ANALYSIS OF TRANSIENT IN PIPELINE CAUSED BY OPENING OR CLOSING OF DOWNSTREAM VALVE

A MINI PROJECT REPORT

MASTER OF TECHNOLOGY

Submitted by

MANISH BHAGAT (234104617)

Submitted to

SREEJA PEKKAT

(Associate Professor Water Resources Engineering and Management)

DEPARTMENT OF CIVIL ENGINEERING

Indian Institute of Technology, Guwahati

ABSTRACT

The analysis of transient events in pipelines, such as pressure surges, water hammer are crucial to understand for ensuring safe and efficient operation. This study focuses on analyzing transients arising from the opening or closing of a downstream valve in a pipeline system using the characteristic method. The characteristic method is a powerful tool for modeling transient flows in pipelines, considering the wave propagation and interactions with various system elements. Through mathematical modeling and simulation, this study investigates the temporal and spatial changes in pressure and flow rates within the pipeline network during valve operations. The effects of pipe material properties, fluid characteristics, valve types, and operating conditions on transient behaviors are systematically examined This research contributes to enhancing the understanding of transient phenomena in pipelines and provides valuable guidelines for designing resilient and safe pipeline systems.

TABLE OF CONTENT

CONTENT- Page no

0.OBJECTIVE -- 3
1.INTRODUCTION ---------------------------------- 3-4
2.PHYSICS OF TRANSIENT FLOW--------------5-7
3. ANALYSIS OF TRANSIENT FLOW-----------6-7
4.VALVE-- 7
5. METHODOLOGY---------------------------------8
6. GOVERNING EQUATIONS----------------------8
7. METHOD OF CHARACTERISTICS------------9-13
8. BOUNDARY CONDITIONS ---------------------13-15
9. COMPUTER PROGRAME ----------------------17-24
10.RESULT ---25-28
11.REFERENC--- 29

OBJECTIVE – ANALYSIS OF TRANSIENT EVENT IN PIPE LINE BY METHOD OF CHARACTERISTIC.

1.INTRODUCTION

In a pipeline system, system flow control like opening and closing of valves, and starting and stopping of pumps when these operations are performed very quickly, they can cause hydraulic transient phenomena. Transients are important in hydraulic systems because they can cause rupture of pipe and pump casings, pipe collapse, vibration, excessive pipe displacements, pipefitting, and support deformation and/or failure, and vapor cavity formation.

When transient conditions exist, the life expectancy of the system can be adversely impacted, resulting in pump and valve failures and catastrophic pipe rupture. Hence, transient control has become an essential requirement for ensuring safe operation of water pipeline systems. To protect the pipeline systems from transient effects, an accurate analysis and suitable protection devices should be used.

Spectacular accidents have occurred because of transient-state pressures (intermediate flow while changing from one steady state to another is called transient flow) exceeding the design pressure of a conduit. These accidents, which are due to design or operating errors or equipment malfunction, have resulted in loss of life and money.

Fig-1 Photos of damage due to transient-state pressures are shown in

Transient flow in pipelines is a critical aspect of fluid transport systems, characterized by unsteady variations in flow parameters such as pressure, velocity, and density. Understanding and accurately predicting transient flow phenomena are essential for ensuring the reliable and safe operation of pipelines, particularly in industries such as oil and gas, water distribution, and chemical processing.

2.Physics of Transient Flow

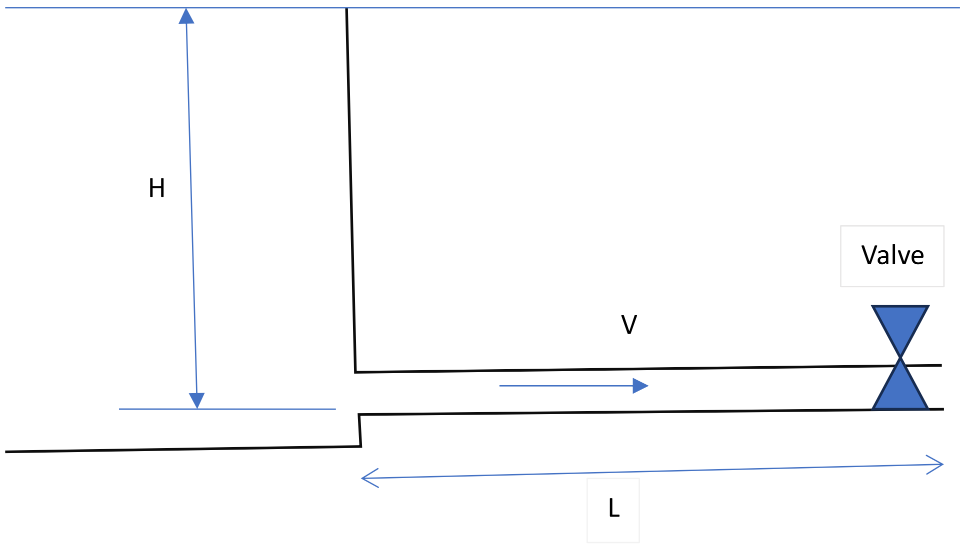


Fig-2 Reservoir and single pipe line

The following discussion of different flow conditions in a piping system will help you understand the preceding definitions.

