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# Formation of Hydraulic Transients in Penstocks and Its Impacts on Different Materials

Rahul Kumar Garg[1*] and Arun Kumar[2]

*Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Uttarakhand 247667, India*
*[1*]rahulgargmech@gmail.com, [2]aheciitr.ak@gmail.com*

## *Abstract*

*Hydraulic transients, also referred as water hammer (WH) or pressures surges, is an unsteady flow phenomenon commonly generated in pressurized pipeline systems and hydraulic turbines of the Hydro Power Station (HPS). Significant disturbances in the flow of HPS may cause rapid variations in flow parameters of the fluid system during plant operational conditions such as startup, shutdown, load rejection and acceptances. These disturbances due to the plant operational conditions generate WH, which results undesirable low or high pressures in the penstock. It is normally associated with long penstock, where the pressure wave does not return from the end of the penstock before the closure of valve/turbine fully. Eventually, if not protected rightly, the penstock may rupture and, in some cases, loss of human life may occur. In this paper, a review of the available studies summarizing the effect of hydraulic transients on HPS and its effect on different materials of the penstock. Also new available materials for penstock fabrication such as GRP and HDPE compared with traditional penstock fabrication material like Mild Steel and Concrete.*

**Keywords:** *Water hammer, Transient flow, Penstock, Materials, Method of Characteristics (MoC)*

## 1. Introduction

Hydropower is the clean and green source of renewable energy. The cost of hydroelectricity is relatively low compared to others sources and is one of the primary resource of generating electricity globally due to commitment of all nations for reducing carbon emission. Energy production without problems and interruptions is crucial for HPS. Therefore, their design studies especially focus on reliable and safe operation. Smooth and undisturbed service of a HPS is always desirable for its safe operation at all types of changes in its hydraulic parameters like flow rate and head of the system. However, during the power generation, when the turbine flow changes, some disturbance may be developed and may cause a rapid or sudden fluctuation in the flow velocity of the fluid in the hydraulic conveyance system known as penstock. A penstock generally refers to a steel conduit or steel-lined tunnel connecting a reservoir or surge tank to a powerhouse [1][2][3] This may cause extreme positive or negative pressures in the penstock resulting in damages like buckling, wear and tear due to cyclic stresses, vibration and rupture or collapse [4]. Fig.1 show the schematic of an HPS.

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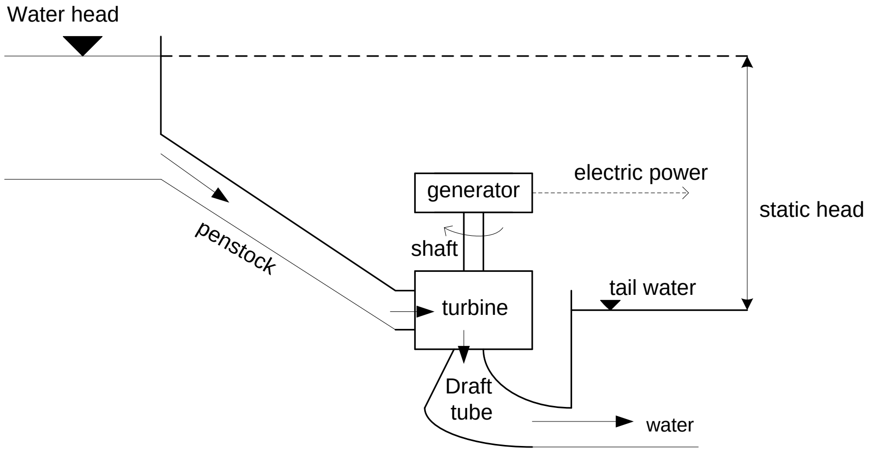

Figure 1. Schematic of a Hydroelectric Power Station (HPS)

There are various possible causes for the disturbed working of HPS during operation like power failures, rapid load rejection or, a sudden valve or gates opening or closure, equipment malfunctions, breaking of pipe, and human mistakes. Every disturbance in flow rate or other hydraulic parameters causes pressure fluctuations in penstock. Penstocks are to be designed design to withstand a negative water hammer of about 25 to 40 percent of head, depending on the governor opening time. The positive water hammer will depend on both the set governor time and the type of turbine [5]. The maximum positive water hammer should be kept as 25 percent of minimum gross head for impulse units, and for reaction, units should be in the range of 25 to 50 percent of maximum gross head [1]. Turbines, valves and other equipment may also get damaged or malfunction due to this undesirable effect of the WH. Furthermore, it is also possible that if the penstock' pressure goes down below the vapor pressure of the fluid, the fluid will vaporize alike to boiling or cavitation of water. This vaporize water is called column separation formation [6]. Both positive and negative transient pressures in penstock of HPS are presents in [Figure 2].

