Hydraulic Transient Analysis for Penstock of Rajwakti Small Hydro Power Plant

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Abstract: *The term hydraulic transient describes the effect of unsteady flow of fluid in pipeline. It is attend by the rise and fall of pressure from the steady state condition. Therefore it is necessary to analyze hydraulic transient in pipeline for economical design and safety purpose. The governing equations for hydraulic transient are equation of continuity and momentum. Its control is of great importance in hydraulic installations, water supply systems, aircraft, and fuel system e.t.c. In the present study an attempt has been made to analyze hydraulic transient in an existing penstock of small hydropower plant of Rajwakti, in Chamoli district, Uttarakhand, India. The HAMMER software has been used. Transient caused due to various operation condition of turbine has been considered. It is concluded from the results obtained that the most vulnerable location for sever transient pressure is near to the turbine end. When the valve of turbine closes suddenly the head rise more rapidly than the other operating condition. As the closure time increases the maximum transient pressure decreases. Material having low modulus of elasticity shows better control on hydraulic transient pressure.*

Keywords: *Penstock; Water Hammer; Closure Time; Maximum Transient Pressure*

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Introduction

Hydropower is one of the most reliable and efficient renewable energy sources, contributing significantly to sustainable energy generation. Small hydropower plants (SHPPs), particularly run-of-river schemes, have gained increasing attention because of their low environmental impact, shorter construction periods, and cost-effectiveness. In these systems, water is conveyed through long headrace tunnels and pressurized penstocks, making them susceptible to hydraulic transients during operational changes (Kendir and Özdamar, 2013; Riasi and Tazraei, 2017).

The penstock, which conveys water under high pressure to the turbine, is highly vulnerable to hydraulic transients caused by rapid operational changes such as valve closure, startup, shutdown, and load rejection. These transients may produce excessive pressure surges, cavitation, structural damage, and even penstock failure, making accurate transient analysis essential for the safe and reliable operation of hydropower systems (Yu et al., 2014; Riasi and Tazraei, 2017).

Hydraulic transients have been extensively studied because of their impact on the safety and performance of pressurized water conveyance systems. While early studies relied on analytical solutions based on one-dimensional water hammer theory, the complexity of modern hydropower systems has made advanced numerical methods essential for accurately predicting transient hydraulic behaviour under practical operating conditions (Yu et al., 2014).

The Method of Characteristics (MOC) is the most widely adopted numerical technique for hydraulic transient analysis owing to its stability, computational efficiency, and ability to simulate complex hydraulic systems. By solving the governing continuity and momentum equations along characteristic lines, MOC accurately predicts transient pressure and discharge, making it the standard method used in commercial hydropower transient analysis software (Yu et al., 2014; Riasi and Tazraei, 2017).

Recent studies have emphasized that reliable transient analysis requires simultaneous consideration of both hydraulic and mechanical processes within the complete water conveyance system. The transient response depends not only on pipeline geometry but also on frictional losses, pipeline elasticity, reservoir boundary conditions, turbine operating characteristics, governor response, and surge protection devices. Zeng et al. (2013) developed a nonlinear hydro-turbine model incorporating surge tank dynamics and elastic water hammer effects, demonstrating that coupled hydraulic–mechanical modelling significantly improves prediction accuracy during rapid load changes. Their study highlighted the importance of analysing hydraulic transients as an integrated system rather than considering individual components independently.

Various surge protection devices have been proposed to mitigate the adverse effects of water hammer. Among them, surge tanks remain one of the most effective solutions because they temporarily absorb or supply water during transient events, thereby reducing pressure fluctuations within the penstock. Kendir and Özdamar (2013) demonstrated that optimized surge tank geometry can effectively attenuate transient pressures while reducing construction costs. In addition, pressure relief valves, overflow structures, and differential surge tanks have been investigated to improve hydraulic performance. However, previous studies indicate that the effectiveness of these devices depends strongly on their interaction with the overall hydraulic system, emphasizing the need for integrated transient simulations rather than isolated component analyses (Riasi and Tazraei, 2017).

