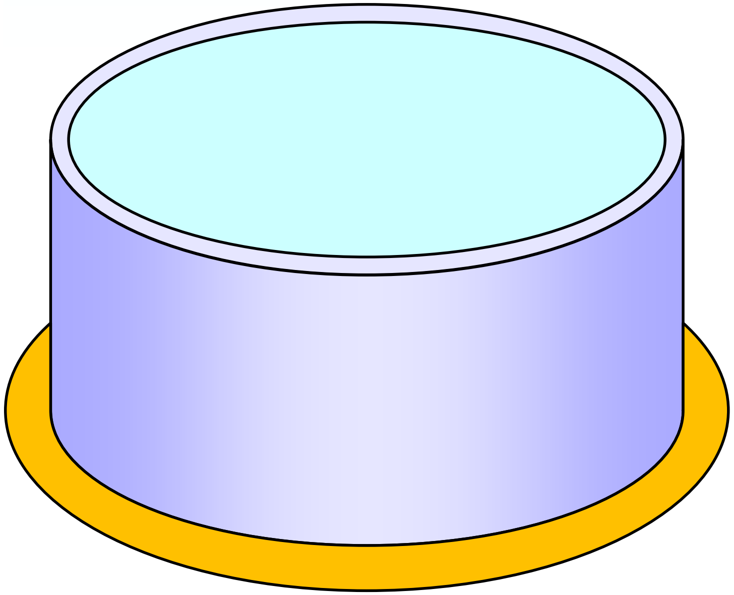
# 10

## *Advanced RC Structures*

# Water Tank 1



- Types of Water Tanks
- Design Codes
- Design Strength
- Circular Tank

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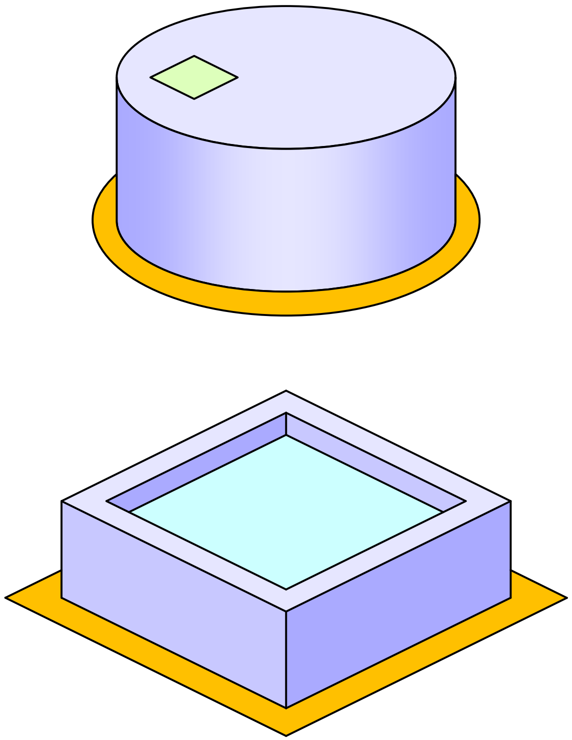
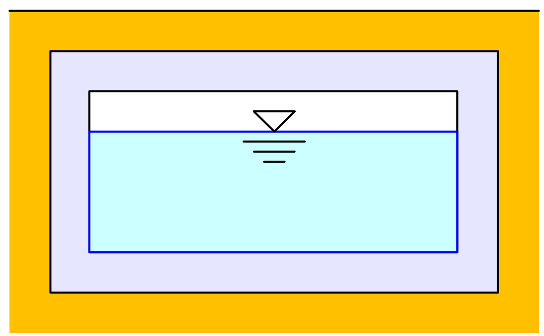
SCHOOL OF CIVIL ENGINEERING

