Drainage and Drainage Structures

- Definition:
  - Highway drainage is the process of collecting, transporting, and disposing of surface water and underground water encountered within the limits of the ROW and adjacent territory.
- The serviceability of a highway is greatly dependant upon the adequacy of its drainage system.
- Drainage costs 20 – 25% of the total highway cost.
  - Proper drainage design is essential.
  - It is an integral part of an economic road design.
- Good drainage design… good highway location that avoid
  - Poorly drained areas
  - Unstable soil
  - Frequently flooded areas
  - Unnecessary stream crossings

Drainage and Drainage Structures

- Highways by their nature cut across natural drainage ways and streams…
  - Adequate and economical drainage is absolutely essential for
    - The protection of the environment
    - Safeguarding the lives of the persons using the highway
- Problems resulting from poor drainage
  - Standing water on pavements is a danger to traffic safety
  - Seepage water into pavement and subgrade leads to…
    - Development of soft spots & breakup of the surfacing
  - Streams have the power to…
    - Destroy roadways by force & holdup traffic by flooding

Drainage and Drainage Structures









Drainage and Drainage Structures

- Requirements of highway drainage system
  - Surface water from carriageway and shoulder should effectively be drained
  - Surface water from adjoining land should be prevented from entering the roadway
  - Flow of surface water across the road and shoulders and along slopes shouldn't cause formation of cross ruts or erosion
  - Seepage and other sources of underground water should be drained off by the subsurface drainage system
  - In water logged areas special precautions should be taken

Drainage and Drainage Structures

Environmental considerations







Environmental, Social, and Economic impacts…

Drainage and Drainage Structures

- Factors to be considered in drainage design
  - Size of the area to be drained
  - Expected maximum rainfall
  - Slop of the surrounding terrain / possible rate of runoff
  - Characteristics of the soil (incl.: permeability, tendency to erode)
  - Presence of springs or other underground water
  - General elevation of the ground water level
  - Minimum depth of cover required to protect pipes from traffic loads

Drainage and Drainage Structures

- Surface Drainage
  - The measure taken to control the flow of surface water is generally termed as surface drainage.
  - Structures that provide for surface drainage include:
    - Roadway Crown, Shoulder, Side Ditches, Cross-sectional Ditches (Fords), Culverts, Bridges.
  - The flow of surface water adjacent to highways is frequently accompanied by detrimental soil erosion resulting in
    - Destruction of productive soils,
    - Clogging of ditches and drainage structures

Soil erosion is likely to happen if the velocity of water exceeds 0.61 m/s.

Drainage and Drainage Structures

- Surface Drainage
  - Hydrological study:- To determine amount of water
  - Hydraulic study:- To design the drainage facility

  - Hydrological study
    - Precipitation: Rain, Hail, or Snow
      - Important – Rainfall intensity and duration
    - Runoff: difference b/n amount of rainfall and loss due to infiltration, evaporation, transpiration, interception, & storage

Drainage and Drainage Structures

- Surface Drainage
  - Methods to determine surface runoff
    - Rational method (Lloyed-Daves) [≤ 10 km²]
    - Talbot method (10 – 100 km²)

  - Rational method

    Where:

    $$Q = 0.278\,CIA$$

    $$Q_d = 2Q$$

    - Q = Discharge (m³/sec)
    - C = Runoff coefficient (represent rate of runoff to rainfall)
    - I = Rainfall intensity (mm/hr)
    - A = Catchment area (km²) [If A is in ha, 1 ha = 100 km²]

Drainage and Drainage Structures

Surface Drainage

Values of runoff coefficient (C) – Rational method

Types of Surface	Runoff Coefficient, *C*
RURAL AREAS	
Concrete or sheet asphalt pavement	0.8 – 0.9
Asphalt macadam pavement	0.6 – 0.8
Gravel roadways or shoulders	0.4 – 0.6
Bare earth	0.2 – 0.9
Steep grass areas (slope 2 : 1)	0.5 – 0.7
Turf meadows	0.1 – 0.4
Forest area	0.1 – 0.3
Cultivated fields	0.2 – 0.4
URBAN AREAS	
Flat residential, ≈ 30% of area impervious	0.4
Flat residential, ≈ 60% of area impervious	0.55
Moderately steep residential, ≈ 50% of area impervious	0.65
Moderately steep residential, ≈ 70% of area impervious	0.8
Flat commercial, ≈ 90% of area impervious	0.8

NB: For flat slopes or permeable soil, use the lower values
For steep slopes or impermeable soil, use the higher values

Drainage and Drainage Structures

Surface Drainage

- Hydraulic Design

  Once the peak runoff has been determined for a particular catchment, the next step is the hydraulic design of the drainage system to carry it.