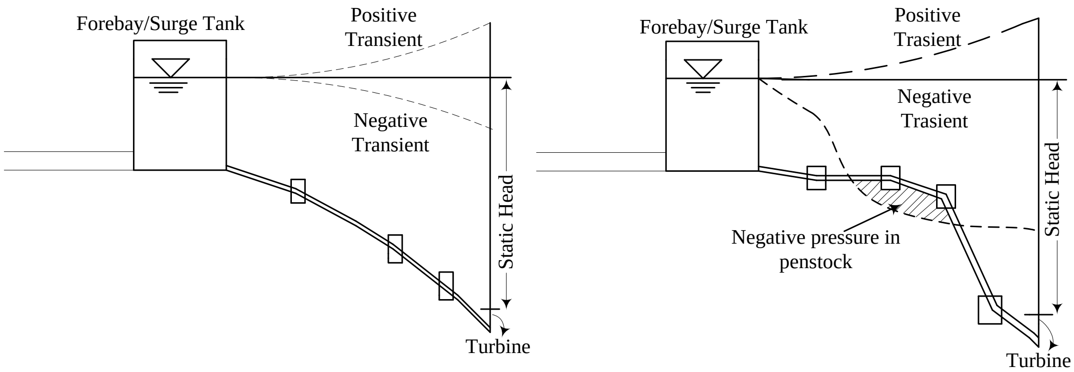

Figure 2. Transient pressure in penstock [7]

The initial equations that provided a quantitative assessment of the pressures produced by Menabrea in 1858 and Michaud in 1878; afterwards, Joukovsky in 1898 and, independently, Allievi in 1903 completed Michaud's work, by correcting his results and developing a more comprehensive theory. Joukovsky was the first that introduced the term water hammer (WH) which later on used worldwide to refer only to the elastic model, while the phenomenon related to the rigid column model, i.e., mass oscillations, took the name "surge". These theories allowed to compute only the maximum value obtained at the beginning of the transients; then Alive in 1913 was able to compute the different phases, under simplifying assumptions, with the so-called chained equations [8-10]. Evangelista, in the sixties of twentieth century developed a numerical method based on the characteristics, which is still used worldwide and implemented in computer programs [11]. In the thirties of the same century graphical methods appeared [12], that allowed, to compute the value of the pressures during the development of the transient. Since then, the work of Streeter and Wylie [10] and Chaudhry [9] are highlighted globally in the most of transients studies. Hydraulic transients are a potential problem in penstock if [1]

$$\frac{L*V_0}{H} > (3.3\ m/s) \tag{1}$$

If the conditions specified in Eq. (1) met, then there will be need to further investigation of the possibility of water hammer problem. There are two types of equations namely Joukovsky and Michaud-Allievi, which mentioned in the literature for calculating the magnitude of WH force in the penstock or pressurized pipelines. The hydraulic transients in the penstock or pipeline of HPS can calculated according to the theory developed by Joukovsky and Michaud-Allievi [13].

The magnitude of the pressure waves in penstock depends on the several factors as given below [14].

- Penstock length and configuration, the longer the penstock stronger will be the hydraulic transients
- penstock profile; (either buried, embedded or exposed penstock)
- Mean flow velocity of water
- Elastic properties of penstock material and water
- Time taken to close or open the valve
- Possible contents of dissolved gases in the water; Gas bubbles normally reduces transients
- Formation and appearance of vapors pockets (cavities) in the water

## 2. Causes of hydraulic transients in HPS

Transient pressures are the result of flow changes with time ( $dQ/dt$ ) in the hydraulic system. Hydraulic conduits have resistance, inertia and elasticity. During the steady state, only fluid resistance forces are considered. During the transient, both the inertial and elastic forces are included in the analysis. The forces generated are due to the conduit inertia, while the elasticity tends to limit the pressure variations. In HPS, flow changes usually caused by operation of inlet valve, turbines or pump, and are influenced by their hydraulic characteristics. This usually specified as a flow variation with time or head. When flow changes occur due to an orderly procedure such as shut down, start up, load changes, or gates/valves movements, the pressures can controlled closely. Operating requirements for turbines or pumps, however, can result in rapid flow variations in the conduits. Coupled with a high velocity in the penstock due to economic considerations, they can lead to unacceptable operation or unacceptable pressure variations. The common causes of hydraulic transients in the HPS are as described below [15,16]