# Types of Water Tanks

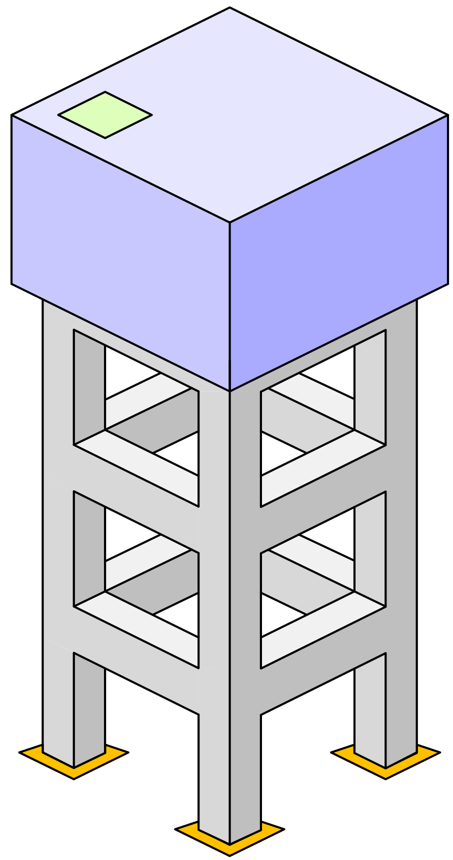
Base on the location, water tanks can be classified into 3 categories.



On ground tanks



Underground tanks

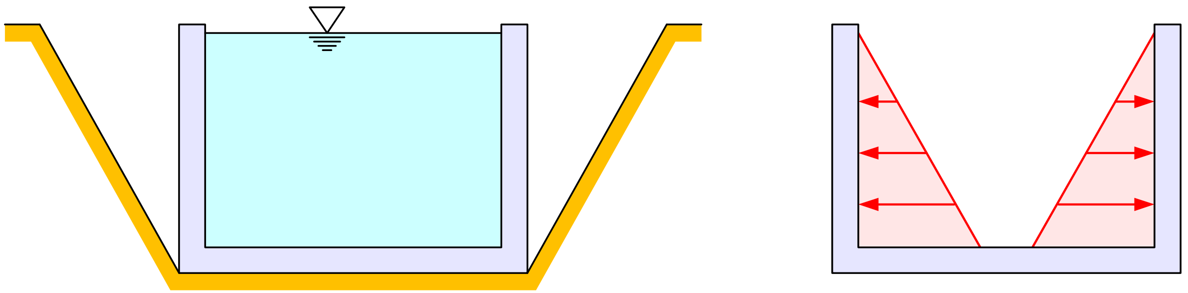


Overhead tank

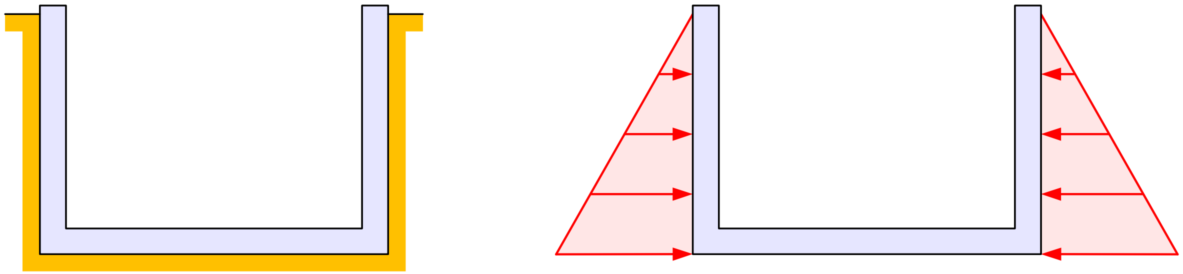
# Underground Tank

## Loading Conditions

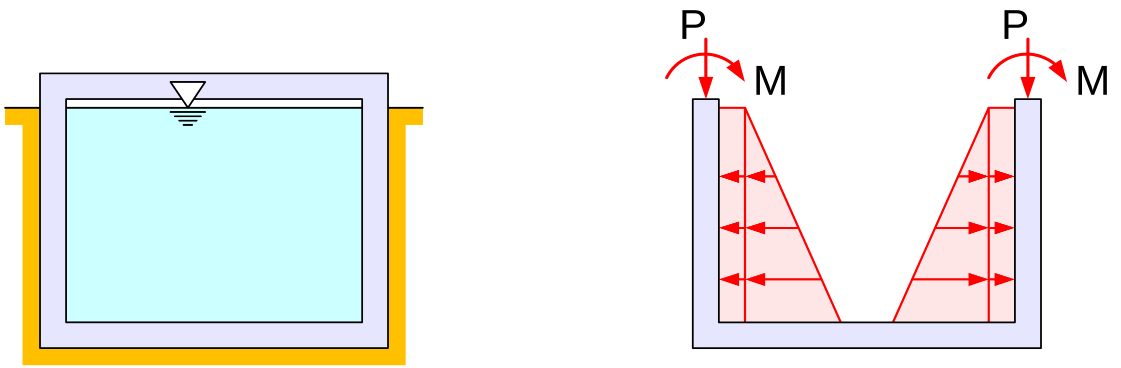
**Condition 1**
Leakage test
prior to backfilling