Similarly, Yu et al. (2014) analysed hydraulic transients in a diversion-type hydropower station equipped with a differential surge tank using the Method of Characteristics. Their study showed that load rejection represents one of the most critical operating conditions because it generates severe pressure fluctuations and surge tank oscillations. They further demonstrated that pressure-reduction orifices and overflow structures significantly improve transient performance by limiting excessive pressure rise and stabilizing system oscillations. These investigations confirm that project-specific transient analysis is essential for identifying critical operating scenarios and designing effective hydraulic protection measures.

Despite considerable advances in hydraulic transient modelling, important research gaps remain. Most previous investigations have focused on developing numerical methodologies, optimizing surge tank configurations, or evaluating individual protection devices. Comparatively fewer studies have examined project-specific hydraulic transient behaviour in small hydropower plants, where transient response is strongly influenced by the actual geometry of the water conveyance system, hydraulic boundary conditions, operational sequences, and protection arrangements. Consequently, conclusions derived from generalized models cannot always be directly applied to individual hydropower projects (Yu et al., 2014; Riasi and Tazraei, 2017). Furthermore, many studies have analysed individual hydraulic components independently, whereas practical transient behaviour results from the coupled interaction among reservoirs, tunnels, surge tanks, penstocks, turbines, and downstream waterways. Comprehensive system-level analysis therefore provides a more realistic assessment of hydraulic safety and pressure-wave propagation (Zeng et al., 2013; Yu et al., 2014).

The need for project-oriented transient analysis has become increasingly important for diversion-type and run-of-river hydropower plants, which typically incorporate long penstocks, steep hydraulic gradients, and limited storage capacity. These characteristics make such systems highly sensitive to rapid operational changes, particularly during emergency shutdown and load rejection. Accurate transient simulation enables engineers to evaluate pressure envelopes, verify hydraulic safety, optimize operational procedures, and reduce the risk of pressure-induced structural damage before plant commissioning (Riasi and Tazraei, 2017).

In this context, the Rajwakti Small Hydro Power Plant provides an appropriate case study for investigating hydraulic transient behaviour under practical operating conditions as shown in Figure 1. This study performs a comprehensive transient analysis of the penstock system by evaluating pressure-wave propagation and transient pressure distribution during representative operating scenarios. Particular emphasis is placed on determining the maximum and minimum pressure envelopes, assessing hydraulic stability, and verifying the adequacy of the existing hydraulic design under transient loading. By applying established numerical transient analysis techniques to an actual small hydropower project, the study provides engineering insights for improving hydraulic safety, operational reliability, and long-term performance of diversion-type hydropower systems. The findings are expected to contribute to the planning, design, and rehabilitation of similar hydropower installations while demonstrating the importance of incorporating project-specific transient analysis into hydraulic engineering practice.

