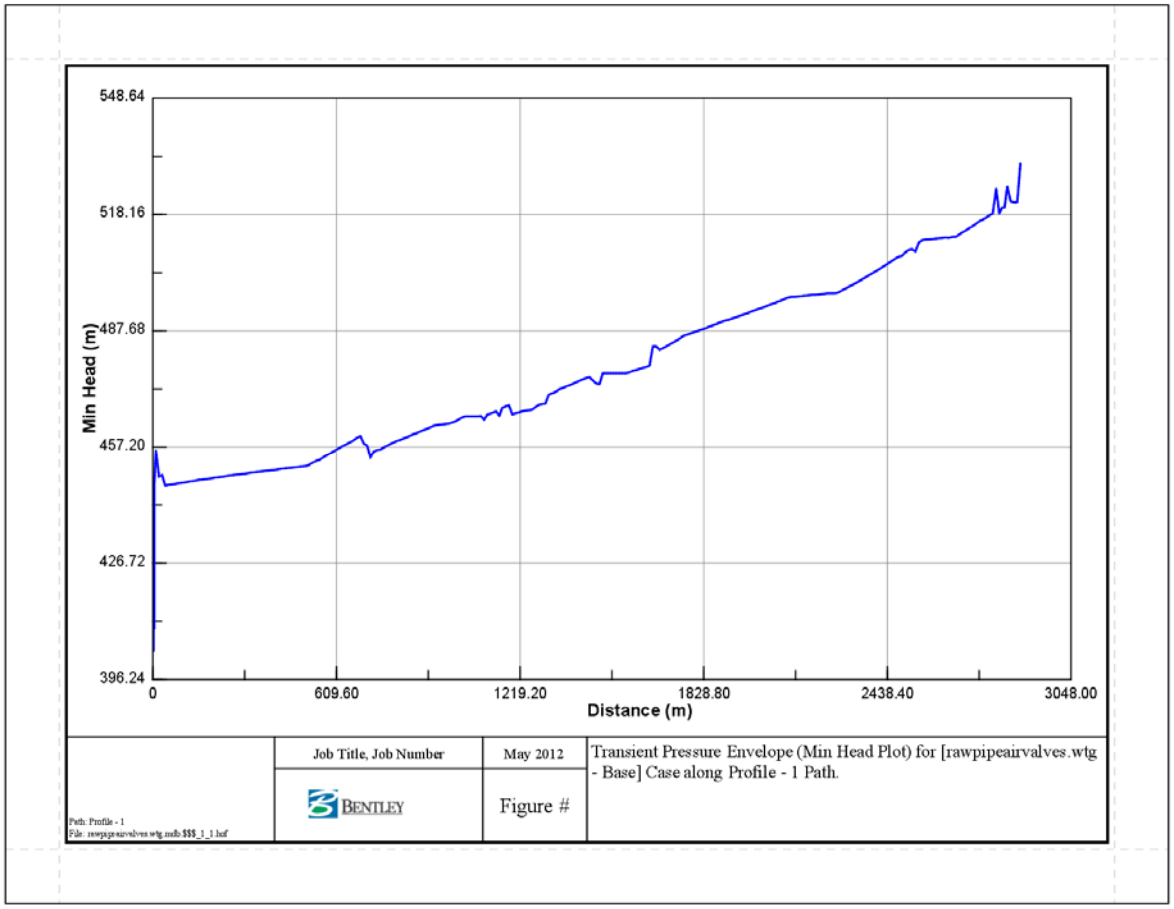
Fig(٣-٤-a) Max pressure without valve



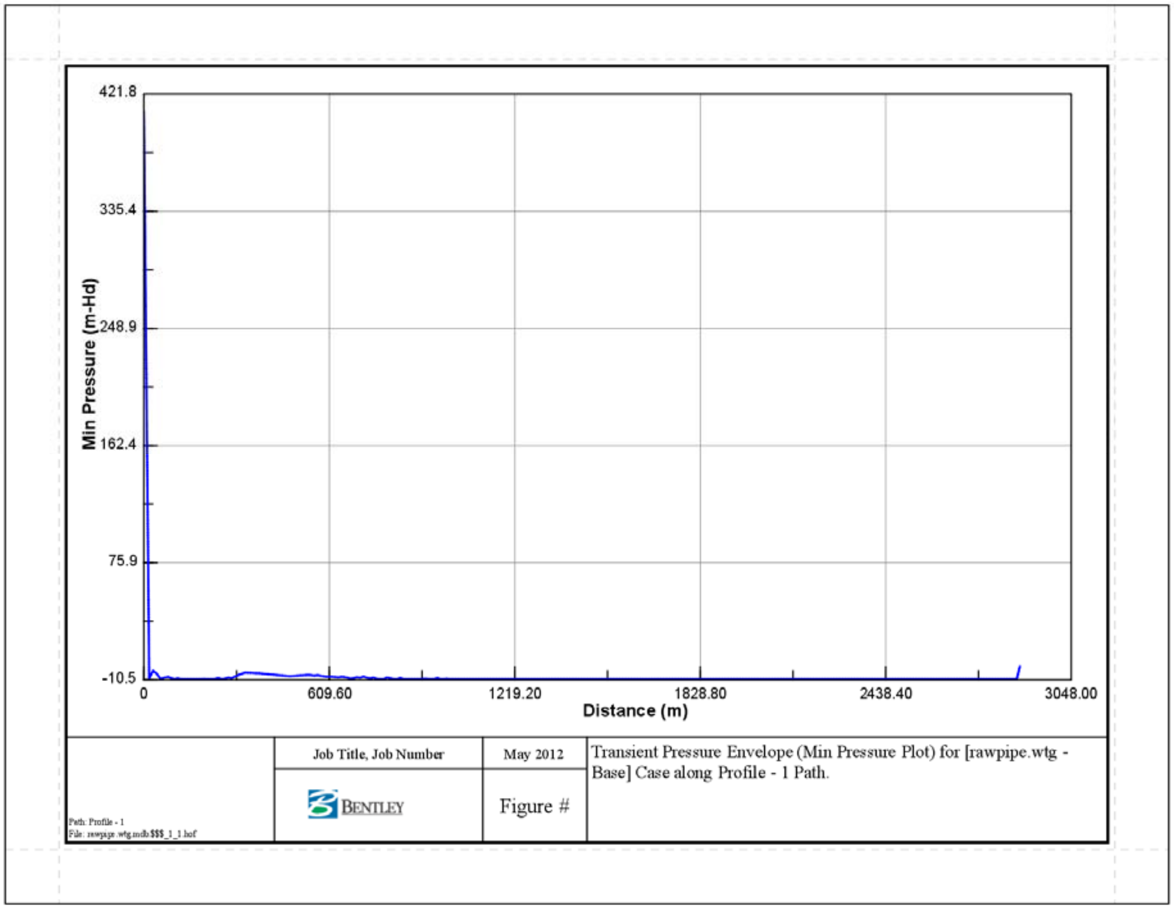
Fig(٣-٤-b) Max pressure with valve



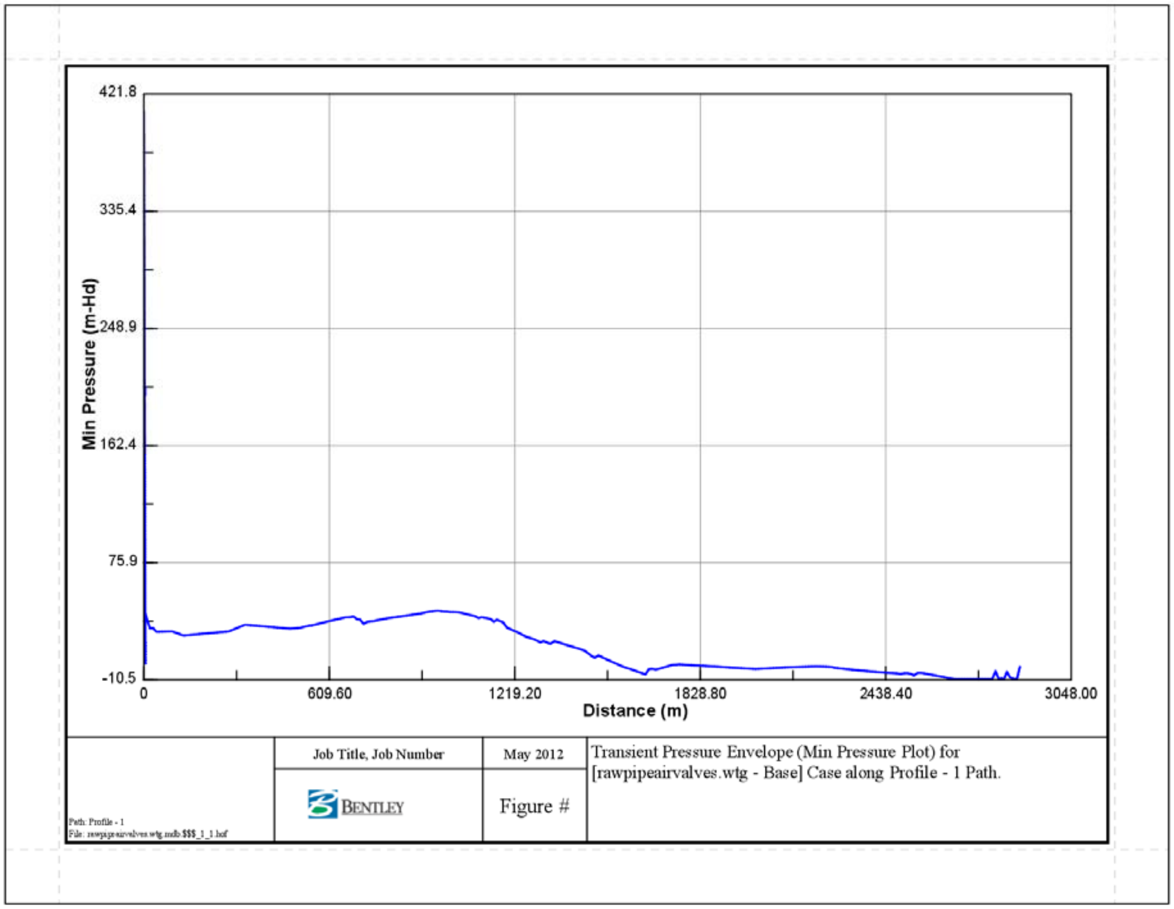