  - The Manning equation:

$$Q_d = A \cdot v = A \cdot \frac{R^{2/3} \cdot S^{1/2}}{n}$$

  - Where:

Q = Design discharge (m^3/sec)
A = Cross sectional area of the channel (m^2)
v = Velocity of flow (m/sec)
R = Hydraulic radius
S = the slop of the channel
n = Manning's roughness coefficient
P = wetted perimeter

$$R = \frac{A}{P}$$

Drainage and Drainage Structures

Surface Drainage

Values of Manning's roughness coefficient

Type of lining	Value of n
Ordinary earth, smooth graded	0.02
Jagged rock or rough rubble	0.04
Rough concrete	0.02
Bituminous lining	0.02
Smooth rubble	0.02
Well maintained grass	
depth of flow > 150mm	0.04
depth of flow < 150mm	0.06
Heavy grass	0.10

Drainage and Drainage Structures

Surface Drainage

Maximum safe velocity if channel erosion is to be prevented

Type of lining	Allowable velocity (m/s)
Well – established grass on any good soil	2
Meadow type of grass with short, plaint blades, heavy stand, such as blue grass	1.5
Bunch grasses, exposed soil b/n plants	0.5 – 1.2
Grains, staff-steamed grasses	0.5 – 1.0
Earth without vegetation	
fine sand or silt, little or no clay	0.3 – 0.6
ordinary form loam	0.5 – 1.0
stiff clay, highly colloidal	1.2
clay and gravel	1.2
coarse gravel	1.2
soft shale	1.5

Drainage and Drainage Structures

Surface Drainage

- Best hydraulic sections
  - a) Semi-circular cross-section
    - This x-section is the best hydraulic section
      - for a given Q, S, and n ⟹ smallest A and P
      - for a given A, S, and n ⟹ max. Q and min. P
  - b) Rectangular cross-section
  - c) Trapezoidal cross-section
  - d) Circular cross-section
    - full

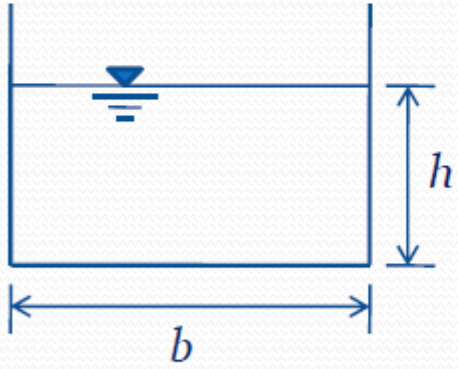
$$A = \pi r^2 \quad , \quad P = 2\pi r$$

$$R = \frac{A}{P} = \frac{\pi r^2}{2\pi r} = \frac{r}{2}$$

Drainage and Drainage Structures

Surface Drainage

- Best hydraulic sections
  - Rectangular section



$$A = bh \quad \Rightarrow \quad b = A/h$$

$$P = 2h + b = 2h + A/h$$

$$\frac{dP}{dh} = 2 - \frac{A}{h^2} = 0$$

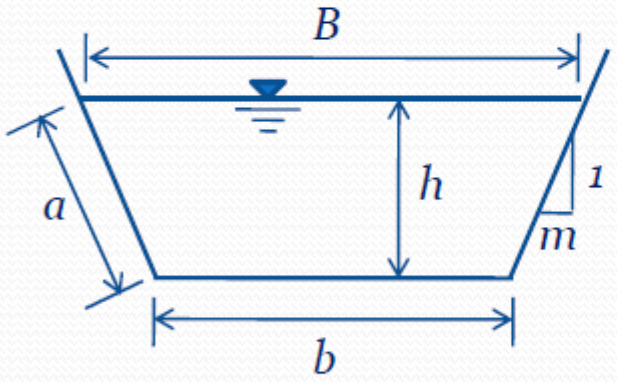
$$\Rightarrow \qquad A = 2h^2 \quad \text{and} \quad b = 2h$$

$$R = \frac{A}{P} = \frac{2h^2}{2h + 2h} = \frac{h}{2}$$

Drainage and Drainage Structures

Surface Drainage

- Best hydraulic sections
  - Trapezoidal section



$$A = \left(\frac{B+b}{2}\right)h = \frac{(b+2mh+b)\cdot h}{2}$$

$$\Rightarrow A = \frac{(2b+2mh)\cdot h}{2} = (b+mh)\cdot h$$

$$\Rightarrow b = A/h - mh$$

$$a = \sqrt{(mh)^2 + h^2} = h\sqrt{1+m^2}$$

$$P = 2a + b = 2h\sqrt{1+m^2} + (A/h - mh)$$

$$\frac{dP}{dh} = 2\sqrt{1+m^2} - A/h^2 - m = 0$$

$$\Rightarrow A/h^2 = 2\sqrt{1+m^2} - m$$

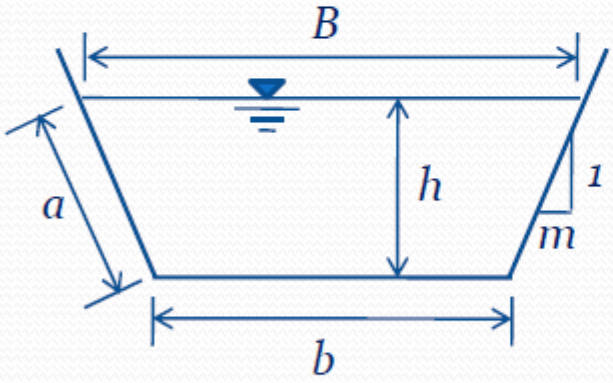
$$\Rightarrow A = h^2\left(2\sqrt{1+m^2} - m\right)$$