- Rapid changes in valve settings
- Starting and stopping of pumps or turbines

- Rapid or sudden variation in load conditions
- Filling or emptying pipelines
- Mechanical vibration of system components (e.g. seals and guide vanes)
- Draft tube instability due to vortex rope
- Water column separation
- Periodic motion of components
- Periodic motion of components

Pressure pulsations from valves, pumps and turbine WH generation in the penstock generally depends upon the manner of valves closure events. There are four types of valve closures, independent of type of valve are present in [Table 1] [17].

Table 1. Classification of Valve/Guide vane closure**[17]**

| Time of Closer, $T_C$ | Type of Closure | Maximum Head, $\Delta H_{max}$ | Phenomenon |
|---|---|---|---|
| 0 | Instantaneous | $(a*V_0)/g$ | WH |
| $\leq \frac{2L}{a}$ | Rapid/Sudden | $(a*V_0)/g$ | WH |
| $> \frac{2L}{a}$ | Gradual | $< (a*V_0)/g$ | WH |
| $>> \frac{2L}{a}$ | Slow | $<< (a*V_0)/g$ | Surge |

Here $\frac{2L}{a}$ is termed as critical time and defined as the time required for pressure wave generated due to closure of valve to travel once from the point of origin to reservoir over the length of pipe and back to the point of origination.

## 2.1. Method of calculations of hydraulic transients

### 2.1.1. According to Joukovsky

Joukovsky published the best well-known equation in transient flow theory, and usually known as the fundamental or basic expression of WH [18]. It states that the intensity of WH is directly proportional to the velocity of wave propagation. The velocity of wave propagation depends on the elasticity of the penstock's wall material as well as liquid compressibility [19]. The pressure surge calculation using Joukovsky equation describes the behavior of the flow during sudden closure of the shut-off element with a closing time of 0 second. The Joukovsky equation may be expressed as Eq. (2)

$$\Delta P = \pm \rho a V_0 \text{ or } \Delta H = \pm \frac{a*V_0}{g} \tag{2}$$

### 2.1.2. According to Michaud - Allievi

Michaud-Allievi equations used to calculate maximum pressure surge level at the shut-off element, which develops because of slow closure of valve. The correlation used by Michaud-Allievi is expressed an Eqs. (3) and (4).

$$\Delta H = \frac{2*V_0*L}{g*T_C} \tag{3}$$

$$\Delta P = \frac{2*\rho*L*V_0}{T_C} \tag{4}$$

## 3. WH wave velocity

WH wave velocity is defined as the velocity at which disturbances move through a hydraulic system. It expresses the ratio of the conduit inertia properties to the elastic properties [16]. The transient head is directly proportional to the WH wave speed. Its magnitude is dependent on the density and the bulk modulus of the liquid, elasticity, diameter, and wall thickness of the pipe, and the presence of free air and gas [20]. The more rigid the pipe wall is more will be WH wave velocity [21]. The WH wave velocity for elastic pipes with circular cross-section estimated by using Korteweg's correlation is expressed by an Eq. (5) as follows [9,10]

$$a = \sqrt{\frac{1}{\rho(\frac{1}{K}+\frac{D}{(E*t_C)})}} \tag{5}$$

whereas, for cylindrical rigid pipes, the WH wave velocity can calculated according to Eq. (6).

$$a = \sqrt{\frac{K}{\rho}} \tag{6}$$

Eq. (5) and (6) will be depend on the factors which are described in Table 2 [22].

Table 2 Factors on which WH wave velocity depends [22]

| Fluid Properties | Pipe/Penstock's Properties |
|---|---|
| Density, Specific weight of the liquid<br>Amount of air, and so forth<br>Bulk modulus of liquid | Diameter<br>Thickness<br>Modulus of elasticity of pipe material |

The velocity of propagation of pressure wave through the penstock may be influenced by other factors such as cavitation due to drop in pressure, the presence of gas or of solid particles [23]. It is estimated that the maximum WH wave speed in a tunnel through rocks is about 1430 m/s, 1250 m/s in steel, 1000 m/s in concrete as well as in ductile iron, 600 m/s in GRP, 400 m/s in PVC and about 200 m/s in PE pipes [24]. Values of different young's Modulus of Elasticity and Poisson's ratio for various penstock materials are listed in Table 3[25].