Let us consider a pipeline of length L in which water is flowing from a constant-level, upstream reservoir to a valve located at the downstream end, as shown in Fig.2. Assume that the valve is instantaneously closed at time $t = t_o$ from the full-open position to the half-open position. This will reduce the flow velocity through the valve, thereby increasing the pressure at the valve. The increased pressure will produce a pressure wave that will travel back and forth in the pipeline until it is dissipated because of friction and the flow conditions have become steady again. This time, when the flow conditions have become steady again, we will call t_o .

Based on the preceding definitions, we may classify these flow regimes into the following categories:

1. Steady flow for $t < t_o$
2. Transient flow for $t_o \leq t < t_f$
3. Steady Flow again for $t \geq t_f$

Transient-state pressures are sometimes reduced to the vapor pressure of a liquid that results in separating the liquid column at that section; this is referred to as liquid-column separation. If the flow conditions are repeated after a fixed time interval, the flow is called periodic flow, and the time interval at which the conditions are repeated is called period.

Pressure change produced by velocity

$$\Delta H = \frac{a}{g}\Delta v$$

This above equation is also known as Basic water hammer Equation.

Wave speed ($\boldsymbol{a}$)

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

If we assume the conduit walls to be slightly deformable instead of rigid then above formula would be modified to

$$a = \sqrt{\frac{\frac{K}{\rho}}{1+(\frac{KD}{eE})}}$$

Where D is inside diameter of conduit, 'e' is the wall thickness and 'E' is the modulus of elasticity of the conduit wall material.

3. ANALYSIS OF TRANSIENT FLOW

The analysis of transient-state conditions in closed conduits may be classified into two categories:

3.1 Lumped system approach:

lumped-system approach and distributed-system approach. In the lumped-system approach, the conduit walls are assumed rigid, and the liquid in the conduit is assumed incompressible, that is, it behaves like a rigid mass so that the flow velocity at any given instant of time is the same from one end of the conduit to the other. In other words, the flow variables are functions of time only. Therefore, ordinary differential equations describe the system behavior. The flow velocity in each conduit may be considered individually in a multiconduit system.

3.2 Distributed system approach:

In the distributed-system approach, the liquid is assumed to be slightly compressible. Therefore, the flow velocity may vary along the length of the conduit in addition to the variation in time. That is, the flow variables are now functions of not only time but also of distance. Partial differential equations therefore describe the system behavior.

If the rate of change of flow velocity is slow, a lumped-system approach yields acceptable results; for rapid changes, however, a distributed-system approach must be used. The distributed-system approach is somewhat more complex than the lumped-system approach.

4.Valve

A valve is a device used to control the flow of water. The control is achieved by closing, opening or partially obstructing various passageways. Valves have many applications and plumbing valves are the most commonly used valves in everyday life. Technically, valves are considered to be pipe fittings, and there are many different valve designs. Each of the many different valve designs has its own advantages and disadvantages. The gate valve slides up and down like a gate, the globe valve closes a hole placed in the valve, the angle valve is a globe valve with a 90° turn, and the check valve allows the fluid to flow only in one direction. From a functional point of view, valves can be divided into the following groups

1. Valves which are either completely open or completely closed (on – off function)

2. Valves which can be used for a continuous control of the flow

3. Valves which only allow flow in one direction

4. Valves for special purposes such as pressure reducing valves, safety valves, air

5. METHODOLOGY

For Transient Analysis Various methods of analysis were developed for the problem of transient flow in pipes. They range from approximate analytical approaches whereby the nonlinear friction term in the momentum equation is either neglected or linearised, to numerical solutions of the nonlinear system.

5.1 GOVERNING EQUATIONS

To analyze the transient-state conditions in a pipeline, we need the equations describing these flows. In this section, we derived the equations by making the following assumptions: The fluid is slightly compressible, the walls of the conduit are linearly elastic and are slightly deformable, and the head losses during the transient state may be computed by using the steady-state formula.

Hence, the spatial variation of density and the flow area A due to the variation of the inside pressure with x may be neglected

Small variation of density and A is indirectly taken into account by considering the wave velocity 'a' to have a finite value

If the fluid is considered to be incompressible and the conduit walls are assumed rigid,

then the wave velocity becomes infinite and pressure or velocity change is felt instantaneously throughout the system

CONTINUITY: $$\frac{\partial p}{\partial t} + v\frac{\partial \mathrm{p}}{\partial \mathrm{x}} + \rho a^2 \frac{\partial \mathrm{v}}{\partial \mathrm{x}} = 0$$

MOMENTUM: $$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\theta + \frac{fv|v|}{2D} = 0$$

These equations are a set of first order partial differential equations.

5.1.1 SIMPLIFIED EQUATION

In most of the engineering applications the convective acceleration terms $v\frac{\partial p}{\partial x}$ and $v\frac{\partial v}{\partial x}$ are small

Similarly the slope term also is very small Therefore dropping these terms from the governing equations,

we get

Continuity equation: $\frac{\partial p}{\partial t} + \rho a^2 \frac{\partial \mathrm{v}}{\partial \mathrm{x}} = 0$

Momentum equation: $\frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{fv|v|}{2D} = 0$

6. METHOD OF CHARACTERISTICS

The method of characteristics simplifies the hyperbolic equations describing the flow by converting them to the natural coordinates of the system, otherwise known as the characteristics. The resulting characteristic equations obtained are solved numerically on either a grid of characteristics or on a rectangular coordinate grid.

This method is the most popular approach for handling hydraulic transients. Its thrust lies in its ability to convert the two partial differential equations (PDEs) of continuity and momentum into four ordinary differential equations that are solved numerically using finite difference techniques.