$$\Rightarrow \quad h = \sqrt{\frac{A}{2\sqrt{1+m^2} - m}}$$

Drainage and Drainage Structures

Surface Drainage

- Best hydraulic sections
  - Trapezoidal section



$$P = 2h\sqrt{1+m^2} + (A/h - mh)$$

$$P = 2h\sqrt{1+m^2} + \frac{h^2\left(2\sqrt{1+m^2} - m\right)}{h} - mh$$

$$= 2h\sqrt{1+m^2} + 2h\sqrt{1+m^2} - mh - mh$$

$$= 4h\sqrt{1+m^2} - 2mh$$

$$= 2h\left(2\sqrt{1+m^2} - m\right)$$

$$R = \frac{A}{P} = \frac{h^2\left(2\sqrt{1+m^2} - m\right)}{2h\left(2\sqrt{1+m^2} - m\right)} = \frac{h}{2}$$

$$b = A/h - mh$$

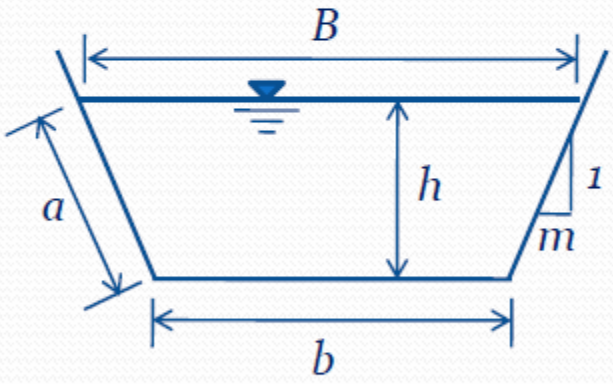
$$= h\left(2\sqrt{1+m^2} - m\right) - mh = 2h\left(\sqrt{1+m^2} - m\right)$$

$$B = b + 2mh = 2h\left(\sqrt{1+m^2}\right)$$

Drainage and Drainage Structures

Surface Drainage

- Best hydraulic sections
  - Trapezoidal section



$$P = 2h\sqrt{1+m^2} + A/h - mh$$

$$\frac{dP}{dm} = \frac{1}{2}\cdot 2h\left(1+m^2\right)^{-1/2}\cdot 2m - h = 0$$

$$= \frac{2mh}{\sqrt{1+m^2}} - h = 0 \quad \Rightarrow \quad \frac{2m}{\sqrt{1+m^2}} = 1$$

$$\Rightarrow \qquad 2m = \sqrt{1+m^2}$$

$$\Rightarrow \qquad 4m^2 = 1+m^2 \quad \Rightarrow \quad 3m^2 = 1$$

$$\Rightarrow \qquad m = \sqrt{\frac{1}{3}} = \frac{\sqrt{3}}{3} = 0.577$$

$$\Rightarrow \qquad \alpha = 60^0$$

Drainage and Drainage Structures

Surface Drainage

- Example:

  The drainage area which contributes runoff to a proposed culvert installation is 1.30 km² in extent. The rainfall intensity of the area is 57 mm/hr. The area has an average slope of about 4%. Assuming a runoff coefficient of 0.25, determine the quantity of flow and design the size of the culvert. [NB: If slope of culvert is not given, use S = 10% as a default value]

- Solution:

Given: $C = 0.25$, $I = 57\,\text{mm/hr}$, $A = 1.3\,\text{km}^2$

$$Q = 0.278\,C\,I\,A$$

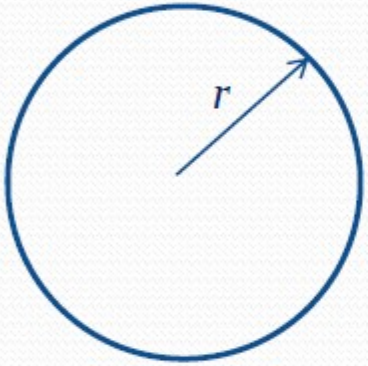
$$= 0.278(0.25 \times 57 \times 1.30) = 5.15\,\text{m}^3/\text{sec}$$

$$Q_d = 2Q = 10.3\,\text{m}^3/\text{sec}$$

Drainage and Drainage Structures

Surface Drainage

- Concrete Pipe



$$n_{avg} = 0.0134$$

$$Q_d = \frac{A}{n} R^{2/3} S^{1/2}$$

$$\Rightarrow \qquad 10.30 = \frac{\pi r^2}{0.0134}\left(\frac{r}{2}\right)^{2/3}\left(\frac{4}{100}\right)^{1/2}$$

$$= r^{3/8}\left(\frac{\pi \cdot (0.04)^{1/2}}{0.0134 \times 2^{2/3}}\right) = 29.54\, r^{8/3}$$



$$\Rightarrow \qquad r = 0.67\,\text{m} \quad \rightarrow \quad \text{say } 0.70\,\text{m}$$