**Condition 2**
Backfilling
prior to adding water



**Condition 3**
Leakage test
prior to backfilling



# Design Considerations

- ✓ The tank may also be subjected to uplift forces from hydrostatic pressure at the bottom when empty.
- ✓ It is important to consider all possible loading conditions on the structure.
- ✓ Full effects of soil loads and water pressure must be designed for without using them to minimize the effect of each other.
- ✓ The effects of water table must be considered for the design loading conditions.

# Design Codes

**ACI 350-06**

ACI 350-06 Code Requirements for Environmental Engineering Concrete Structures

*This report presents recommendations for structural design, materials, and construction of concrete tanks, reservoirs, and other structures commonly used in **water containment, industrial and domestic water, and wastewater treatment works, where dense, impermeable concrete with high resistance to chemical attack is required.***

**Update from ACI 350-01**

The load factor combinations and strength reduction factors of the 2001 code were revised and moved to Appendix C

The changes were made to further unify the design profession on one set of load factors and combinations, and to facilitate the proportioning of concrete building structures that include member other than concrete.

# Design Codes

**ACI 350-06**

**Appendix C**

**ACI350-01**

## Strength Design Method

ACI 350 modifies the load combination :

- **Modification 1** – the load factor for liquid pressure F is increased from 1.4 to **1.7**
- **Modification 2** – increase U by using the sanitary coefficient.

$$\text{Required strength} = \text{Sanitary coefficient} \times U$$

where the sanitary coefficient equals:

**1.3** for flexure

**1.65** for direct tension

**1.3** for shear beyond that of the capacity provided by the concrete

# Design Codes

**ACI 350-06**

**Appendix C**

**ACI350-01**

## C.9.2 – Required strength

$$U = 1.4D + 1.7L$$

$$U = 1.4D + 1.7L + 1.7F$$

$$U = 0.9D + 1.7F$$

## Environmental durability factor

$$\phi S_n \geq S_d U$$

Flexural stress: $S_d = 1.3$

Tensile stress: $S_d = 1.65$

Shear stress: $S_d = 1.3$

## Strength reduction factor

Tension: $\phi = 0.90$

Compression:

- Spiral column $\phi = 0.75$
- Tied column $\phi = 0.70$

Shear: $\phi = 0.85$

# Design Strength

ACI 350-06

Appendix C

ACI350-01

## Flexural Strength

$$\phi S_n \geq 1.3\,U$$

$$\phi M_n \geq 1.3\,(1.4\,M_D + 1.7\,M_L + 1.7\,M_F)$$

## Direct Tension

$$\phi S_n \geq 1.65\,U$$

$$\phi T_n \geq 1.65\,(1.7\,T_F)$$

## Shear Strength

$$\phi V_s \geq 1.3\,(V_u - \phi V_c)$$

# Design Codes

ACI 350-06

## 9.2 – Required strength

$$U = 1.4(D + F)$$

$$U = 1.2(D + F) + 1.6L$$

$$U = 0.9D + 1.2F$$

## Strength reduction factor

Tension: $\phi = 0.90$

Compression:

Spiral column $\phi = 0.70$

Tied column $\phi = 0.65$

Shear: $\phi = 0.75$

## Environmental durability factor

$$\phi S_n \geq S_d U$$

$$S_d = \frac{\phi f_y}{\gamma f_s} \geq 1.0$$

where $\gamma = \dfrac{\text{factored load}}{\text{unfactored load}}$

$f_s$ = permissible tensile stress

| $f_s$ (kg/cm$^2$) | normal | severe |
|---|---|---|
| Direct & hoop: | 1,400 | 1,200 |
| Shear: | 1,700 | 1,400 |