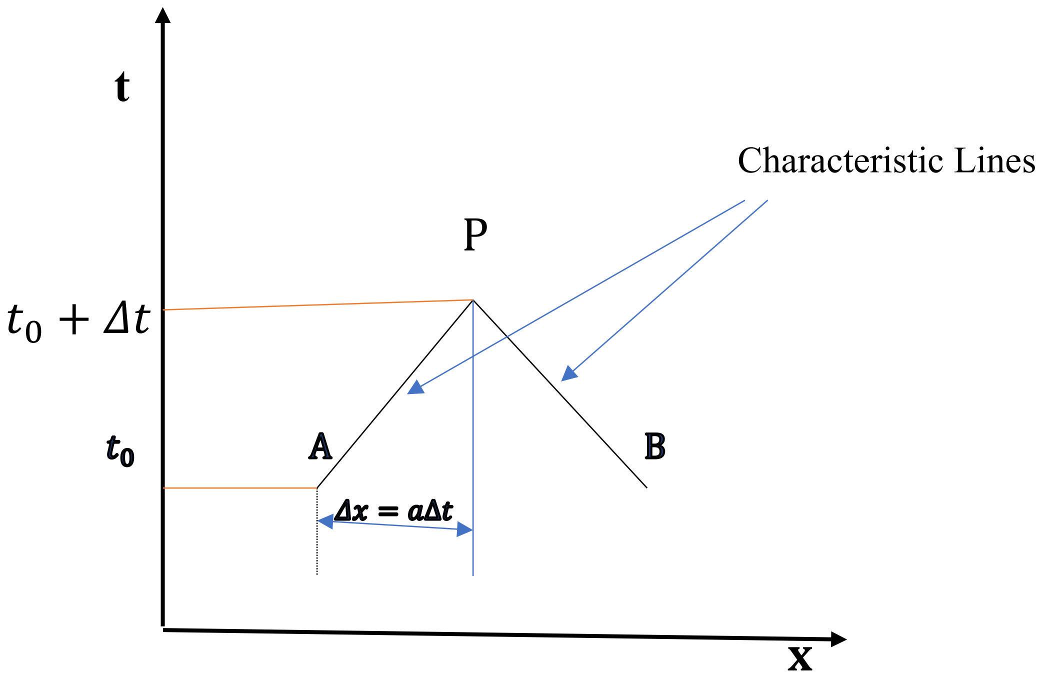


Fig 2- Characteristic Line in x-t plane

A hydraulic transient is generated when the flow momentum of the transported liquid changes due to the rapid operation of the flow control device in the hydraulic system. Mathematically hydraulic transient is analysed by solving the velocity V(x, t) and pressure P(x, t) equations for a well-defined elevation profile of the system, given certain initial and boundary conditions determined by the system flow control operations. In other words, the main goal is to solve a problem with two unknowns, velocity (V) and pressure (P), for the independent variables position (x) and time (t). Alternatively, the equations may be solved for flow (Q) and head (H). The continuity equation and the momentum equation are needed to determine V and P in a one-dimensional flow system. Solving these two equations produces a theoretical result that usually reflects actual system measurements if the data and assumptions used to build the numerical model are valid.

6.1 CHARACTERISTIC EQUATION

Equations describing the transient flow in closed conduit are hyperbolic partial differential equations

CONTINUITY EQUATION: $\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0$

MOMENTUM EQUATION: $\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + RQ|Q| = 0$

Where, R = f / 2DA , a = Wave speed

Using above two equation we get compatibility equation

$$\frac{dQ}{dt} + \frac{gA}{a}\frac{dH}{dx} + RQ|Q| = 0 \quad \text{——— (1) Where } \frac{dx}{dt} = a$$

and

$$\frac{dQ}{dt} - \frac{gA}{a}\frac{dH}{dx} + RQ|Q| = 0 \quad \text{——— (2) Where } \frac{dx}{dt} = -a$$

By imposing the relationship $\frac{dx}{dt} = \pm a$ the independent variable (x) is eliminated and converted the partial difference differential equation(PDE) into ordinary differential equation(ODE) in independent variable ‘t’.$\frac{dx}{dt} = a$

In the x-t plane, $\frac{dx}{dt} = +a$ and $\frac{dx}{dt} = -a$,represent two straight line having slope $\pm a$.

These are called Characteristic lines.

We will now discuss how to solve Equations (1) and (2) multiply these equations by 'dt' and integrate along the characteristic lines AP and BP, after the procedure we get

Along the positive characteristic line AP:

$$(Q_P - Q_A) + \frac{gA}{a}(H_P - H_A) + RQ_A|Q_A|\Delta t = 0$$

Along the positive characteristic line BP:

$$(Q_P - Q_B) - \frac{gA}{a}(H_P - H_B) + RQ_B|Q_B|\Delta t = 0$$

The value of C_p, and C_n, are known and are constant for each time step although they may vary from one time interval to next

$$C_P = Q_A + \frac{gA}{a}H_A + RQ_A|Q_A|\Delta t$$

$$C_n = Q_B + \frac{gA}{a}H_B + RQ_B|Q_B|\Delta t$$

C_a - constant, that depends upon the conduit properties.

$$C_a = \frac{gA}{a}$$

Where the subscripts A, B and P refer to the variables corresponding to points in the x-t plane (Fig 2) These two equations may be written as

Positive Characteristic equation:

$$\boxed{Q_P = C_P - C_a H_P} \text{------------(3)}$$

Negative characteristic equation:

$$\boxed{Q_P = C_n + C_a H_P} \text{-------------(4)}$$

Assume that we know the value of, H and Q at points A and B, and Both these equations have two unknowns, H_p, and Q_p, that we want to determine their values at point 'P' The values of these unknowns can be determined by simultaneously solving these equations, i.e.,

$$Q_p = 0.5(c_p + C_n)$$

7.BOUNDARY CONDTION

The following discussion for the analysis of transient-state condition in a single pipeline (Fig-2) should help you to understand the computational procedure.