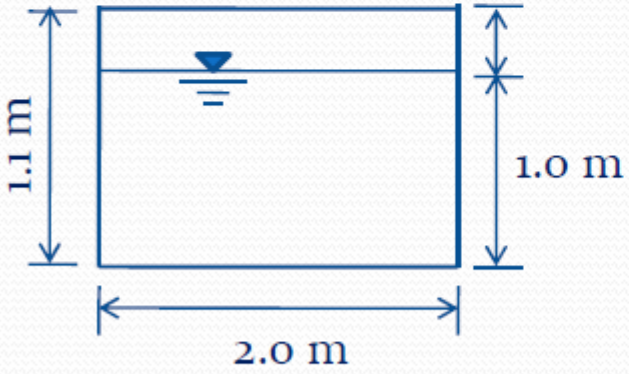
Drainage and Drainage Structures

Surface Drainage

- Box Culvert

$$n_{avg} = 0.021 \quad \text{(masonry lining)}$$

$$Q_d = \frac{A}{n} R^{2/3} S^{1/2}$$



$$\Rightarrow \quad 10.30 = \frac{2h^2}{0.021}\left(\frac{h}{2}\right)^{2/3}\left(\frac{4}{100}\right)^{1/2}$$

$$= 12\,h^{8/3}$$

$$\Rightarrow \quad h = 0.944\,\text{m} \quad \approx 1.0\,\text{m}$$

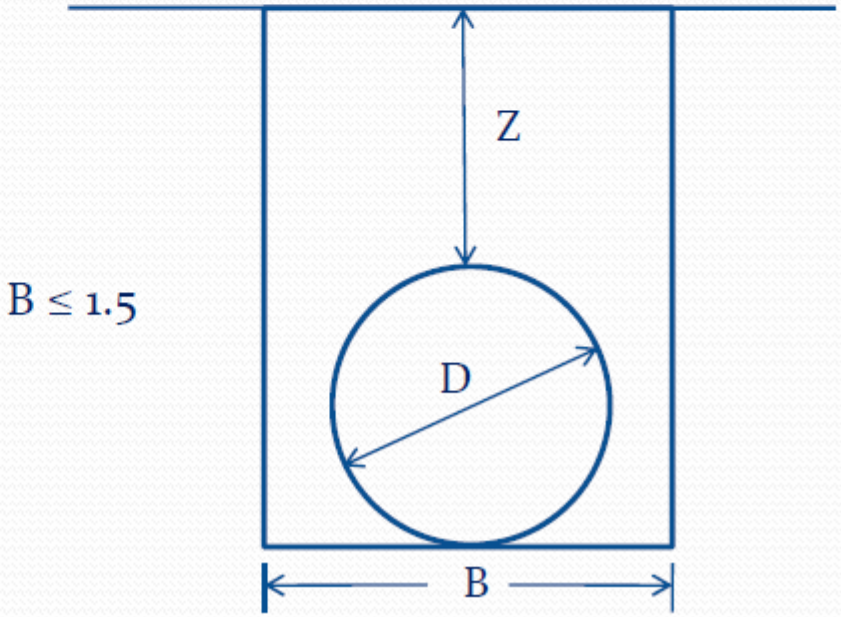
$$\rightarrow \quad \text{take h} = 1.10\,\text{m (to make it atm. flow)}$$

$$b = 2h = 2.0\,\text{m}$$

Drainage and Drainage Structures

Surface Drainage

- Pressure due to external loads
  - a) Overburden pressure on the culvert
  - b) Traffic loading



Large Z implies..... ??
Small Z implies..... ??

Drainage and Drainage Structures

Surface Drainage

- Overburden pressure
  - Flexible pipes – steel pipe

$$p = k \gamma B D$$

  - Ridged pipes – concrete, cast iron, etc...

$$p = k \gamma B^2$$

Where:

p = Applied pressure per meter

k = A Coefficient (Value depends on type of pipe & characteristic of foundation and backfill)

B = Trench width (m)

γ = Unit weight of the back fill (KN/m^3)

D = Diameter of pipe or culvert (m)

Drainage and Drainage Structures

Surface Drainage

- Overburden pressure – Values of k

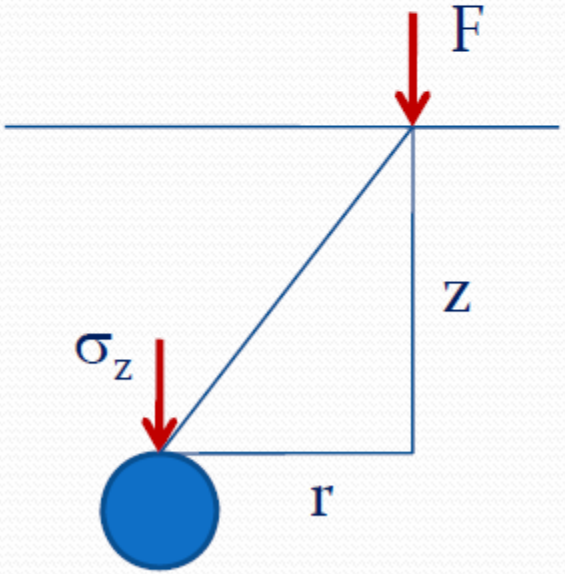
	Unit weight	Dry sand & gravel	Saturated top soil	Clay	Saturated clay
Z/B	γ —>	16	16	19.2	20.8
1		0.84	0.86	0.88	0.90
2		1.45	1.50	1.55	1.62
3		1.90	2.00	2.10	2.26
4		2.22	2.33	2.49	2.65
5		2.45	2.60	2.80	3.03
6		2.60	2.78	3.04	3.33
7		2.75	2.95	3.23	3.57
8		2.80	3.03	3.37	3.76
9		2.88	3.11	3.48	3.92
10		2.92	3.17	3.56	4.04

Drainage and Drainage Structures

Surface Drainage

- Traffic load transmitted to the culvert

  Boussinesq's Equation:



$$\sigma_z = \frac{F}{2\pi} \cdot \frac{3z^3}{\left(r^2 + z^2\right)^{5/2}}$$

or

$$\sigma_z = \frac{F}{z^2} \cdot \frac{3/2\pi}{\left(1 + \left(\frac{r}{z}\right)^2\right)^{5/2}}$$