# Design Codes

**ACI 350-06**

ACI 350-06 Code Requirements for Environmental Engineering Concrete Structures

> *This report presents recommendations for structural design, materials, and construction of concrete tanks, reservoirs, and other structures commonly used in* ***water containment, industrial and domestic water, and wastewater treatment works, where dense, impermeable concrete with high resistance to chemical attack is required.***

## Working Stress Design

- Allowable stress for Grade 60 (4,200 kg/cm$^2$) reinforcing steel is 2,100 kg/cm$^2$ (0.5$f_y$) → SD40 use 1,700 kg/cm$^2$
- Allowable stress in hoop tension for Grade 60 reinforcing steel as is 1,400 kg/cm$^2$ ($f_y$/3) → SD40 use 1,300 kg/cm$^2$

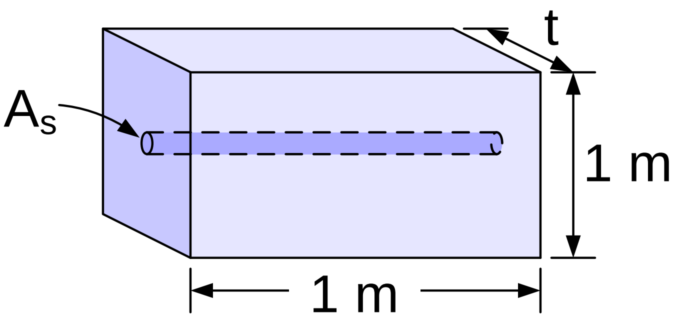
# Wall Thickness

ACI 350-06

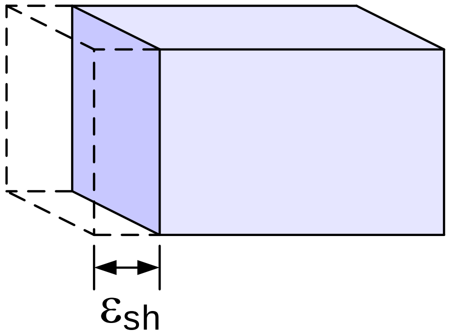
- Typically, in the design of reinforced concrete members, the tensile strength of concrete is ignored.
- Any significant cracking in a liquid containing tank is unacceptable. The stress in the concrete from ring tension is kept at minimum to prevent excessive cracking.
- The allowable tensile strength of concrete is usually between 7% an 12% of the compressive strength. $f_r = 2\sqrt{f'_c}$
- According to ACI 350, reinforced cast in place concrete walls 3 meter high or taller, which are in contact with liquid, shall have a minimum thickness of 30 cm.

# Shrinkage in Concrete Section

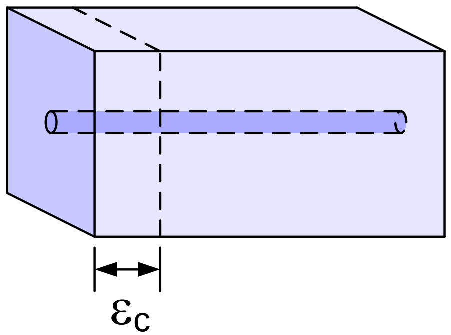
- Shrinkage will shorten the 1-unit long block a distance of $\varepsilon_{sh}$, which denotes the shrinkage per unit length.