Fig(٣-٥-a) Min head without valve



Fig(٣-٥-b) Min head with valve



Fig(٣-٦-a) Min pressure without valve



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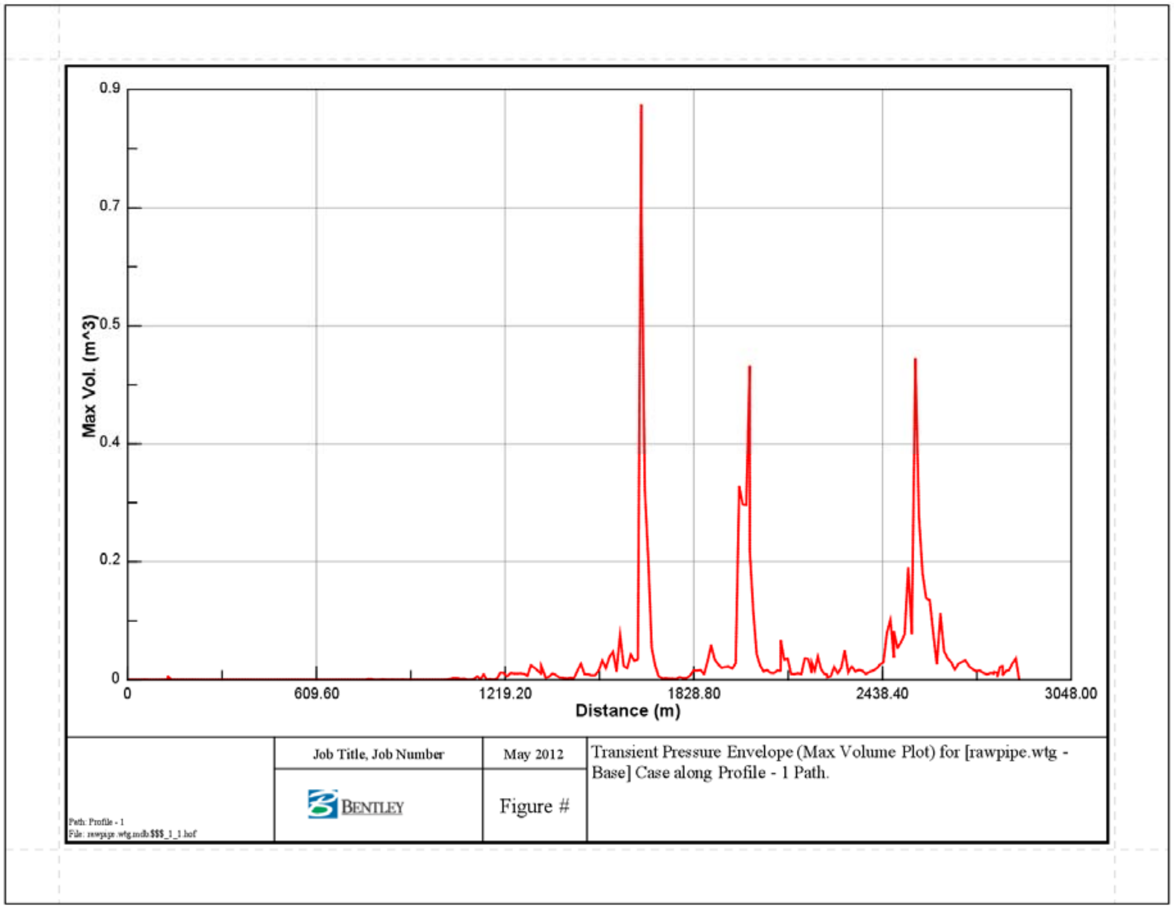
Job Title, Job Number

May 2012

Figure #

Transient Pressure Envelope (Min Pressure Plot) for [rawpipeairvalves.wtg - Base] Case along Profile - 1 Path.