The pipeline is divided into a number of reaches. The ends of a reach are called sections, nodes, or grid points. The nodes at the upstream end and at the downstream end of a pipe are called boundary nodes, and the remaining nodes are called the interior nodes. To start the calculations, the piezometric head and discharge at $t = t_o$ are determined at the computational nodes. These are called the initial conditions. Then, by using Eqs (3) and (4), the conditions at the interior nodes at time $t_o + \Delta t$ are computed. At the boundaries, however, we have only one equation: Eq. (4) at the downstream end and Eq. (3) at the upstream end. To determine the second unknown from these equations at the boundary nodes, we need another equation. This additional equation is provided by the condition imposed by the boundary. By solving this equation simultaneously with the positive or negative characteristic equations, we develop the boundary conditions, which are then used to determine the transient conditions at the boundaries. To illustrate this procedure, we will develop in the following section boundary conditions for an opening or closing valve.

we may develop the boundary conditions by solving the positive or negative characteristic equations simultaneously with the condition in posed by the boundary. This condition may be in the form of specifying head, discharge. or a relationship between the head and discharge. For example, head is constant in the case of a constant-level reservoir, flow is always zero at a dead end, and the flow through an orifice is related to the head loss through the orifice. The following simple examples should clarify the development of the boundary conditions. In these derivations, we will use two subscripts to denote variables at different nodes: The first subscript will denote the number of the pipe and the second subscript will refer to the number of the node on that pipe. If a pipe is divided into n reaches, and the first node is numbered as 1. the last node will be n+1.

8.VALVE AT DOWNSTREAM

Unlike the three boundaries where either head or discharges were specified at the boundary,

the condition imposed by the valve boundary is a relationship between the head and discharge

through the valve

Steady state flow through a valve discharging into air can be written as

$$Q_{i,n+1} = C_d A_v \sqrt{2gH_{i,n+1}} \text{-------------} 5$$

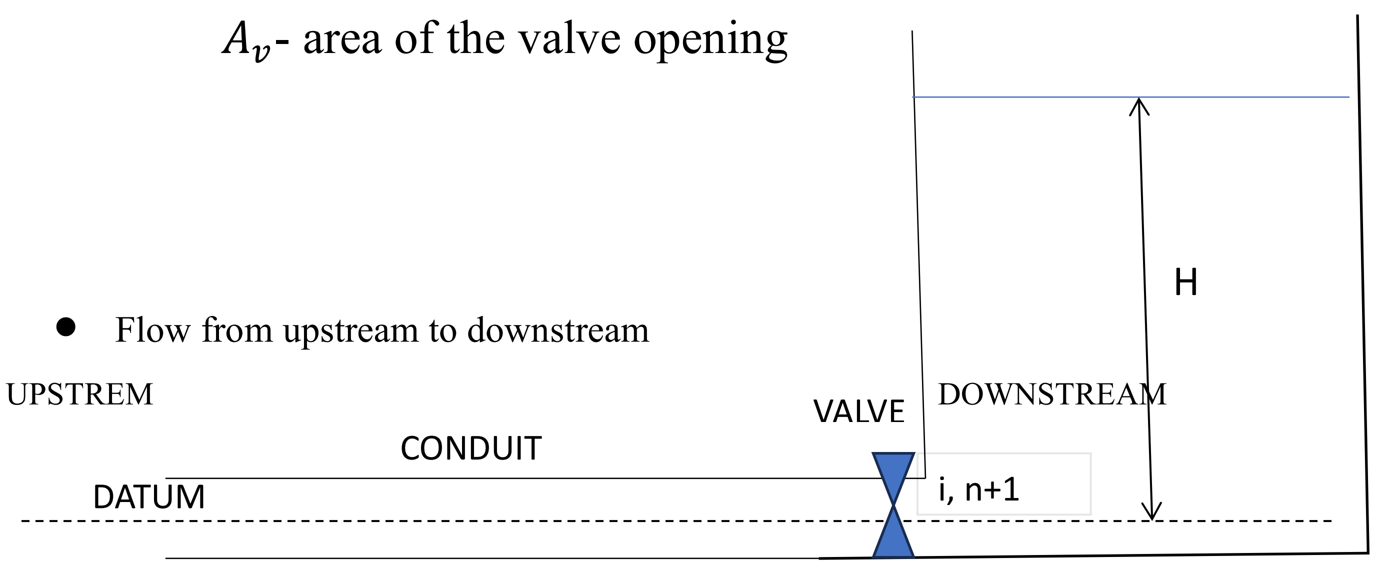
Where 'Q' represents the steady state conditions