- The presence of the steel bar prevents some of the shortening of the concrete $\varepsilon_s < \varepsilon_{sh}$




- The steel shortens a distance $\varepsilon_s$ and accordingly is subject to compressive stress $f_s$, while concrete will elongate a distance ($\varepsilon_{sh}$ - $\varepsilon_s$ ) and will subject to tensile stress $f_{ct}$



# Shrinkage in Concrete Section

$$\varepsilon_{sh} = \varepsilon_s + \varepsilon_c$$

$$\varepsilon_s = \varepsilon_{sh} - \varepsilon_c$$

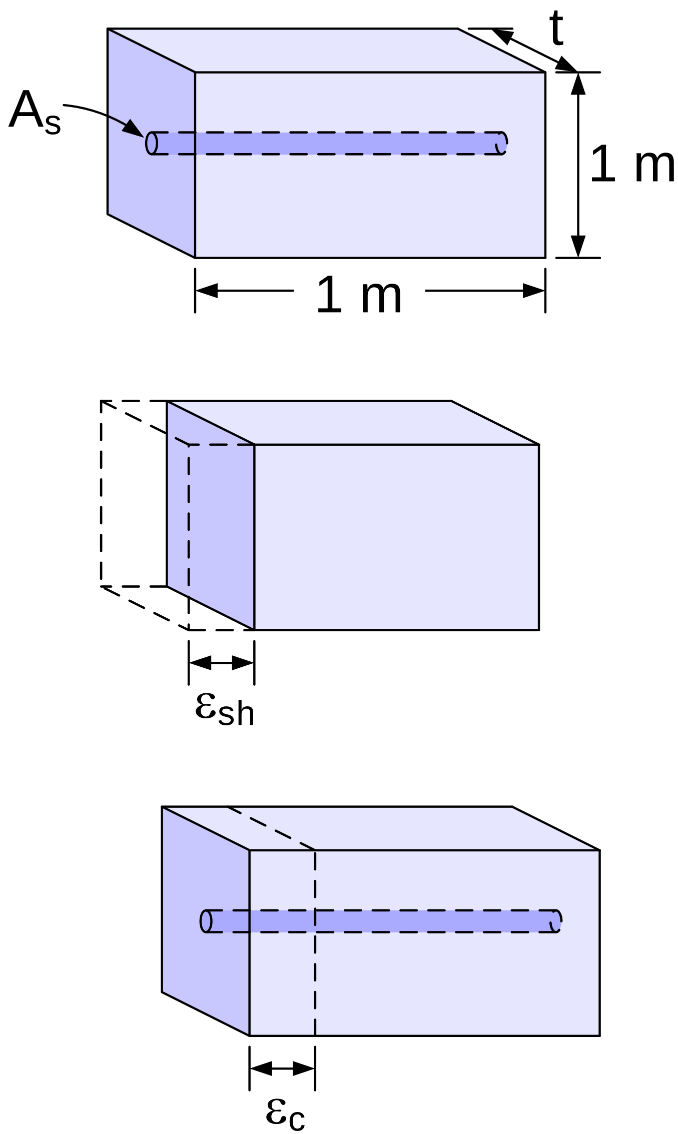
$$\frac{f_s}{E_s} = \varepsilon_{sh} - \frac{f_{ct}}{E_c}$$