Fig(٣-٦-b) Min pressure with valve



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Job Title, Job Number

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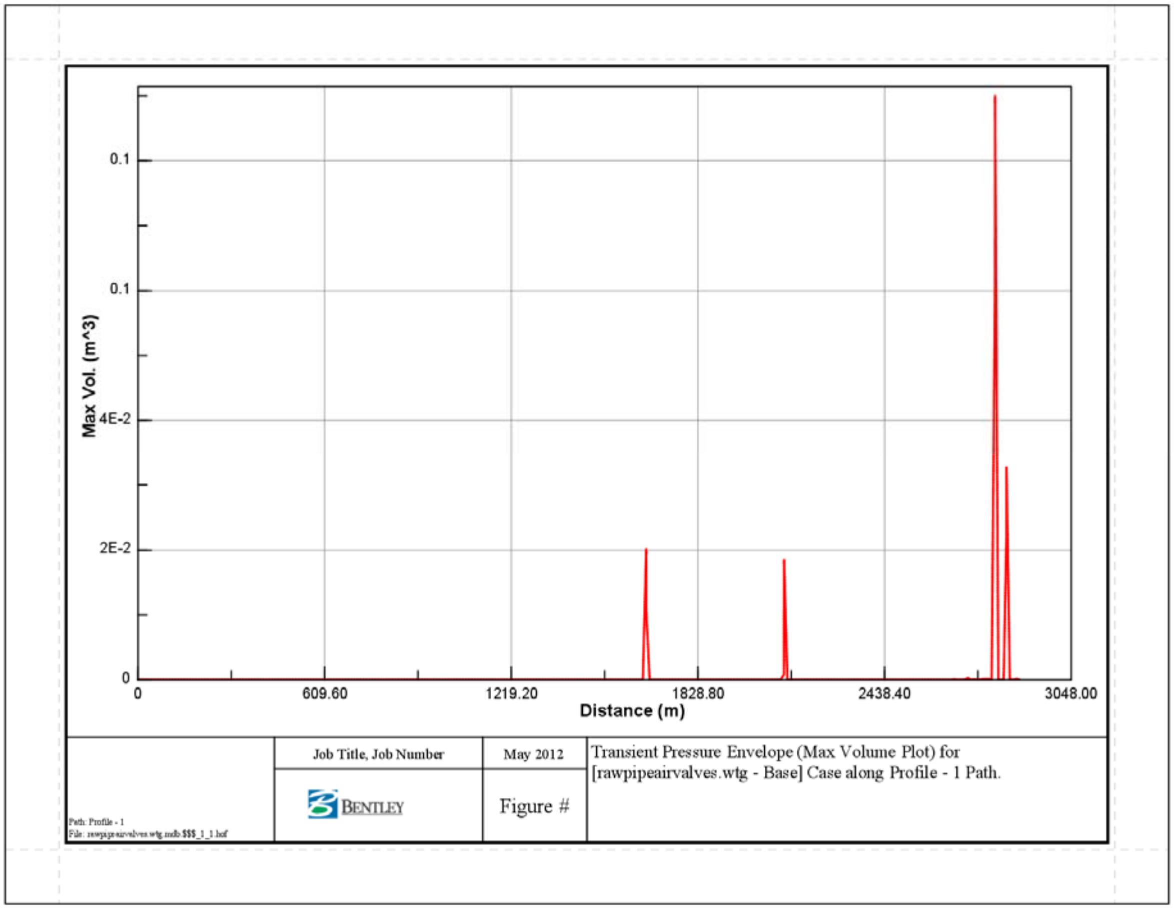
Figure #

Transient Pressure Envelope (Max Volume Plot) for [rawpipe.wtg - Base] Case along Profile - 1 Path.

Fig(٣-٧-a) Max volume without valve



Fig(٣-٧-b) Max volume with valve

٣-٤-CONCLUSION

Water hammer will continue to challenge engineers, operators, and managers of water systems because it is associated with systems that cannot be exactly defined due to the size and length of the water distribution system with undulating profile or the lack of definition of the system components such as valves or pumps. By knowing how to avoid situations that will create water hammer or pulsations during the process, or while trouble shooting, you can eliminate a lot of problems, failed valves and equipment, and costly downtime.

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Bentley HAMMER V٨i Edition User’s Guide

Appendix I

Transient Calculation Summary: Base

Transient Calculation Summary

Time Step	٠.٠١٢	Specific Gravity	٠.٩٩٨
Number of Time Steps	١٢٣٣٩	Wave Speed (Global)	١٢٠٠
Total Simulated Time	١٦٠	Vapor Pressure	-٩٧.٩
Number of Nodes	٢٩	Number of Report Paths	١
Number of Pipes	٢٨		

Transient Initial Conditions Summary

Label	Start Node	Head (Initial at Start Node, Transient) (m)	Stop Node	Head (Initial at Stop Node, Transient) (m)
P-٢	J-٢	٥٣٦.٩	J-٣	٥٣٦.٩
P-٣	J-٣	٥٣٦.٩	J-٤	٥٣٦.٦
P-٤	J-٤	٥٣٦.٦	J-٥	٥٣٦.٥
P-٥	J-٥	٥٣٦.٥	J-٦	٥٣٦.٢
P-٦	J-٦	٥٣٦.٢	J-٧	٥٣٥.٩
P-٧	J-٧	٥٣٥.٩	J-٨	٥٣٥.٩
P-٨	J-٨	٥٣٥.٩	J-٩	٥٣٥.٦
P-٩	J-٩	٥٣٥.٦	J-١٠	٥٣٥.٤
P-١٠	J-١٠	٥٣٥.٤	J-١١	٥٣٥.٣
P-١١	J-١١	٥٣٥.٣	J-١٢	٥٣٥.٣
P-١٢	J-١٢	٥٣٥.٣	J-١٣	٥٣٥.١
P-١٣	J-١٣	٥٣٥.١	J-١٤	٥٣٥
P-١٤	J-١٤	٥٣٥	J-١٥	٥٣٤.٧
P-١٥	J-١٥	٥٣٤.٧	J-١٦	٥٣٤.٦
P-١٦	J-١٦	٥٣٤.٦	J-١٧	٥٣٤.١
P-١٧	J-١٧	٥٣٤.١	J-١٨	٥٣٣.٩
P-١٨	J-١٨	٥٣٣.٩	J-١٩	٥٣٣.٤
P-١٩	J-١٩	٥٣٣.٤	J-٢٠	٥٣٣.٢
P-٢٠	J-٢٠	٥٣٣.٢	J-٢١	٥٣٣
P-٢١	J-٢١	٥٣٣	J-٢٢	٥٣٢.٩
P-٢٢	J-٢٢	٥٣٢.٩	J-٢٣	٥٣٢.٥
P-٢٣	J-٢٣	٥٣٢.٥	J-٢٤	٥٣١.٩
P-٢٤	J-٢٤	٥٣١.٩	J-٢٥	٥٣١.٩
P-٢٥	J-٢٥	٥٣١.٩	J-٢٦	٥٣١.٩
P-٢٦	J-٢٦	٥٣١.٩	J-٢٧	٥٣١.٩
P-٢٧	J-٢٧	٥٣١.٩	R-١	٥٣١.٨
Pm١	R-٢	٤٠٩.٧	PMP-٢	٤٠٩.٧
P-٣٤	PMP-٢	٥٣٧.١	J-٢	٥٣٦.٩