C_d coefficient of discharge

$H_{i,n+1}$ Head u/s of the valve

A_v- area of the valve opening

- Flow from upstream to downstream



If we assume that the transient flow through a valve may be described by an equation similar to that for steady flow equation, then

$$Q_{p\ i,n+1} = (C_d A_v)_p \sqrt{2gH_{p\ i,n+1}} \text{-------}6$$

Dividing Equation (6) by (5), in obtained equation squaring both sides

$$Q_p^2 = \frac{(Q\tau)^2}{H} H_p \text{--------------------------------}7$$

Where τ- Represents the variation of discharge coefficient with valve opening.

$$\tau = \frac{(C_d A_v)_p}{(C_d A_v)}$$

Substitution of this Hp into valve equation from the +ve characteristic equation, we get for Q_p,

$$\boxed{Q_{p\ i,n=1} = 0.5\left(-C_v \pm \sqrt{C_v^2 + 4C_{p\ i}C_v}\right)}$$

where $C_v = \frac{(Q\tau)^2}{(C_a H)}$ For an orifice, the opening remains constant.

Therefore, the above equations may be used with, $\tau = 1$ corresponds to a valve opening at which the flow through the valve is Q, under a head of H.

Now H_p can be calculate from positive characteristic Equation.

9. COMPUTER PROGRAM

To calculate the hydraulic transient in pipeline or conduit due to valve closure by the 'PYTHON' Computer program stated as below this code will give varying discharge and varying pressure head after valve closing.

```
import numpy as np
import math
import sympy as sp
import pandas as pd
import matplotlib.pyplot as plt

#Analysis of transient Flow in pipe line

# fluid properties
K = 2 * 10**9  # Pascals
rho = 1000  # kg/m3

# pipe properties
D = 0.4  # m
```

```
E = 2.15 * 10**9  # Pascals
e = 0.01  # m
L = 300  # length of pipe, m
f = 0.05  # Darcy's friction factor
pi = math.pi
g = 9.80655
A = (pi/4)*D*D
R = f/(2*D*A)
a = sp.sqrt((K/rho)/(1+(D*K)/(E*e)))
a = float(a.evalf())  # Convert a to a numerical value

# reservoir properties
H_res = 20  # m
Cd = 0.8
Q_res = Cd * A * sp.sqrt(2*g*H_res)
k_entry = 0.5

# Discretization
n = 10  # no. of sections
del_x = L/n
```

```
del_t = del_x/a

# initial conditions
H_0 = []
Q_0 = []
for node in range(1, 12):
    H_0.append(H_res)
    Q_0.append(Q_res)

H_matrix = np.array([H_0])
Q_matrix = np.array([Q_0])

j = 1
while j*del_t <= (12*L)/a:
    H_values = []
    Q_values = []
    for i in range(1, 12):
        # Characteristic equations
        Ca = (g*A)/a
        if i-2 >= 0:
```

```
        Cp = Q_matrix[j-1, i-2] + Ca*H_matrix[j-1, i-2] -
R*Q_matrix[j-1, i-2]*abs(Q_matrix[j-1, i-2])*del_t
    else:
        Cp = None
    try:
        Cn = Q_matrix[j-1, i] - Ca*H_matrix[j-1, i] -
R*Q_matrix[j-1, i]*abs(Q_matrix[j-1, i])*del_t
    except IndexError:
        Cn = None

    # reservoir boundary
    if i == 1:
        k1 = Ca*(1 + k_entry)/(2*g*A*A)
        Qp = (-1 + sp.sqrt(1 + 4*k1*(Cn +
Ca*H_res)))/(2*k1)
        Hp = (Qp - Cn)/Ca
        H_values.append(Hp)
        Q_values.append(Qp)

    # valve boundary
```

```python
    elif i == n+1:
        Cv = 0
        Qp = 0.5*(-Cv + sp.sqrt((Cv**2) + (4*Cp*Cv)))
        Hp = (1/Ca)*(Cp - Qp)
        H_values.append(Hp)
        Q_values.append(Qp)

    # Method of characteristic
    else:
        Qp = 0.5*(Cp + Cn)
        Hp = (Cp - Cn)/(2*Ca)
        H_values.append(Hp)
        Q_values.append(Qp)

H_values = np.array(H_values)
Q_values = np.array(Q_values)

H_matrix = np.vstack([H_matrix, H_values])
Q_matrix = np.vstack([Q_matrix, Q_values])
```