2. Case Study

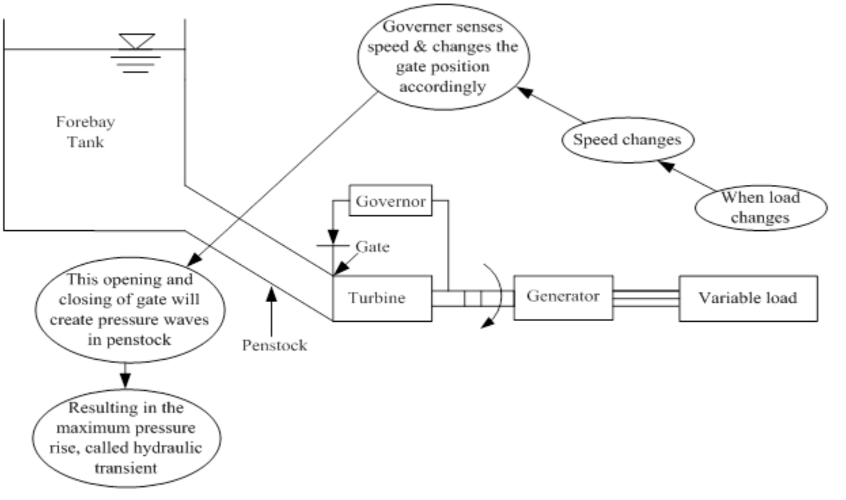


Figure 1 Basic illustration of generation of hydraulic transients

To study the hydraulic transient behavior of penstock, Rajwakti small hydro power plant has been selected. It is a grid connected hydropower plant. The penstock length of Rajwakti small hydropower plant is 1km, therefore it is suitable for the analysis of hydraulic transient and to see the behavior of its effect on penstock. The effect of operation of gate opening of turbine on water hammer pressure or fluctuation of extra pressure due to hydraulic transient may studied smartly. The general information of site has been given in the Table 1.

Table 1 General Information of the Selected Site

District	Chamoli
Tehsil	Ghat
State	Uttarakhand
Country	India
Lattitude	30°18'33" N
Longitude	79°19'46" E

Rajwakti Small Hydro-electric Plant (SHP) is located in Karanprayag tehsil in Chamoli District of Uttarakhand. This plant is situated at a distance of 196 km from Rishikesh (nearest railhead) and at a distance of 235 km from Dehradun (nearest airport). This SHP is approachable through road via Deoprayag, Sri Nagar, Rudraprayag, Karanprayag, and Nandprayag.

Rajwakti SHP is a run-off-river scheme for electricity generation by exploiting hydro-power potential of Nandakini, a tributary of Alaknanda River which has not been harnessed so far. Nandakini River meets Alaknanda River near Nandprayag. Nandakini River is a perennial river and is fed by rain and partially by snow. The catchment area is hilly with an altitude of 6620 m above mean sea level. The catchment area at the diversion site is approximately 545 km^2. The diversion structure of the project is situated near Paunkola Malla village and the power house is located near Rajwakti village. This hydroelectric project does not involve storage, submergence or disposition of debris in the stream and thus its construction does not influence environment and ecological conditions of the project area.

Figure 2 Penstock of Rajwakti SHP

Rajwakti small hydro project is one of the most suitable sites where optimum combination of head and discharge is available for comparatively shorter water conductor length. The power generated by this hydroelectric project is fed to 66 kV Uttarakhand Power Corporation Limited (UPCL) Grid, which is available at

Figure 3 Surge tank pipe of Rajwakti SHP

Nandprayag. Figure 2 shows the penstock of Rajwakti small hydropower plant. Material used for penstock of Rajwakti small hydropower plant is mild steel, diameter is 2.2 m, thickness is 8mm, there are seven expansion joint between entire length of penstock, length of penstock is 980 m. Figure 3 shows the surge tank pipe and there are two small diameter pipe parallel to the surge pipe is for spilling of extra water from surge tank.

Analysis

Starting of the turbine and sudden stoppage of the turbine due to load acceptance and load rejection respectively because transient in the penstock. The software (HAMMER) can be used to analyze these transient. Transient caused by sudden stoppage of turbine are usually severe and the penstock should be designed to withstand the resulting positive and negative pressures caused by these hydraulic transient. The calculation of transients for different material of penstock and different closure time is discussed. Simulation has been done for 800 seconds.