Table 3 Physical properties of different penstock materials [25]

| Material | Young's Modulus of Elasticity E,(GPa) | Poisson's Ratio (ϵ) |
|---|---|---|
| Ductile Iron | 172 | 0.30 |
| Mild Steel | 200-212 | 0.28 |
| Concrete | 20-30 | 0.15 |
| PVC | 2.4-3.5 | 0.46 |
| HDPE | 0.89 | 0.40-0.45 |

| | | |
|---|---|---|
| GRP | 50 | 0.35 |

## 4. Governing equations

The classical theory of liquid transient flow in pressurized pipes have some basic assumptions for the development of the WH equations [26]. The assumptions are based on:

- Flow in the pipeline, which is function of distance and time.
- The elastic deformations of liquid under pressure.
- The dynamic fluid-pipe interaction.
- Hydraulic losses.
- The liquid velocity.

The governing equations for the transient/unsteady flow derived from the basic law of physics: the laws of conservation of mass and energy. These laws represent the continuity and momentum equation respectively. The simplified form of the continuity and momentum equations for WH expressed as in Eqs. (7) and (8) [9,10,20]:

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{7}$$

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + R\,Q\,|Q| = 0 \tag{8}$$

Eqs. (7) and (8) are the basic expressions for 1D problem of WH and represent the effects of fluid compressibility and elasticity of the conduit as well as the inertial effects of fluid acceleration and deceleration respectively. Both of the equations that represent the transients flow in closed conduits are a group of quasi-linear, hyperbolic partial differential equations (HPDE) with no conceivable solution.

Method of characteristics (MOC) is widely used method for the calculation of transient behavior of the fluid in the penstock or pressurized pipeline system because of its simplicity in calculations and superior performance compared to other available methods. This method also known as the method of characteristics curves and it is a mathematical method used to solve partial differential equations (PDE) [27]. The unique feature of this method is that it converts the partial differential equations into ordinary differential equation (ODE) [28]. These ordinary equations then may solved by using any numerical scheme. MOC is an iterative-based method that exhibits slow convergence [29]. The basic approach adopted for the solution of Eqs. (7) and (8) are the method of characteristic (MOC). The ‘compatibility equations’ can be obtained from Eqs. (7) and (8) as [25]

$$Hp_i = C_p - B * Qp_i \qquad C^+ \tag{9}$$

valid along the characteristics line defined by $\Delta x = a * \Delta t$.

$$Hp_i = C_p + B * Qp_i \qquad C^- \tag{10}$$

valid along the characteristics line defined by $\Delta x = -a * \Delta t$.

Eqs. (9) and (10) are generally referred to as $C^+$ and $C^-$ (see-plus and see-minus) equations. Here $Hp_i$and $Qp_i$ represents the head and flow at a point i in the system as seen in Fig. 3. Eqs. (9) and (10) allow the calculation of interior points if values of $Q$ and $H$ are known at all sections for preceding step, either the initial conditions or as the results of a previous stage of the calculation [10,30]. Further, the known quantities are in Eqs. (9) and (10) can express as:

$$C_P = H_{i-1} + B * Q_{i-1} - R * Q_{i-1} * |Q_{i-1}| \qquad (11)$$

$$C_M = H_{i+1} - B * Q_{i+1} + R * Q_{i+1} * |Q_{i+1}| \qquad (12)$$

where

$$B = \frac{a}{g*A} \; and \; R = \frac{f*\Delta x}{2*g*D*A^2}$$

The values of $Hp_i$ and $Qp_i$ can be calculated easily with the help from Eqs. (11) and (12)