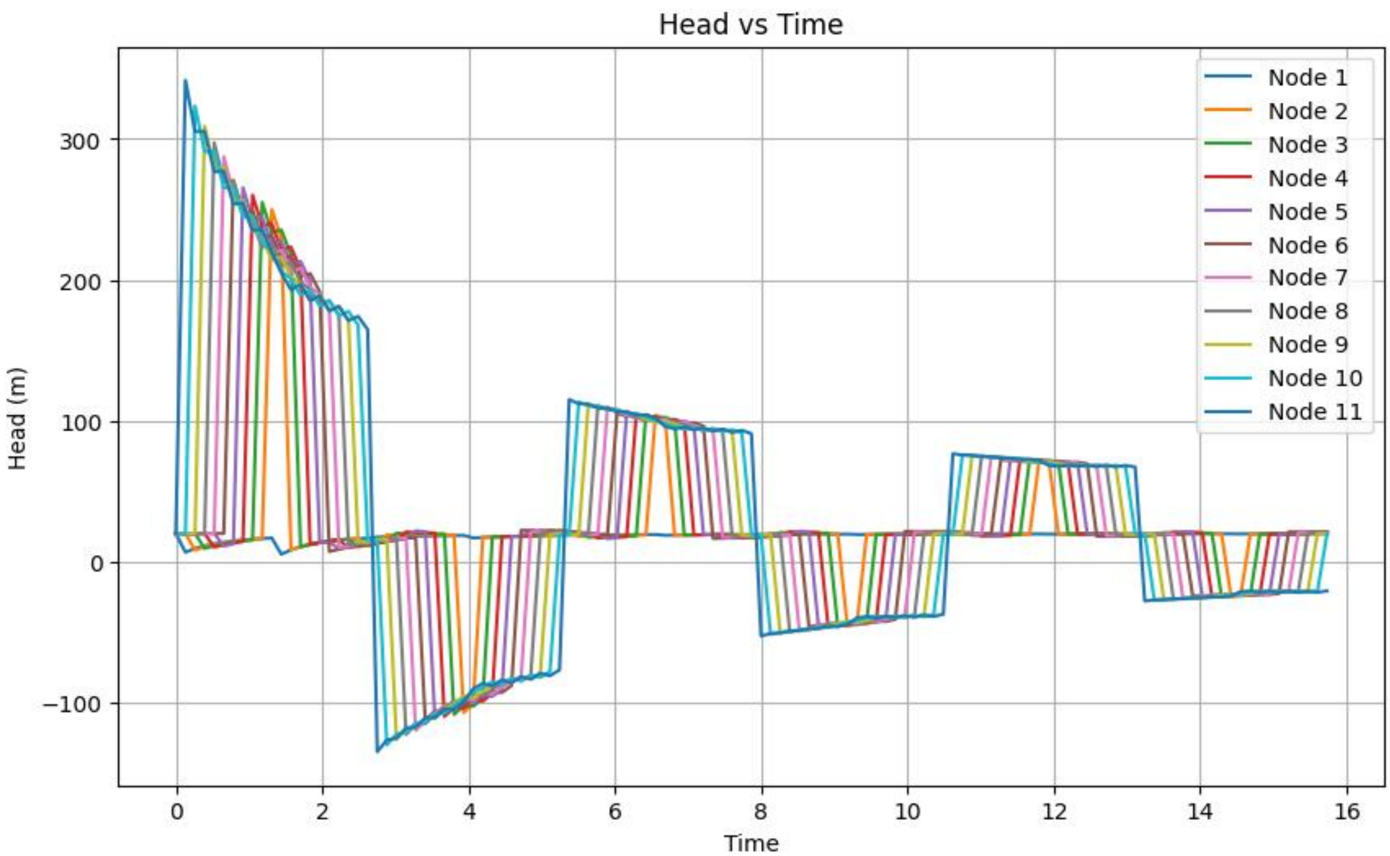
```
    j += 1

H_final = pd.DataFrame(H_matrix)
Q_final = pd.DataFrame(Q_matrix)




# Assuming you have calculated time values somehow,
e.g., using np.linspace()
time_values = np.linspace(0, (12*L)/a, H_final.shape[0])

# Plotting head vs time
plt.figure(figsize=(10, 6))
for i in range(H_final.shape[1]):
    plt.plot(time_values, H_final[i], label=f'Node {i+1}')
plt.title('Head vs Time')
plt.xlabel('Time')
plt.ylabel('Head (m)')
plt.legend()
plt.grid(True)
```

```
plt.show()

# Plotting discharge vs time
plt.figure(figsize=(10, 6))
for i in range(Q_final.shape[1]):
    plt.plot(time_values, Q_final[i], label=f'Node {i+1}')
plt.title('Discharge vs Time')
plt.xlabel('Time')
plt.ylabel('Discharge (m^3/s)')
plt.legend()
plt.grid(True)
plt.show()
import matplotlib.pyplot as plt

# Extract data for the 8th node
node_index = 7  # 8th node index is 7 (zero-based
indexing)
H_node_8 = H_final[node_index]
Q_node_8 = Q_final[node_index]
```