Module

Module has been made with the help of software using the data collected from the

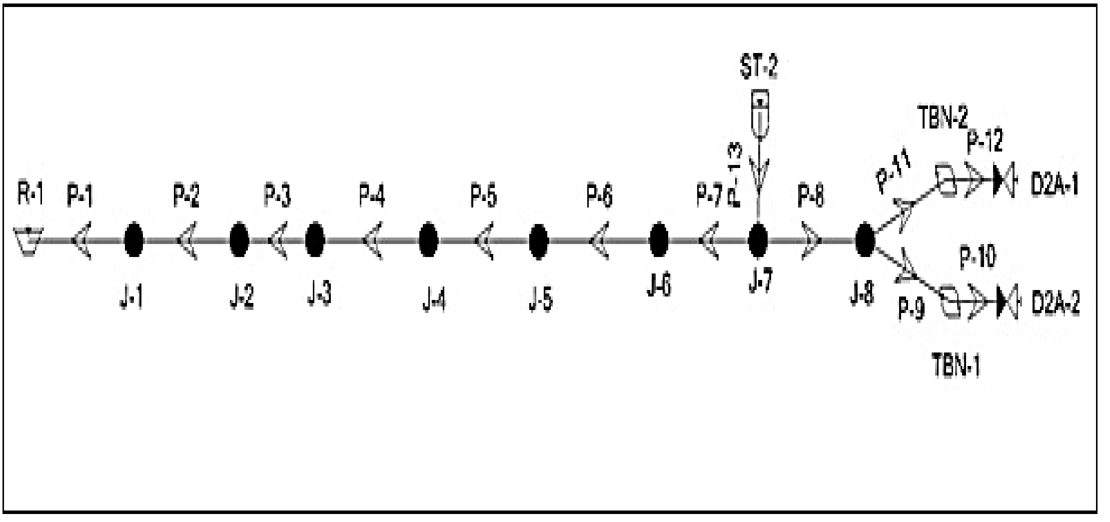


Figure 4 Module of Rajwakti small hydropower Plant

site. Figure 4 shows the module of Rajwakti small hydropower plant.
The Symbols used in module are explained in Table 2.

Table 2 Elaboration of Symbols

S.No.	Symbol	Name
1	R1	Forebay
2	P	Penstock pipe
3	J	Expansion joint
4	ST	Surge Tank
5	TBN	Turbine
6	D2A	Atmosphere

The Figure 5 shows the elevation profile of expansion joint along the length of penstock, brown line for base- elevation and blue line for base-hydraulic grade.

Calculation

The effect of hydraulic transient has been investigated on different materials of the penstock such