Where:

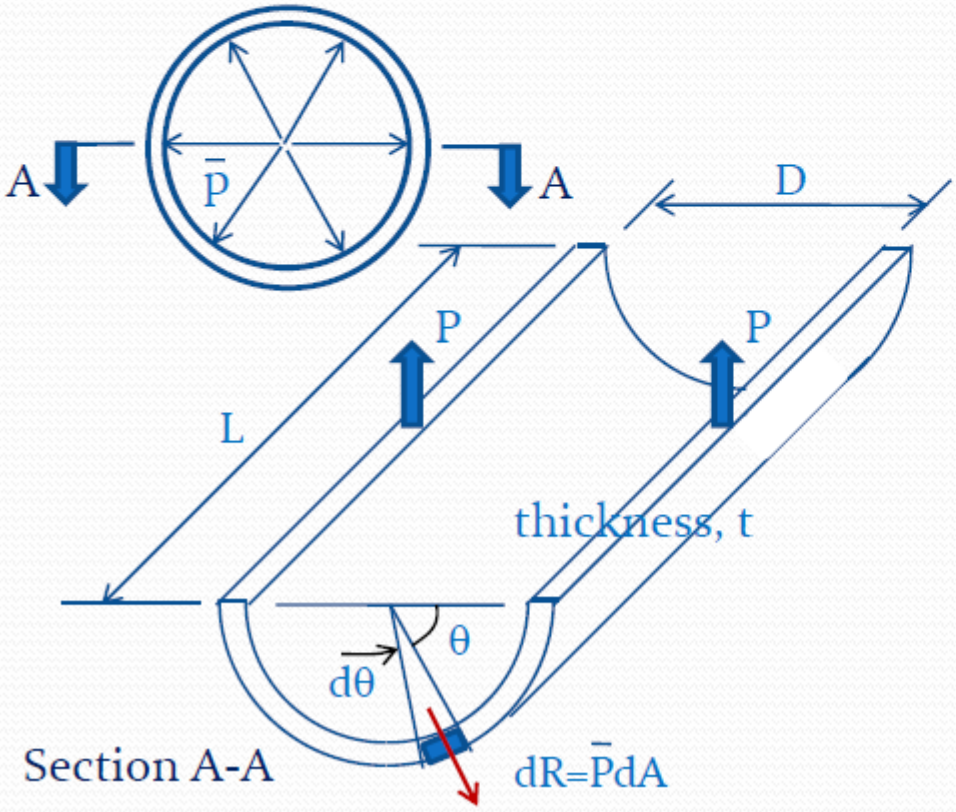
F = Concentrated load from traffic

σ_z = Stress induced to the culvert

Drainage and Drainage Structures

Surface Drainage

- Analysis of Thickness:
  - Thin wall cylinder principles



$$dR = \bar{p}\,dA = \bar{p}L(D/2)d\theta$$

$$dR_V = dR\,Sin\theta = \bar{p}L(D/2)Sin\theta\,d\theta$$

$$R_V = \int_0^{\pi} \frac{\bar{p}LD}{2} Sin\theta\,d\theta = \frac{\bar{p}LD}{2}\left[-Cos\theta\right]_0^{\pi}$$

$$R_V = \bar{p}DL$$

$$\sum V = 0 \quad \Rightarrow \quad R_V = \bar{p}DL = 2P$$

Stress in the longitudinal section

$$\sigma = \frac{P}{A_w} = \frac{\bar{p}DL}{2tL} = \frac{\bar{p}D}{2t} \Rightarrow \boxed{t = \frac{\bar{p}D}{2\sigma}}$$

Drainage and Drainage Structures

Example:

The catchment area which contributes runoff to the proposed culvert installation is 28.3 ha of bare earth, 40.5 ha of forested area and 101.2 ha of cultivated fields. The rainfall intensity is 64 mm/hr and the average slope of the terrain is 3%. Determine the quantity of flow and design a circular culvert if n=0.011. The pipe is buried in a trench 1.5 m wide and backfilled with dry sand. The top of the pipe is 3.2 m below the road. The pipe passes at a perpendicular direction under a two carriage way road which carries a critical vehicle whose loading is shown below.

(Density of dry sand, γ = 16 KN/m^3)