$$Hp_i = \frac{C_p + C_M}{B} \; and Qp_i = \frac{C_p - C_M}{(2*B)}$$

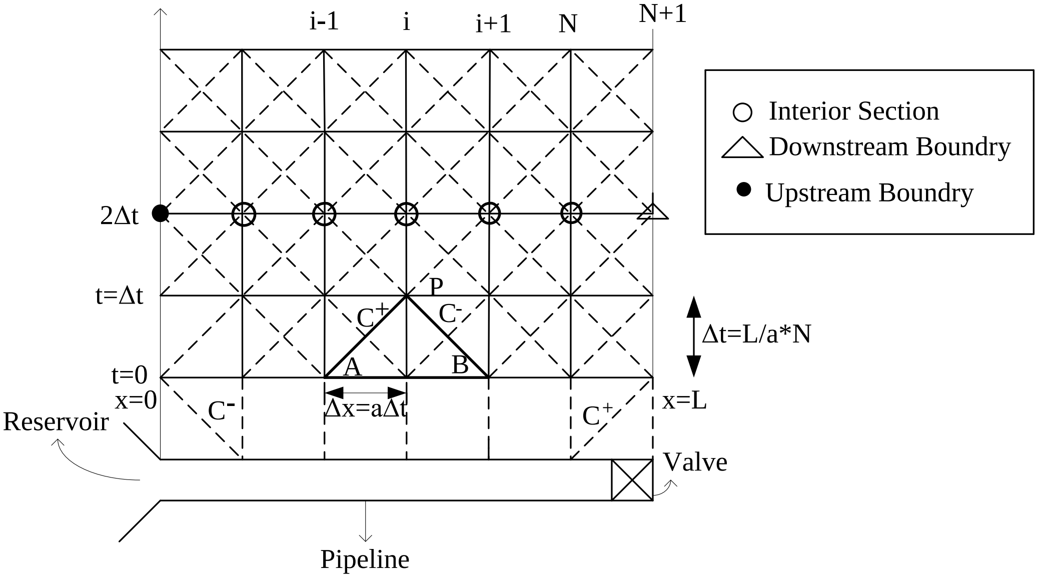

Figure 3. Characteristic grid for a reservoir-pipeline-valve system with specified time intervals

## 5. Penstock with different material

The analysis of hydraulic transient is essential for the selection of penstock material, its pressure classes and for specifications of surge protection devices. The main aim of material selection process is to choose the best material with low in cost, long life, and low maintenance cost, lightweight, lower transportation, strength and toughness, and installation cost and high performance. Formation of Hydraulic transients in penstock is greatly influenced by its material. More rigid means higher transients formation and if the materials are elastic then, there will be less transients wave produced in the penstock [21]. A key thermodynamic characteristic of any penstock pipe is the Standard Dimension Ratio (SDR) and is define as the ratio of outside diameter to the wall thickness. SDR values are lower for plastic pipes or like HDPE and uPVC then for metals like Steel and Iron because of the difference in the strength [20]. As shown in Eq. (13), the thermal resistance (R) of a penstock is inversely proportional to the pipe materials and thermal conductivity and directly proportional to the natural log of the SDR.

$$R = \frac{ln\,(SDR)}{2\pi K} \qquad (13)$$

It is necessary for the safe operation of the HPS that the formation of transients are kept in under acceptable limits. Mild Steel is the most commonly used material for the fabrication of the penstock for high head HPS. However, at lower heads concrete, fiberglass, plastic and HDPE can be used. HDPE, uPVC and GRP are the new materials for penstock fabrication. The use of these new materials is economically competitive with other traditionally used materials like steel. The materials for the fabrication of penstock of HPS classified into two main categories [17].

- Quesi-rigid materials (metal and concrete pipes)
- Viscoelastic materials( uPVC, HDPE, GRP)

The most commonly used penstock pipe materials are mild steel, HDPE and concrete. Rigid or unplasticized PVC (uPVC) and glass reinforced plastic (GRP) are other new options that have been sometimes used for penstock pipe material. The decision as to which pipe material to use for the penstock is based on the flow required, head and surge pressure, durability, allowable head loss, ease of fabrication, specific site conditions and cost of material [7]. All materials briefly discussed one by one in next section.

### 5.1 Mild steel

Due to high strength and durability, the most common used penstock material is mild steel for HPS. Mild steel provides a greater versatility for pipe diameter and thickness. Mild steel penstocks have good resistance to mechanical damage but can be more susceptible to corrosion when the pipelines buried. These pipes are generally heavy and hence manufactured in small segment, thus making transportation and installation easier [17].

### 5.2. Ductile iron

These pipes have cement coating on internal surface, which gives better corrosion protection and low friction loss. It is a heavy material, and tends to a difficult and more costly installation. Ductile iron permits for multiple jointing options like bolted gland, push-in spigot and socket with a flexible seal, or occasionally flanged [17,31].

