AAiT

Addis Ababa Institute of Technology

School of Civil and Environmental Engineering

Water Distribution Modelling

Lecture By Fiseha Behulu (PhD)

Lecture-5:
Water Hammer Theory

<u>Prepared By</u>

Fiseha Behulu, AAiT

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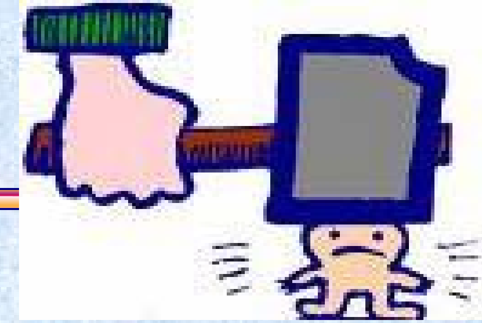
Contents of the Course

1. Components of Water Supply
2. Basic Principles of Pipe Flow (Hydraulics)
3. The Modeling Theory
4. Model Calibration
5. Optimization in WDS
6. **Water Hammer Theory**
7. Water Supply Project Design (Application of Tools)

Water Hammer

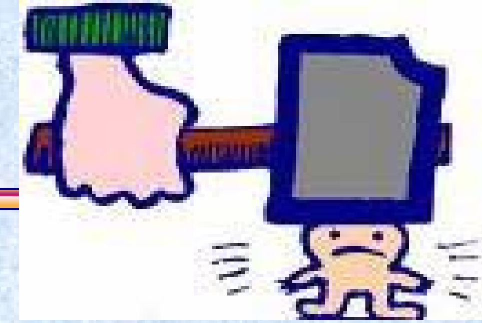
- Basic phenomenon
- Modelling
- Mitigating measures

Water Hammer - problems



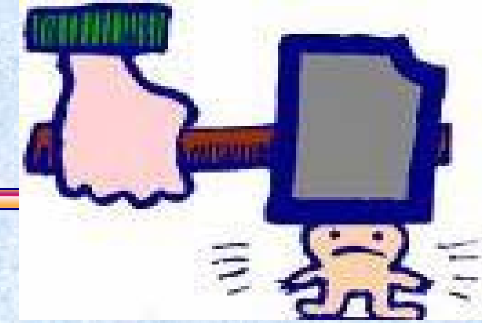
- Learning objective
  - Understand the transient phenomenon in water distribution system design.
  - Identify system which need transient analysis
  - Avoid dangerous and costly blunders in designing pipe line system
  - Evaluate corrective measures for problems
  - Explain the influence of specific hardware on water hammer

Water Hammer - problems



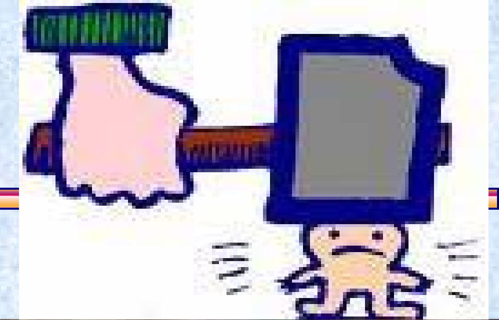
Pipe burst during commissioning

Water Hammer - problems

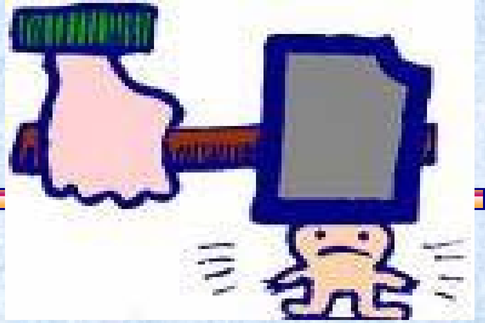


Check valve closure forms severe motion of pipes

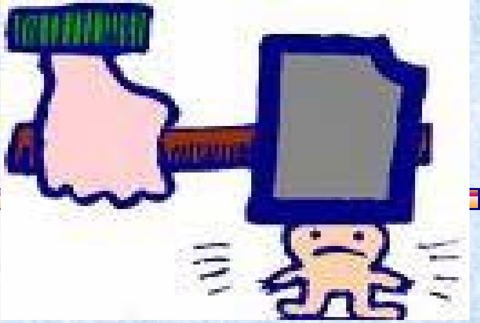
Water Hammer - problems



Water Hammer - problems

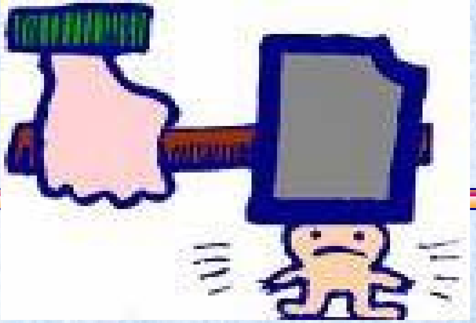


Water Hammer - Definition



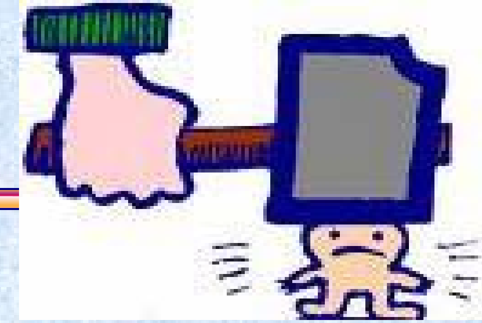
- Momentary increase in pressure , which occurs in a water system when there is a sudden change of direction or velocity of water (Lahlou,2003).

Water Hammer – the origin



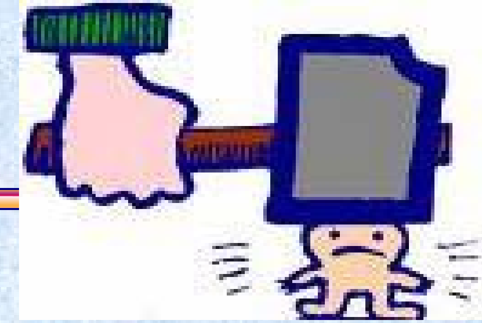
- Changes in the fundamental flow values at any instant.
  - Pressure
  - Flow
- Exchange of kinetic and potential energy
  - Velocity changes <=> pressure changes

Water Hammer- concept



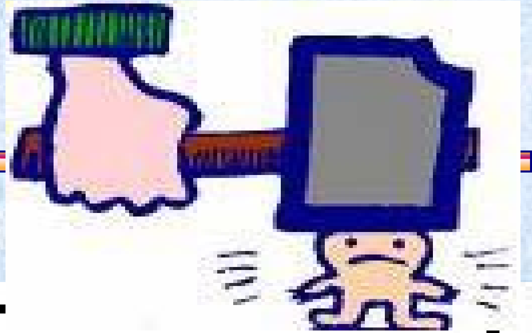
- Changes propagate through the pipe system as high speed waves
  - Water hammer
  - Surges
    - But surge is a lesser form of water hammer. A slow motion of mass oscillation of water caused by internal pressure fluctuation in the system

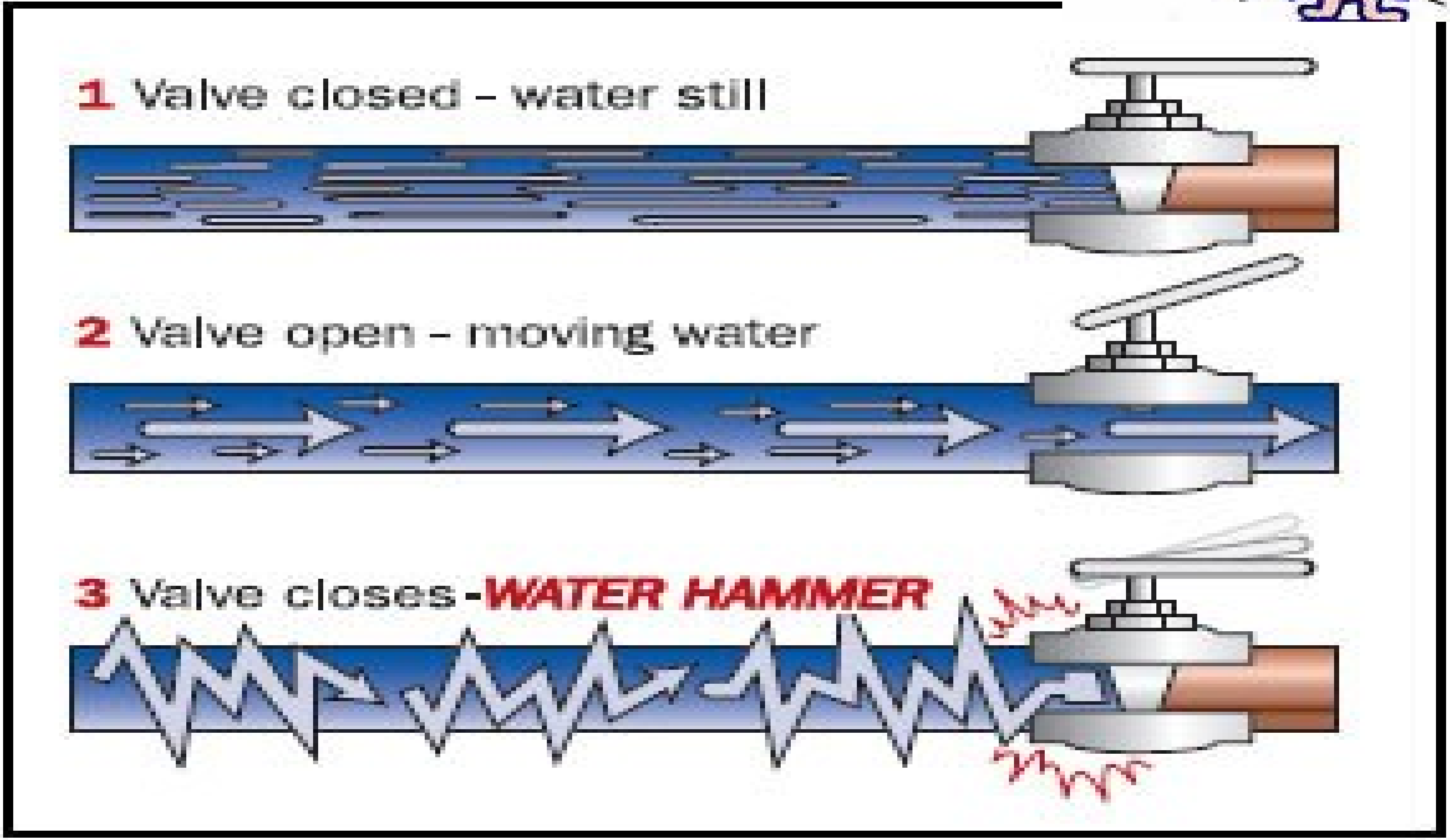
Water Hammer- concept



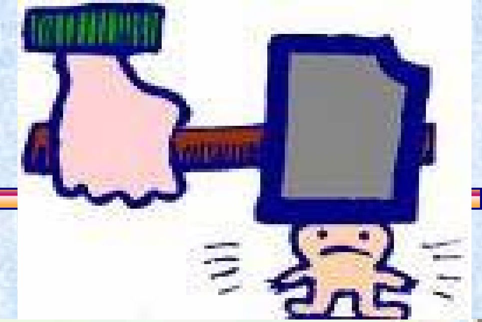
- Evaluating a hydraulic transient involves determining the values during the time interval T_t *of the functions* $V(x, t)$ *and* $p(x, t)$ *that result from a flow control operation performed* in a time interval T_M.

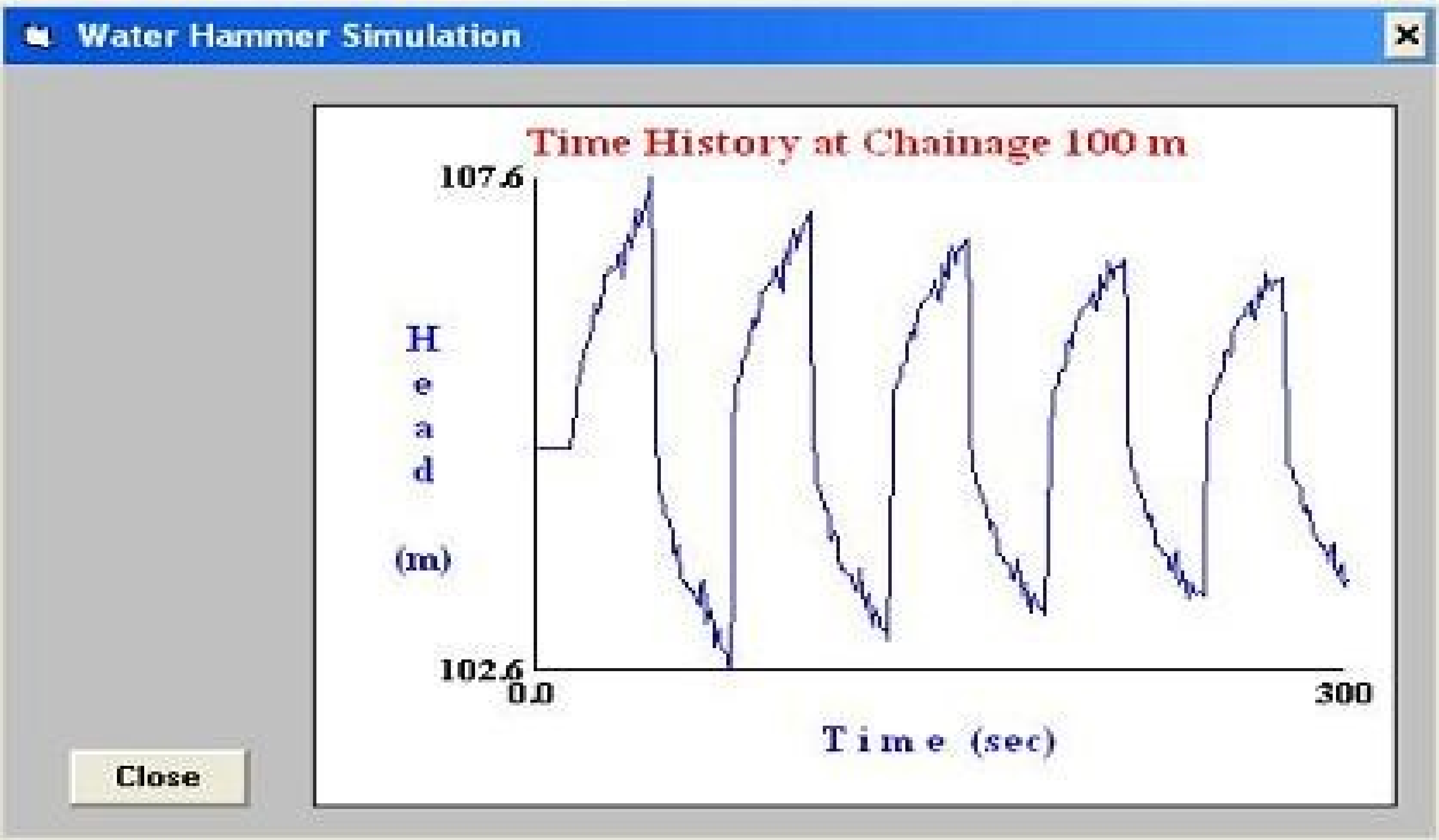
Water Hammer –
Physical Principles

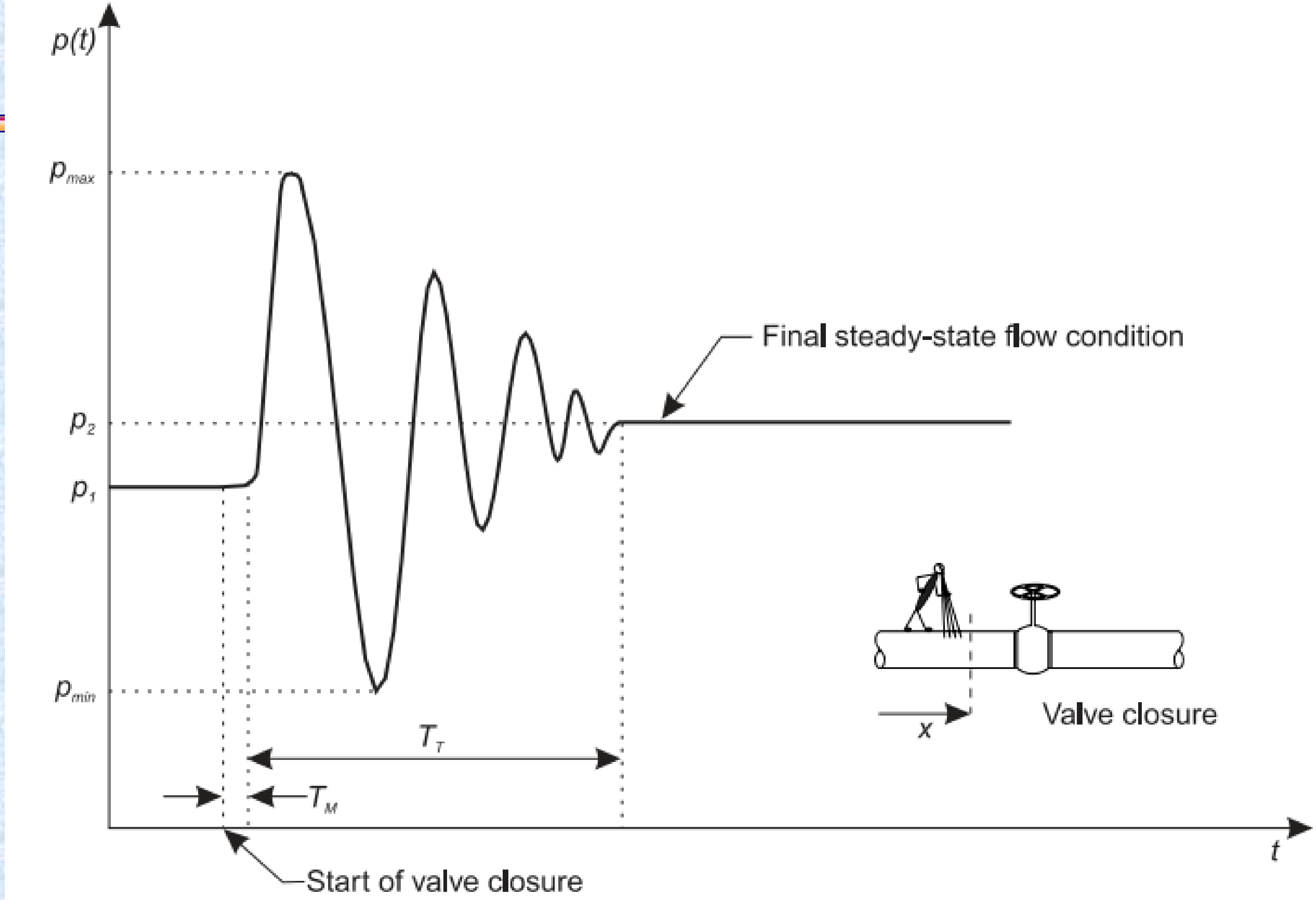




Water Hammer - Phenomenon

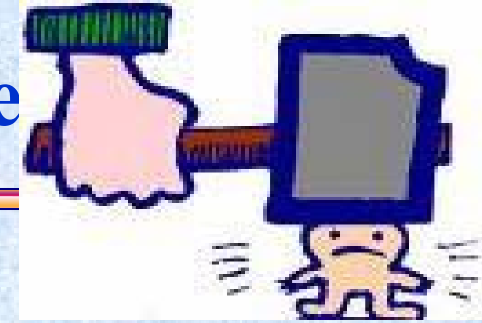






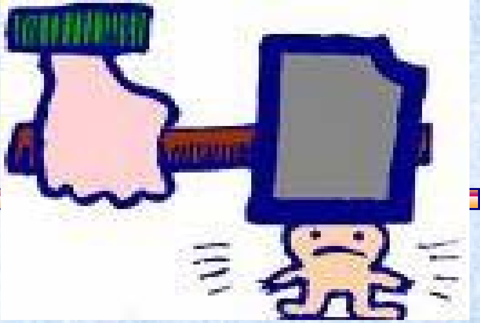
Hydraulic Transient at Position x in the system (Walski, Page 575)

Water Hammer- conce



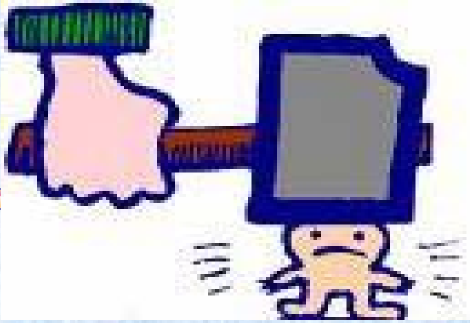
- Phenomenon reflections
  - High pressure
  - Low pressure (cavitations)

Water Hammer- Cavitation



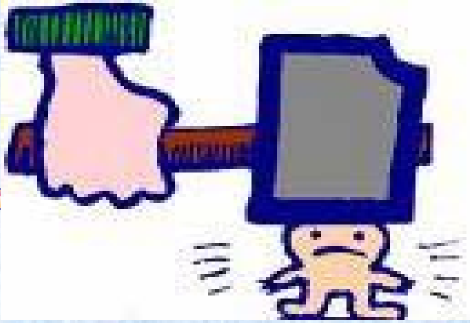
- Pressure below a certain level
- Variants
  - Gaseous cavitation
    - Dissolved gases (oxygen, carbon dioxide)
    - Small gas pocket form in the pipe
  - Vaporous cavitation (column separation)
    - Pressure below the vapor pressure of the liquid

Water Hammer- Cavitation



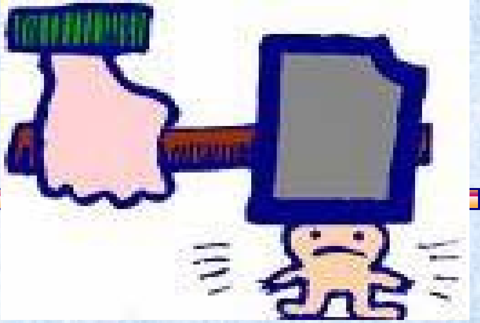
- Vaporous cavitation (column separation)
  - Vaporization of the water itself
  - Vapor pocket formation and collapse
  - Result in pipe flexure

Significance



If transient pressures are excessively high, the pressure rating of the pipeline may be exceeded, causing failure through pipe or joint rupture, or bend or elbow movement. Excessive negative pressures can cause a pipeline to collapse or groundwater to be

Water Hammer - problems



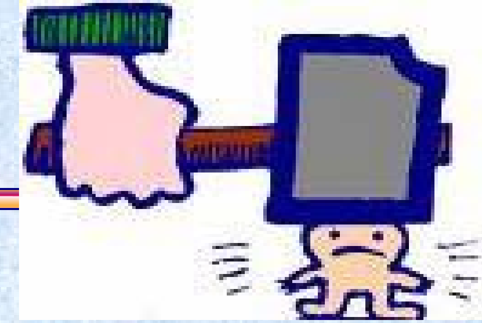
- Damage to
  - Pipes
  - Fittings and valves

→ **System failure**

- Water quality problems

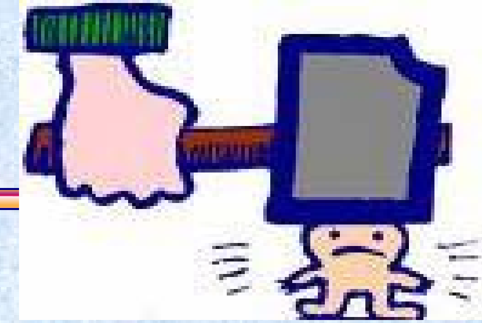

HOTEL

Water Hammer - causes



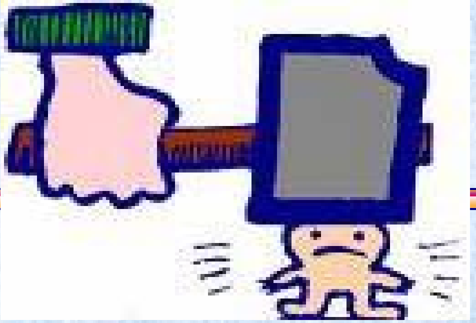
- System design variable's fluctuation
  - Pressure and flow change
  - Demand fluctuations, and
  - Tank level changes