Extreme Pressures and Heads

End Point	Upsurge Ratio	Max. Pressure (kPa)	Min. Pressure (kPa)	Max. Head (m)	Min. Head (m)
P-٢:J-٢	٢.٦٤	٢٩٥٥.٢	-٩٢.٩	٧٢٤.٤٦	٤١٣.٠٢
P-٢:J-٣	٢.٦٧	٢٩٠٠.٥	-٩٧.٩	٧٢٢.٣٨	٤١٦.٠٢
P-٣:J-٣	٢.٦٧	٢٩٠٠.٥	-٩٧.٩	٧٢٢.٣٨	٤١٦.٠٢
P-٣:J-٤	٢.٦٦	٢٩١٣.٣	-٨٧	٧٢٢.٤٤	٤١٥.٨٨
P-٤:J-٤	٢.٦٦	٢٩١٣.٣	-٨٧	٧٢٢.٤٤	٤١٥.٨٨
P-٤:J-٥	٢.٥٦	٢٩١٤.٨	-٥٠.٥	٧١٨.١	٤١٥.١٢
P-٥:J-٥	٢.٥٦	٢٩١٤.٨	-٥٠.٥	٧١٨.١	٤١٥.١٢
P-٥:J-٦	٢.٤٥	٢٦٧٣.٨	-٧٦.٦	٦٩٧.٨٢	٤١٦.٧٩
P-٦:J-٦	٢.٤٥	٢٦٧٣.٨	-٧٦.٦	٦٩٧.٨٢	٤١٦.٧٩
P-٦:J-٧	٢.٤٤	٢٦٩٤.٤	-٨٥	٦٩٨.٥٣	٤١٤.٥٤
P-٧:J-٧	٢.٤٤	٢٦٩٤.٤	-٨٥	٦٩٨.٥٣	٤١٤.٥٤
P-٧:J-٨	٢.٣٩	٢٦٢١.٩	-٩٤.١	٦٩١.٨٣	٤١٤.٣١
P-٨:J-٨	٢.٣٩	٢٦٢١.٩	-٩٤.١	٦٩١.٨٣	٤١٤.٣١
P-٨:J-٩	٢.٤	٢٦٢٩.٥	-٩١	٦٩٢.٢٢	٤١٤.٢٥
P-٩:J-٩	٢.٤	٢٦٢٩.٥	-٩١	٦٩٢.٢٢	٤١٤.٢٥
P-٩:J-١٠	٢.٣٧	٢٥٩٥.٢	-٩٧.٩	٦٨٨.٧٢	٤١٣.٥٥
P-١٠:J-١٠	٢.٣٧	٢٥٩٥.٢	-٩٧.٩	٦٨٨.٧٢	٤١٣.٥٥
P-١٠:J-١١	٢.٣٧	٢٦٢٠.٣	-٨٩.٢	٦٩٠.٣٣	٤١٣.٤٨
P-١١:J-١١	٢.٣٧	٢٦٢٠.٣	-٨٩.٢	٦٩٠.٣٣	٤١٣.٤٨
P-١١:J-١٢	٢.٤	٢٦١٩.٢	-٩٥.٢	٦٩١.٤٣	٤١٤.٠٩
P-١٢:J-١٢	٢.٤	٢٦١٩.٢	-٩٥.٢	٦٩١.٤٣	٤١٤.٠٩
P-١٢:J-١٣	٢.٣١	٢٣٧١.٣	-٩٧.٩	٦٧٢.٢٩	٤٢٠
P-١٣:J-١٣	٢.٣١	٢٣٧١.٣	-٩٧.٩	٦٧٢.٢٩	٤٢٠
P-١٣:J-١٤	٢.٣٩	٢٣٧٢.٤	-٩٧.٩	٦٧٦.١	٤٢٣.٦٩
P-١٤:J-١٤	٢.٣٩	٢٣٧٢.٤	-٩٧.٩	٦٧٦.١	٤٢٣.٦٩
P-١٤:J-١٥	٢.٨	٢١٧٠	-٩٧.٩	٦٧٧.٢٨	٤٤٥.٥٥
P-١٥:J-١٥	٢.٨	٢١٧٠	-٩٧.٩	٦٧٧.٢٨	٤٤٥.٥٥
P-١٥:J-١٦	٢.٧٧	٢١٧٦.٢	-٩٧.٩	٦٧٦.٦٦	٤٤٤.٢٩
P-١٦:J-١٦	٢.٧٧	٢١٧٦.٢	-٩٧.٩	٦٧٦.٦٦	٤٤٤.٢٩
P-١٦:J-١٧	٤.١٢	١٩٢٩.٥	-٩٧.٩	٦٨٣.٣٩	٤٧٦.٢٣
P-١٧:J-١٧	٤.١٢	١٩٢٩.٥	-٩٧.٩	٦٨٣.٣٩	٤٧٦.٢٣
P-١٧:J-١٨	٣.٩١	١٨٩١.٦	-٩٧.٩	٦٧٧.٨	٤٧٤.٥٢
P-١٨:J-١٨	٣.٩١	١٨٩١.٦	-٩٧.٩	٦٧٧.٨	٤٧٤.٥٢
P-١٨:J-١٩	٤.٥٤	١٦٦٥.٩	-٩٧.٩	٦٦٦.١٦	٤٨٥.٩٥
P-١٩:J-١٩	٤.٥٤	١٦٦٥.٩	-٩٧.٩	٦٦٦.١٦	٤٨٥.٩٥
P-١٩:J-٢٠	٤.٦٨	١٦٢٢.٧	-٩٧.٩	٦٦٣.٥٨	٤٨٧.٧٨
P-٢٠:J-٢٠	٤.٦٨	١٦٢٢.٧	-٩٧.٩	٦٦٣.٥٨	٤٨٧.٧٨
P-٢٠:J-٢١	٤.٦٧	١٦١١.٦	-٩٧.٩	٦٦٢.٤٥	٤٨٧.٧٨
P-٢١:J-٢١	٤.٦٧	١٦١١.٦	-٩٧.٩	٦٦٢.٤٥	٤٨٧.٧٨
P-٢١:J-٢٢	٤.٧٥	١٥٩٩.٧	-٩٧.٩	٦٦٢.٠٢	٤٨٨.٥٦
P-٢٢:J-٢٢	٤.٧٥	١٥٩٩.٧	-٩٧.٩	٦٦٢.٠٢	٤٨٨.٥٦
P-٢٢:J-٢٣	٧.٠٦	١٣٥٥.٢	-٩٧.٩	٦٥١.٣٩	٥٠٢.٩٢
P-٢٣:J-٢٣	٧.٠٦	١٣٥٥.٢	-٩٧.٩	٦٥١.٣٩	٥٠٢.٩٢
P-٢٣:J-٢٤	٣٥.٩٨	١٠٣٨.٥	-٩٧.٩	٦٣٥.١١	٥١٩
P-٢٤:J-٢٤	٣٥.٩٧	١٠٣٨.٥	-٩٧.٩	٦٣٥.١١	٥١٩
P-٢٤:J-٢٥	٣٠.٩٨	١٠٥٤.٩	-٩٧.٩	٦٣٦.٢٤	٥١٨.٤٥
P-٢٥:J-٢٥	٣٠.٩٨	١٠٥٤.٩	-٩٧.٩	٦٣٦.٢٤	٥١٨.٤٥
P-٢٥:J-٢٦	٥٤.٨٩	١٠١٩.٧	-٩٧.٩	٦٣٤.١٨	٥٢٠
P-٢٦:J-٢٦	٥٤.٨٩	١٠١٩.٧	-٩٧.٩	٦٣٤.١٨	٥٢٠
P-٢٦:J-٢٧	٥٨.٣١	١٠١٦.٤	-٩٧.٩	٦٣٣.٩٥	٥٢٠.١
P-٢٧:J-٢٧	٥٨.٣١	١٠١٦.٤	-٩٧.٩	٦٣٣.٩٥	٥٢٠.١
P-٢٧:R-١	٠	٠	٠	٥٣١.٨	٥٣١.٨
Pm١:R-٢	١	٤٠٠٩.٩	٤٠٠٩.٩	٤٠٩.٧٢	٤٠٩.٧٢
Pm١:PMP-٢	١٤.٨٦	١٠٠	-٢٧.٧	٤١٩.٢٢	٤٠٦.١٧