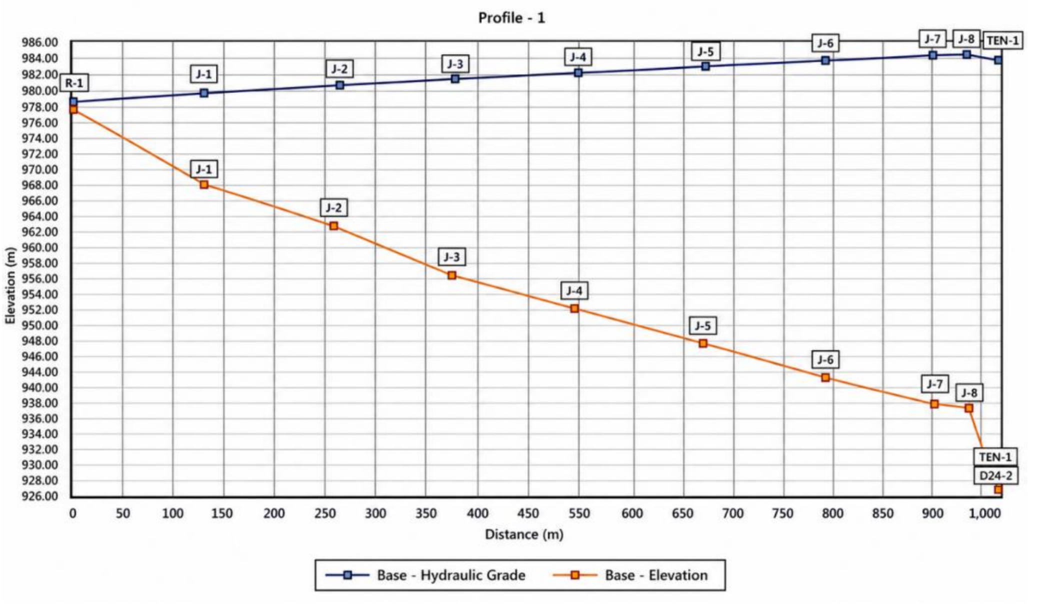


Figure 5 Profile of module of Rajwakti SHP

as Steel, Ductile iron, Concrete, Fiber glass roving and poly vinyl chloride (PVC). The time of closing of valve of turbine has also been varied viz. 5s, 10s, 20s, 40s, 60s, 90s, 120s, 150s and 180 seconds. For the analysis, penstock length from P9 to TBN1 has been taken and only temporal graphs with respect to this location are considered because it is clearly seen from spatial graph that maximum transient pressure is formed near the turbine end. The following graph has been obtained from the analysis of Steel Penstock for 5 second closure as shown in Figures 6 and 7. Three parameters:pressure, vapourvolume and flow have been selected for the study of module with respect to length of penstock and time. Similar graphs were obtained for different material of different closure time but value of parameters were different. The graphs are drawn with different colors shown the variation of parameter. The significance of these colors are given in the Table 3 below:

Table 3 Color Description for Graphs Showing Variation with Distance

S.No.	Colour	Description
1	Red curve Lower	Spatial variation of maximum hydraulic transient Pressure
2	Blue Curve	Spatial variation of pressure without hydraulic transient
3	Green Curve	Spatial variation of pressure initially under steady state condition
4	Yellow Curve	Spatial variation of minimum hydraulic transient pressure
5	Red Curve Upper	Spatial variation of vapour volume