$$f_s = \varepsilon_{sh}E_s - \frac{E_s}{E_c}f_{ct}$$

$$f_s = \varepsilon_{sh}E_s - n f_{ct}$$

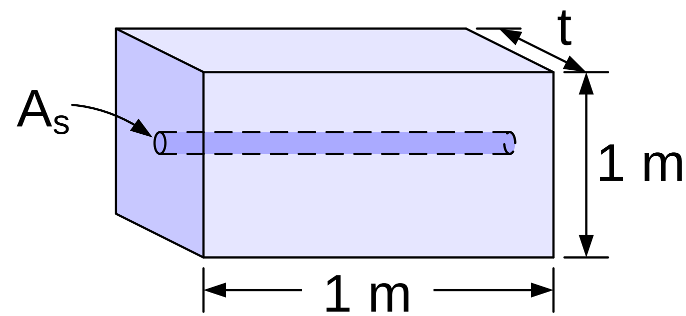
**[T = C]** $$A_s f_s = A_c f_{ct}$$

$$A_s(\varepsilon_{sh}E_s - n f_{ct}) = A_c f_{ct}$$



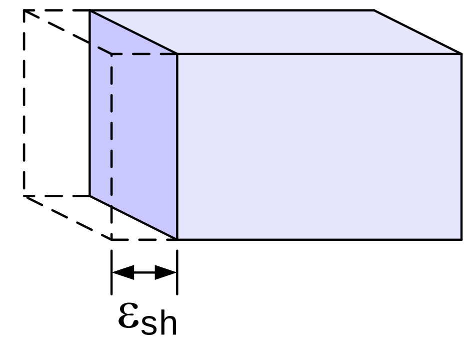
# Tensile Stress in Concrete

$$A_s \varepsilon_{sh} E_s = (nA_s + A_c) f_{ct}$$

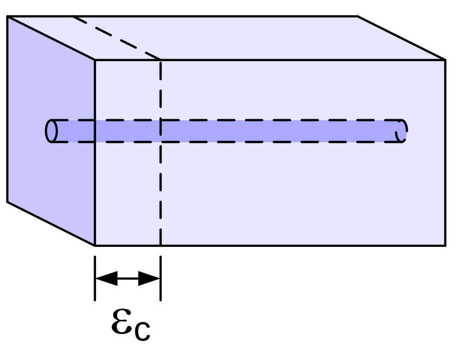



Tensile stress in concrete :

Due to shrinkage : $$f_{ct} = \frac{\varepsilon_{sh} E_s A_s}{A_c + nA_s}$$




Due to tension T : $$f_{ct} = \frac{T}{A_c + nA_s}$$

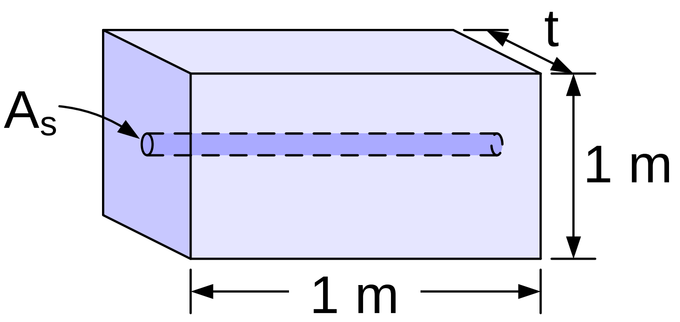



$$f_{ct} = \frac{T + \varepsilon_{sh} E_s A_s}{A_c + nA_s}$$

# Wall Thickness

For a rectangular section of 100 cm height and t width

$A_c = 100\,t$ and $A_s = T / f_s$




$$f_{ct} = \frac{T + \varepsilon_{sh} E_s \dfrac{T}{f_s}}{100\,t + n \dfrac{T}{f_s}}$$

$$t = \frac{\varepsilon_{sh} E_s + f_s - n f_{ct}}{100\, f_s f_{ct}} T$$

- The coefficient of shrinkage $\varepsilon_{sh} \approx 0.0002\text{-}0.0004$ for reinforced concrete
- The value of $\varepsilon_{sh} = 0.0003$ is traditionally used with success.

**EAXAMPLE-1 :** Wall Thickness t required to prevent crack resulting from shrinkage plus tensile forces for $f'_c$ = 280 kg/cm$^2$, $f_y$ = 4,000 kg/cm$^2$ and $E_s$ = $2.04\times10^6$ kg/cm$^2$

$$f_{ct} = 2.0\sqrt{280} = 33.47 \text{ kg/cm}^2$$

$$f_s = 1{,}700 \text{ kg/cm}^2$$

$$E_c = 15{,}100\sqrt{280} = 252{,}671 \text{ kg/cm}^2$$

$$n = \frac{E_s}{E_c} = \frac{2.04\times10^6}{252{,}671} \approx 8$$

$$t = \frac{\varepsilon_{sh}E_s + f_s - n f_{ct}}{100 f_s f_{ct}} T = \frac{0.0003\times2.04\times10^6 + 1{,}700 - 8\times33.47}{100\times1{,}700\times33.47} T$$