Water Hammer - causes

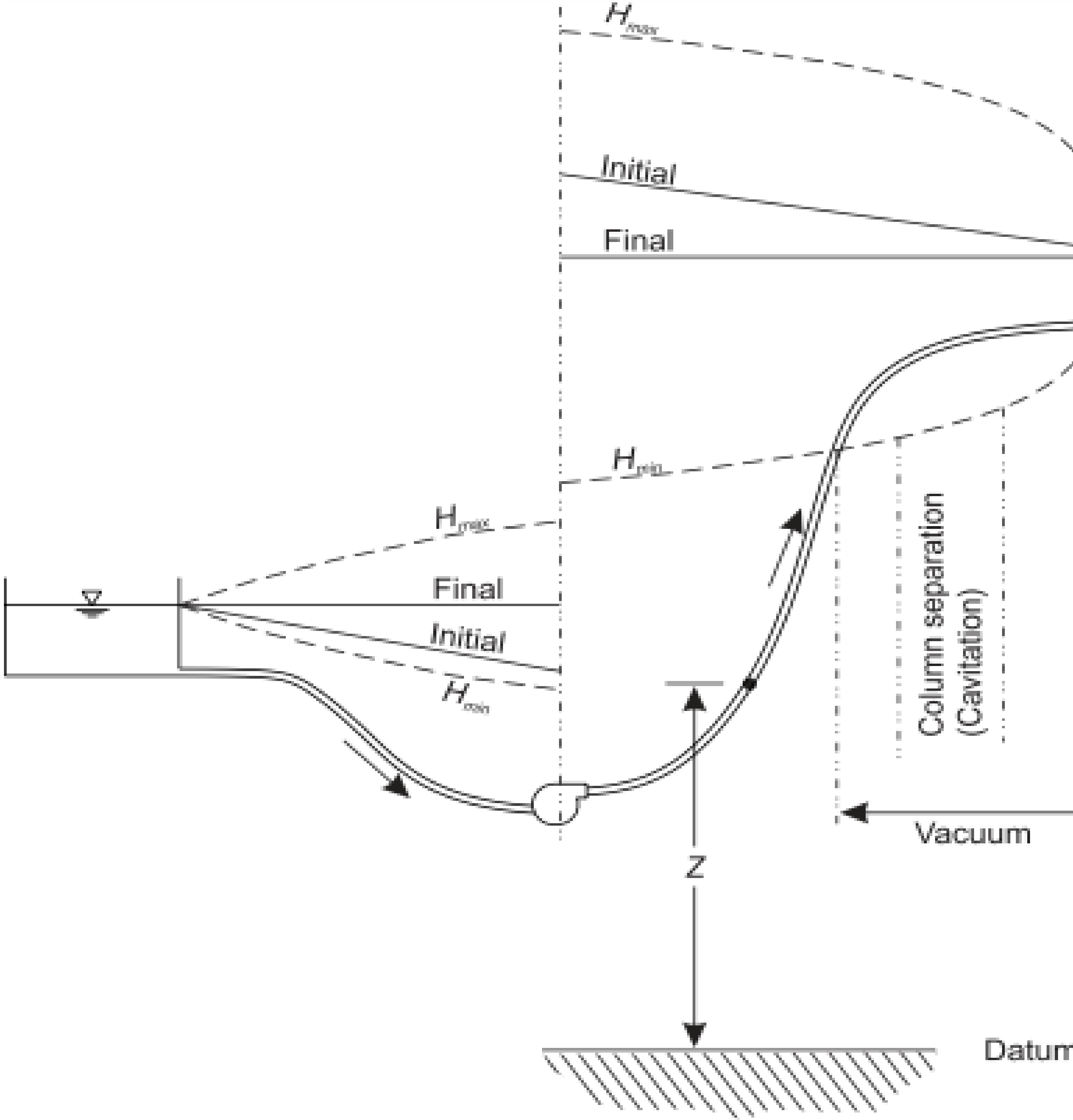


- Unforeseen events
  - Power outage
  - Equipment malfunction
- Operational issues
  - Valve closure
- Entrained air and temperature changes

Water Hammer Evaluation

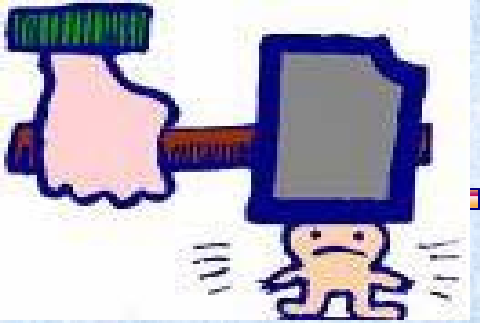


- Evaluating a system for potential transient impacts involves determining the values of head (H_{max} *and* H_{min}) *at incremental positions in the system. These head values correspond* to the minimum and maximum pressures of the transient pressure wave, depicted as p_{max} *and* p_{min}



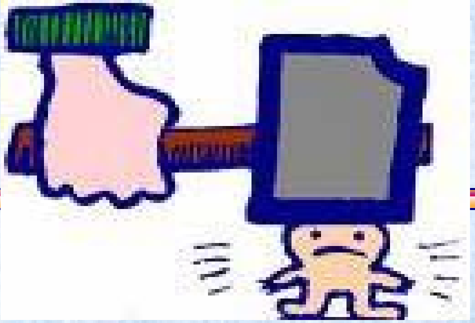
H_{max}
Initial
Final
H_{min}
H_{max}
Final
Initial
H_{min}
Column separation (Cavitation)
Vacuum
Z
Datum

Water Hammer - physics



- Thrust
  - V(x,t)
  - P(x,t)
  - Alternatively for Q and H
- A problem of two unknowns
- Equations
  - Continuity equation
  - Momentum equations

Water Hammer – physical principles

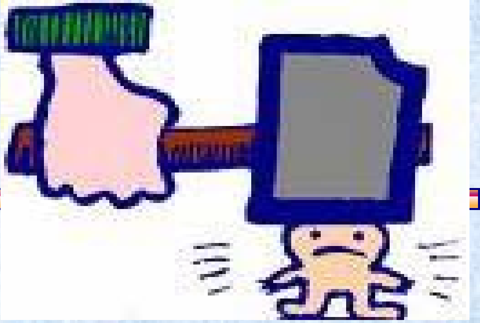


- Two modes of analysis

    - Rigid model

    - Elastic model

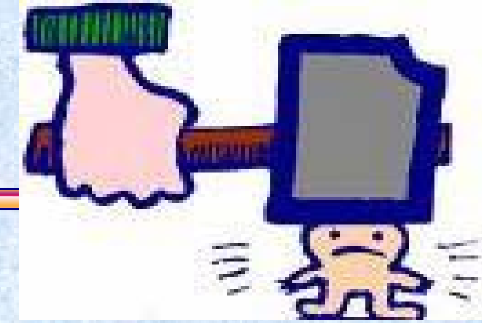
Water Hammer – Rigid Model



- Rigid models
  - Assumptions
    - – pipeline not deformable
    - - liquid incompressible
  - Liquid travel mode – mass oscillation

Flow control operations affect only inertial and frictional aspects

Water Hammer – Rigid Model



- Basic rigid model

$$H_1 - H_2 = \frac{fL}{2gDA^2}|Q|Q + \frac{L}{gA}\frac{dQ}{dt}$$

where

H_1 = total head at position 1 in a pipeline (ft, m)

H_2 = total head at position 2 in a pipeline (ft, m)

f = Darcy-Weisbach friction factor

L = length of pipe between positions 1 and 2 (ft, m)

g = gravitational acceleration constant (ft/s^2, m/s^2)

D = diameter (ft, m)

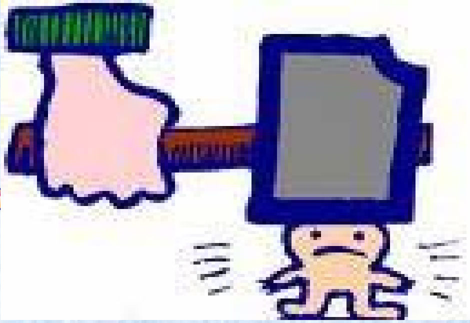
A = area (ft^2, m^2)

Q = flow (cfs, m^3/s)

dQ/dt = derivative of Q with respect to time

Steady state -Darcy Weisbach Otherwise Three unknowns

Water Hammer – physical principles



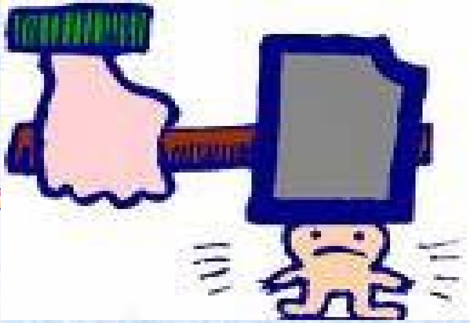
- Then three unknowns need to be determined:
  - *H1(t)* (the upstream head),
  - *H2(t) (the downstream head), and*
  - *Q(t) (the instantaneous flow in* the conduit).

- To determine these unknowns, the engineer must know the boundary conditions at both ends of the pipeline.

Water Hammer – Rigid Model

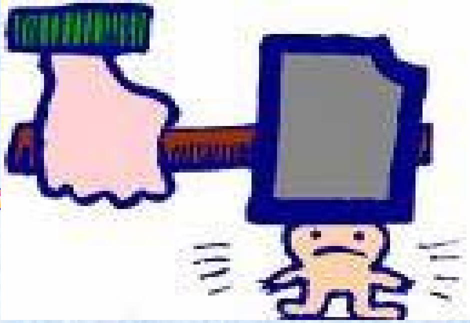
- Limitations
  - Limited in its interpretations of wave propagation caused by flow control operations.
  - Not applicable to rapid changes in flow
- Surge analysis
  - Head changes occur slowly
  - Are minor

Elastic Model -



- For short closing interval – Elastic Model
  - Assumptions
    - Liquid compressible
    - Material elasticity
  - Wave propagation phenomenon
  - Wave speed
    - Elasticity of pipeline and fluid

Elastic Model -



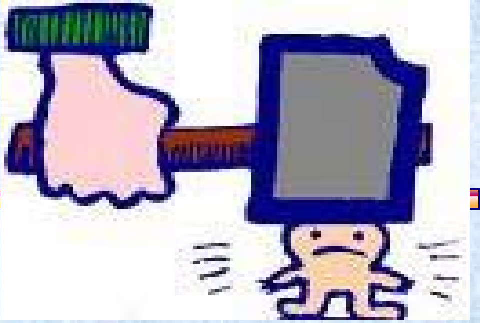
- Elasticity of medium (liquid)
  - Elasticity coefficient

Elastic Model –

Force

Deformation

Elastic Model –



$$E_v = -\frac{dp}{dV/V} = \frac{dp}{(d\rho)/\rho} \qquad (13.2)$$

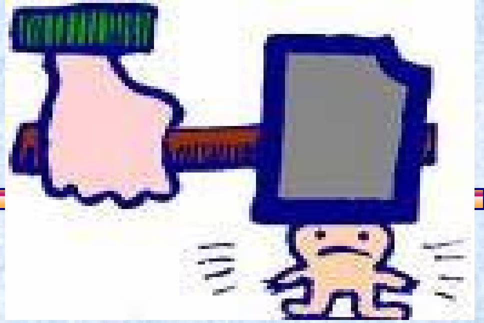
where E_v = volumetric modulus of elasticity (M/LT^2)

dp = static pressure rise (M/LT^2)

dV/V = incremental change in liquid volume with respect to initial volume

$d\rho/\rho$ = incremental change in liquid density with respect to initial density

Elastic Model



■ **Example – Computing Modulus of Elasticity for a Fluid.** Assume that a 0.26-gal (1-liter) volume of water at ambient temperature with a density of 1.94 slugs/ft^3 (1,000 kg/m^3) is subjected to a pressure of approximately 290 psi (20 bar). In this case, the volume would decrease by approximately 0.055 in^3 (0.9 cm^3), or by 0.09%. Compute the modulus of elasticity for water.

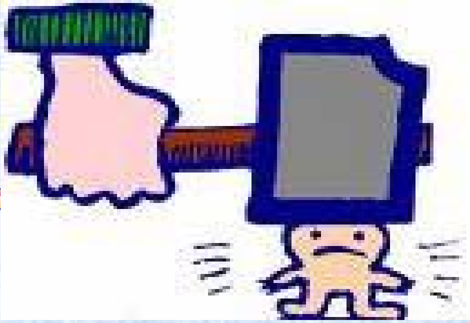
Using Equation 13.2, the modulus of elasticity can be computed as

$$E_v = -290 \text{ psi}/-0.0009 = 3.2 \times 105 \text{ psi}$$

or

$$E_v = -20 \text{ bars}/-0.0009 = 2.2 \times 104 \text{ bars} = 2.2 \times 109 \text{ Pa} = 2.2 \text{ GPa}$$

Elastic Model



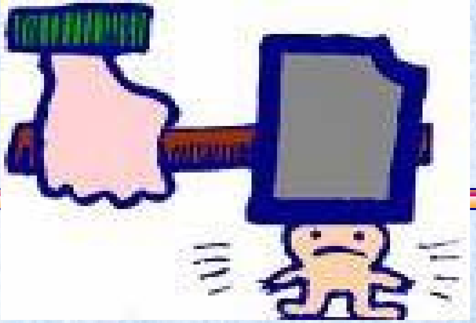
A relationship between a liquid's modulus of elasticity and density yields its characteristic wave celerity, as shown in Equation 13.3.

$$a = \sqrt{\frac{E_v}{\rho}} = \sqrt{\frac{dp}{d\rho}}$$

where a = characteristic wave celerity of the liquid (L/T)

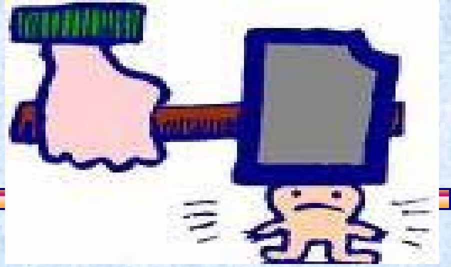
Case - Rigid pipe system

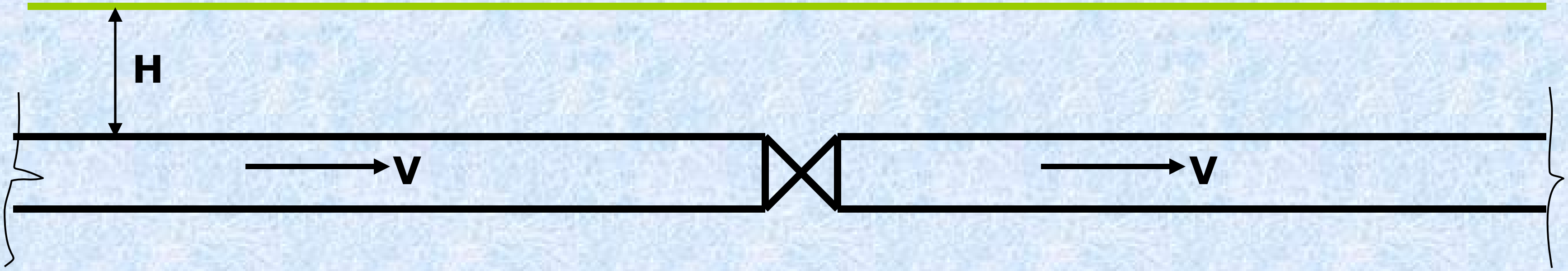
Elastic Model -

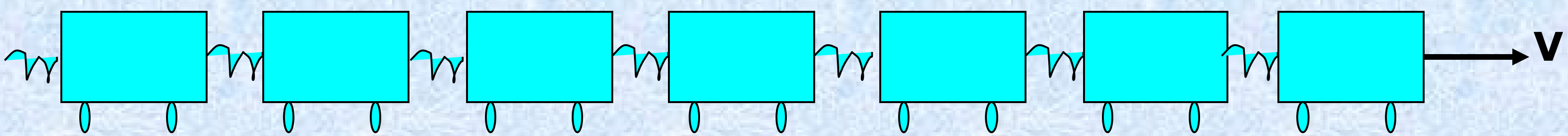


Medium	Wave Speed (a) – m/s
Water	1438
Air	340
Water (1% free air)	125

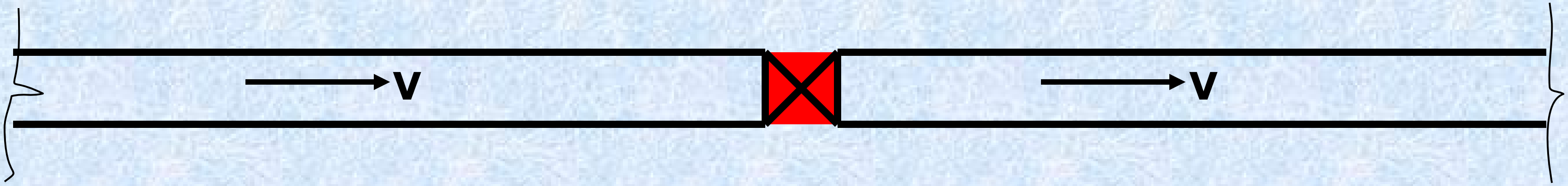
Water Hammer - physical principles

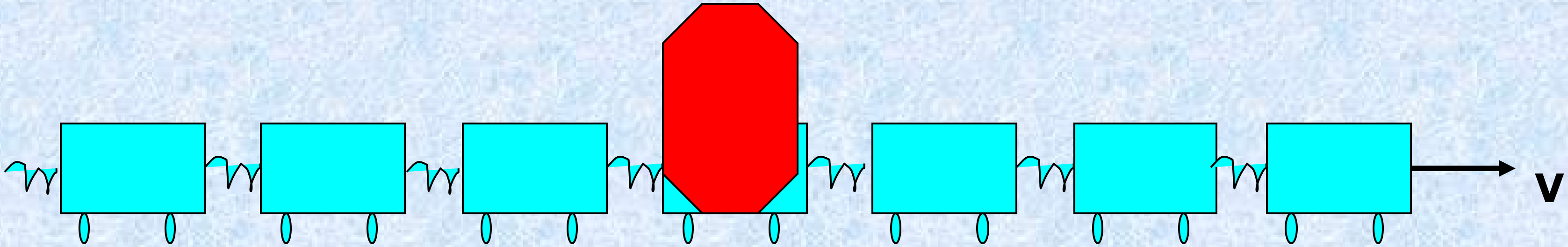




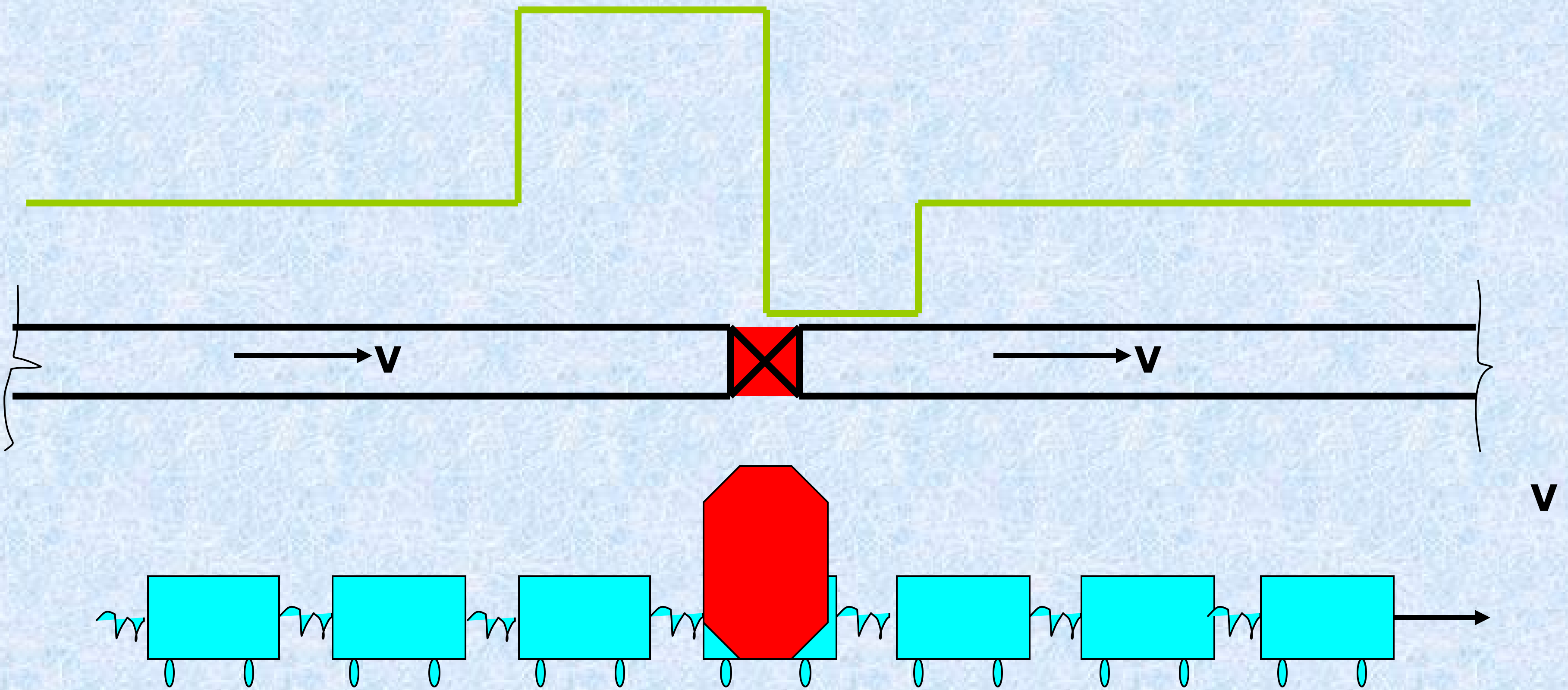


Water Hammer - physical principles

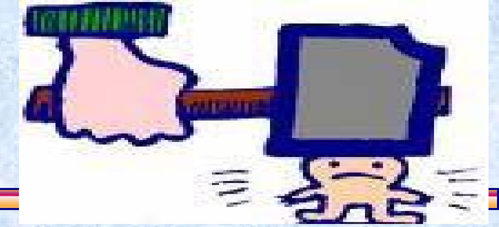




Water Hammer - physical principles



Water Hammer
- physical principles



- Closure - abrupt pressure change

$$\Delta x = at \qquad (1.5)$$

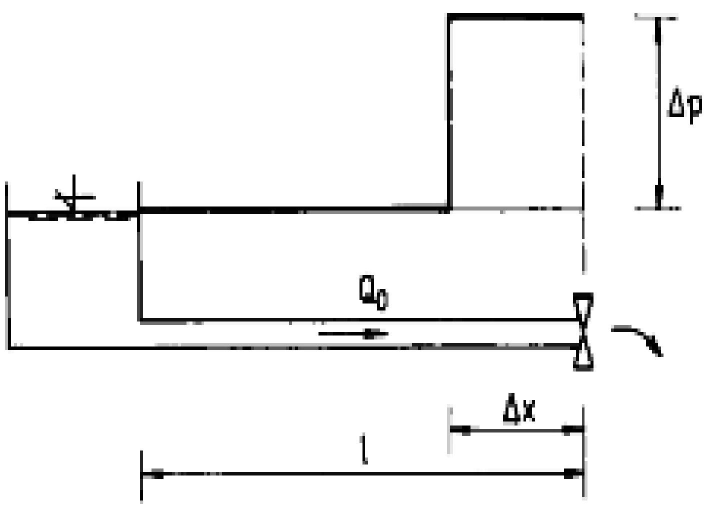
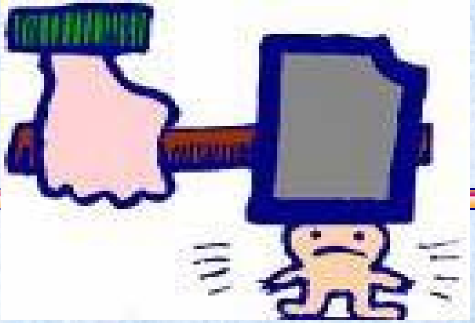
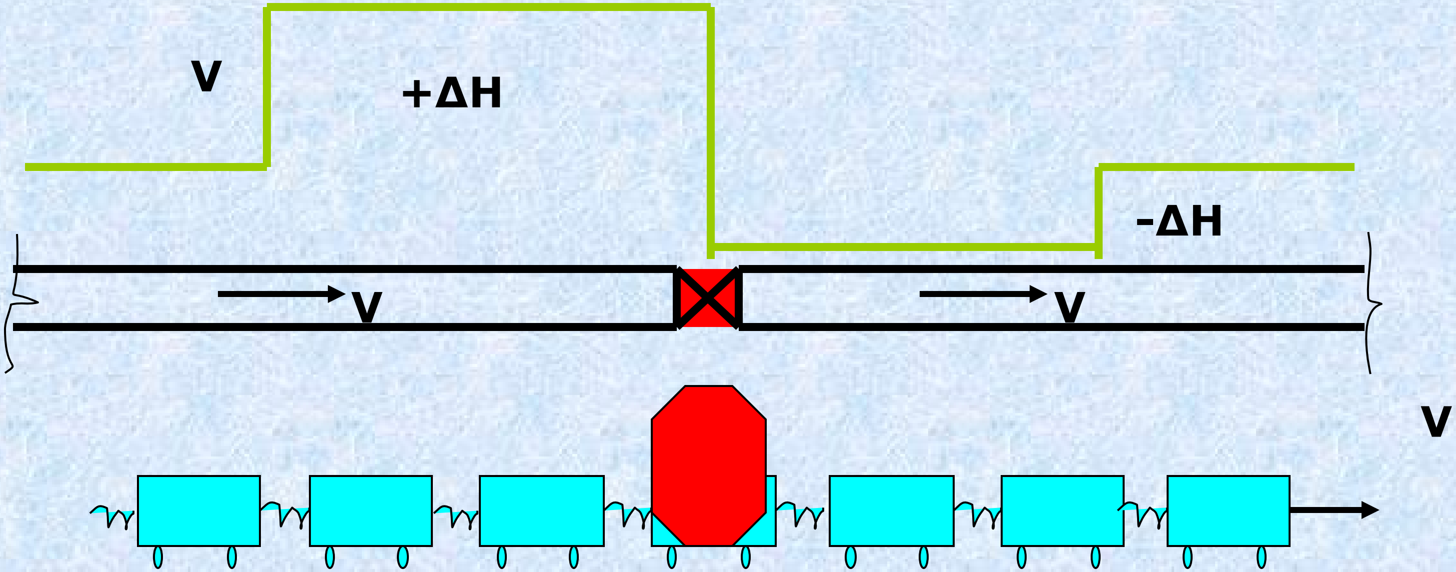


Fig. 1.3 Outflow of a compressible liquid from a reservoir through a pipe-line and an abrupt closing of the pipe-line.