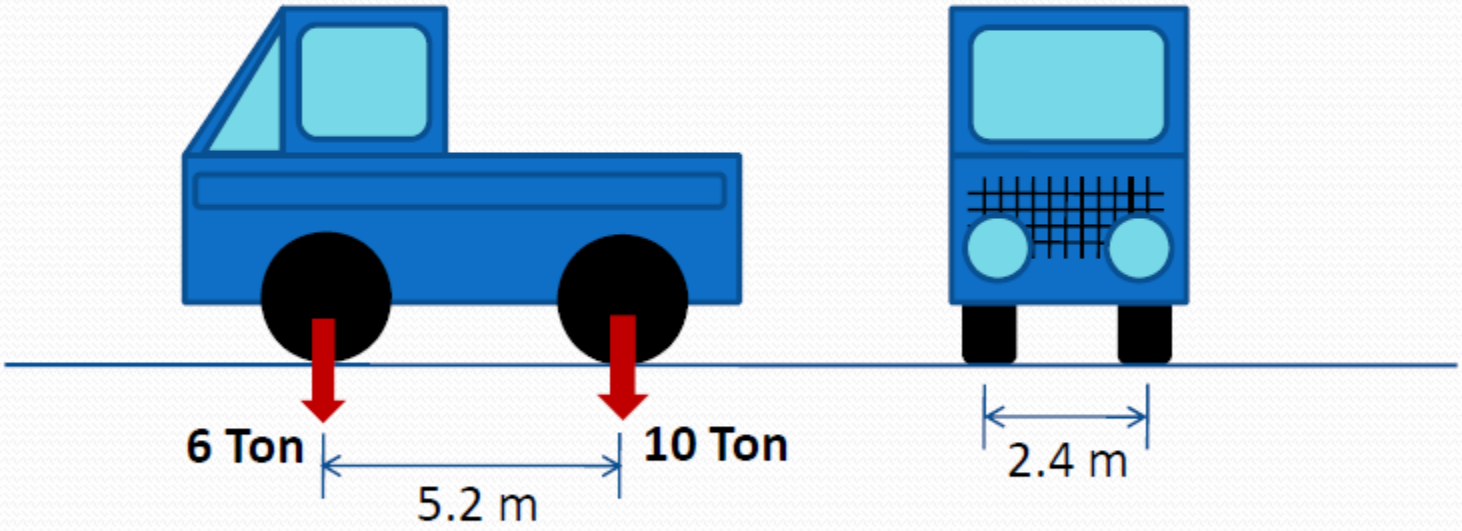
Find the required thickness of the pipe if

a) the pipe is made of steel, σ_{all} = 25 MPa

b) the pipe is made of concrete, σ_{all} = 3 MPa

Drainage and Drainage Structures

Example:



Drainage and Drainage Structures

Example:

- Solution:

Weighted average C_W

A1	=	28.3 Ha	C1	=	0.55
A2	=	40.5 Ha	C2	=	0.2
A3	=	101.2 Ha	C3	=	0.3
Sum		170 Ha			

$$Q = 0.278\, I \sum A_i C_i$$

$$C_W = \frac{C_1 A_1 + C_2 A_2 + C_3 A_3}{A_1 + A_2 + A_3} = 0.318$$

$$Q = 0.278\, CIA = 0.278 \times 0.318 \times 64 \times (170/100) = 9.618\,\mathrm{m^3/sec}$$

$$Q_d = 2Q = 19.24\,\mathrm{m^3/sec}$$

$$\mathrm{Q_d} = \frac{A}{n} R^{2/3} S^{1/2} = \frac{\pi r^2}{0.011}\left(\frac{r}{2}\right)^{2/3} (0.10)^{1/2} = \frac{r^{8/3}}{0.0176}$$

$$\Rightarrow \quad r = (0.3382)^{3/8} = 0.665 \quad \rightarrow \quad r = 0.65\,m \ \ (\mathrm{b/c\ Q_d = 2Q})$$

$$D = 2r = 1.30\,m$$

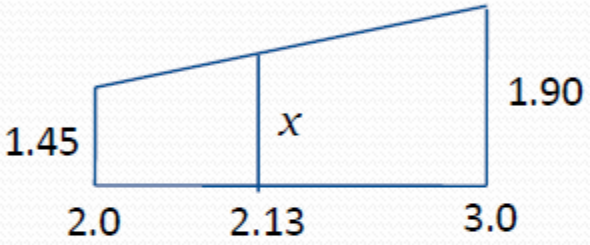
Drainage and Drainage Structures

Example:

- Overburden pressure:

$$\frac{Z}{B}=\frac{3.2}{1.5}=2.13$$

Value of k →



$$x=1.45+(0.13+0.45)/1.0=1.51=k$$

Steel pipe : $p_{st}=k\gamma BD=1.51\times16\times1.5\times1.30=47.112\,\mathrm{KN/m^3}$

Concrete pipe : $p_c=k\gamma B^2=1.51\times16\times1.5^2=54.36\,\mathrm{KN/m^3}$

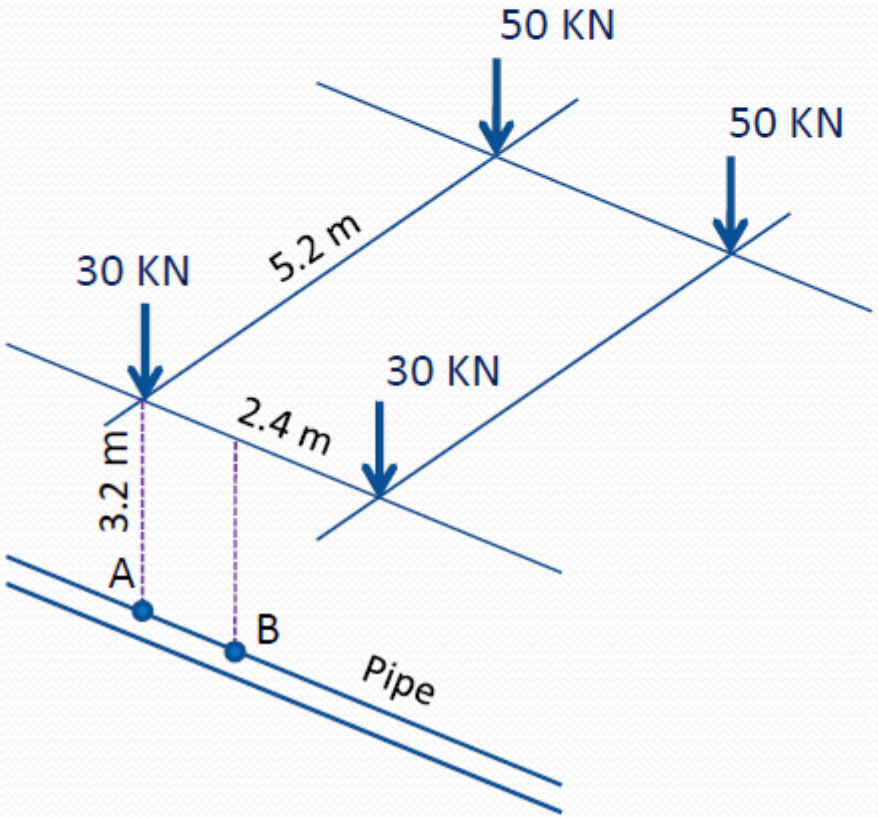
$\Rightarrow \quad \sigma_{st}=p_{st}/D=36.24\,\mathrm{KN/m^2}$