P-٣٤:PMP-٢	٢.٤٨	٣١١٢.٣	-٩١.٧	٧٢٧	٣٩٩.٦٣
P-٣٤:J-٢	٢.٦٤	٢٩٥٥.٢	-٩٢.٩	٧٢٤.٤٦	٤١٣.٠٢

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Table (٣-١) Junction Without valve

Id	Label	Elevation (m)	Head (Max)m	Head (Min) (m)	Pressure (Max) (kPa)	Pressure (Min) (kPa)	Vapor Volume (Max) (L)
25	J-2	422.51	724.46	413.02	2955.2	-92.9	0
28	J-5	420.28	718.1	415.12	2914.8	-50.5	0
30	J-7	423.23	698.53	414.54	2694.4	-85	0
32	J-9	423.56	692.22	414.25	2629.5	-91	0
34	J-11	422.6	690.33	413.48	2620.3	-89.2	0
35	J-12	423.81	691.43	414.09	2619.2	-95.2	0
36	J-13	430	672.29	420	2371.3	-97.9	0.1
37	J-14	433.69	676.1	423.69	2372.4	-97.9	0.3
39	J-16	454.3	676.66	444.29	2176.2	-97.9	5.3
41	J-18	484.52	677.8	474.52	1891.6	-97.9	3.4
42	J-19	495.95	666.16	485.95	1665.9	-97.9	496.1
44	J-21	497.78	662.45	487.78	1611.6	-97.9	26.7
45	J-22	498.56	662.02	488.56	1599.7	-97.9	8.1
46	J-23	512.92	651.39	502.92	1355.2	-97.9	73.8
48	J-25	528.45	636.24	518.45	1054.9	-97.9	10.9
49	J-26	530	634.18	520	1019.7	-97.9	21.3
100	J-3	426.02	722.38	416.02	2900.5	-97.9	5.6
101	J-4	424.77	722.44	415.88	2913.3	-87	0
102	J-6	424.62	697.82	416.79	2673.8	-76.6	0
103	J-8	423.93	691.83	414.31	2621.9	-94.1	0
104	J-10	423.56	688.72	413.55	2595.2	-97.9	0.5
105	J-15	455.55	677.28	445.55	2170	-97.9	27.7
106	J-17	486.24	683.39	476.23	1929.5	-97.9	1544.1
107	J-20	497.78	663.58	487.78	1622.7	-97.9	60.8
108	J-24	529	635.11	519	1038.5	-97.9	12.2
109	J-27	530.1	633.95	520.1	1016.4	-97.9	13.9