Water Hammer
- physical principles



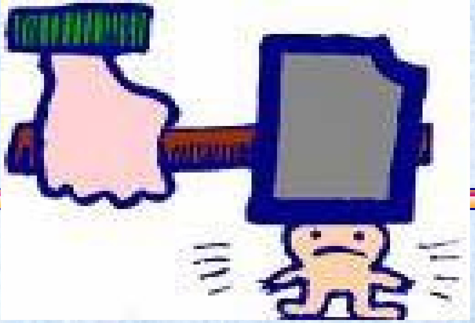


-Over pressure and negative pressure waves

- Head and velocity related

- pressure waves travel through system

Equations



$$\Delta p = -\rho a \Delta V \text{ or } \Delta H = -\frac{a}{g}\Delta V$$

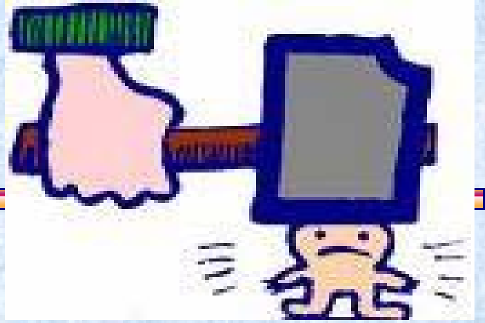
where

Δp	=	change in pressure (psi, Pa)
ρ	=	fluid density (slugs/ft^3, kg/m^3)
a	=	characteristic wave celerity of the fluid (ft/s, m/s)
ΔV	=	change in fluid velocity (ft/s, m/s)
ΔH	=	change in head (ft, m)

Water Hammer- physical principles

a	ρ	ΔV	ΔP
980	1000	0.1	98000
980	1000	0.2	196000
980	1000	0.3	294000
980	1000	0.4	392000
980	1000	0.5	490000
980	1000	0.6	588000
980	1000	0.7	686000
980	1000	0.8	784000
980	1000	0.9	882000
980	1000	1	980000

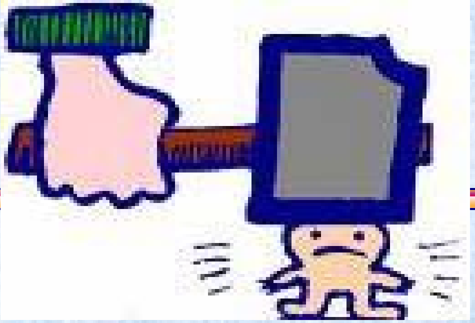
Water Hammer- physical principles



Water Hammer- physical principles

Approximate Conversions Between common Pressure Units						
Pressure Class	**PN**	**Bar**	**Meters head**	**MPa**	**kPa**	**Psi**
A	3	3	30	0.3	300	45
B	6	6	60	0.6	600	90
C	9	9	90	0.9	900	135
D	12	12	120	1.2	1200	180
E	15	15	150	1.5	1500	225
F	18	18	180	1.8	1800	270
No class Defined	10	10	100	1	1000	150
No class Defined	16	16	160	1.6	1600	240
No class Defined	20	20	200	2	2000	300
No class Defined	25	25	250	2.5	2500	375

Water Hammer- Demarcation

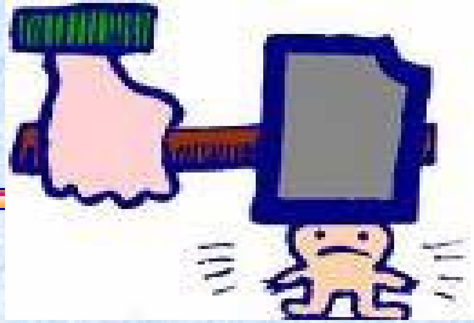


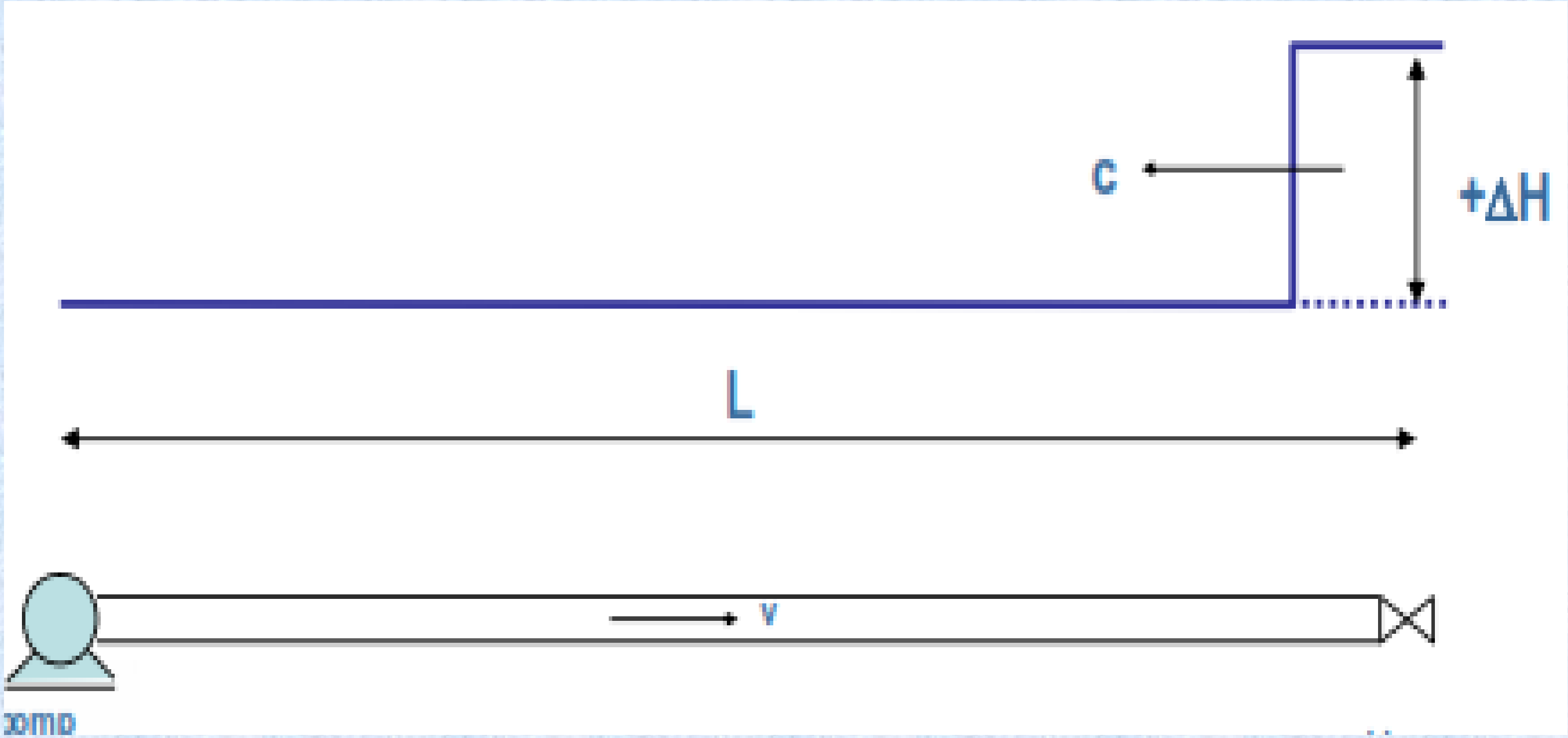
- Characteristics Time

  http://www.acs.psu.edu/drussell/Demos/reflect/reflect.html

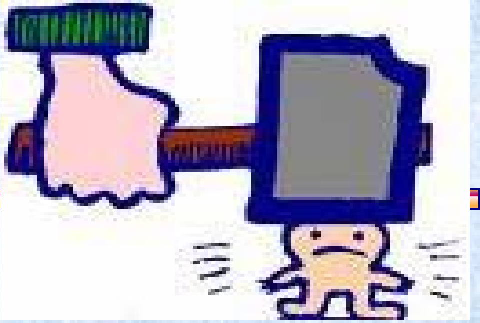
  - **Time for a complete cycle of wave**
  - **Defines the water hammer phenomenon definition**

Water Hammer- Demarcation





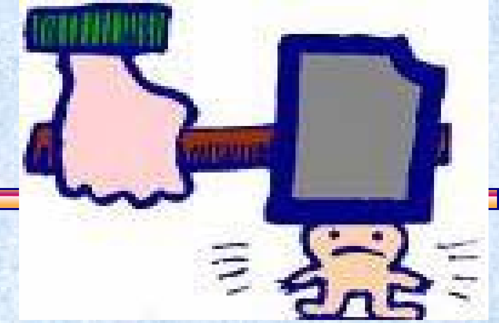
Water Hammer- Demarcation



Classification of flow control operations based on system characteristic time

Operation Time	Operation Classification
$T_M = 0$	Instantaneous
$T_M \leq 2L/a$	Rapid
$T_M > 2L/a$	Gradual
$T_M \gg 2L/a$	Slow

Water Hammer- phenomenon



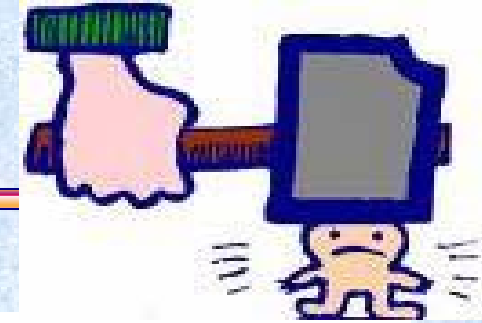
a) At time $0 < t < L/a$, the wave front is moving toward the reservoir. To the right of the front, the water has stopped and the pressure has increased. To the left of the front, the water does not yet "know" that the valve was shut, so it continues to move to the right at the initial head.

b) At time $t = L/a$, the wave front has reached the reservoir and all the water in the pipe has stopped and is compressed. However, the head in the pipe is above the water level in the reservoir. This difference in head must be relieved, so the water begins to move to the reservoir.

c) At time $L/a < t < 2L/a$, the wave front moves toward the valve, and water to the left of the front moves toward the reservoir. Water to the right of the front is motionless and is compressed.

d) At time $t = 2L/a$, the wave front has reached the valve and water is moving away from the valve toward the reservoir. Of course, the water cannot continue to move away from a dead end, so another wave cycle begins.

Water Hammer- phenomenon



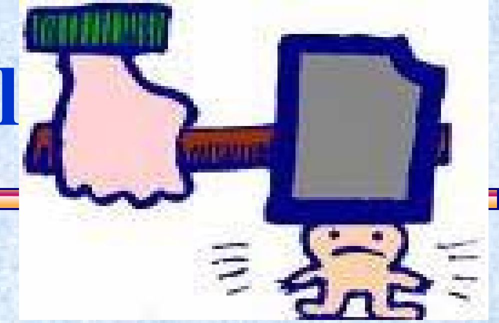
e) At time $2L/a < t < 3L/a$, the wave front is moving away from the valve. To the right of the front, pressures are below static pressure and velocity is zero. To the left, velocity continues in the direction of the reservoir, but the pressure is static.

f) At time $t = 3L/a$, the wave has again reached the reservoir. However, the head in the pipe is below the water level in the reservoir and the water is at a low density. Another wave cycle must start.

g) At time $3L/a < t < 4L/a$, the wave is once again moving back toward the valve. This time, the pressure to the left is at the static value and water is moving into the pipe. To the right, velocity is zero and the pressure is below static.

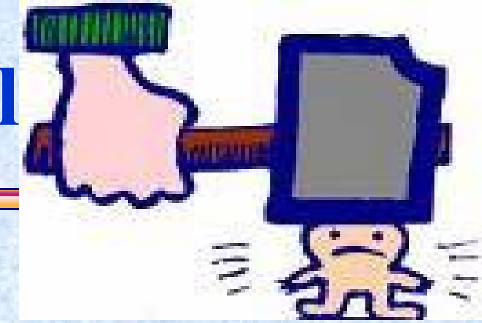
h) At time $t = 4L/a$, the wave has reached the closed valve again and conditions are the same as they were at $t = 0$. The wave will start again and would continue indefinitely if not for friction and other energy dissipation mechanisms that will eventually dampen the wave.

Water Hammer – Elastic Model



- Boundary conditions
  - Changes in valve settings, accidental or planned
  - Starting or stopping of pumps
  - Changes in power demand in turbines
  - Action of reciprocating pumps
  - Changing elevation of the reservoir
  - Vibration of deformable appurtenances such as valves
  - Unstable pump or fan characteristics

Water Hammer – Elastic Model



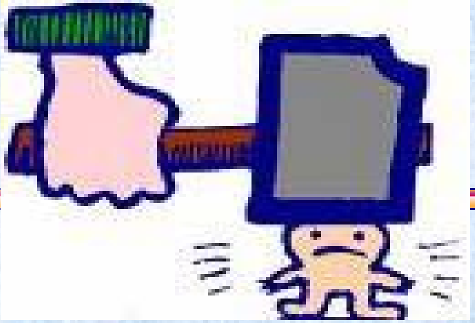
- Joukowsky Equation

$$dH = \pm\frac{a}{g}dV = \pm\frac{a}{gA}dQ = \pm BdQ$$

where
- H = head (ft, m)
- a = characteristic wave speed of the liquid (ft/s, m/s)
- g = gravitational acceleration constant (ft/s^2, m/s^2)
- V = fluid velocity (ft/s, m/s)
- A = area (ft^2, m^2)
- Q = flow (cfs, m^3/s)
- B = characteristic impedance, a/gA (s/ft^2, s/m^2)

Joukowski: $\Delta H = \frac{c}{g}\Delta v$ **or:** $\Delta p = \rho\, c\, \Delta v$

Water Hammer – Elastic Model



$$a = \sqrt{\frac{\dfrac{E_v}{\rho}}{1 + \dfrac{E_v \Delta A}{A \Delta p}}} \qquad (13.6)$$

where E_v = volumetric modulus of elasticity of the fluid (lbf/ft^2, Pa)

ΔA = change in cross-sectional area of pipe (ft^2, m^2)

Elastic Model

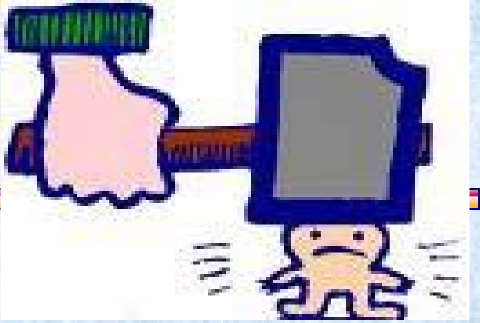


Table 13.3 Physical properties of some common liquids

Liquid	Temperature (°C)	Bulk Modulus of Elasticity (10^6 lbf/ft^2)	Bulk Modulus of Elasticity (GPa)	Density (slugs/ft^3)	Density (kg/m^3)
Fresh Water	20	45.7	2.19	1.94	998
Salt Water	15	47.4	2.27	1.99	1,025
Mineral Oils	25	31.0 to 40.0	1.5 to 1.9	1.67 to 1.73	860 to 890
Kerosene	20	27.0	1.3	1.55	800
Methanol	20	21.0	1.0	1.53	790

Elastic Model

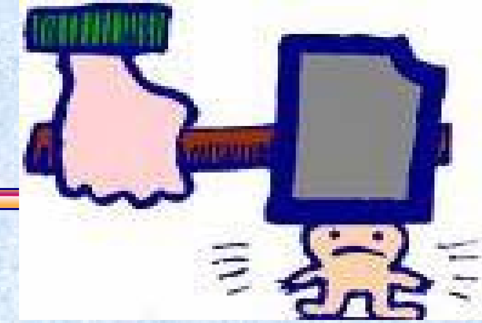
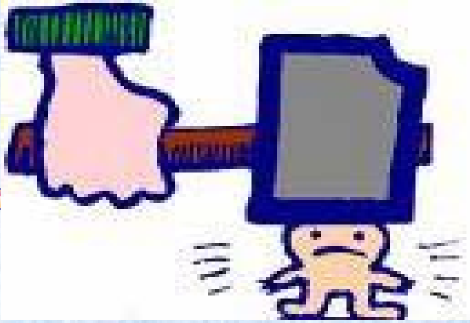
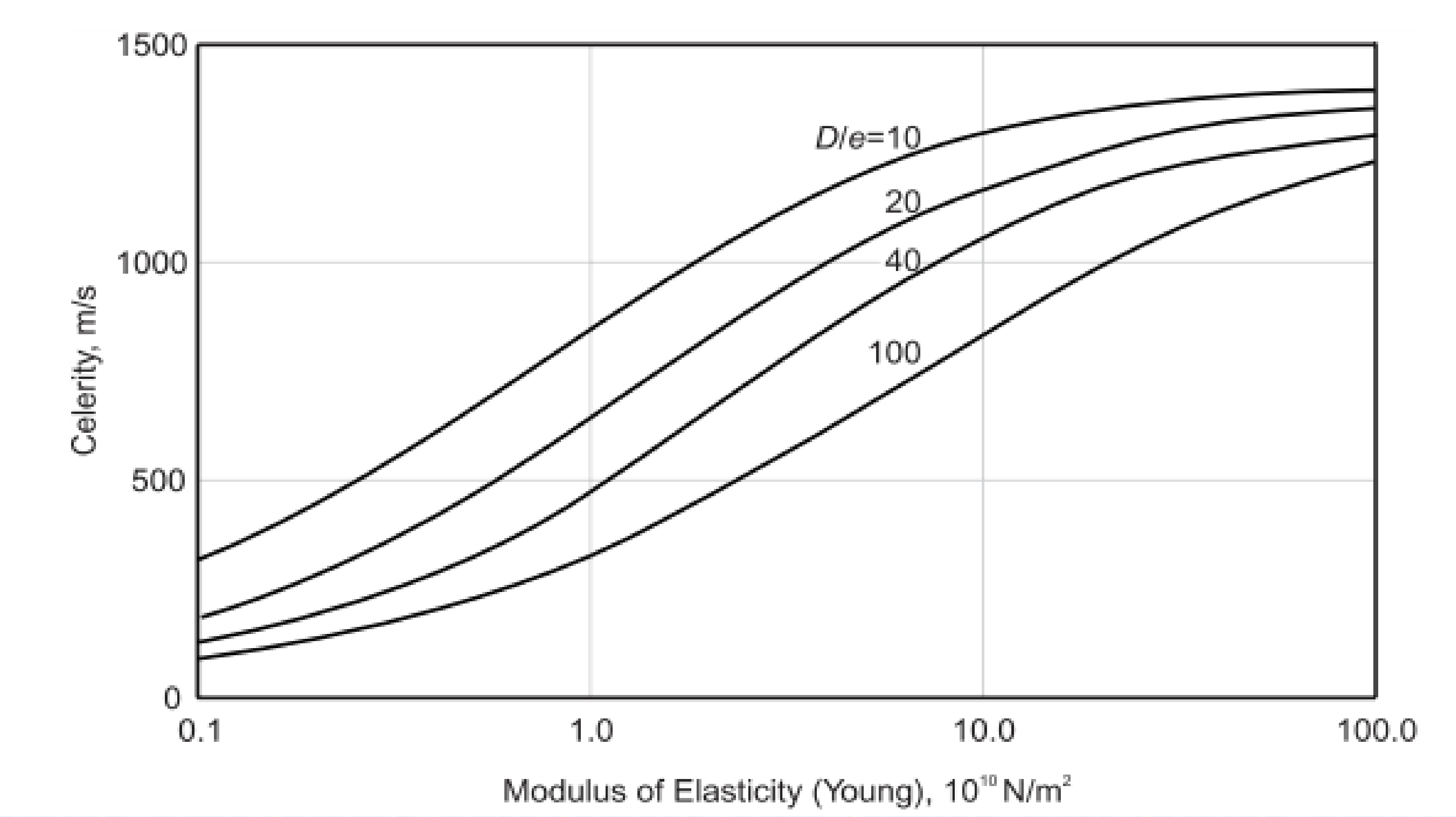


Table 13.2 Physical properties of some common pipe materials

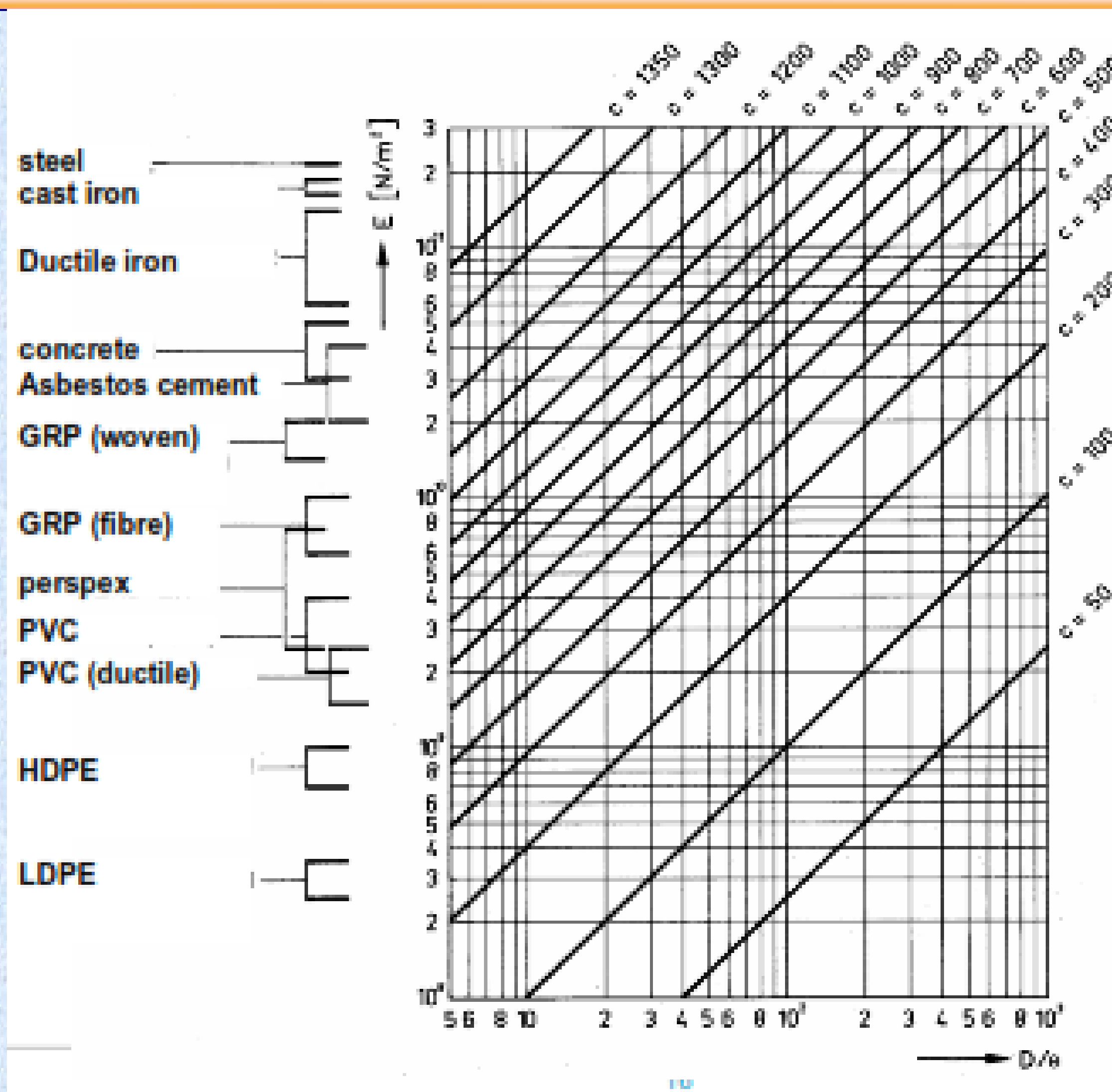
Material	Young's Modulus (10^9 lbf/ft^2)	Young's Modulus (GPa)	Poisson's Ratio, μ
Steel	4.32	207	0.30
Cast Iron	1.88	90	0.25
Ductile Iron	3.59	172	0.28
Concrete	0.42 to 0.63	20 to 30	0.15
Reinforced Concrete	0.63 to 1.25	30 to 60	0.25
Asbestos Cement	0.50	24	0.30
PVC (20°)	0.069	3.3	0.45
Polyethylene	0.017	0.8	0.46
Polystyrene	0.10	5.0	0.40
Fiberglass	1.04	50.0	0.35
Granite (rock)	1.0	50	0.28