### 5.3. Concrete

There are various factors, which make the concrete penstock unsuitable for use, even at moderate pressure. Concrete’s friction loss characteristics can be highly variable. Further, the material’s excessive weight makes transportation and installations difficult. Concrete penstocks typically have rubber ring joints [7,31,32].

### 5.4. GRP

The use of GRP in HPS projects has successfully deployed. GRP is light in weight but has very high compressive and tensile strength compared to steel. Due to the lower value of elasticity, the water hammer effect is considerably low in GRP pipes. Penstocks from GRP can be manufactured for head up to 200 m and diameter up to 4 m. In GRP pipes, the water hammer wave velocity is less than steel so that water hammer pressures are significantly lower. With long penstocks, this can be a considerable advantage [7,32].

### 5.5. HDPE

HDPE is both tough and flexible and can withstand over pressures without risk of failure. HDPE pipe is generally joined by fusion welding so it can install in very long lengths. For long penstock alignments, low-strength pipe, such as HDPE, can used for the upstream length where the head is relatively low. [7,17,31]

### 5.6. Unplasticized Polyvinyl Chloride (uPVC)

uPVC is commonly used penstock material. It has low friction loss and high resistance to corrosion property. It is tends to be cheaper but is only suitable for low-pressure operation and smaller diameter. uPVC is brittle and care has to take to ensure that over pressure above its rating will not occur. The water hammer wave speed in uPVC is about one third of that in steel [32]. It is generally fragile in nature susceptible to mechanical damage from impacts. Its life expectancy as a penstock material is about 5 to 20 years. Various factors, which considered for the selection of penstock material are described in Table 4 [17].

Table 4. Factors for Penstock material Selection [17]

| Parameters | Selection Criteria |
|---|---|
| Economics | Cost (installed cost, including transportation to project site and installation)<br>Expected life of penstock material<br>Cost of repairs and maintenance |
| Service Conditions | Pressure including water hammer effects<br>Soil loads, bearing capacity of soil<br>Corrosion bearing capacity of the soil<br>corrosive nature of water |
| Pipe Properties | Strength including static and fatigue, especially for transients<br>Ductility<br>Corrosion resistance ability<br>Fluid friction resistance<br>Pressure Class |
| Availability | Local availability and trained personnel for installation<br>Diameter and thickness<br>Compatibility with commonly available fittings |

Based on the various commercially available pipes, Indian standards and guidelines the different technical parameters of various types of penstock material have compared and given in [Table 5] [7,17,33]

Table 5. Properties of different penstock materials [7,17,33]

|  | Materials |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Properties | Ductile iron | Mild Steel | Concrete | PVC | HDPE | GRP |

| | | | | | | |
|---|---|---|---|---|---|---|
| Ultimate Tensile Strength (kg/cm$^2$) | 4200 | 4100 | Composite Pipe | 600-800 (Decreased with temperature) | 265-280 (Decreased with temp) | 1020-3060 |
| Maximum Working Pressure (kg/cm$^2$) | 77 to 32 | Depends upon thickness | 5 | 12.5 | 16 | 15 |
| Weight of pipe | Medium | Medium | Heavy | Light | Light | Light |
| Diameter in general use (mm) | 80 to 1200 | 220 to 508 (for around 70 bar) 610 to 2032 (for pr. around 25 bar) | 150 to 300 | 20 to 315 | 16 to 750 | 400 to 1600 |
| Structural Strength (kg/cm$^2$) | 5000 | 4000 | 250-300 | 150-200 | 200-250 | 250-300 |
| Design Friction Manning's Co efficient | 0.011 | 0.013 | 0.013 | 0.011 | 0.011 | 0.011 |
| Useful life (Years) | 90 | 40 | 20 | 20 | 20 | 20 |
| Response to Surge | Good resistance properties to water hammer, high strength for supporting earth loads | Can withstand high working/surge pressure, Easy to weld | Medium beam strength and rigidity, low in initial cost | Light weight, very smooth, very durable | Light weight, very durable, very smooth, good rigidity | Light in weight, long service life, low maintenance cost |

The properties of the material which are used for penstock selection are also compared relatively and shown in [Table 6] [34] which describes the possibilities of using different kinds of materials based on various factors. The more the number of 'stars' the more favorable is the material type under different characteristics.