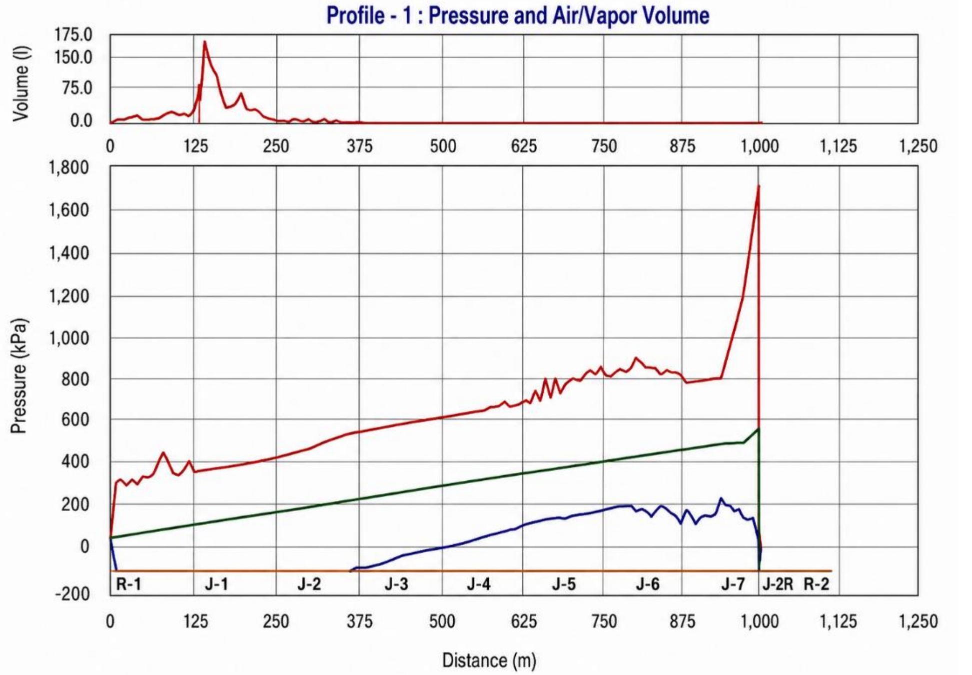


Figure 6 Variation of Pressure and Vapour Volume with penstock length

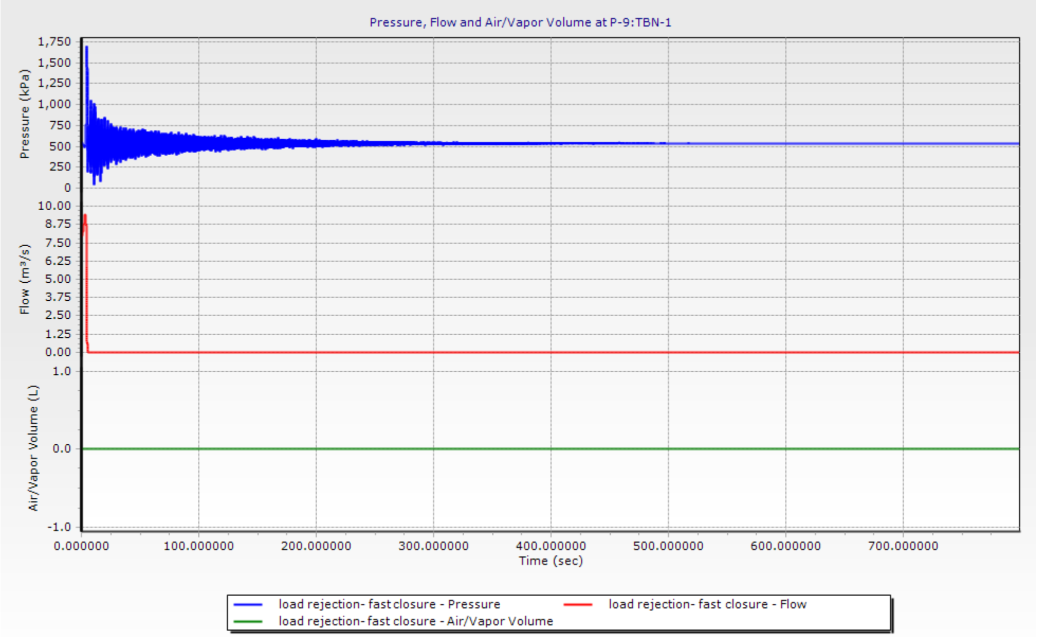


Figure 7 Variation of Pressure, Flow and Vapour Volume with closure time

Results and Discussion

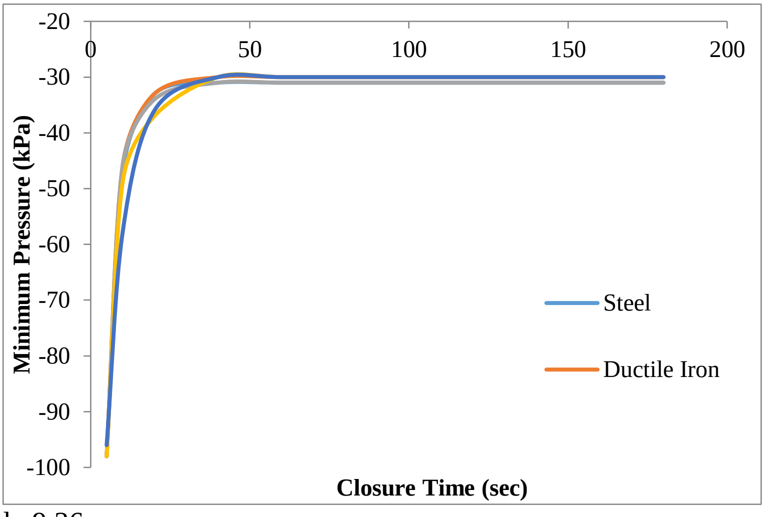
Effect of Closure Time

The effect of time of closure on the hydraulic transient pressures and head were studied. Nine times viz. 5s, 10s, 20s, 40s, 60s, 90s, 120s, 150s and 180 seconds were chosen. Different graphs

have been plotted to show the variation maximum pressure, minimum pressure, maximum head, minimum head, pressure head and maximum upsurge ratio for different valve closure time of turbine for different material of penstock as shown in Figures 8, 9, 10, 11 and 12.