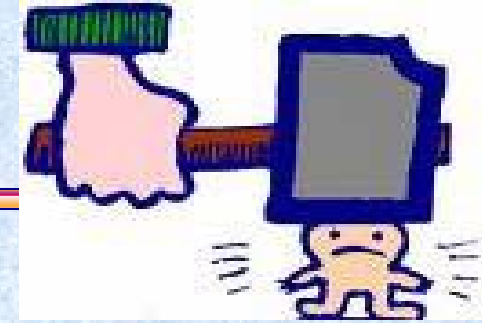
Elastic Model



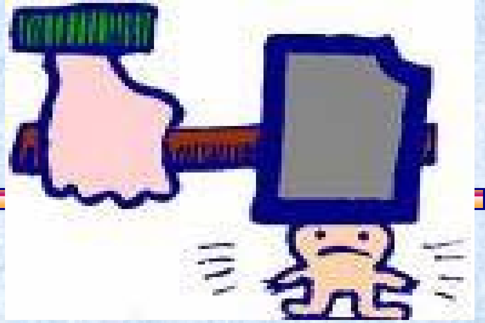


Elastic Model





A Comparison of the Models



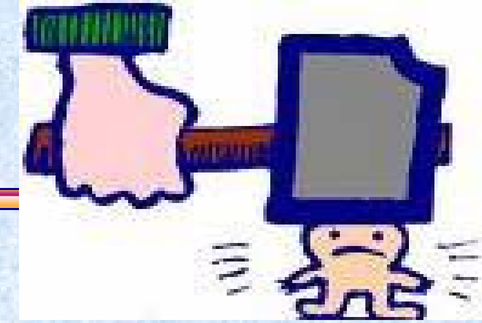
$$\frac{\Delta p_{rigid}}{\Delta p_{elastic}} \propto \frac{L\frac{dV}{dt}}{(a)dV}$$

where Δp_{rigid} = change in pressure computed with rigid model

$\Delta p_{elastic}$ = change in pressure computed with elastic model

dV/dt = fluid acceleration

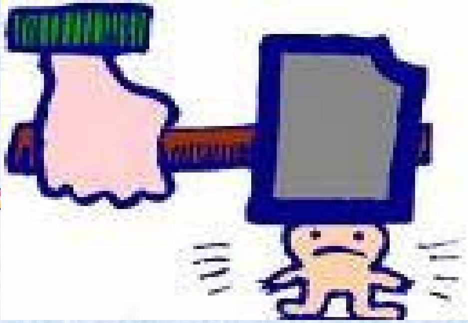
Application

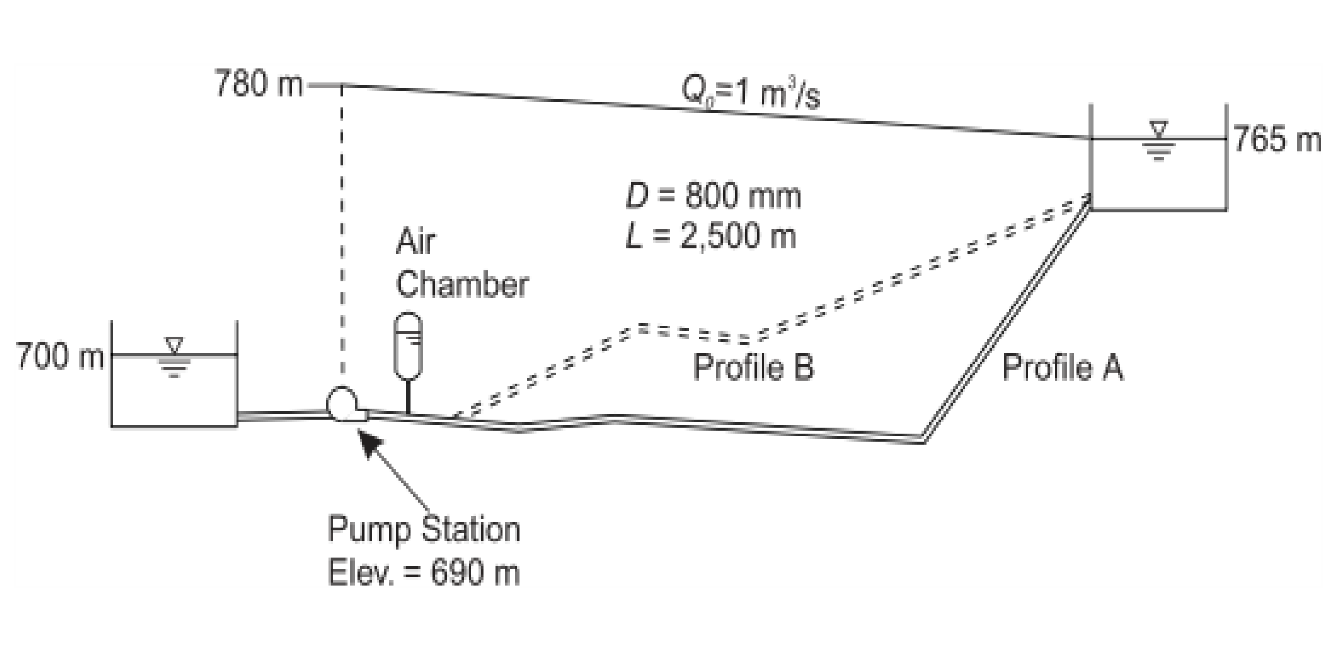


- Example

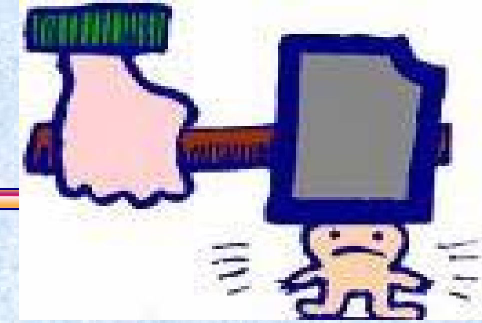
Example – Analysis of a Piping System. A pumping station located at an elevation of 690 m (2,263 ft) delivers 1 m^3/s (35.3 ft^3/s) of water from a suction well with a water surface elevation of 700 m (2,296 ft), as shown in Figure 13.15. The water is delivered through a check valve and 2,500 m (8,200 ft) of 800-mm (31-in.) pipe to a reservoir with a water surface elevation of 765 m (2,510 ft). The wave speed *a* is approximately 980 m/s (3,220 ft/s). The pump station includes a double suction pump that operates at 880 rpm and is driven by a 1,000 kW (1,341 HP) motor. The combined inertia of the pump and motor is approximately 150 kg-m^2 (3,562 lbm-ft^2).

Application

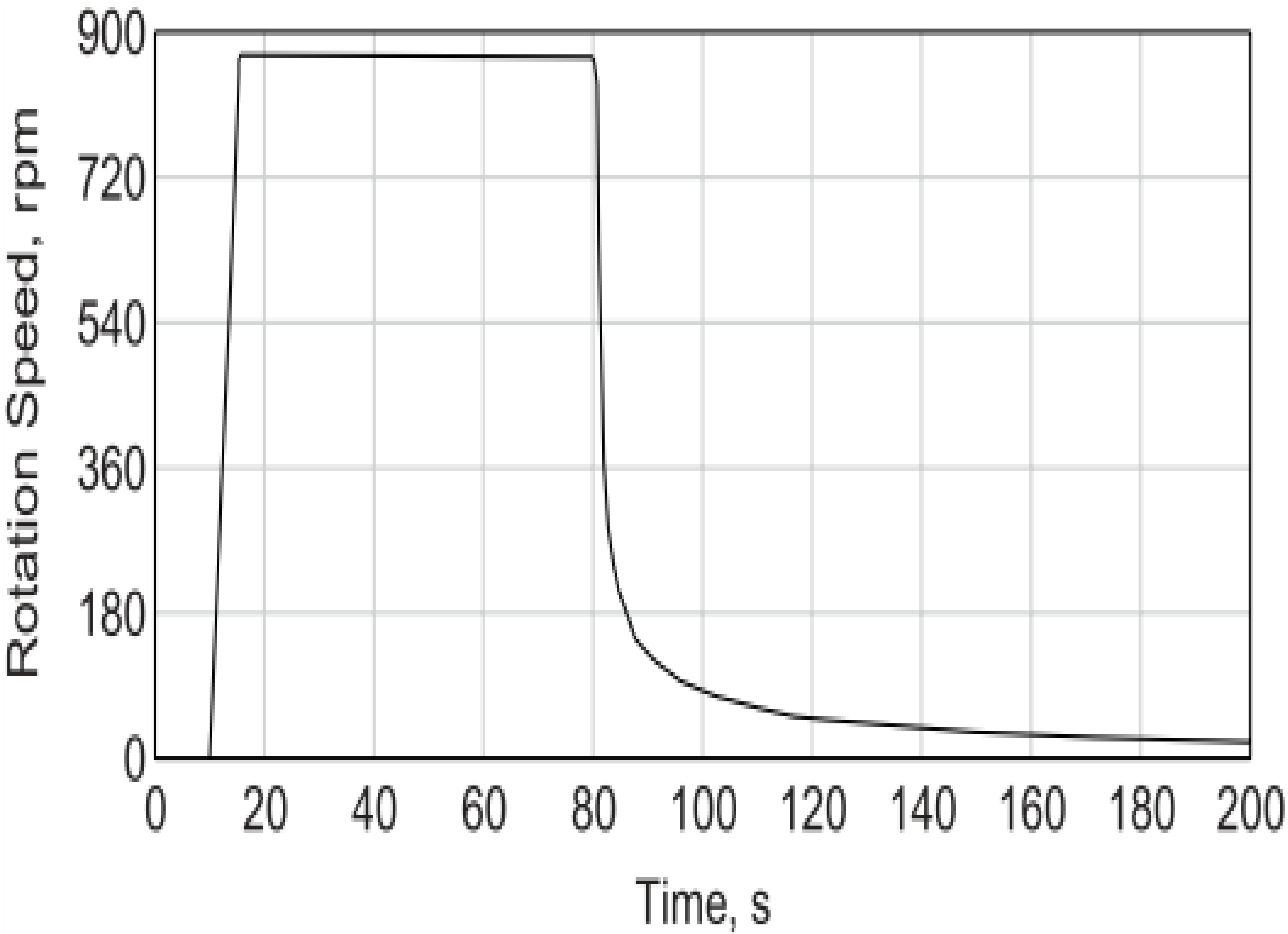




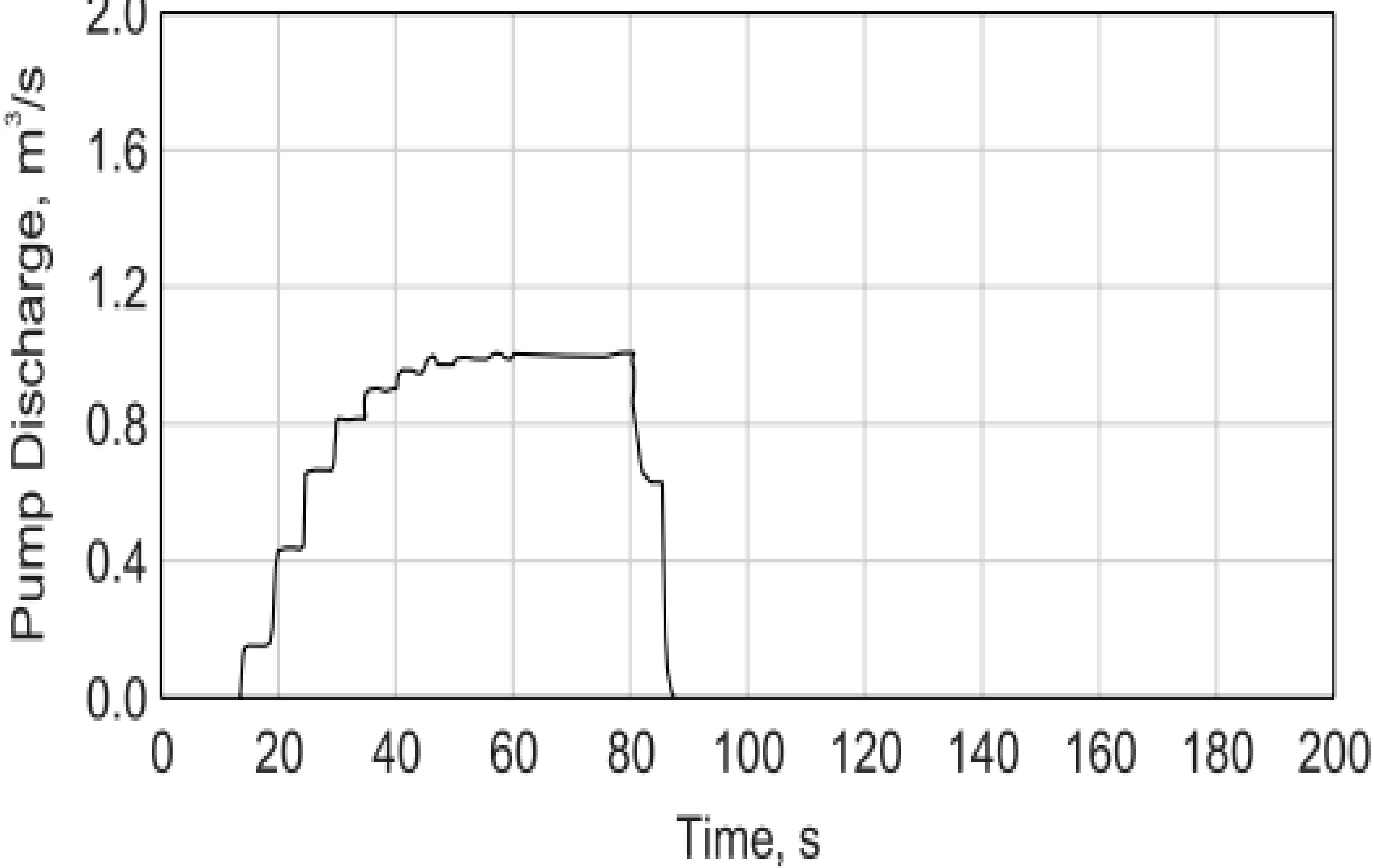
Application



The pump is started at time $t = 10$ seconds and takes approximately 4 seconds to ramp up to full speed [see Figure 13.16(a)]. A blow-off valve located at the pump discharge opens to relieve flow during pump start-up, and then gradually closes to direct water down the transmission main [Figure 13.16(b)]. At time $t = 80$ seconds, a pump shutdown caused by a loss of electric power occurs. This incident is indicated by the abrupt drop-off in speed and flow in Figures 13.16(a) and (b). The shutdown is considered an emergency condition. Figure 13.16(c) shows the simulation results from a transient analysis computer program for the period including the pumping operations at time $t = 10$ seconds (pump start) and $t = 80$ seconds (pump failure).

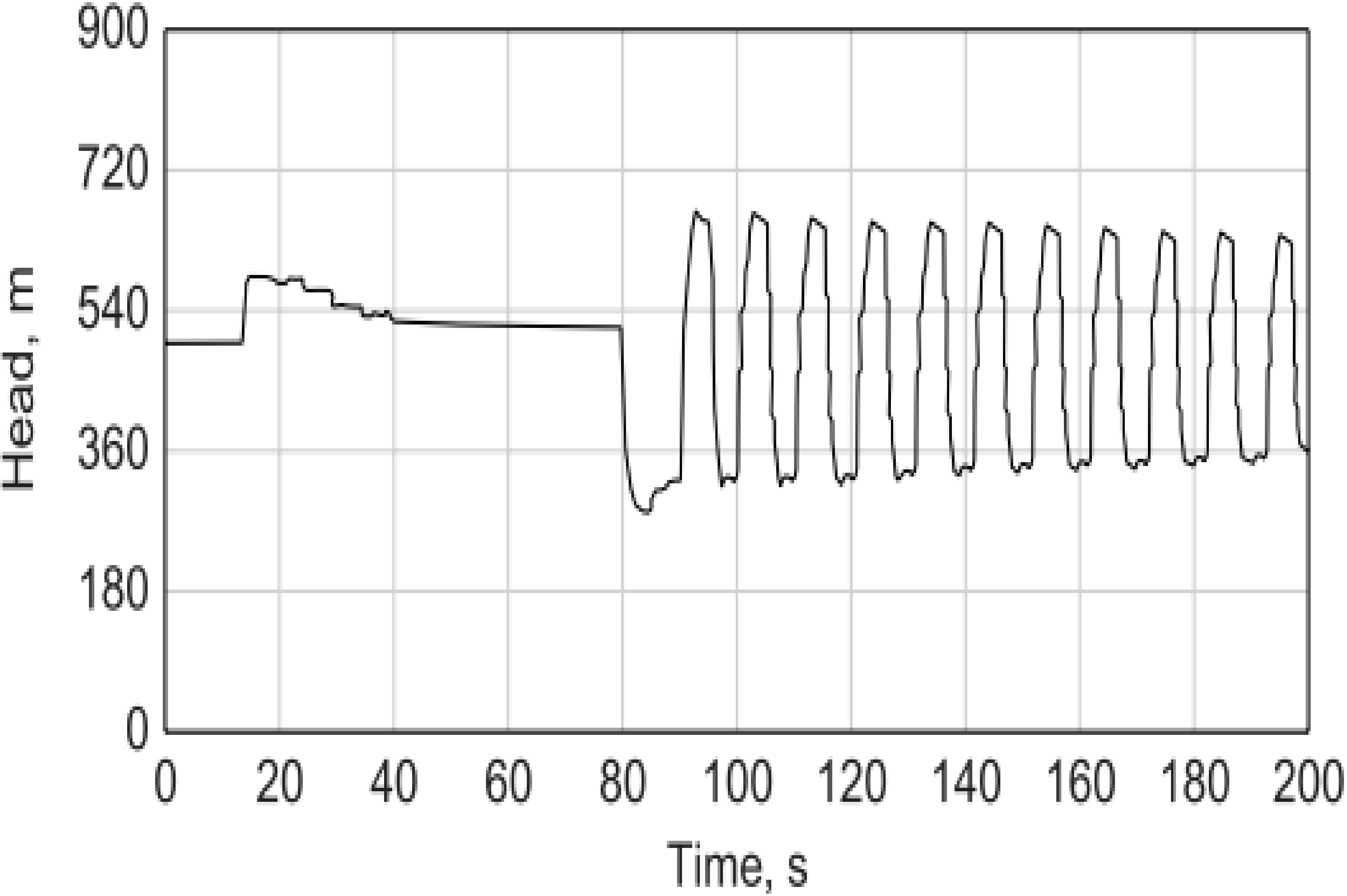


(a) Pump Rotation



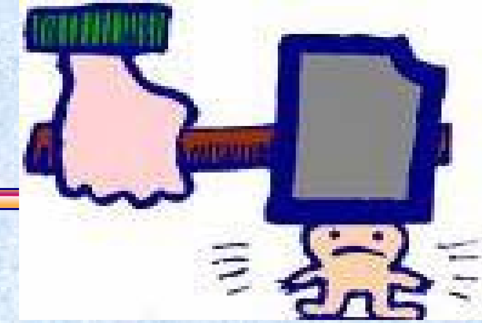
2.0
1.6
1.2
0.8
0.4
0.0
Pump Discharge, m³/s
0
20
40
60
80
100
120
140
160
180
200
Time, s

(b) Pump Flow



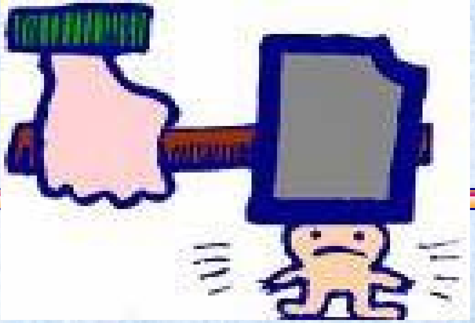
(c) Heads in the Pump Discharge

Water Hammer- Mitigation



- Possible strategy’s
  - Minimizing possibility of transient conditions during design
  - Install transient control devices

Water Hammer- Mitigation



- The basis

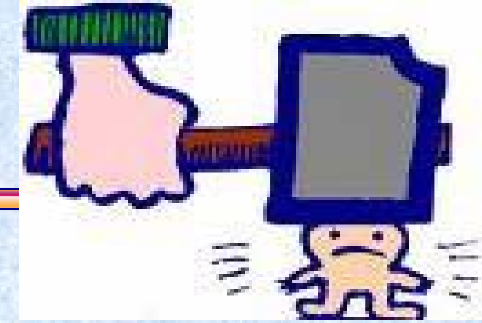
$$\Delta p = \rho a \Delta V \; or \; \Delta H = \frac{a}{g}\Delta V$$

$$dH = \pm\frac{a}{g}dV = \pm\frac{a}{gA}dQ = \pm B dQ$$

Water Hammer- Mitigation Philosophy

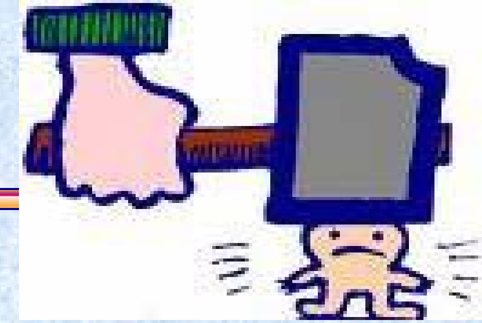
- Philosophy
  - Reduce wave speed
  - Reduce rate of "Δv"
  - Limit local pressure
  - Geometrical modification

Water Hammer- Mitigation



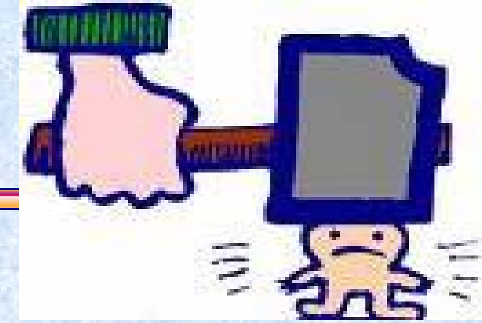
- System modifications
- Moderating the transient initiation event
- Emergency control procedures
- Anti- surge devices

Water Hammer- Mitigation



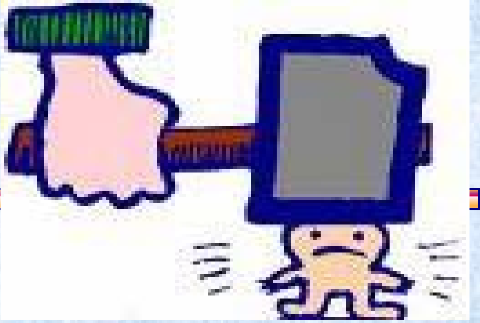
- System modifications
  - Emergency flow control analysis
  - Route re-arrangement
  - Pipe thickness selection (low head system)
  - Pipe material selection
  - Depth of overburden
  - Location and design of air valves
  - Pipe size