Table 6. Relative comparison of properties of various materials [34]

| aterial | Friction | Weight | Corrosion | Cost | Jointing | Pressure |
|---|---|---|---|---|---|---|
| Ductile Iron | **** | * | **** | ** | **** | **** |
| Mild Steel | *** | *** | *** | **** | **** | ***** |
| Concrete | * | * | ***** | *** | *** | * |
| PVC | ***** | ***** | **** | **** | **** | ***** |
| HDPE | ***** | ***** | ***** | ** | ** | ***** |
| GRP | ***** | ***** | *** | * | **** | ***** |

Material selection for the penstock plays an important role for controlling the transients in acceptable limits. Right material selection gives good control on the formation of wave speed, which causes water hammer and reduces wear and tear of the penstock and other equipment.

## 6. Impact of penstock material on hydraulic transients

All penstocks of any material experience transient regularly. Penstock material plays an important role in the formation of WH in the HPS. Various researchers across the globe analysis the WH effect on penstock material by experimentally or analytically.

Authors in [35] experimentally reported the transient's effect on water and sewage pipes system on the basis of pressure measurement and the strain in pipes during field conditions. Both axial and circumferential strains recorded for different pipe materials like cast iron, stainless steel and PVC plastics. Their investigation shows that the soil load effect on a buried pipe was to decrease the strain in the pipe, and support the pipe during transient events. Soares et al. [36] studied and investigated the transients analysis in PVC by implementing an inverse transient method. Duan et al. [37] highlighted the significance of viscoelastic behavior of pipes and effect of unsteady friction, which shows that the viscoelastic effect is more critical if the retardation time, is less than the wave travel time along the pipeline length. Keramat et al. [38] proposed a new model for WH modeling of plastic pipes with a time-dependent Poisson's ratio. In this model, the time dependency of Poisson's ratio considered for linear viscoelastic pipes. Ferrante et al. [39] investigated the presence of hysteretic effect for the leakage in plastic pipes. It observed that the pipe material could play an important role to determine the relationship between total head inside the pipe and leak discharge. Bords [40] studied the main problem which was connected with applying the WH model in plastic pipes. Certain parameters like wave speed, retardation time and creep compliance analyzed.

Covas et al. [41,42] in his two-part paper studied the effect of viscoelasticity in polymer pipelines. The experimental and theoretical results were compared. The creep-function of the pipeline material was experimentally determined. A mathematical model and MOC-based numerical solution was proposed which considered the pipe-wall viscoelasticity by the Kelvin-Voigt model. Pezzinga et al. [43] studied the 2-D features of hydraulic transients in pressurized viscoelastic pipes by means of a micro genetic algorithm based on pressure traces. The 2-D analysis shows that the viscoelastic models generally have smooth velocity profiles with respect to the elastic model. Lee et al. [44] also studied the effect of FSI using frequency domain analysis. A method proposed for extracting a system's frequency response function using conventional signals of valve closure and the effects of various faults, friction and pipe wall viscoelasticity on this response function were analyzed with the corresponding impacts in the time domain.

Kawaguchi et al [45] studied resistance of the WH effect on three different types of glass fiber-reinforced thermoplastics. It investigated that the appearance of the fracture surfaces was attributable to the breaking of the glass fibers at the fracture surface, which hardly observed in other types of fracture, such as tensile fracture. Sun et al. [46] studied and investigate the water hammer wave speed of fiber-reinforced plastic composite pipes based on three different fixed means.

Apollonio et al [47] performed creep functions test for analysis of transient conditions in HDPE pipes. Transient pressure data were collected at different pipe sections. Some specific features observed which are typical of plastic pipes. In their observations, a significant damping of excess pressures observed in comparison to what typically obtained for rigid pipes. A numerical transient solver used for numerical simulation of experimental tests. After comparison of numerical results with experimental data, it was found that the viscoelastic model precisely predicts observed transient pressure. Evangelista et al. [48] analysis the pipe-wall viscoelasticity effect during the transient events in HDPE branched pipes systems, from both numerical and laboratory point of view. It observed that a significant propagation and reflection coefficients occurred at the pipe junction. Mitosek et al. [49] given some modification in governing equations of WH. After conducting various numerical experiments, conclusion was that the purposed approach leads to better agreement between the computational and experimental results.