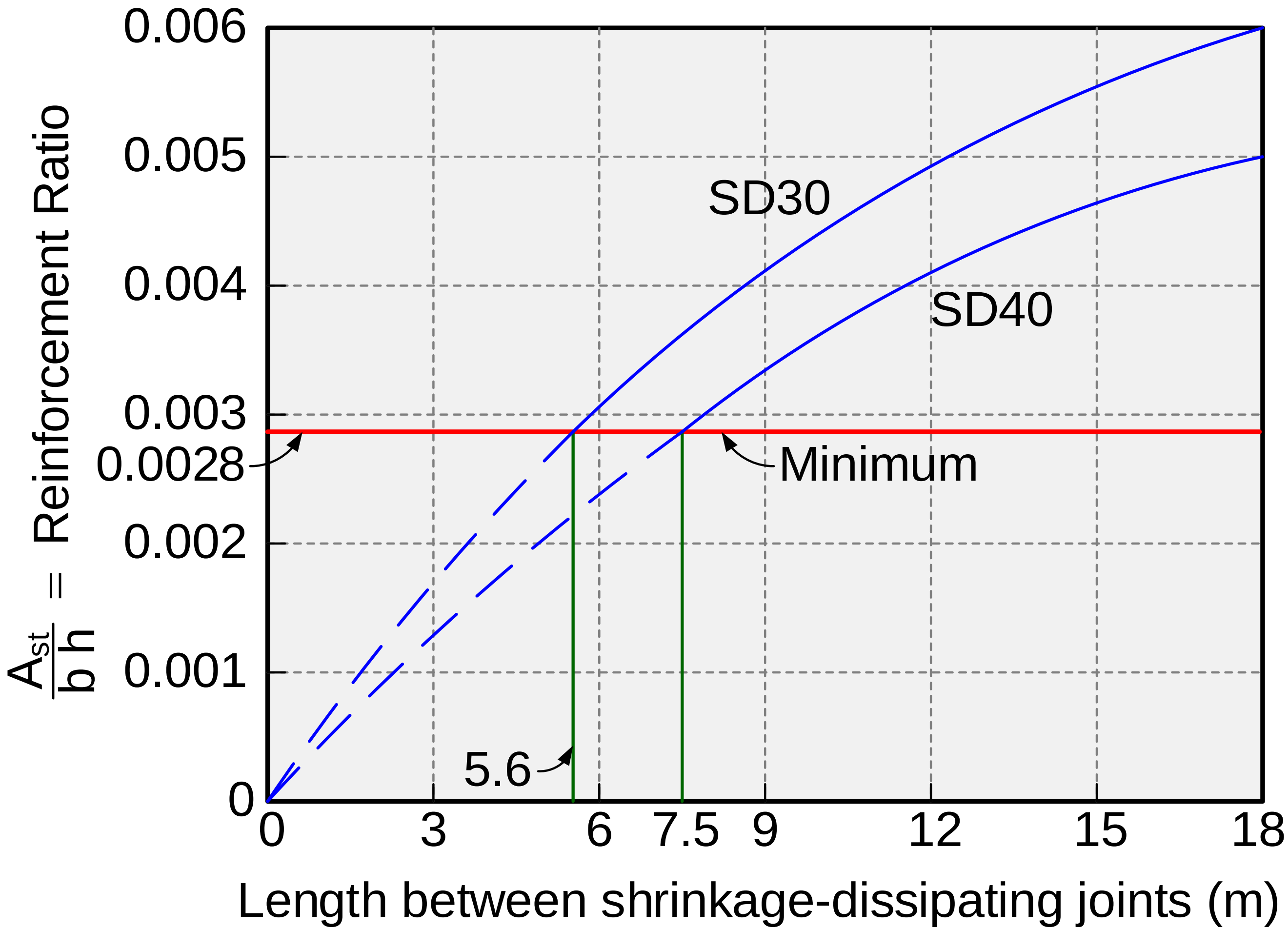
$$t = 0.000359\, T \quad \text{where T is in kg}$$

$$t = 0.359\, T \quad \text{where T is in tons}$$

# Minimum Reinforcement

ACI 350-06

Temperature and Shrinkage Effects




Reinforcing bar :