Water Hammer- Mitigation



- Wave speed reduction methods
  - Determinants of wave speed
    - Elastic wall properties
    - Geometry
    - Liquid compressibility
    - Free gas content
  - Strategy
    - Bleeding in air
    - Pipe system configuration
    - Flexible hose

Water Hammer- Mitigation



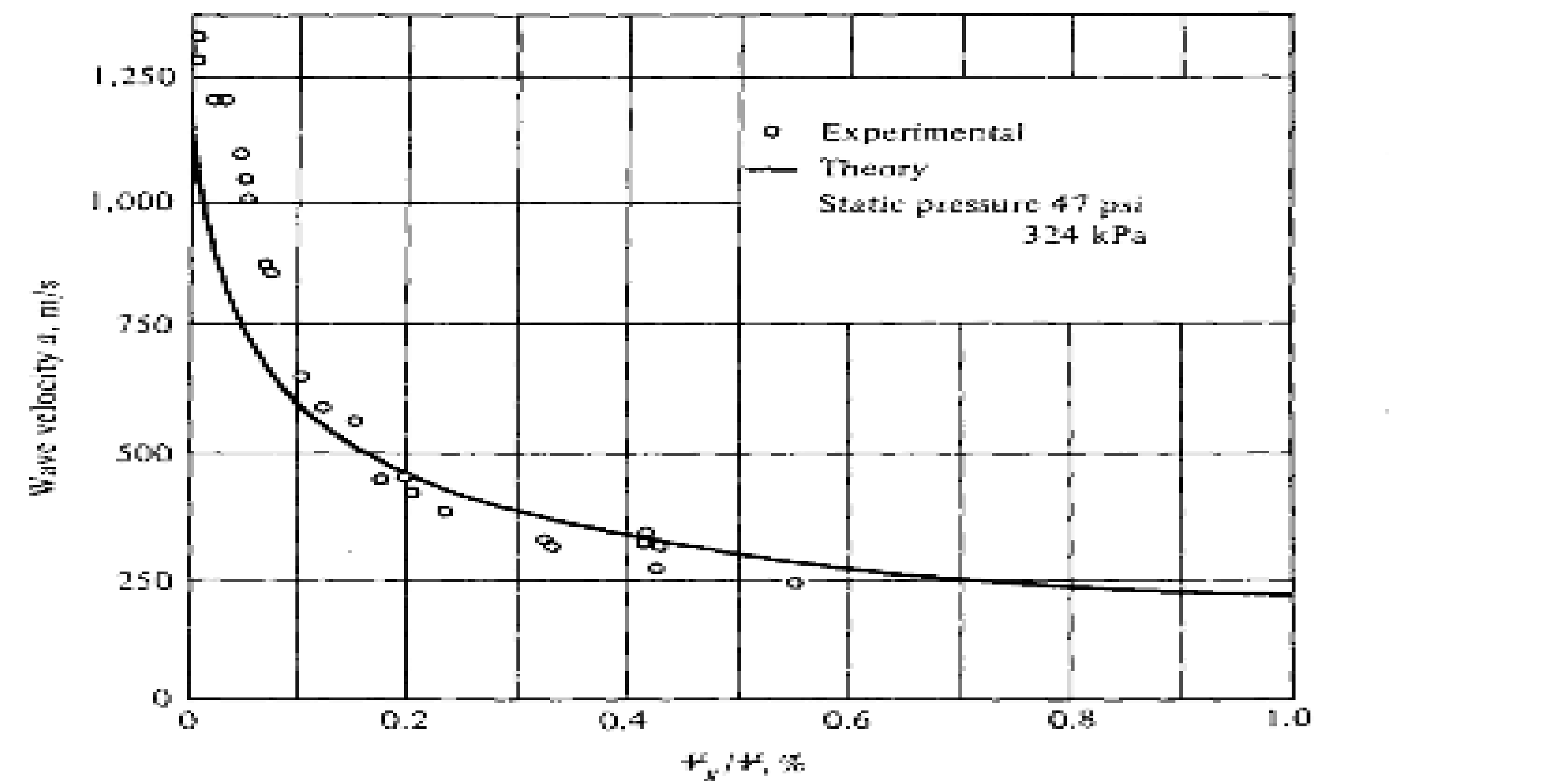
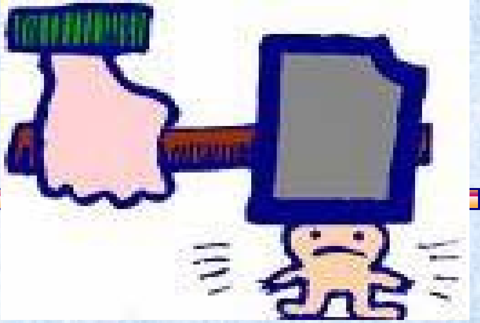


Figure 1-5 Propagation velocity a of a pressure wave in pipeline for varying air content (theoretical and experimental results).

Water Hammer- Mitigation

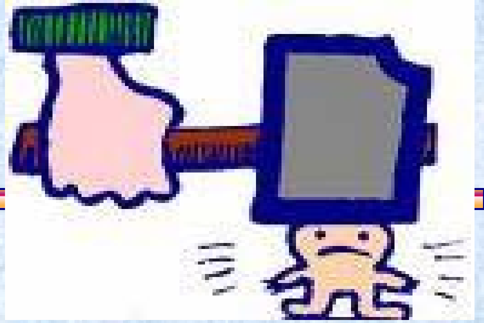


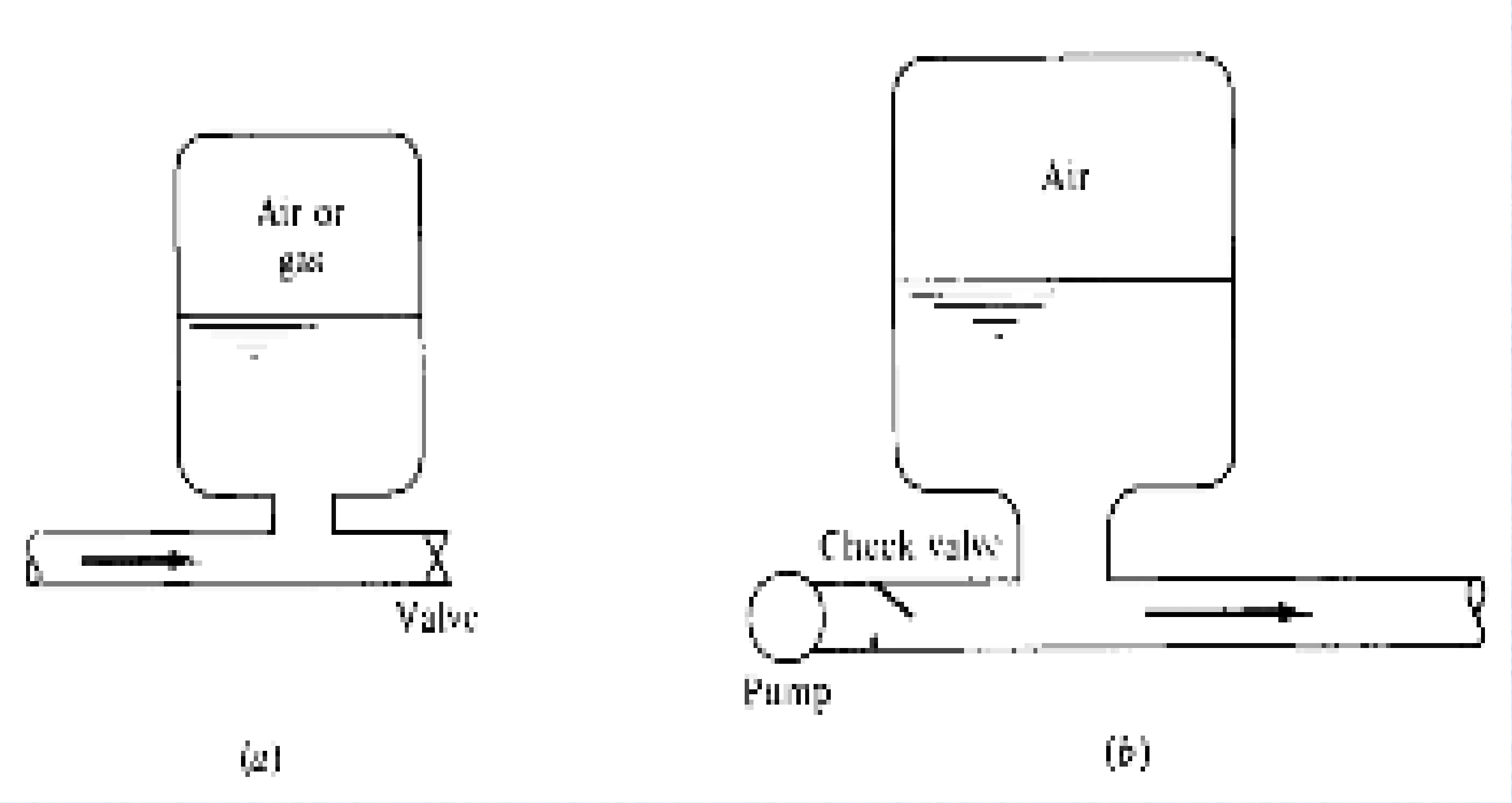
- Reduce rate of "ΔV"
  - Air vessel
  - Water tower
  - One way tank
  - Combined devices
  - Soft start/stop or frequency driven pumps
  - Slower valve manipulations
  - Flywheel on pumps

Water Hammer- Mitigation

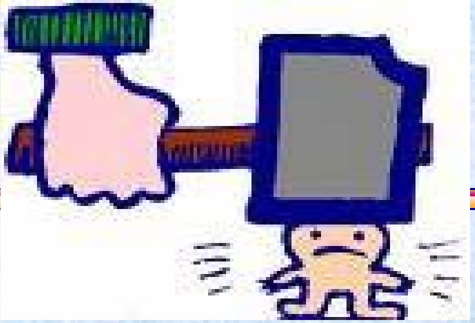
- Air Chamber
  - Pressure control
  - Container filled with system liquid and gas
  - Pros
    - Function over wide range of pressure discharge combination
  - Cons
    - Maintaining air volume
    - Biological contamination