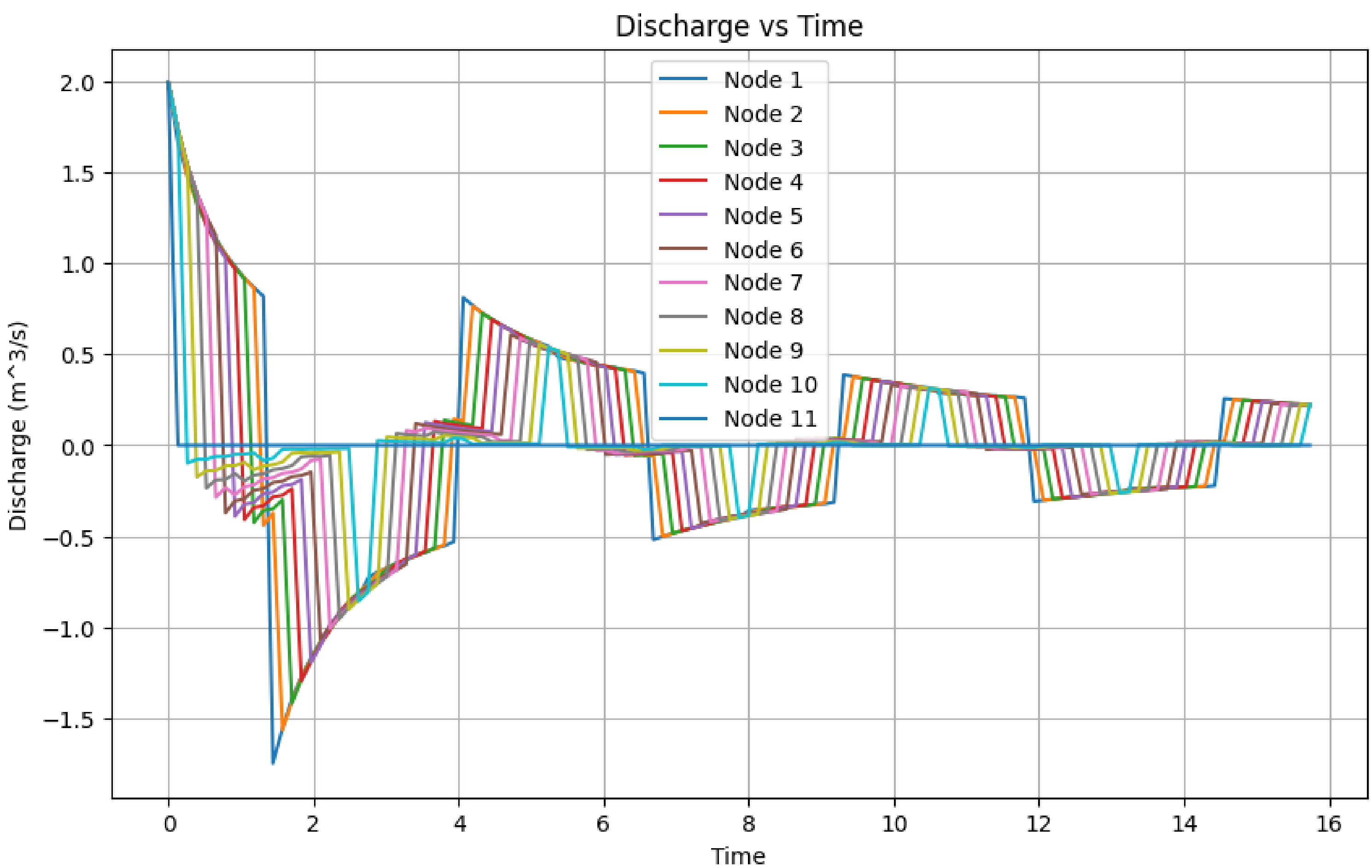
```
# Plotting head vs time for the 8th node
plt.figure(figsize=(10, 6))
plt.plot(time_values, H_node_8, label='Node 8')
plt.title('Head vs Time (Node 8)')
plt.xlabel('Time')
plt.ylabel('Head (m)')
plt.legend()
plt.grid(True)
plt.show()

# Plotting discharge vs time for the 8th node
plt.figure(figsize=(10, 6))
plt.plot(time_values, Q_node_8, label='Node 8')
plt.title('Discharge vs Time (Node 8)')
plt.xlabel('Time')
plt.ylabel('Discharge (m^3/s)')
plt.legend()
plt.grid(True)
plt.show()
```