Table (٣-٢)Junction with valve

Id	Label	Elevation (m)	Head (Max) (m)	Head (Min) (m)	Pressure (Max) (kPa)	Pressure (Min) (kPa)	Vapor Volume (Max) (L)
25	J-2	422.51	683.66	447.69	2555.9	246.4	0
28	J-5	420.28	680.04	450.48	2542.3	295.6	0
30	J-7	423.23	669.89	458.81	2414	348.2	0
32	J-9	423.56	663.03	458.77	2343.8	344.6	0
34	J-11	422.6	657.34	463.24	2297.4	397.7	0
35	J-12	423.81	655.91	463.74	2271.6	390.7	0
36	J-13	430	652.95	465.7	2182	349.4	0
37	J-14	433.69	651.83	467.54	2134.9	331.3	0
39	J-16	454.3	644.21	472.36	1858.7	176.8	0
41	J-18	484.52	628.29	485.09	1407.1	5.5	0
42	J-19	495.95	615.88	493.39	1173.7	-25.1	0
44	J-21	497.78	601.59	497.23	1016	-5.4	0
45	J-22	498.56	599.1	497.53	983.9	-10.1	0
46	J-23	512.92	583.74	507.14	693.1	-56.6	0
48	J-25	528.45	555.74	518.45	267	-97.9	0.1
49	J-26	530	557.09	520	265.1	-97.9	0.1
100	J-3	426.02	684.9	448.2	2533.7	217	0
101	J-8	423.93	668.99	459.68	2398.4	349.9	0
102	J-10	423.56	658.85	462.03	2302.9	376.6	0
104	J-15	455.55	645.63	471.63	1860.3	157.4	0

Table (٣-٣) Pipe without valve

Id	Label	Scaled L(m)	Length (m)	Start	Stop	D (mm)	Material	Haz-Wil C	Wave Speed (m/s)	Vel (Max) (m/s)	Vel (Min) (m/s)	P. (Max) (kPa)	P.(Min) (kPa)	Hl (Friction) (m)
53	P-2	7.08	37.2	J-2	J-3	900	steel	125	958	1.39	-1.06	2955.2	-97.9	0.07
54	P-3	6.75	148.3	J-3	J-4	900	steel	125	958	1.39	-1.13	2913.3	-97.9	0.27
55	P-4	6.65	54.38	J-4	J-5	900	steel	125	958	1.39	-1.19	2932.3	-91.1	0.1
56	P-5	7.4	146.97	J-5	J-6	900	steel	125	958	1.39	-1.17	2914.8	-76.6	0.27
57	P-6	7.18	183.82	J-6	J-7	900	steel	125	958	1.39	-1.22	2713.9	-85	0.34
58	P-7	8.71	14.91	J-7	J-8	900	steel	125	958	1.39	-1.2	2697.1	-94.1	0.03
59	P-8	7.84	131.66	J-8	J-9	900	steel	125	958	1.39	-1.25	2656	-97.9	0.24
60	P-9	8.82	100	J-9	J-10	900	steel	125	958	1.39	-1.28	2632.1	-97.9	0.18
61	P-10	9.15	55.38	J-10	J-11	900	steel	125	958	1.39	-1.3	2620.3	-97.9	0.1
62	P-11	8.93	29.82	J-11	J-12	900	steel	125	958	1.39	-1.29	2620.3	-97.9	0.06
63	P-12	7.95	114.8	J-12	J-13	900	steel	125	958	1.39	-1.36	2619.2	-97.9	0.21
64	P-13	7.74	50	J-13	J-14	900	steel	125	958	1.41	-1.38	2373.9	-97.9	0.09
65	P-14	7.4	175.85	J-14	J-15	900	steel	125	958	1.84	-1.49	2372.4	-97.9	0.32
66	P-15	7.96	13.7	J-15	J-16	900	steel	125	958	1.5	-1.5	2176.2	-97.9	0.03
67	P-16	8.27	310.45	J-16	J-17	900	steel	125	958	1.75	-1.53	2239.6	-97.9	0.57
68	P-17	8.93	77.52	J-17	J-18	900	steel	125	958	2.24	-1.53	1929.6	-97.9	0.14
69	P-18	9.02	272.48	J-18	J-19	900	steel	125	958	2.24	-1.74	1915	-97.9	0.5
70	P-19	9.53	100	J-19	J-20	900	steel	125	958	1.69	-1.71	1695.7	-97.9	0.18
71	P-20	9.01	100	J-20	J-21	900	steel	125	958	1.57	-1.72	1663.9	-97.9	0.18
72	P-21	9.02	50	J-21	J-22	900	steel	125	958	1.56	-1.74	1680.6	-97.9	0.09
73	P-22	7.49	215.63	J-22	J-23	900	steel	125	958	1.98	-1.83	1621.3	-97.9	0.4
74	P-23	7.32	323.68	J-23	J-24	900	steel	125	958	1.97	-1.98	1355.2	-97.9	0.6
75	P-24	6.63	10.69	J-24	J-25	900	steel	125	958	1.87	-1.99	1054.9	-97.9	0.02
76	P-25	6.3	17.25	J-25	J-26	900	steel	125	958	1.89	-2.01	1054.9	-97.9	0.03
77	P-26	9.72	9.3	J-26	J-27	900	steel	125	958	1.9	-2.01	1019.7	-97.9	0.02
78	P-27	10	43.79	J-27	R-1	900	steel	125	958	1.92	-2.02	1016.4	-97.9	0.08
115	Pm1	2.95	17.45	R-2	PMP-	900	steel	125	0	1.39	-0.03	4009.9	-27.7	0.03
116	P-34	12.67	74.89	PMP-	J-2	900	steel	125	0	1.39	-1	3112.3	-97.9	0.14