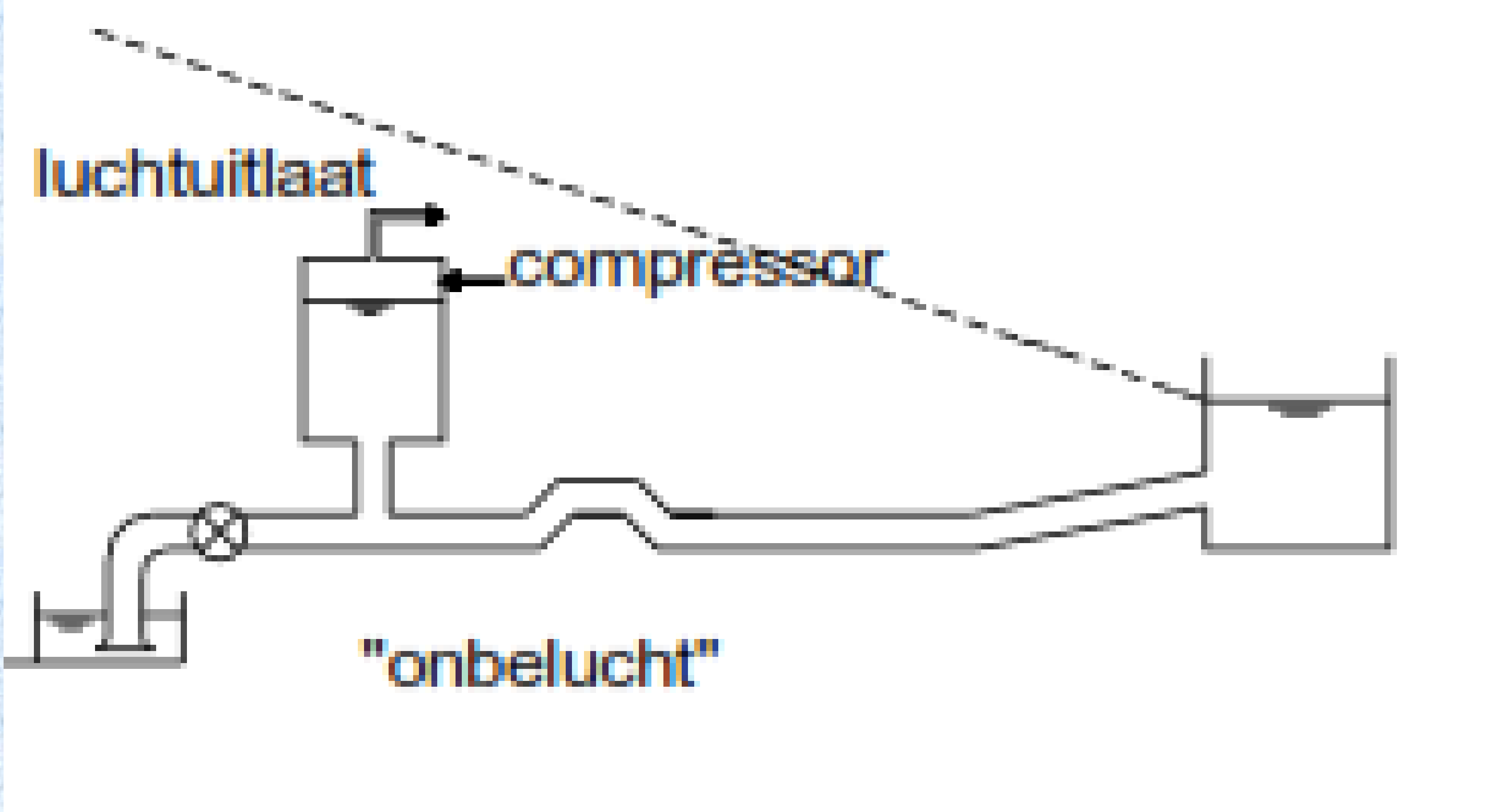
Water Hammer- Mitigation



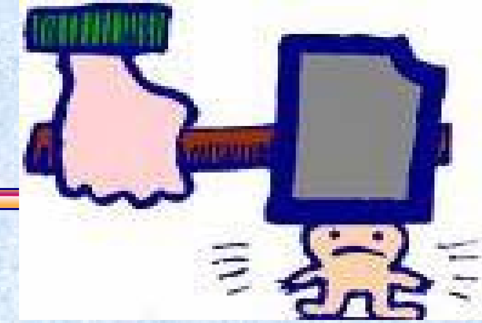


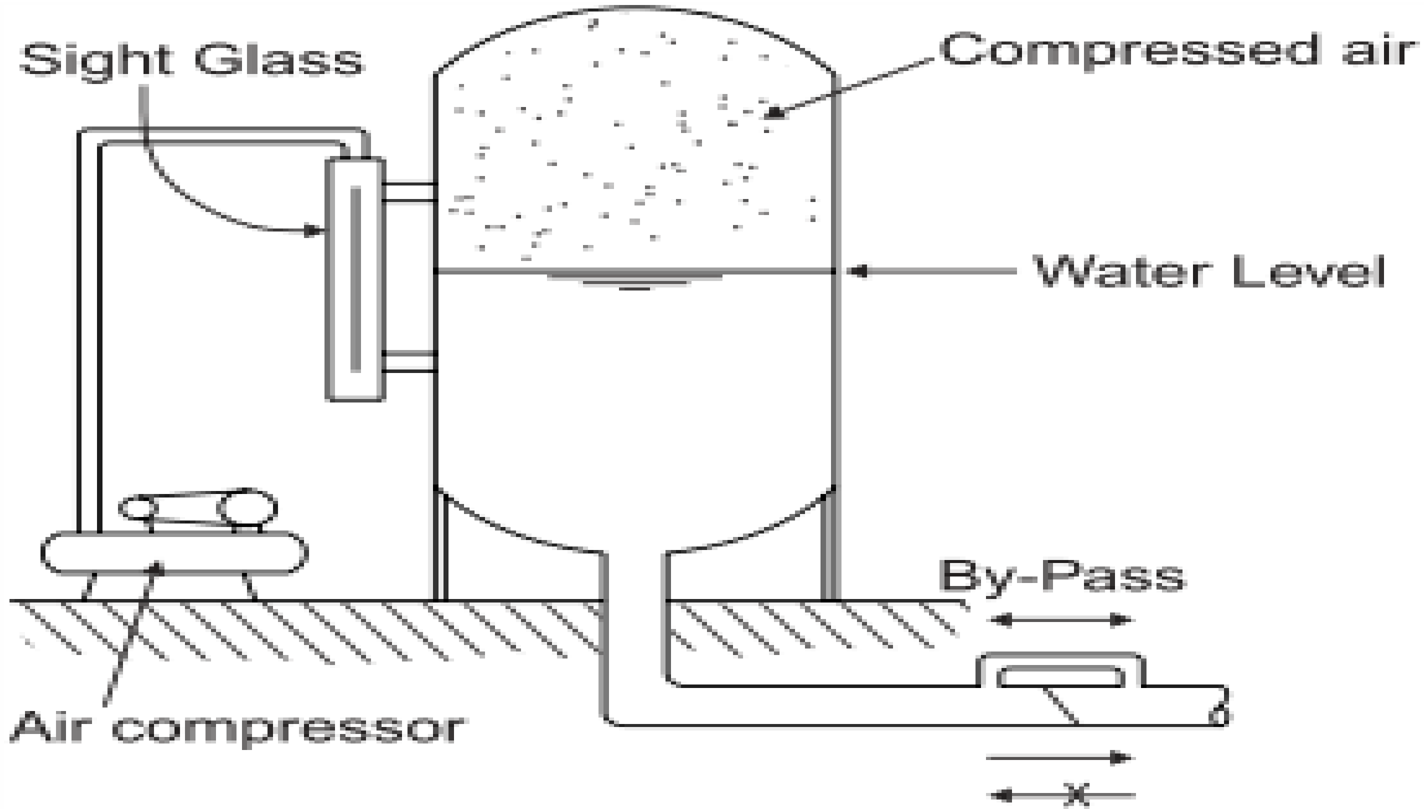
Water Hammer- Mitigation





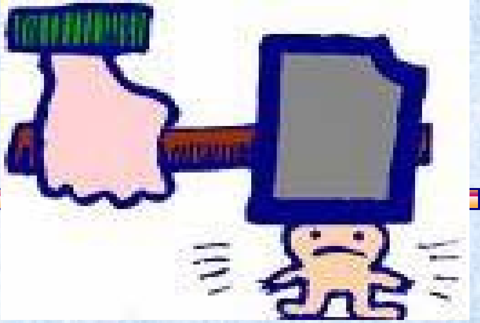
Water Hammer- Mitigation

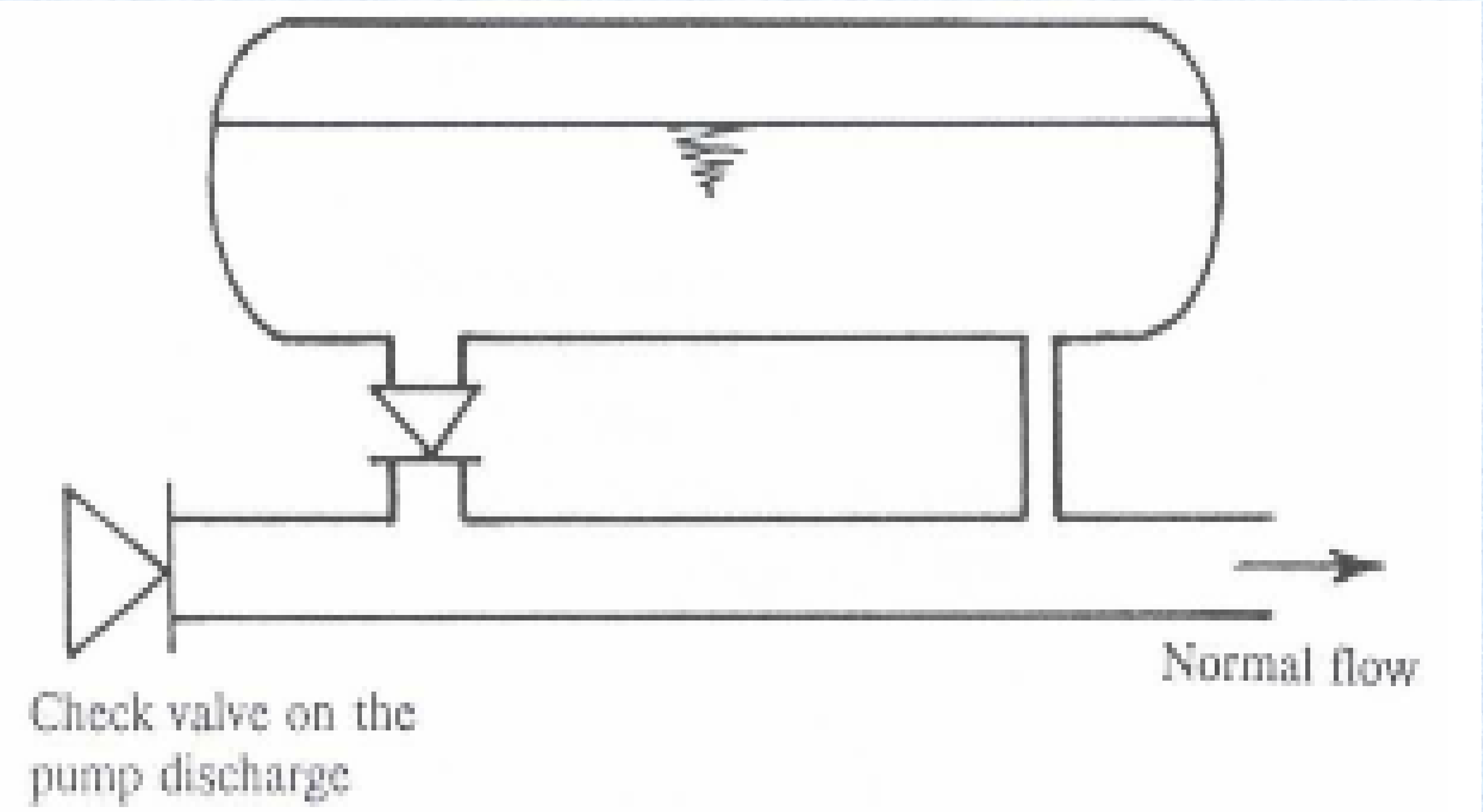




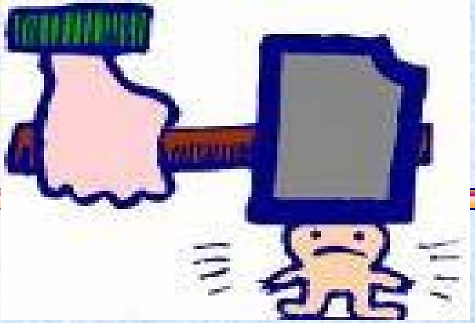
(a) Air Chamber

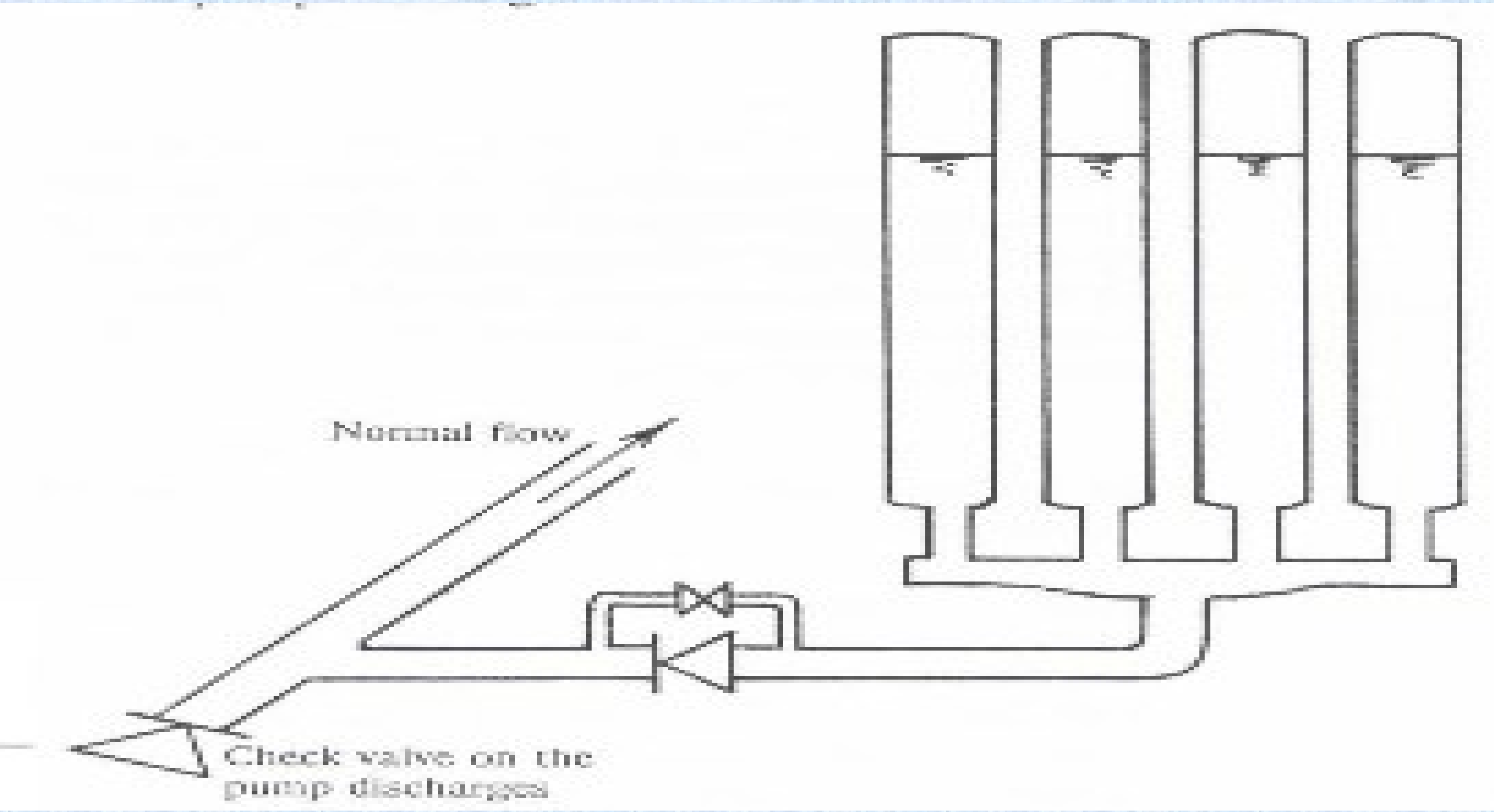
Water Hammer- Mitigation





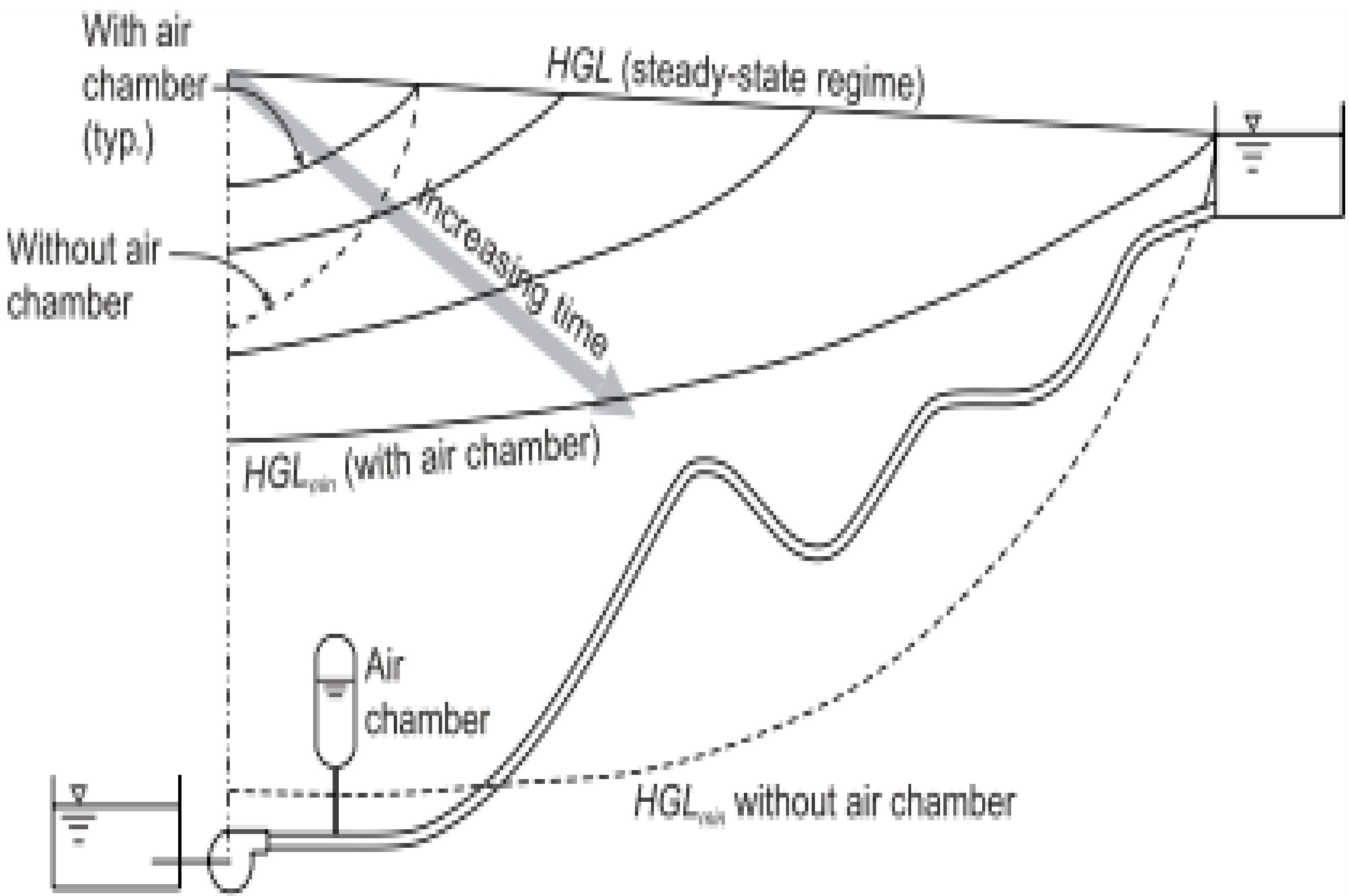
Water Hammer- Mitigation





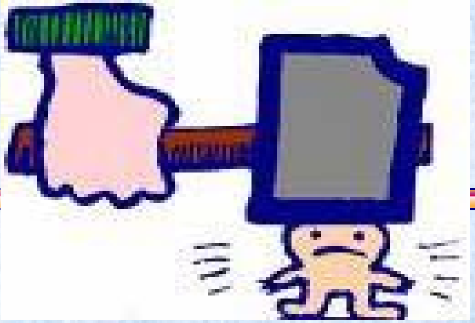
Water Hammer- Mitigation

- Examples : Air Vessel



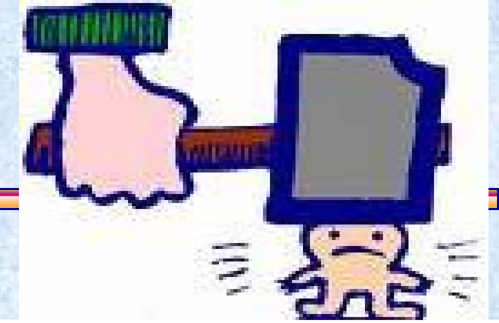
(a) Protection with Air Chamber

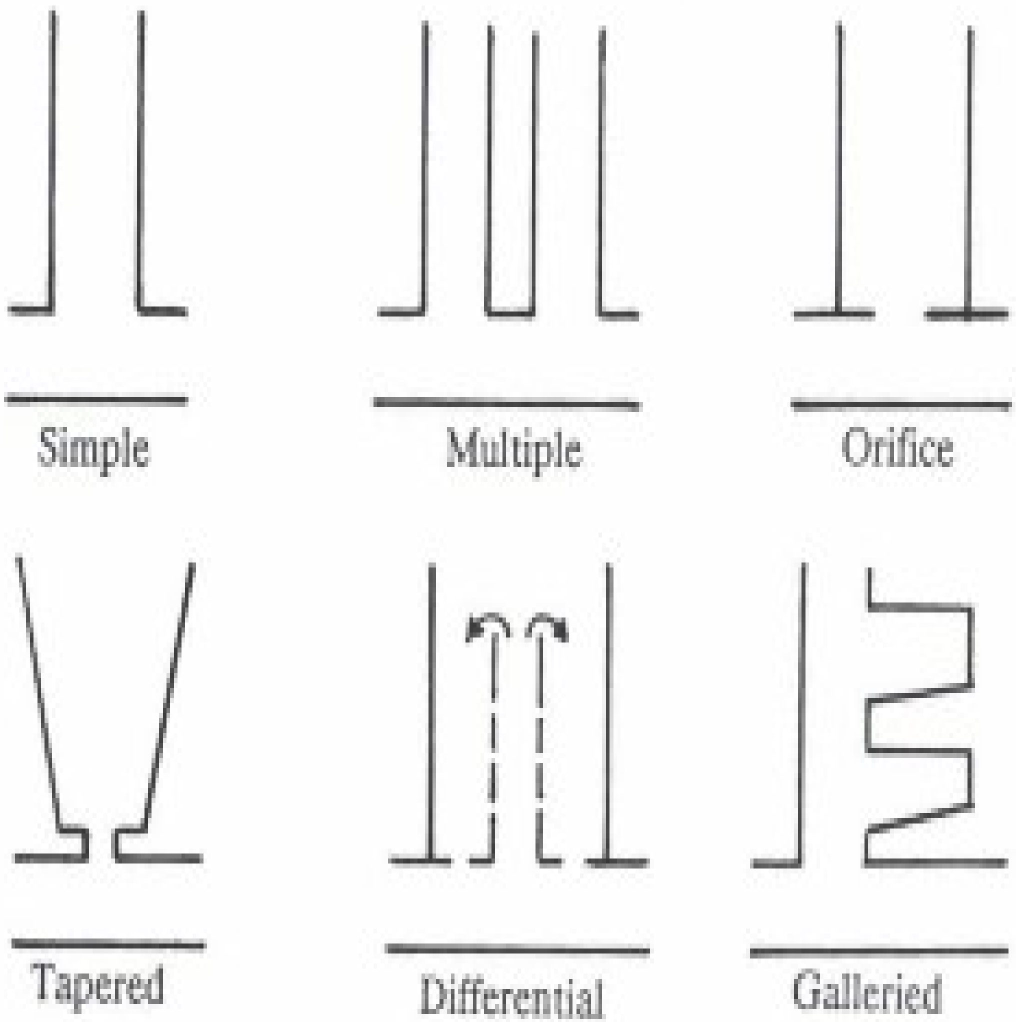
Water Hammer- Mitigation

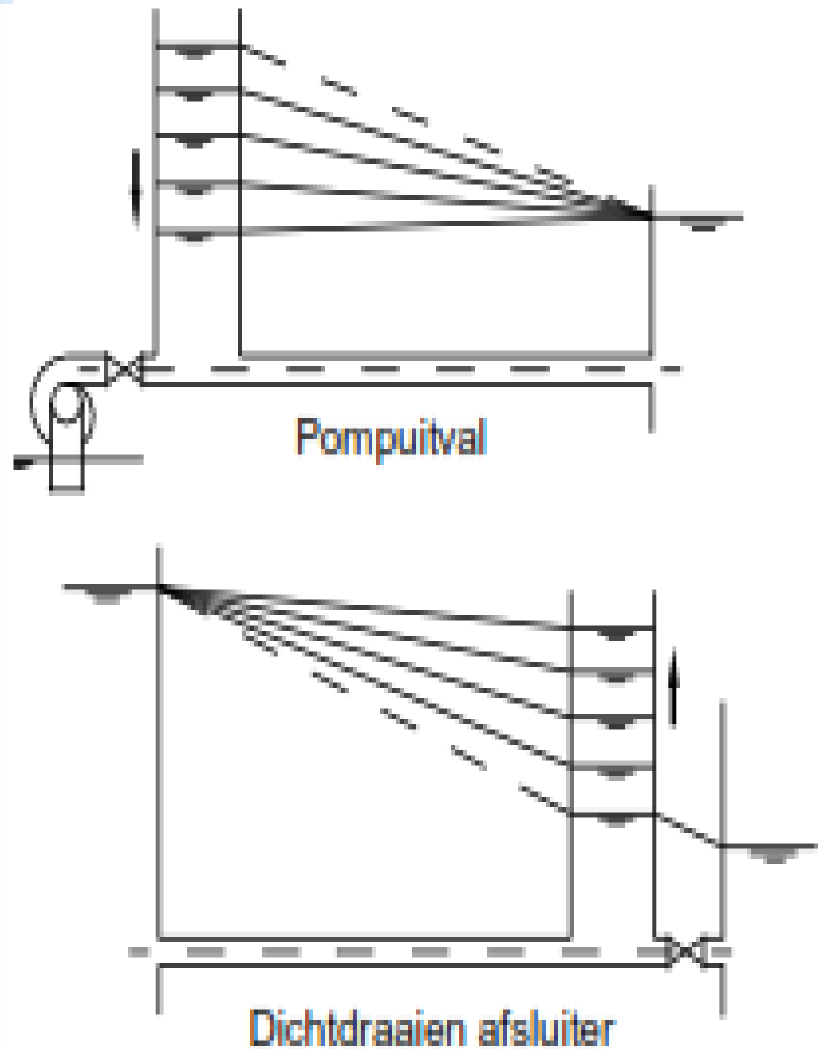


- Water Tower/Surge Tank :
  - Open tanks connected to the piping system.
  - Several forms of arrangement
    - Number
    - Arrangement
    - Nature of restriction
  - Pros :
    - Simple and reliable
    - Relatively large storage capacity

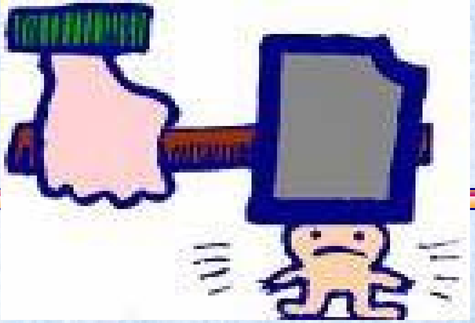
Water Hammer- Mitigation





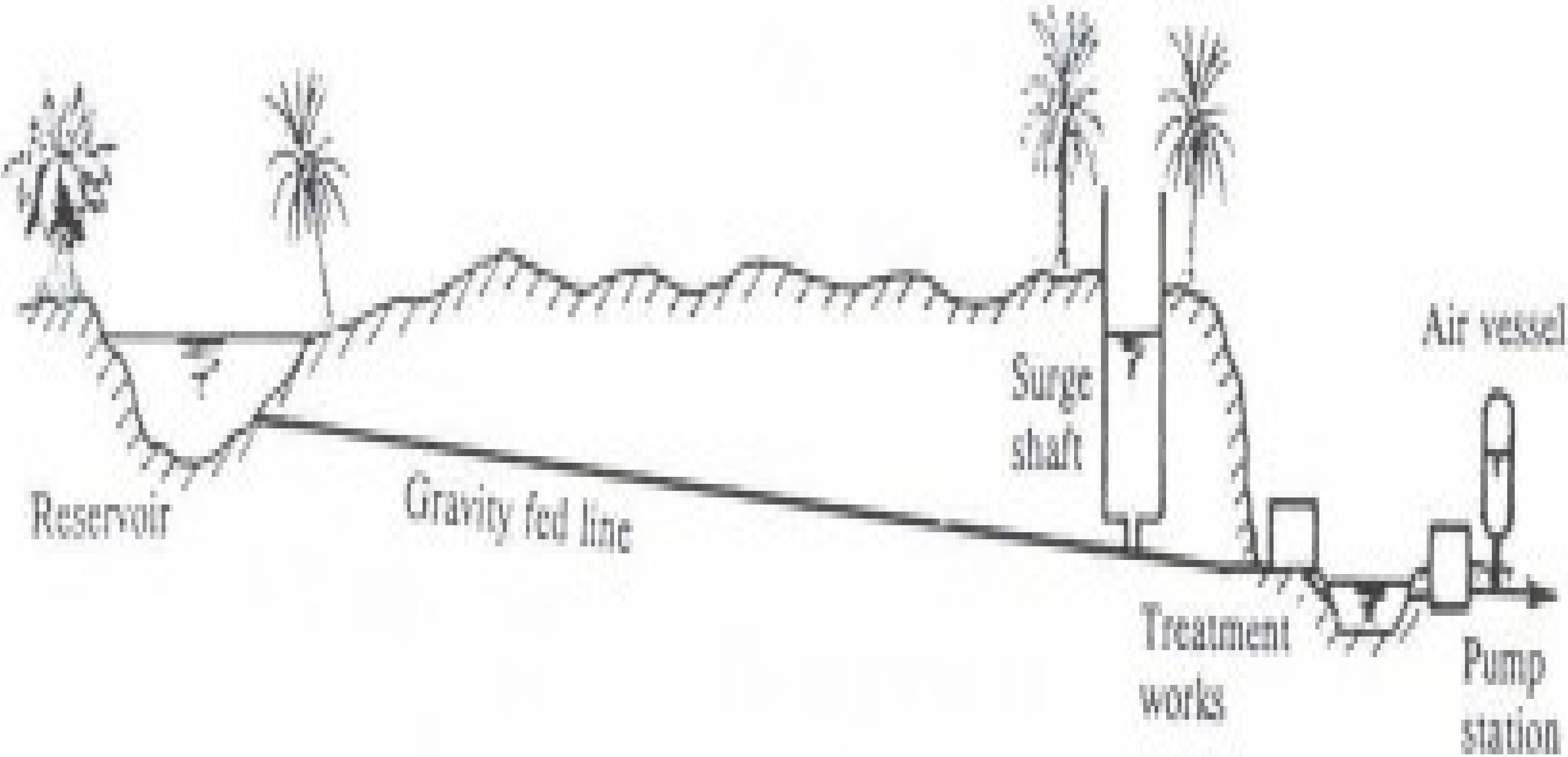


Water Hammer- Mitigation

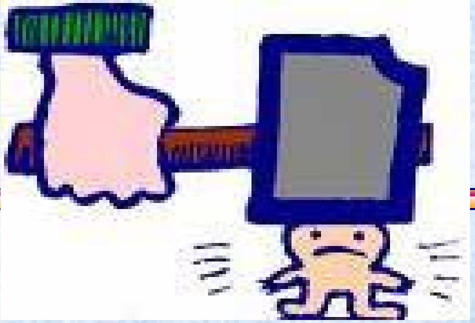


- Cons :
  - Application is limited
  - Rigidity
  - Odor problems
  - Water quality risk
  - Maintenance cost

Water Hammer- Mitigation

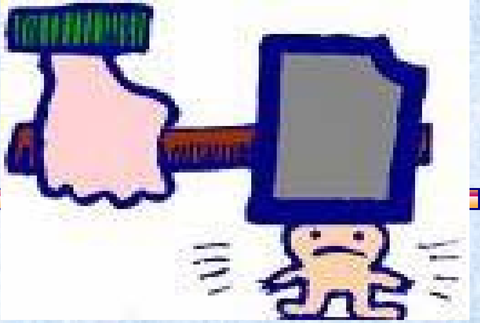


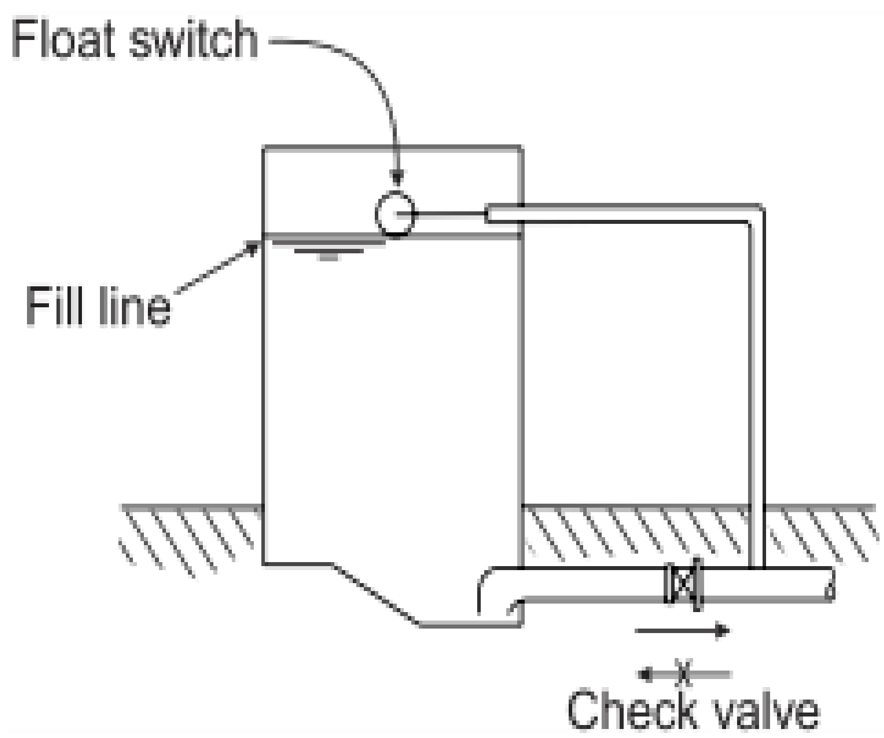
Water Hammer- Mitigation



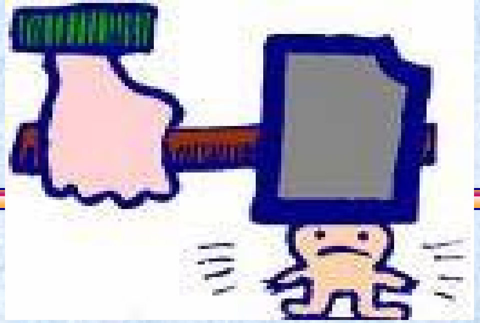
- One way tank
  - A storage vessel under atmospheric pressure
  - Low pressure control
  - Advantage
    - Effective under much lower height.