$\sigma_c=p_c/D=41.82\,\mathrm{KN/m^2}$

Drainage and Drainage Structures

Example:

- Stress analysis:
  - Case 1: Front axle on top of the pipe



$$\sigma_z = \frac{F}{z^2} \cdot \frac{3/2\pi}{\left(1+\left(\frac{r}{z}\right)^2\right)^{5/2}}$$

Drainage and Drainage Structures

Example:

- Stress analysis:
  - Case 1:

Point A1:

$$\sigma_z = \frac{30}{3.2^2}\left(\frac{0.417}{\left(1+(0)^2\right)^{5/2}}+\frac{0.477}{\left(1+(2.4/3.2)^2\right)^{5/2}}\right)$$

$$+\frac{50}{3.2^2}\left(\frac{0.417}{\left(1+(5.2/3.2)^2\right)^{5/2}}+\frac{0.477}{\left(1+\left(\sqrt{5.2^2+2.4^2}/3.2\right)^2\right)^{5/2}}\right)=2.014\,\mathrm{KN/m^2}$$

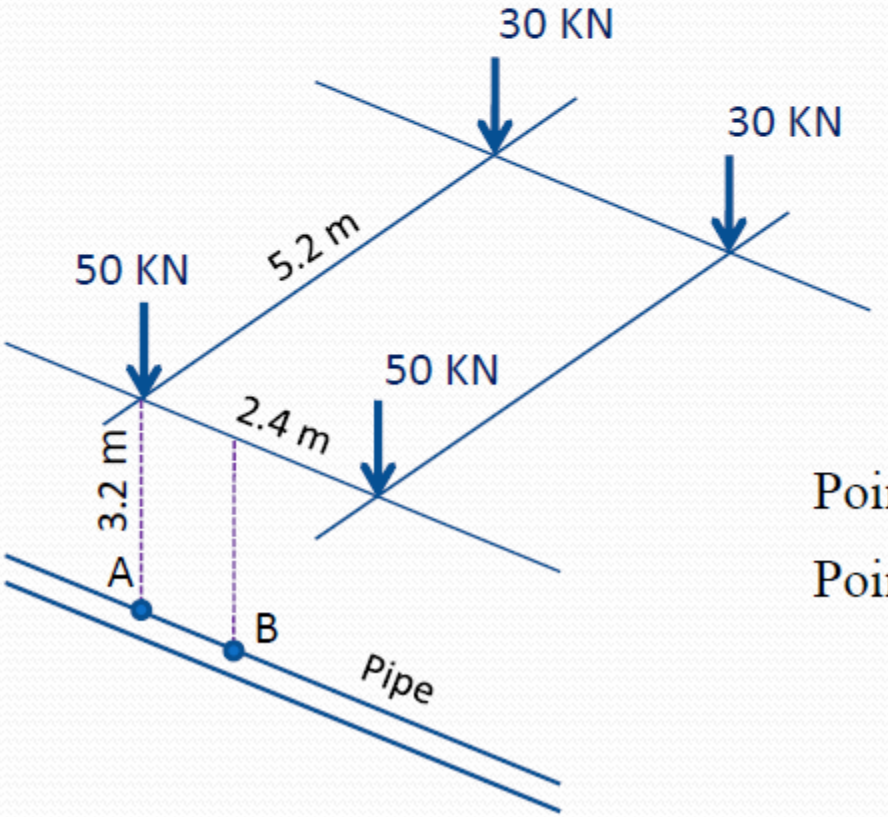
Point B1:

$$\sigma_z = 2\times\left[\frac{30}{3.2^2}\left(\frac{0.477}{\left(1+(1.2/3.2)^2\right)^{5/2}}\right)+\frac{50}{3.2^2}\left(\frac{0.477}{\left(1+\left(\sqrt{5.2^2+1.2^2}/3.2\right)^2\right)^{5/2}}\right)\right]=2.181\,\mathrm{KN/m^2}$$

Drainage and Drainage Structures

Example:

- Stress analysis:
  - Case 2: Rear axle on top of the pipe



$$\sigma_z = \frac{F}{z^2} \cdot \frac{3/2\pi}{\left(1+\left(\frac{r}{z}\right)^2\right)^{5/2}}$$