As expected, the maximum head, maximum pressure, maximum upsurge ratio and maximum pressure head attained is practically for the less closure time 5 seconds. The maximum pressure, head, pressure head and maximum upsurge ratio are minimum for large closure time. The continual decrease in amplitude in successive cycle is due to damping by friction. Eventual equilibrium will be attained quicker in case of larger closure time. However the maximum head at the turbine end attained during the entire process is of interest to the designer.

The maximum hydraulic transient pressure head for 60s closure time has found 9.1m which is almost equal to the design hydraulic transient pressure head of



case study 9.36m.

Figure 8 Variation of Maximum Pressure with respect to Closure Time

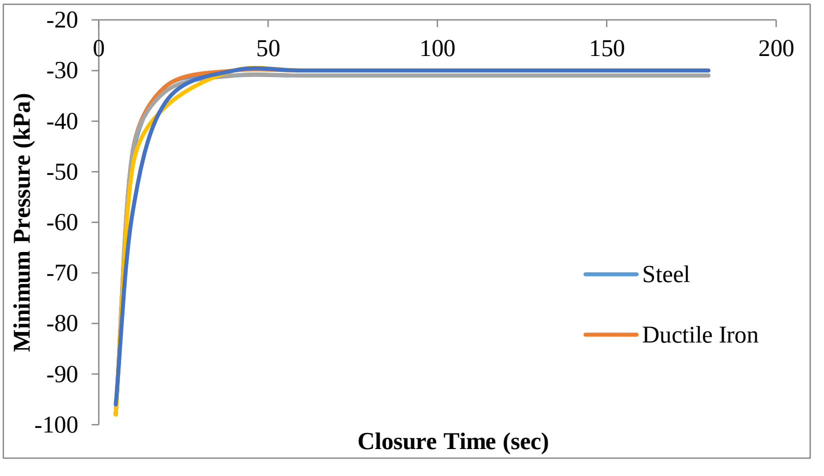


Figure 1. Figure 9 Variation of Minimum Pressure with respect to Closure Time

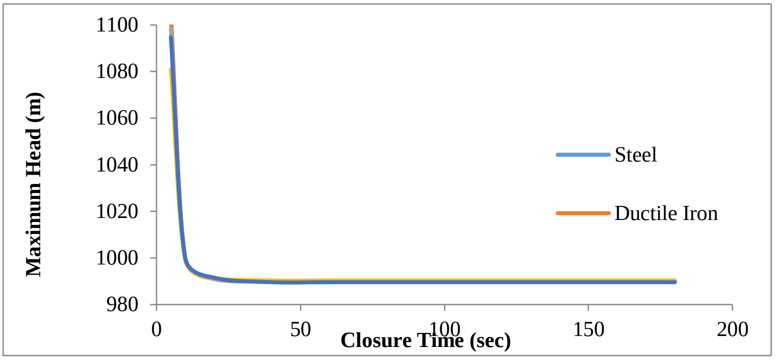


Figure 10 Variation of Maximum head with respect to Closure Time

Effect of material of penstock

The effect of material of penstock on the hydraulic transient was studied for five different materials viz. steel, ductile iron, Concrete, fibre glass roving and Poly vinyl chloride (PVC). The variation of maximum pressure, minimum pressure, maximum head, minimum head, maximum pressure head and maximum upsurge ratio shown in above figure. As expected, the maximum head and pressure attained is theoretical higher for material having higher value of modulus of elasticity because the surge i.e pressure wave velocity increases with increase in modulus of elasticity of material. The maximum pressure and head is higher for case of Steel and lower for case of poly vinyl chloride (PVC) material. Also we see that continual decrease in amplitude in successive cycles is due to damping by friction. As expected the minimum time required for damping in case of concrete because of high friction coefficient and manning roughness factor of concrete. In case of poly vinyl chloride the time taken is minimum to damp the whole energy and get another steady state of flow because of shock absorbing capacity of poly vinyl chloride (PVC).Overall comparison of materials, it