Water Hammer- Mitigation



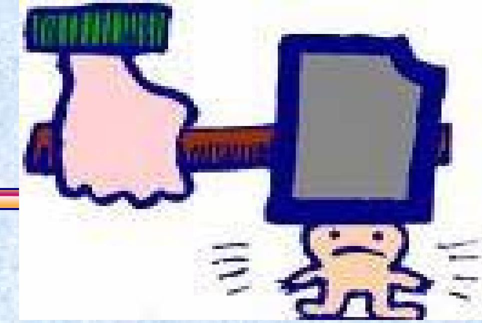


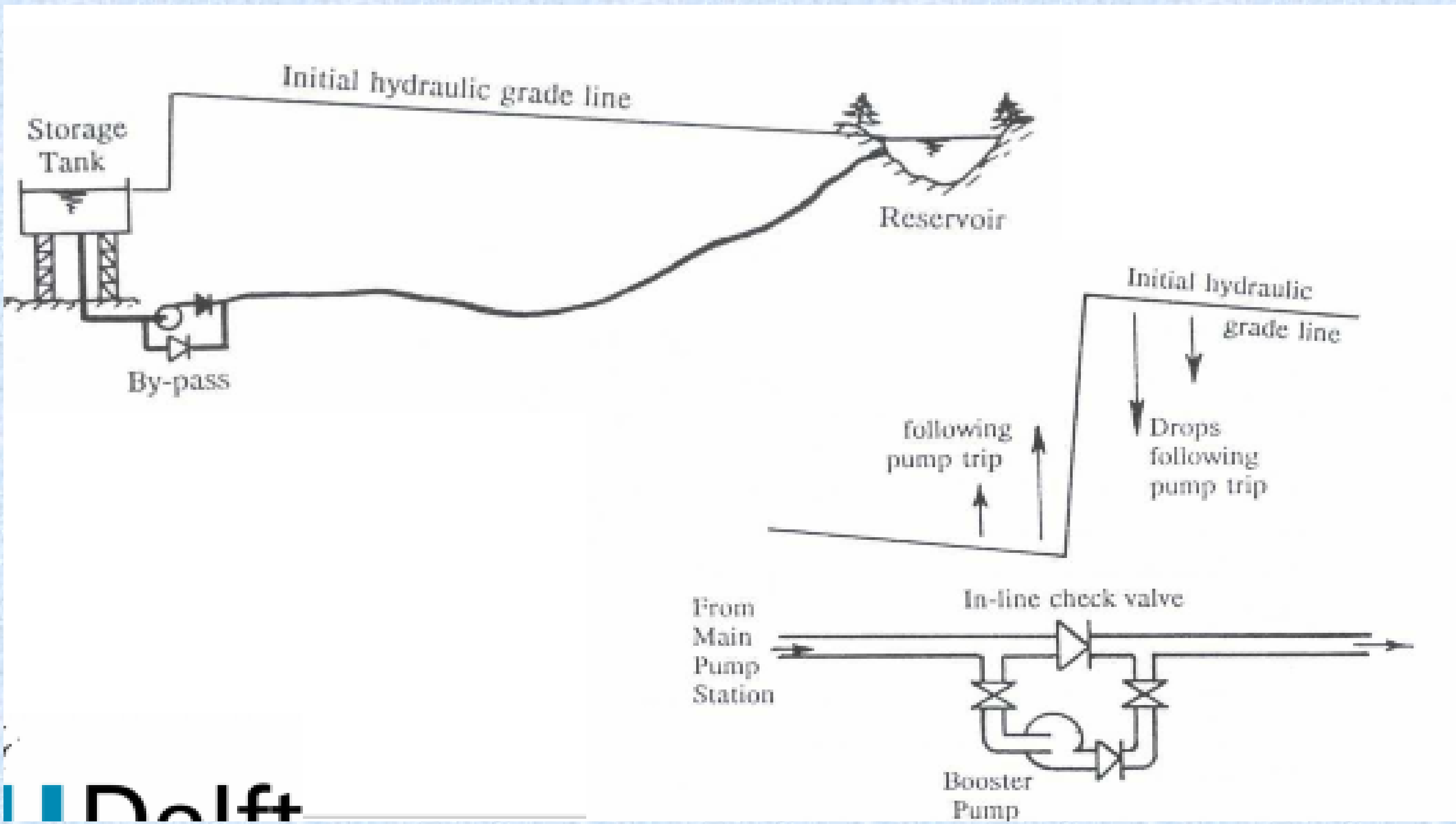
Water Hammer- Mitigation



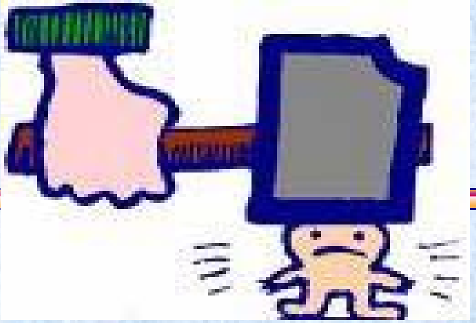
- By-Pass Line
  - Pros
    - No need for check valve
  - Cons
    - Reservoir at sufficient level
    - Late starting of action
    - Limited application

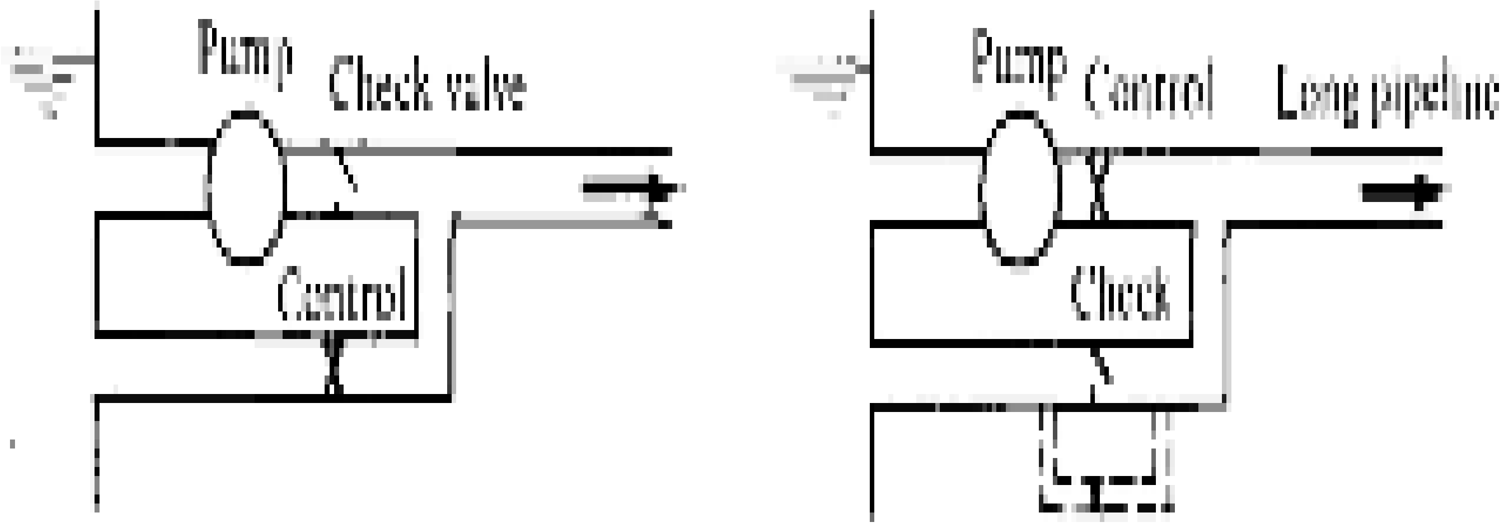
Water Hammer- Mitigation



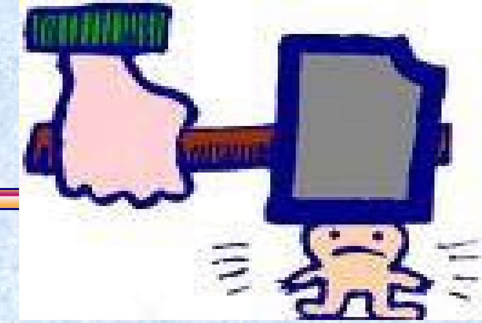


Water Hammer- Mitigation



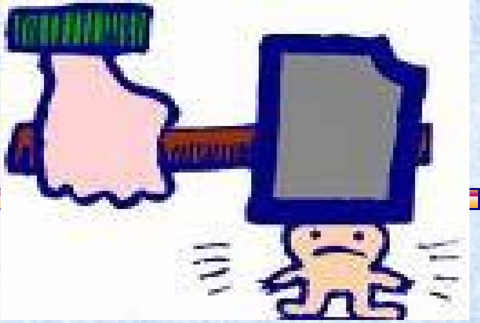


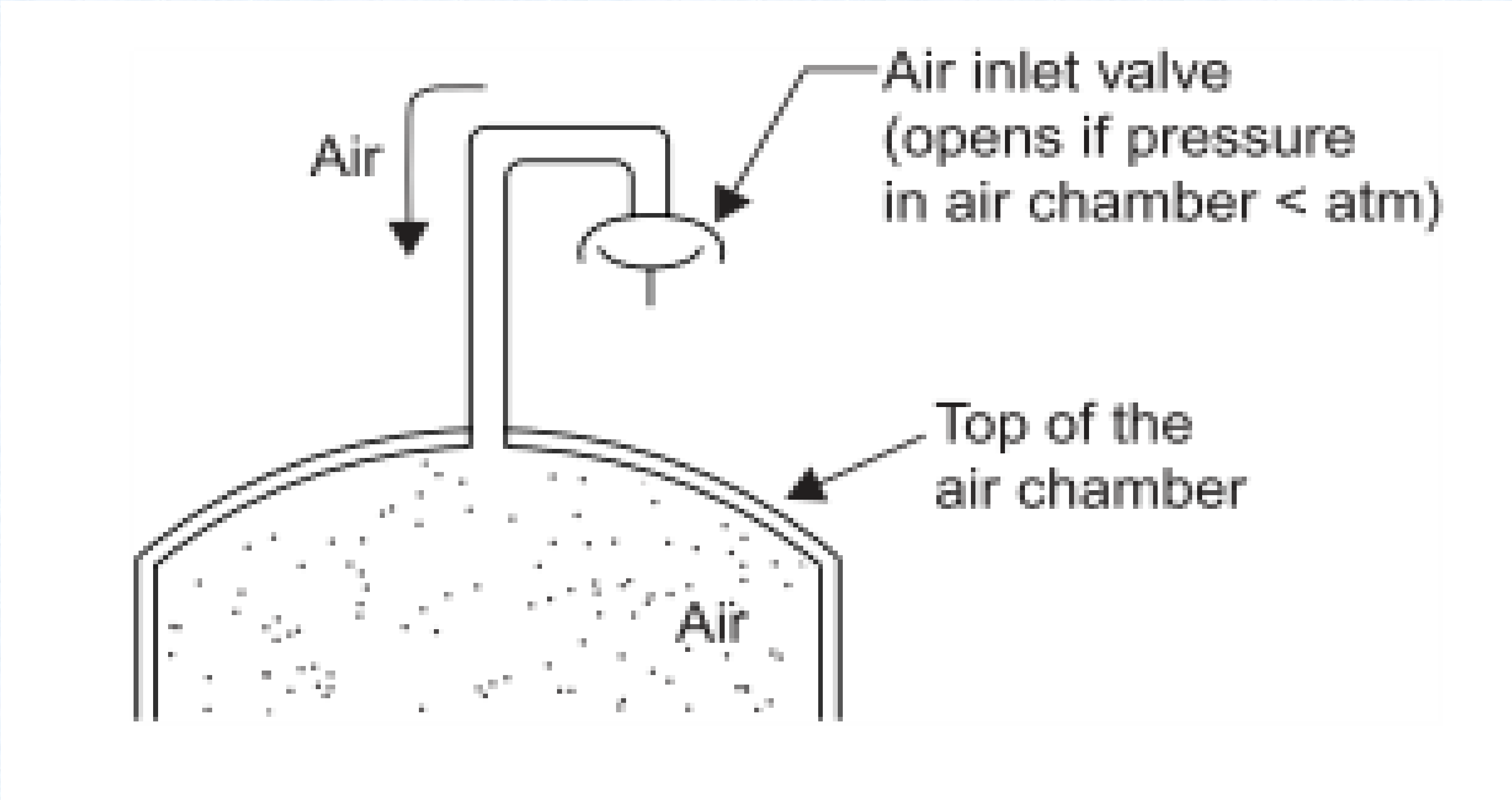
Water Hammer- Mitigation



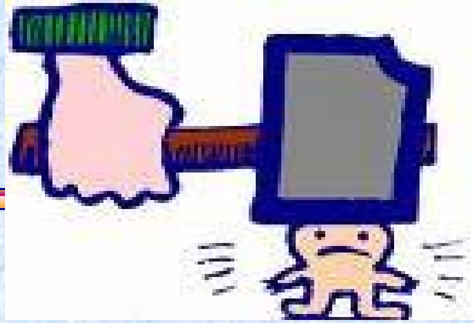
- Combined Devices
  - Say an air chamber with an air inlet valve
  - Pros
    - May lead to an optimum system design
    - Flexibility to operate in both extremes
  - Cons
    - Special check valve arrangement
    - Special design requirements
    - Temperature sensitivity

Water Hammer- Mitigation



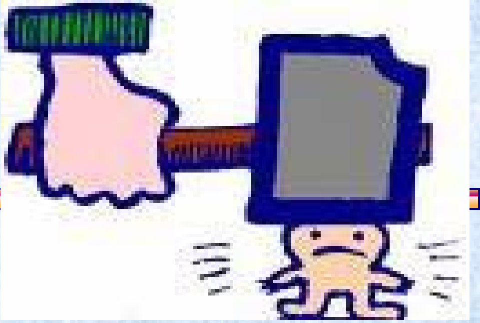


Water Hammer- Mitigation



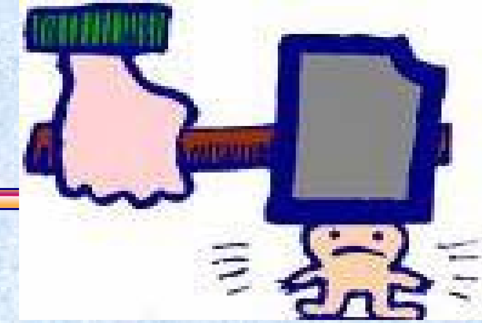
- Soft – starters/FO pumps
  - Pros
    - Beneficial during normal operation
  - Cons
    - Not applicable in power failure

Water Hammer- Mitigation



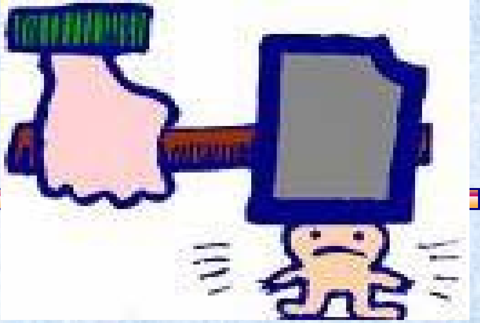
- Slower valve manipulation
  - Pros
    - No expensive anti-surge devices required
  - Cons
    - Manipulations must be slower than several pipe periods
    - Pipeline can not be blocked or opened quickly

Water Hammer- Mitigation

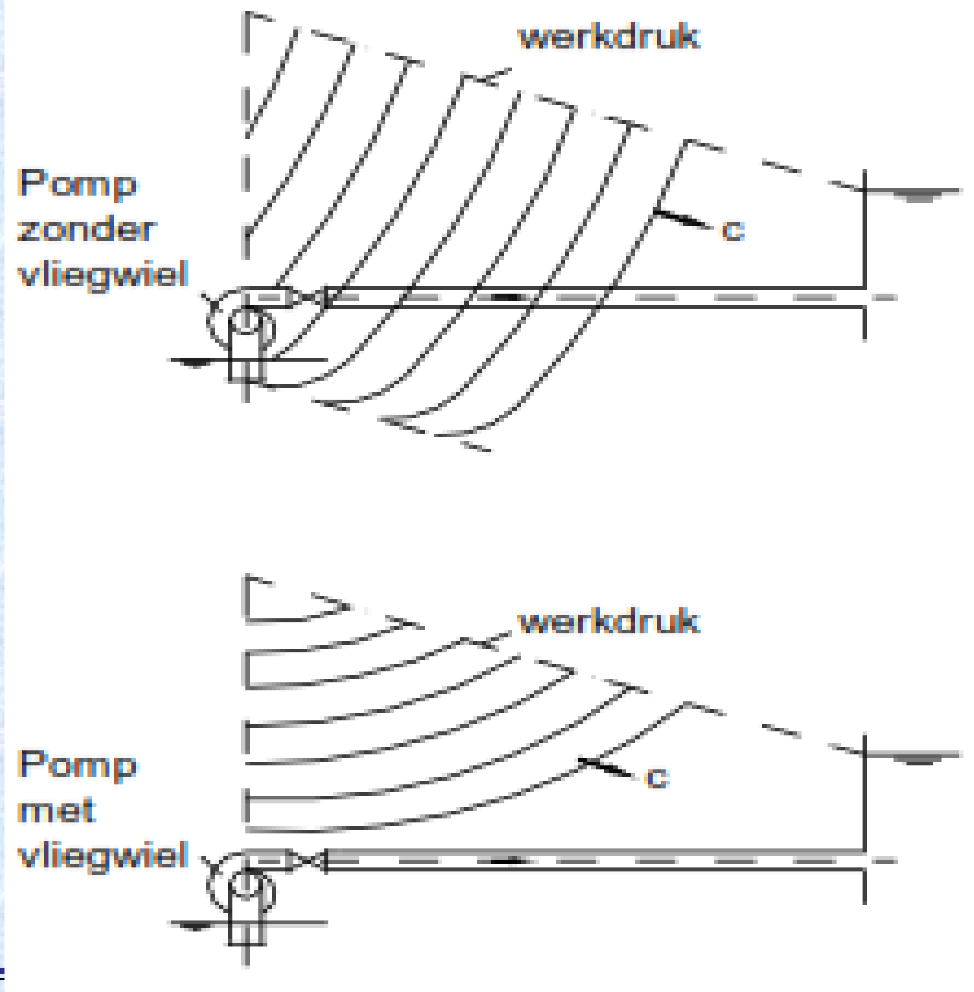


- Flywheel
  - Pro
    - Cheep construction
    - Gradual check valve closure
    - Limited maintenance
  - Cons
    - Effect is limited to several km
    - Pump motor must be large enough to start the flywheel
    - No effect if impeller blocks

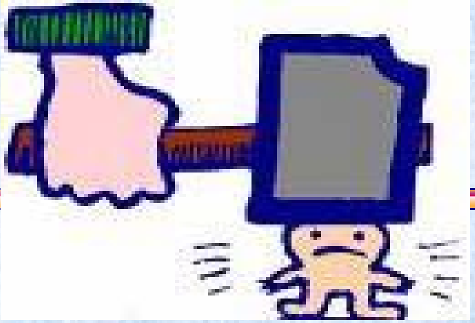
Water Hammer- Mitigation



- Pump start costs more energy. Only economically feasible for pumps that run continuously on fixed speed

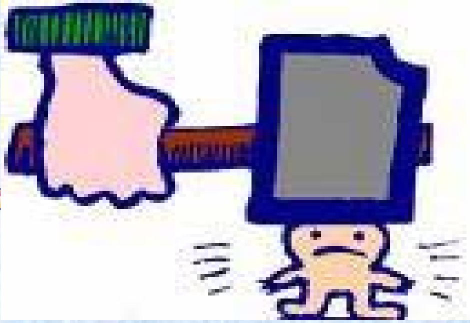


Water Hammer- Mitigation



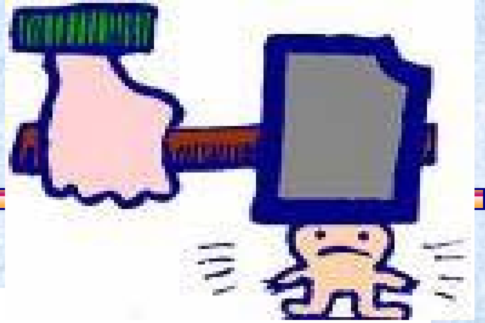
- Limit Pressure
  - Very localized
  - Include :
    - Pressure relief valve (PRV)/Safety valve
    - Air valve/vent/vacuum breaker

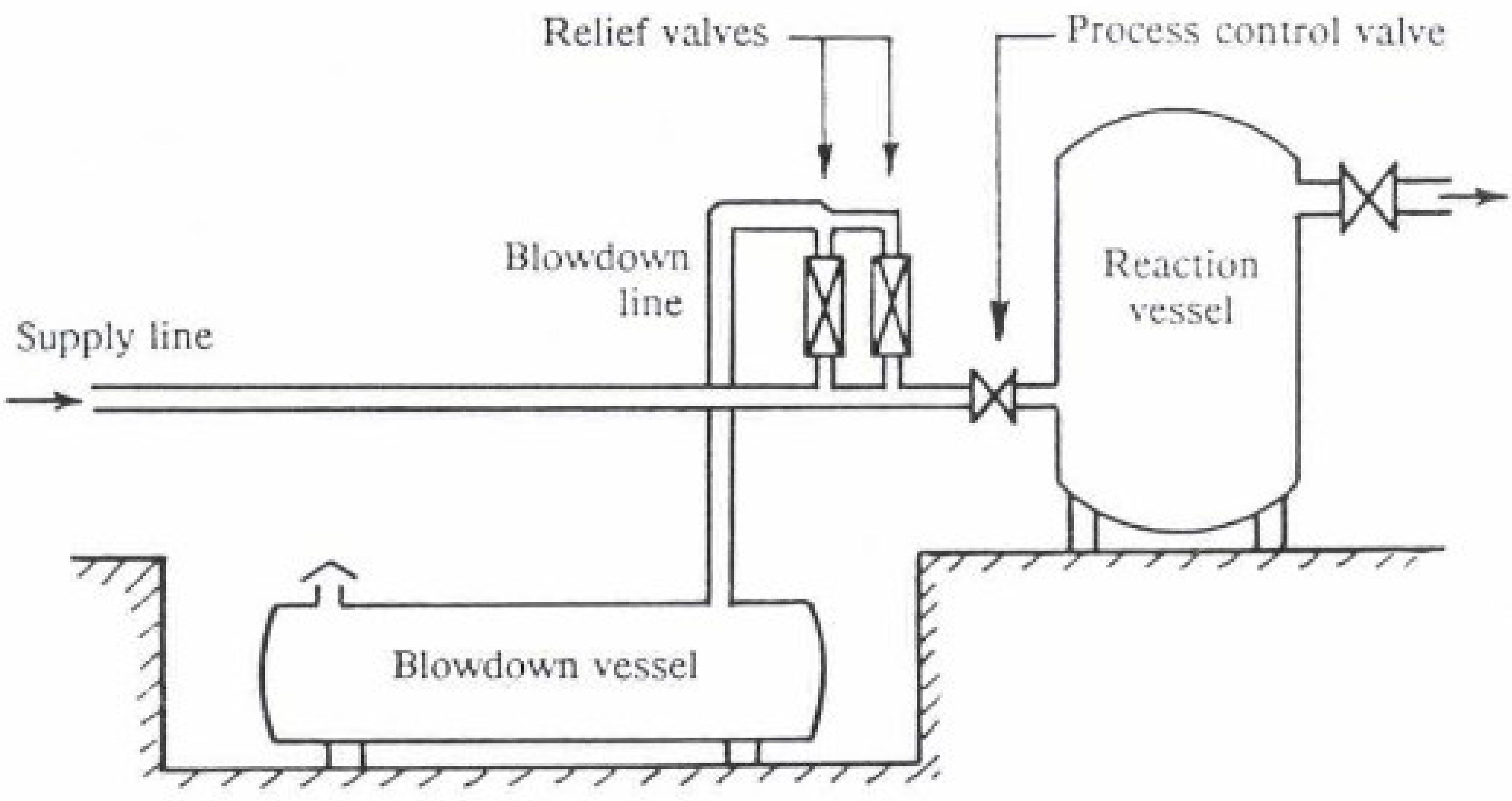
Water Hammer- Mitigation

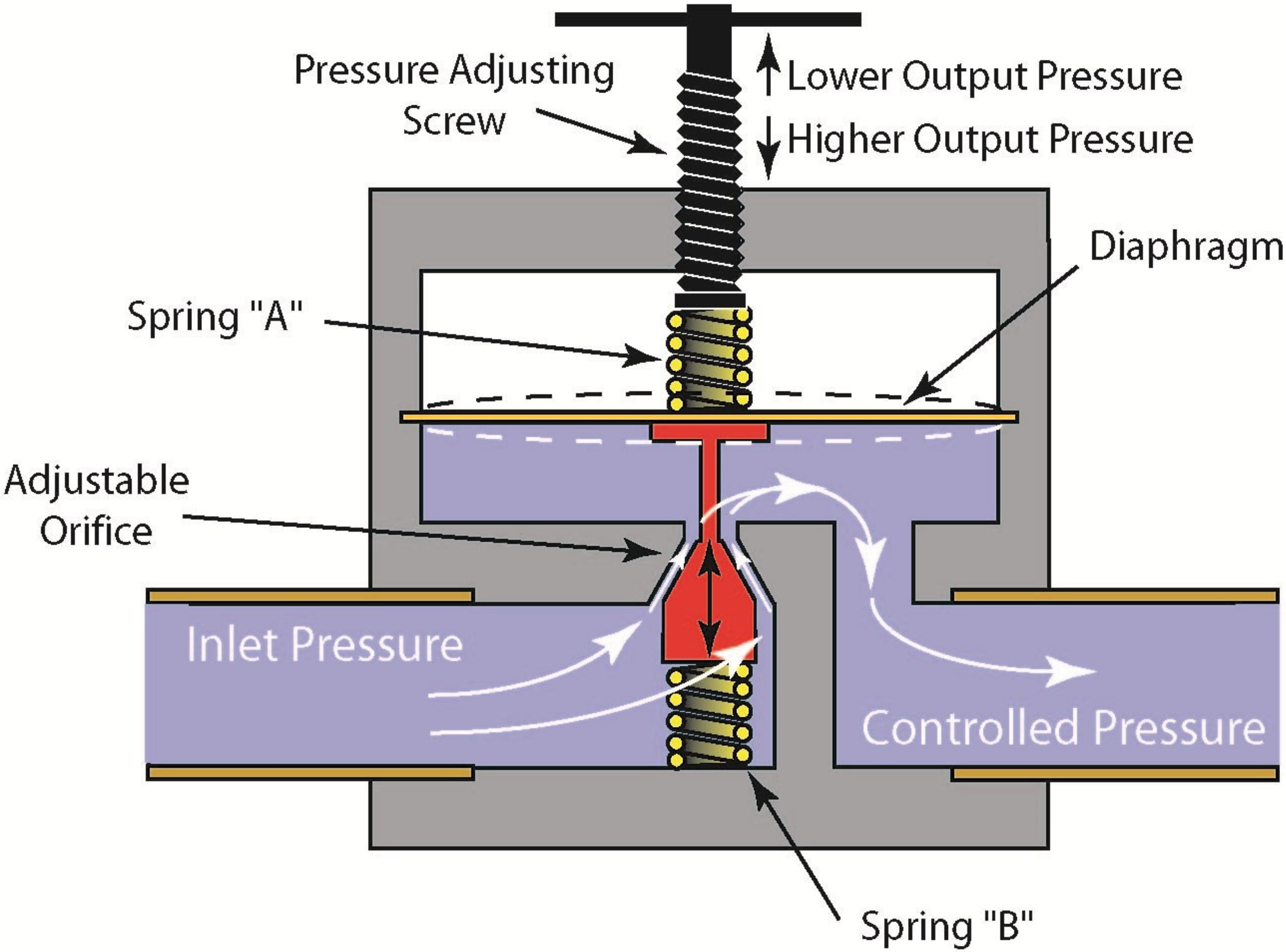


- Pressure relief valve
  - Pro
    - Pressure is limited locally
  - Cons
    - Periodic maintenance required
    - Relief lines to dump ejected liquids
    - Risk of hammering PRV, if PRV capacity is not well sized