10. RESULT AND OUTPUT

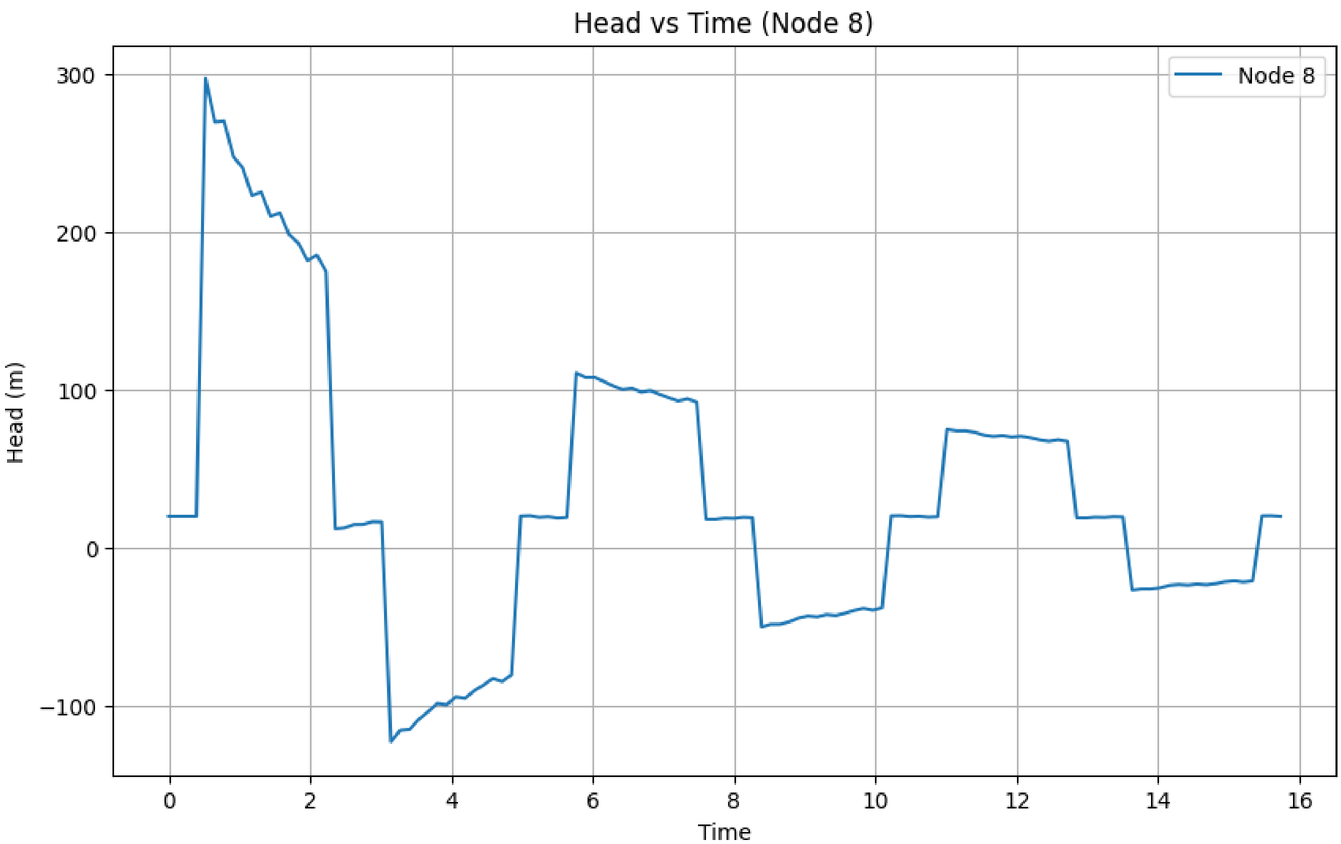
10.1 Graph head vs time for all node



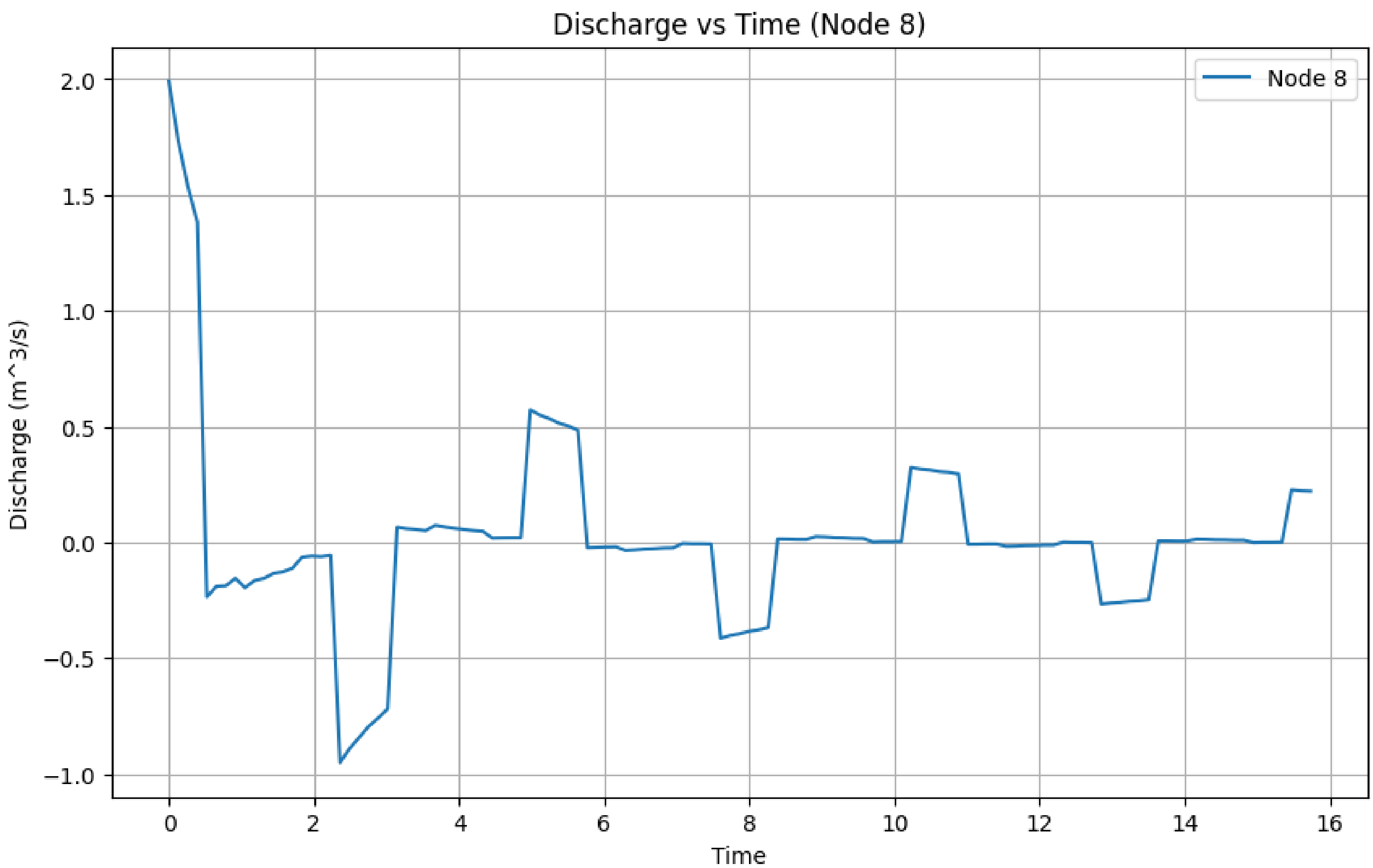
10.2 Graph Discharge vs time for all node



10.3 Graph head vs time for the 8th node



10.4 Graph discharge vs time for the 8th node



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