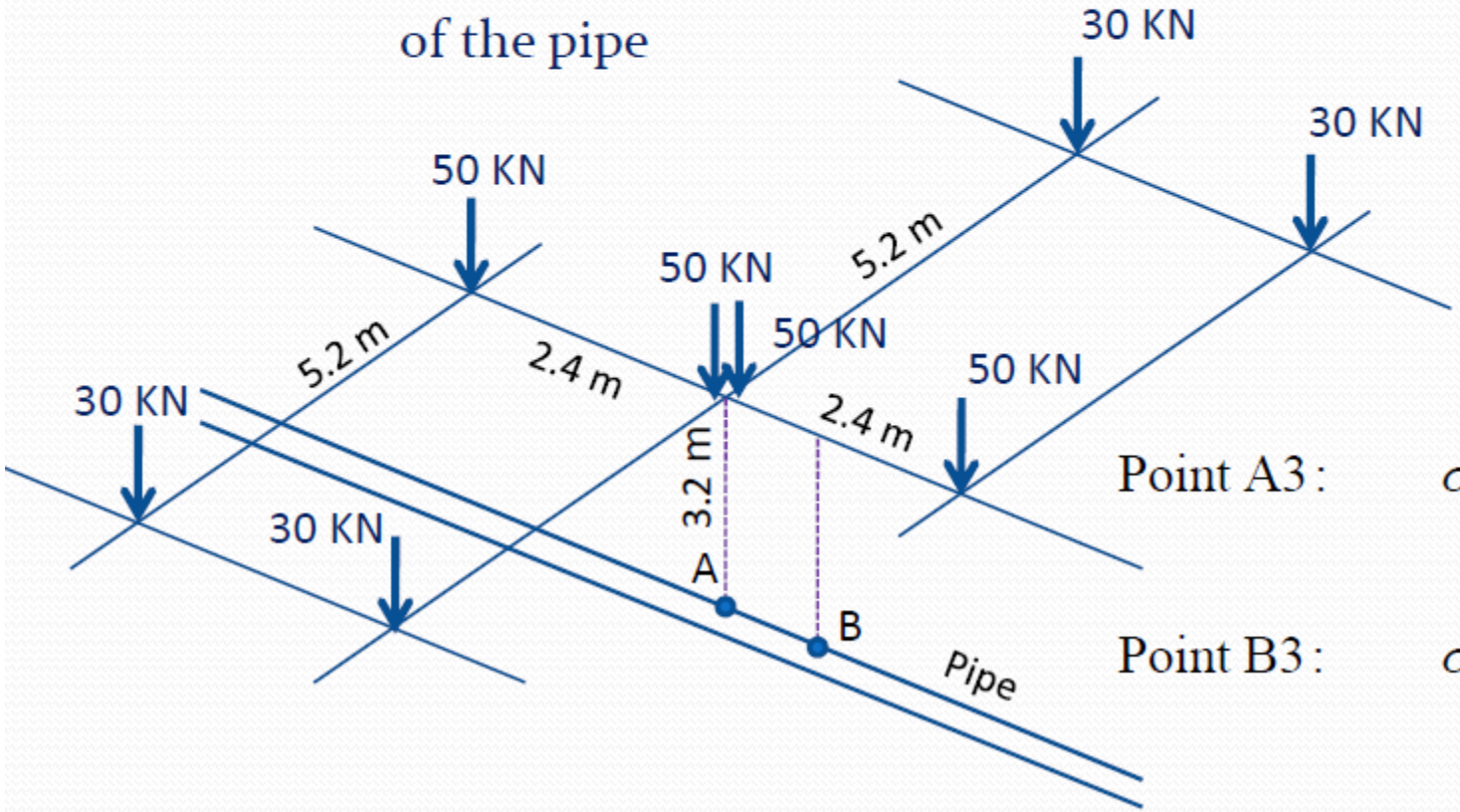
Point A2: $\sigma_z = 3.189\,\mathrm{KN/m^2}$

Point B2: $\sigma_z = 3.456\,\mathrm{KN/m^2}$

Drainage and Drainage Structures

Example:

- Stress analysis:
  - Case 3: Rear axle of vehicles moving in opposite direction on top of the pipe



Point A3: $\sigma_z = 2(\sigma_{z(A2)})$

$= 6.38\,\text{KN/m}^2$

Point B3: $\sigma_z = 5.51\,\text{KN/m}^2$

Drainage and Drainage Structures

Example:

- Stress analysis:
  - Total stress (σ)
    - On steel pipe: $= 36.24 + 6.38 = 42.62\ KN/m^2$
    - On concrete pipe: $= 41.82 + 6.38 = 48.20\ KN/m^2$
  - Thickness of pipe required…
    - Steel pipe:-

$$t = \frac{\bar{p}D}{2\sigma_{all}} = \frac{42.62 \times 1.3}{2\left(25 \times 10^3\right)} = 1.11 \times 10^{-3}\,\text{m} = 0.11\,\text{cm} \rightarrow \text{provide } 2\,\text{mm}$$

    - Concrete pipe:-

$$t = \frac{\bar{p}D}{2\sigma_{all}} = \frac{48.20 \times 1.3}{2\left(3 \times 10^3\right)} = 0.0104\,\text{m} = 1.04\,\text{cm} \rightarrow \text{provide } 2\,\text{cm}$$