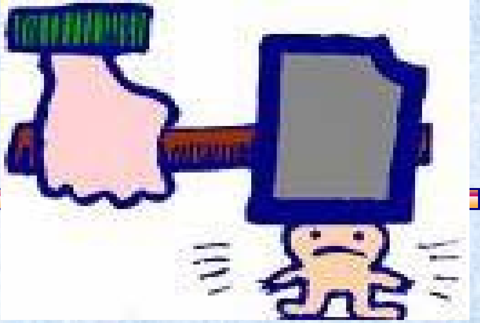
Water Hammer- Mitigation





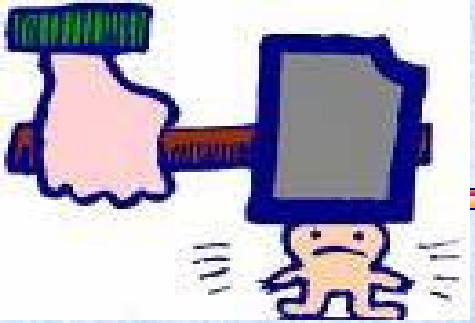

Pressure Adjusting
Screw
Lower Output Pressure
Higher Output Pressure
Diaphragm
Spring "A"
Adjustable
Orifice
Inlet Pressure
Controlled Pressure
Spring "B"

Water Hammer- Mitigation



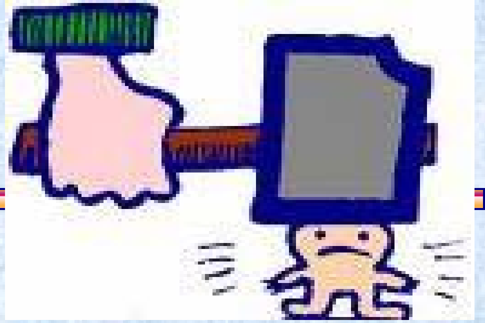
- Damper/ accumulator
  - Gas pocket separated by a membrane
  - Pro
    - No direct contact with the liquid
    - Gas pocket does not dissolve
    - Set pressure provides flexibility
  - Cons
    - Volume limited
    - Activated only after set pressure is exceeded

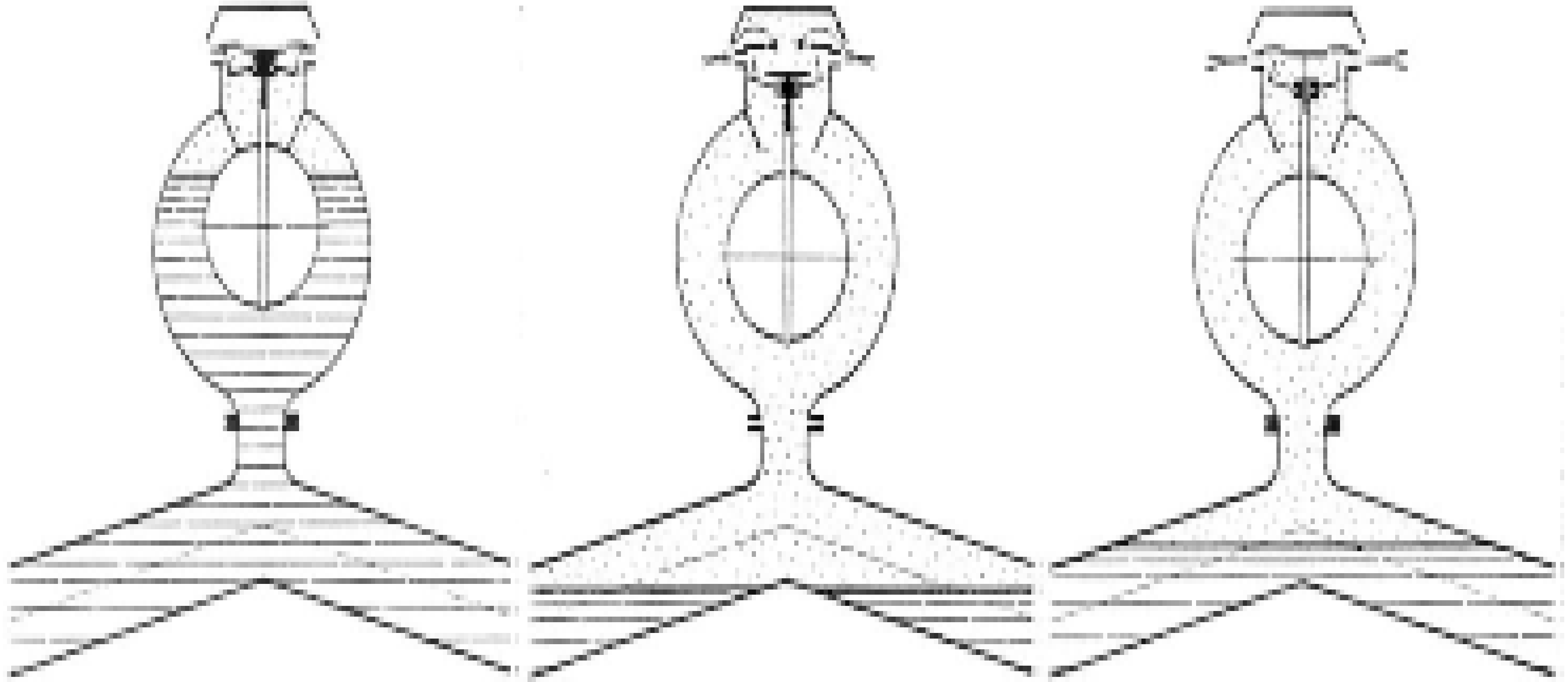
Water Hammer- Mitigation



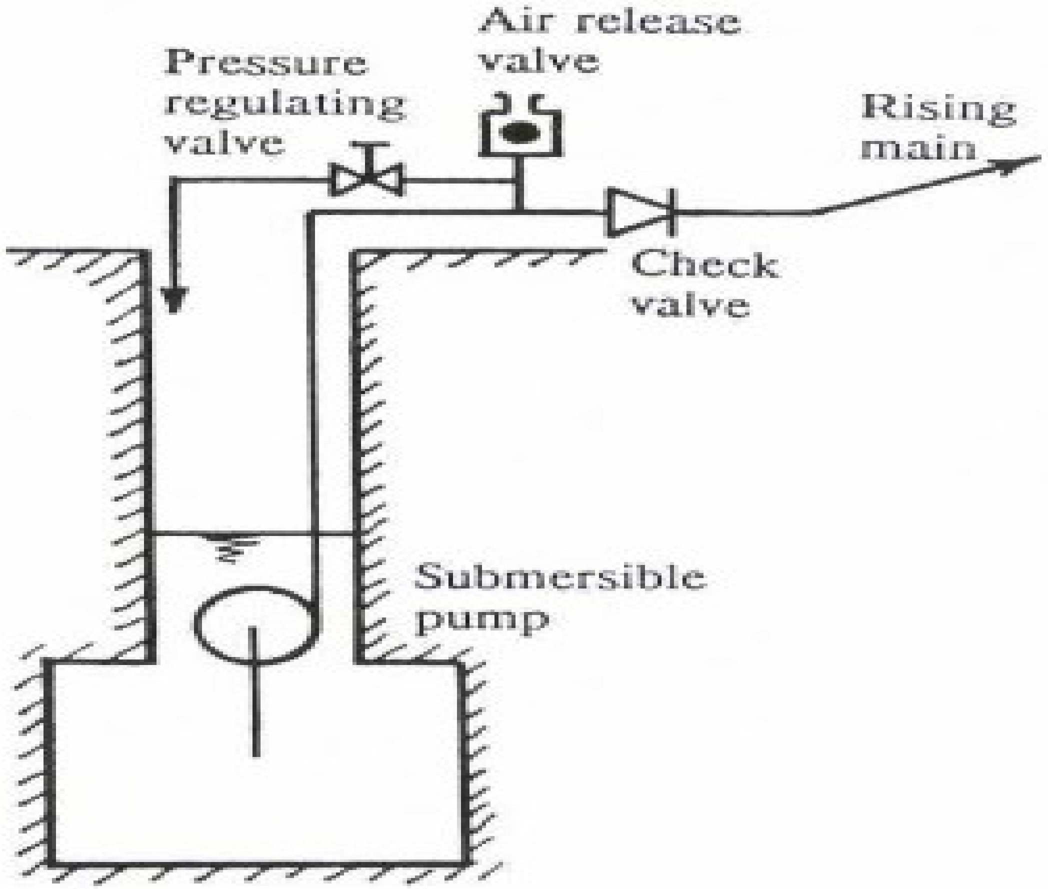
- Air Valve
  - Control high pressure transients
  - Pro
    - Limit pressure locally
  - Cons
    - All incoming air should be released afterwards
    - Accuracy in installation and location
    - Vulnerable to fouling and blocking (i.e. need periodic maintenance)

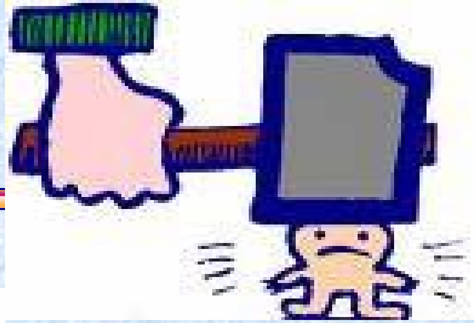
Water Hammer- Mitigation





Water Hammer- Mitigation

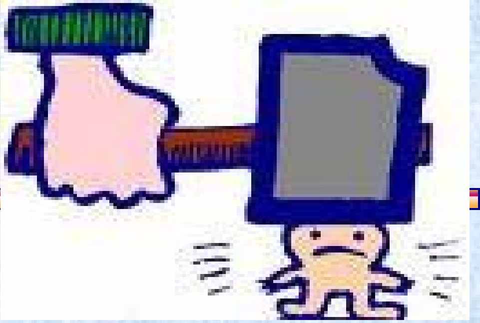


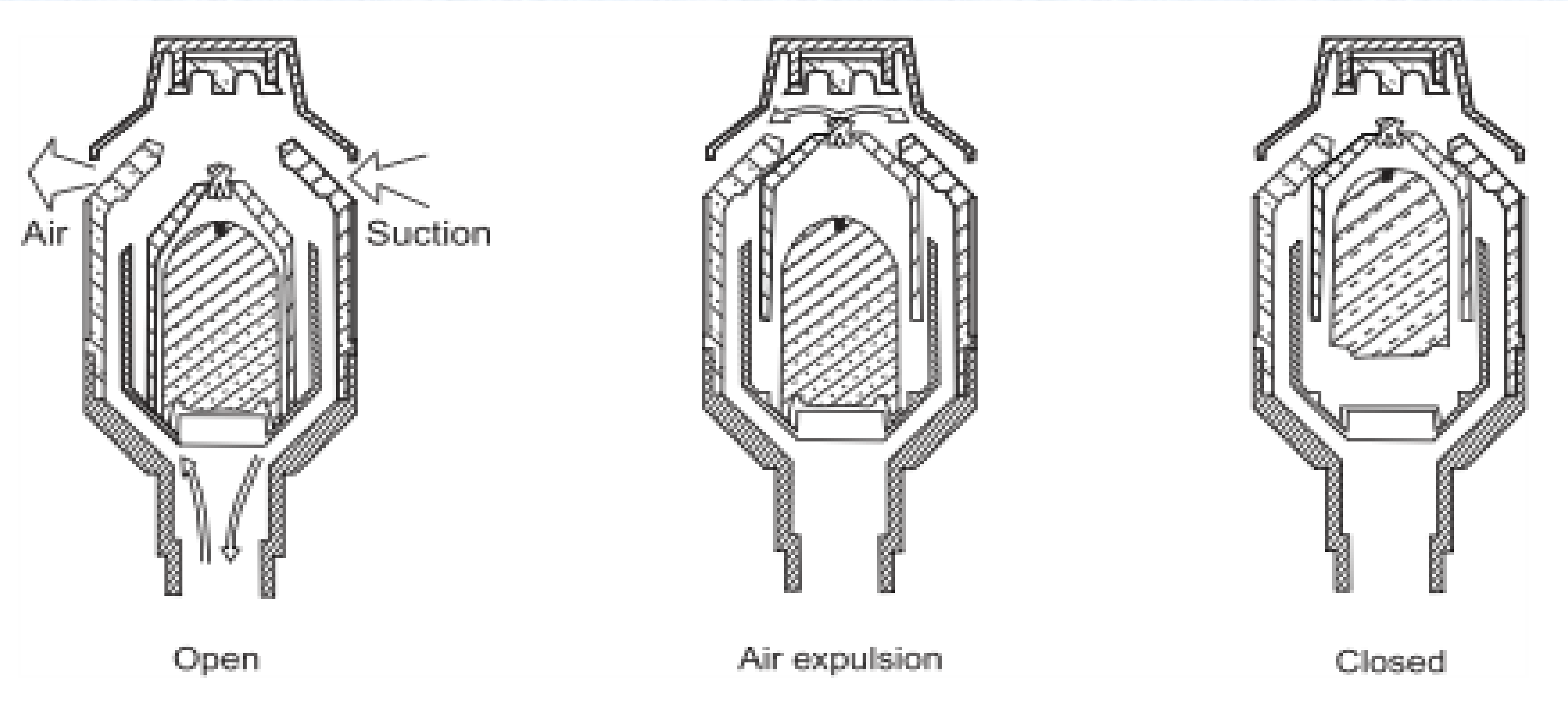


Water Hammer- Mitigation

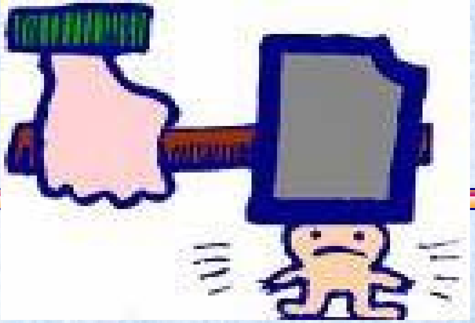
- More effective when high pressure transients occur quickly.
- Air Inlet Valves
  - Located at high points
  - Purpose – control
    - Vacuum condition
    - Potential column separation
  - Modus –operandi
    - Slow air removal
    - Adequate time

Water Hammer- Mitigation



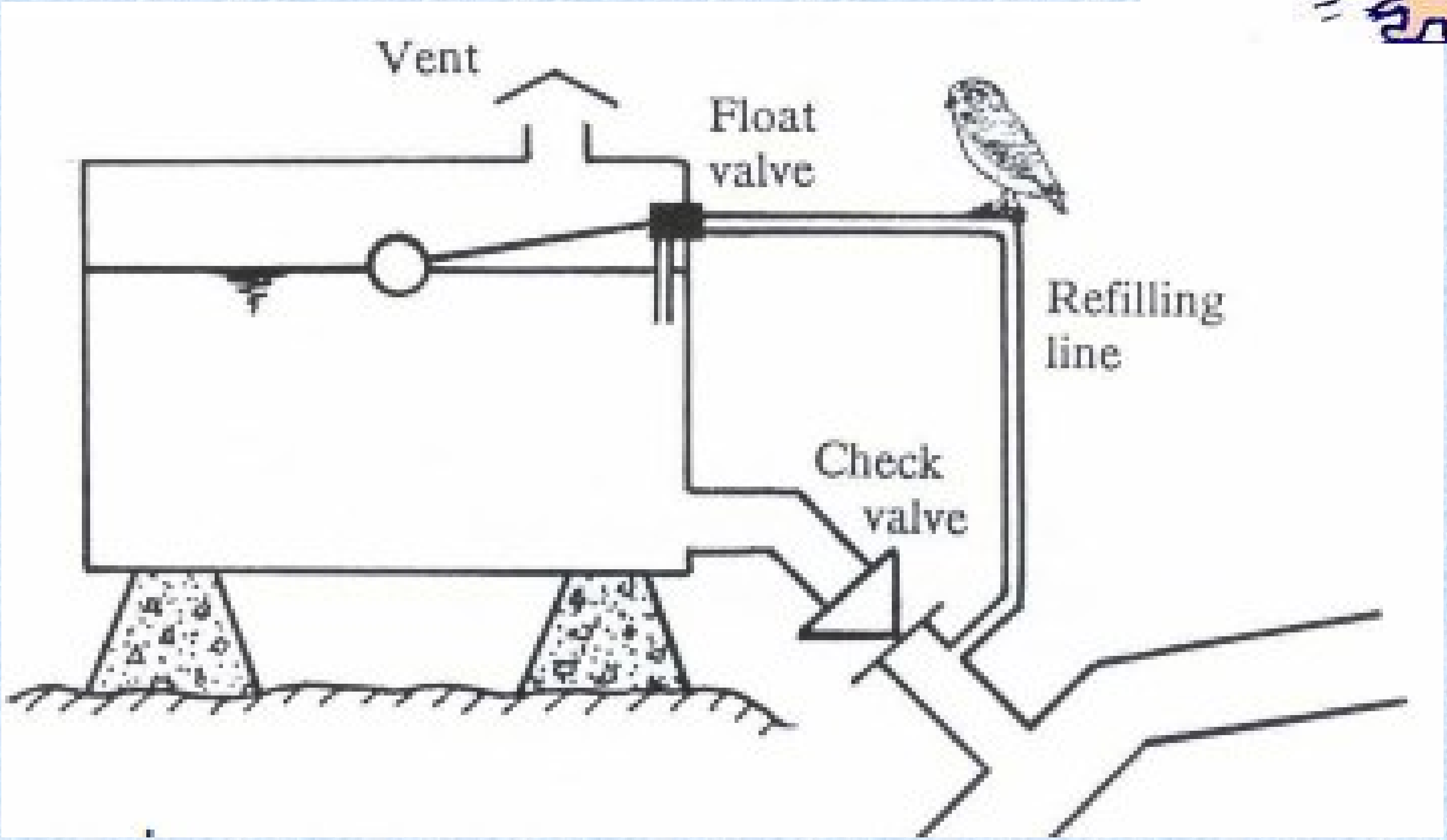


Water Hammer- Mitigation

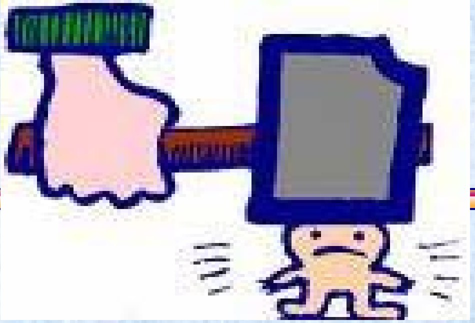


- Feed Tank
  - Pro
    - Simple construction
    - Self refilling
  - Cons
    - Limits negative pressure only
    - Risk of water quality problems

Water Hammer- Mitigation



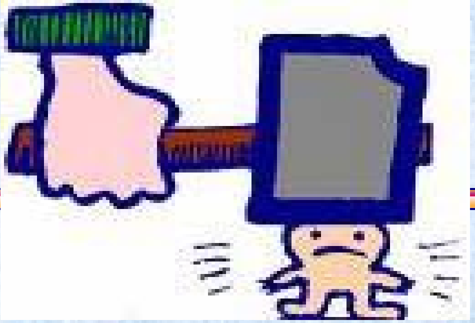
Water Hammer- Mitigation



To control minimum pressures, the following can be adjusted or implemented:

- Pump inertia
- Surge tanks
- Air chambers
- One-way tanks
- Air inlet valves
- Pump bypass valves

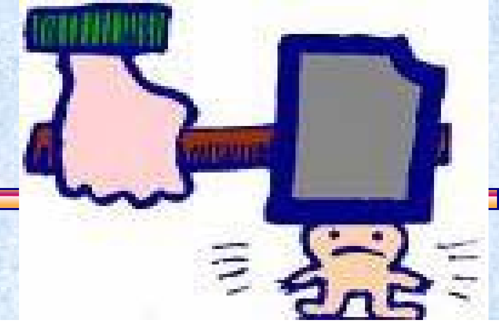
Water Hammer- Mitigation



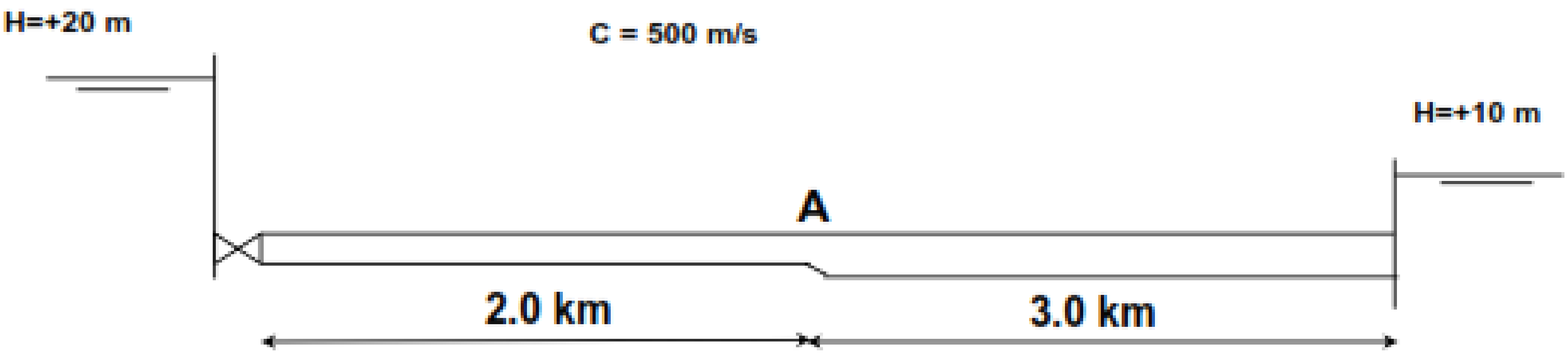
To control maximum pressures, the following can be implemented:

- Relief valves
- Anticipator relief valves
- Surge tanks
- Air chambers
- Pump bypass valves

Excercise



Fast valve opening



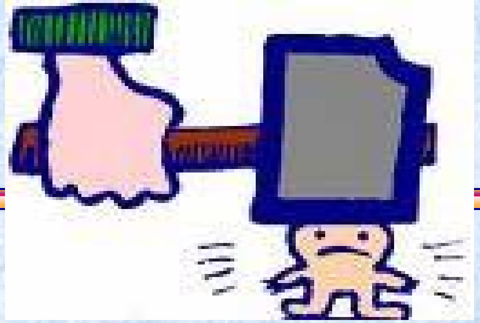
L = 1000 m

D_1 = 300 mm; D_2 = 424 mm

frictionless pipe, conveying water

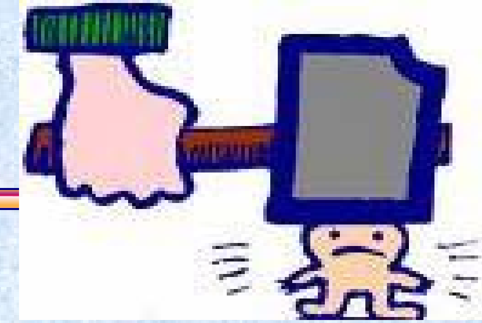
- Draw time graphs of head at 0 km, 2.5 km and 5 km (first 22 s)

Excercise



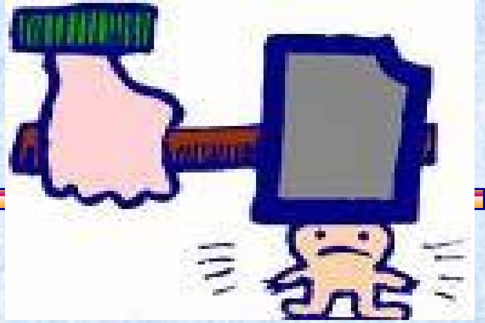
- 13.1 (Advanced Water Distribution Modeling)
- 13.2

Exercise



- Derive Joukowsky's law from Newton's Second Law of motion. You may assume the wave speed equals c.

Information



- WHAMO
  - Water Hammer and Mass Oscillation Program