Table (٣-٤) Pipe with valve

Id	Label	Scaled L (m)	Length (m)	Start	Stop	Diameter	Material	Haz-Wil	Wave Speed (m/s)	Vel (Max) (m/s)	Vel (Min) (m/s)	P (Max) (kPa)	P (Min) (kPa)	Hl (Friction) (m)
52	P-1	9.04	82.76	HT-1	J-2	900	steel	125	1050	1.39	-1.32	2648.5	243.5	0.15
53	P-2	7.08	37.2	J-2	J-3	900	steel	125	1050	1.39	-1.28	2555.9	217	0.07
54	P-3	6.75	148.3	J-3	AV-2	900	steel	125	1050	1.39	-1.32	2533.7	217	0.27
55	P-4	6.65	54.38	AV-2	J-5	900	steel	125	1050	1.39	-1.35	2542.3	246	0.1
56	P-5	7.4	146.97	J-5	AV-3	900	steel	125	1050	1.39	-1.38	2542.3	266.9	0.27
57	P-6	7.18	183.82	AV-3	J-7	900	steel	125	1050	1.39	-1.39	2468.6	266.9	0.34
58	P-7	8.71	14.91	J-7	J-8	900	steel	125	1050	1.39	-1.39	2414	348.2	0.03
59	P-8	7.84	131.66	J-8	J-9	900	steel	125	1050	1.39	-1.42	2398.4	300.9	0.24
60	P-9	8.82	100	J-9	J-10	900	steel	125	1050	1.39	-1.43	2343.8	344.6	0.18
61	P-10	9.15	55.38	J-10	J-11	900	steel	125	1050	1.39	-1.43	2302.9	376.6	0.1
62	P-11	8.93	29.82	J-11	J-12	900	steel	125	1050	1.39	-1.44	2297.4	390.7	0.06
63	P-12	7.95	114.8	J-12	J-13	900	steel	125	1050	1.39	-1.44	2271.6	342.1	0.21
64	P-13	7.74	50	J-13	J-14	900	steel	125	1050	1.39	-1.44	2182	317.1	0.09
65	P-14	7.4	175.85	J-14	J-15	900	steel	125	1050	1.39	-1.43	2141.8	157.4	0.32
66	P-15	7.96	13.7	J-15	J-16	900	steel	125	1050	1.39	-1.43	1860.3	157.4	0.03
67	P-16	8.27	310.45	J-16	AV-7	900	steel	125	1050	1.39	-1.43	1858.7	-63.3	0.57
68	P-17	8.93	77.52	AV-7	J-18	900	steel	125	1050	1.43	-1.4	1461.4	-29.9	0.14
69	P-18	9.02	272.48	J-18	J-19	900	steel	125	1050	1.49	-1.43	1407.1	-25.1	0.5
70	P-19	9.53	100	J-19	AV-8	900	steel	125	1050	1.5	-1.44	1173.7	-25.1	0.18
71	P-20	9.01	100	AV-8	J-21	900	steel	125	1050	1.51	-1.44	1062.4	-13.2	0.18
72	P-21	9.02	50	J-21	J-22	900	steel	125	1050	1.52	-1.51	1016	-10.1	0.09
73	P-22	7.49	215.63	J-22	J-23	900	steel	125	1050	1.6	-1.55	983.9	-56.6	0.4
74	P-23	7.32	323.68	J-23	AV-9	900	steel	125	1050	1.58	-1.58	693.1	-97.9	0.6
75	P-24	6.63	10.69	AV-9	J-25	900	steel	125	1050	1.58	-1.65	269.6	-97.9	0.02
76	P-25	6.3	17.25	J-25	J-26	900	steel	125	1050	1.58	-1.66	267	-97.9	0.03
77	P-26	9.72	9.3	J-26	AV-10	900	steel	125	1050	1.59	-1.66	265.1	-97.9	0.02
78	P-27	10	43.79	AV-1(	R-1	900	steel	125	1050	1.61	-1.68	255.7	-97.9	0.08
83	PMP	3.01	5	R-2	PMP-1	900	steel	125	1050	1.39	-0.06	4009.9	6.9	0.01
84	PU	3.58	5	PMP-	HT-1	900	steel	125	1050	1.39	-0.11	2778.7	335.5	0.01