Kumar and Singal [33] proposed a new method for the selection of best suitable penstock material by using various techniques like MADM, TOPSIS and modified TOPSIS. Four materials are examined by analysis of certain criteria and concluded that TOPSIS and modified TOPSIS method are the best suited for penstock material selection. Tan Wee Choon et al [50] studied the WH effect throughout the pipeline system by taking two materials i.e. steel and PVC. Their investigations showed that lower strength, pipe material wall deals with higher WH effect. Mitosek et al. [51] studied the reservoir influence on pressure wave propagation in steel pipes. Based on the experimental data, an approach to estimate the time of pressure wave; reflection delay in a reservoir was proposed. Mishra et al. studied [52] the effect of hydraulic transients on the mechanical power with changes in the different materials used for the fabrication of the penstock. It was found that penstock fabricated with viscoelastic materials like PVC and HDPE, shows fewer transients affects whereas steel and concrete shows high transients.

Adamkowski et al. [53] invented a model, based on theory of crack growth for evaluation of remaining lifetime of steel penstock in HPS. Kodura A. [54] studied the characteristics of gate closure at WH event in two different pipelines materials like Steel and PE. With the experimental data, a new method of calculation developed for the calculations of the transient flow. Kono Yukio et al. [55] studied the breaking pattern of a penstock after the sudden closure of the valve by assuming initial velocity and specified the yielding stress from elastic condition to plastic conditions. The result of analysis was compared with the condition of actually braked penstock.

Wahba et al. [56] developed and proposed a 2D numerical model to study the transient behavior of laminar fluid in viscoelastic pipes. Results showed that the viscoelasticity effect of pipe wall more pronounced in longer pipes having bigger diameters and large WH wave speed. Abdelaziz et al. [57] proposed a four equation friction model of WH calculations for quasi-rigid pipelines. This proposed model can be used for the development of a new computer code for transient calculations in near future.

## 7. Conclusion

An extensive literature review on formation of hydraulic transients, its effect on pipeline material and diameter has carried out and the following conclusions are drawn:

The processes involved in the formation of hydraulic transients in penstock are studied. The equations associated with WH analyzed with different approaches and methods.

Many researchers studied the effect of various penstock materials on hydraulic transient’s formation through experimental and theoretical investigations. It concluded that non-elastic penstock or pipes generate higher transient’s pressure then viscoelastic materials.

Based on investigation it may conclude that new penstock material like GRP, HDPE have significant effect on reducing the formation of transient waves in the penstock.

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| Nomenclature | | | |
|---|---|---|---|
| A | Cross-sectional area of the pipe ($m^2$); | $\upsilon$ | Kinematic Viscosity; |
| D | Diameter of the pipe (m); | $\rho$ | Mass density of fluid ($kg/m^3$); |
| $t_c$ | Thickness of pipe wall (m); | $\tau$ | Dimensionless time ( $\tau = 4\, \upsilon t/D^2$); |
| f | Darcy-Weishbach friction coefficient; | o | Steady state (initial) conditions; |
| H | Piezometric head in pipe (m); | Abbreviations: | |
| K | Bulk modulus of fluid (Pa); | FSI | Fluid- structure interaction |
| L | Length of pipe (m); | MOC | Method of characteristics |
| $\Delta P$ | Joukovsky pressure rise ($N/m^2$) | FEM | finite element method |
| Q | Discharge ($m^3/s$); | FVM | finite volume method |
| ret | Viscoelastic retardation; | uPVC | Polyvinyl Chloride |
| i | Node number; | HDPE | High -density Polyethylene |
| R | Pipeline resistance coefficient ($s^2/m^5$); | GRP | Glass reinforced polymer |
| Tc | Valve closing time (s); | PE | Polyethylene |
| $V_0$ | Flow velocity (m/s); | MADM | Multiple Attribute Decision Making |
| $\Delta t$ | MOC time step(sec); | TOPSIS | Technique for Order Preference by Similarity to Ideal Solution |
| $\Delta x$ | MOC space step(m); | DVCM | Discrete Vapor Cavity Model |
| $\epsilon$ | Poisson's ratio; | DGCM | Discrete Gas Cavity Model |
| R | Thermal resistance of penstock material(m $^oC/W$); | WH | Water Hammer |
| x | Distance along pipeline (m); | HPS | Hydro Power Station |
| K | Thermal conductivity of penstock material ($W/(m\,^oC)$) | SDR | Standard Dimension Ratio |

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