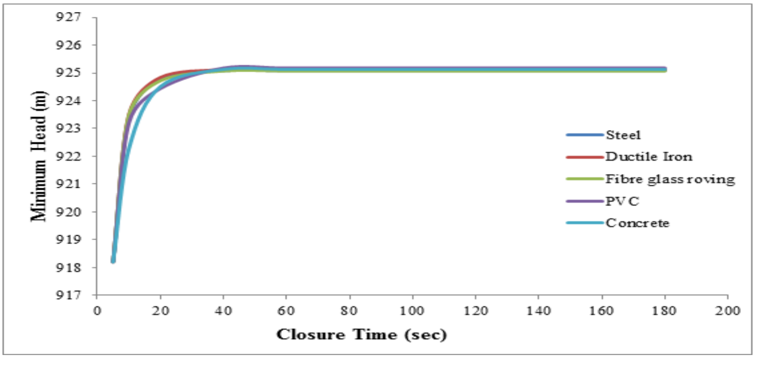


Figure 11 Variation of Minimum head with respect to Closure Time

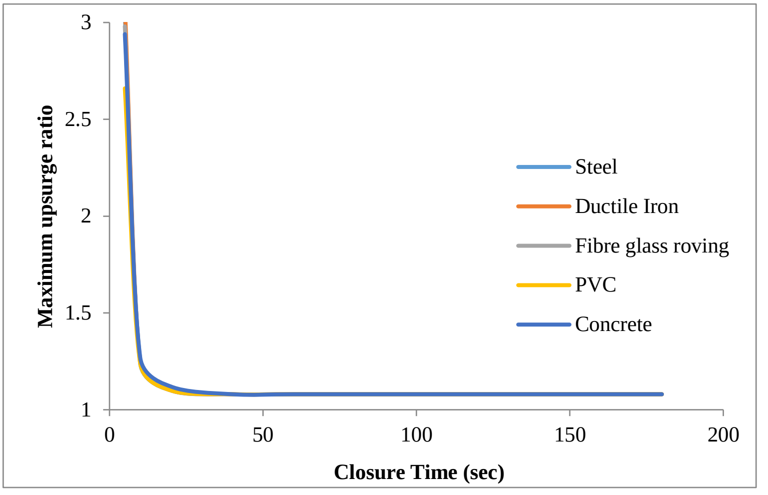


Figure 12 Variation of Maximum upsurge ratio with respect to Closure Time

Conclusions

In the present study an attempt has been made to analyze hydraulic transient for hydropower pipeline (penstock) for different material viz. steel, ductile iron, concrete, fiber glass roving and poly vinyl chloride (PVC) and different closure time viz. 5sec, 10sec, 20sec, 40sec, 60sec, 90sec, 120sec, 150sec and 180sec. An existing penstock of small hydropower plant of Rajwakti, in Chamoli district, Uttarakhand, India has been studied for the parameters by using HAMMER software available in IIT Roorkee.The following conclusion may be drawn from the present study:

- Valve closure time play significant role in the study of hydraulic transient behavior.sudden closure has great impact.
- Material of penstock also play significant role to study the hydraulic transient. Lower the value of modulus of elasticity better to control the hydraulic transient pressure.
- The most vulnerable location for the severe transient pressure near to the turbine end of small hydropower plant.
- The maximum head and maximum transient pressure well near to the time of closure of the turbine valve.
- The sever pressure condition is obtained in the penstock for transient due to sudden closure i.e. load rejection condition.
- Poly vinyl chloride (PVC) is the best option among the materials studied to control transient pressure.

- HAMMER software gives quick hydraulic transient analysis report spatial as well as temporal variation by which we can see the effect of transient for existing power plant.

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