Size ≤ DB32

Spacing ≤ 30 cm

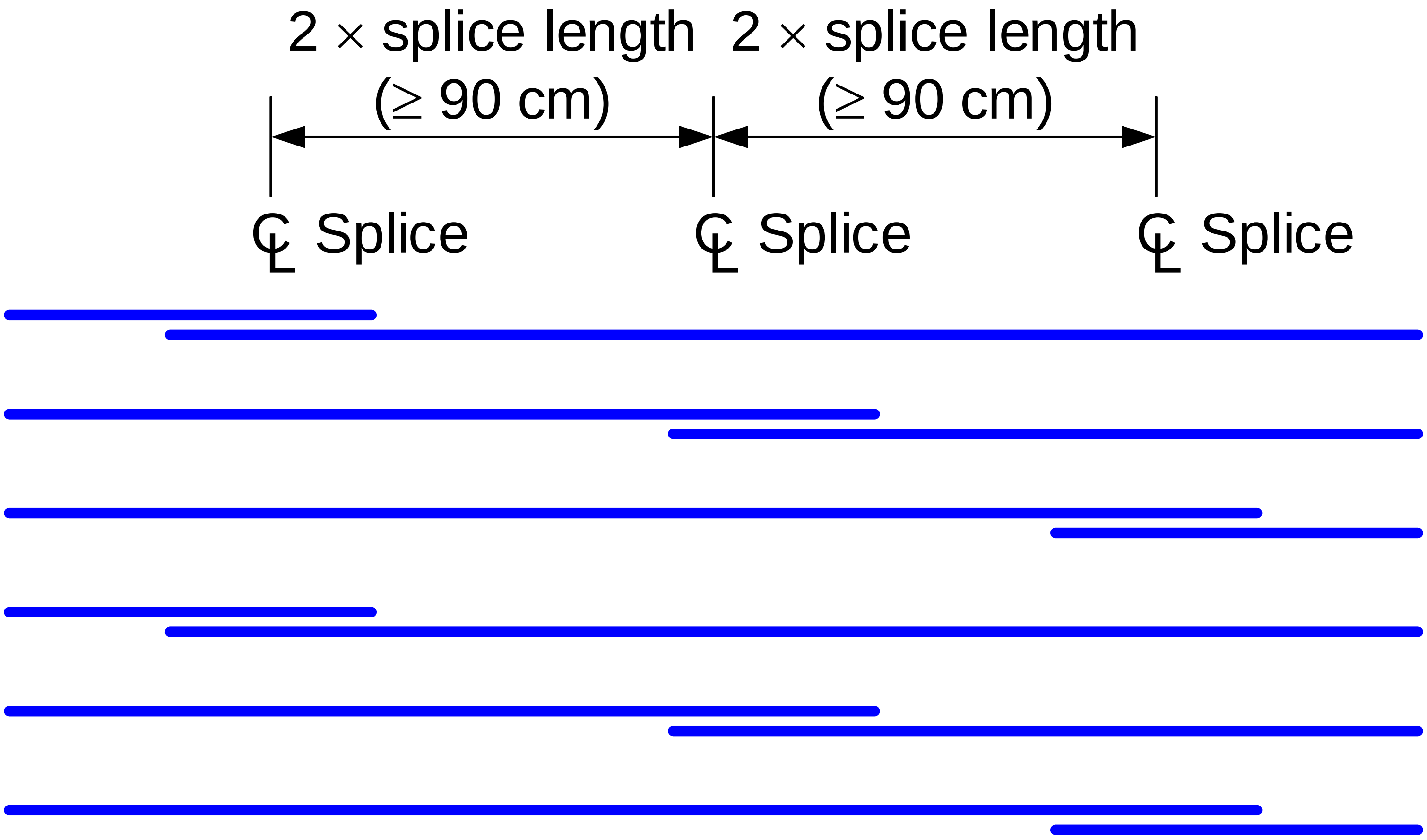
Covering ≥ 5 cm

Wall thickness ≥ 60 cm can have min. reinforcement at each face based on a 30 cm thinckness

# Lap Splices

ACI 350-06

In circular tank, the location of splices should be staggered.

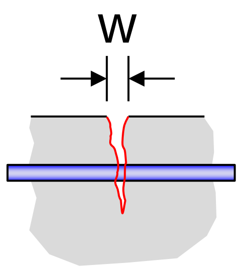


# Crack Control

Crack widths must be minimized to prevent leakage and corrosion of reinforcement

Gergely-Lutz equation :

$$z = f_s \sqrt[3]{d_c A} = \frac{w}{0.013}$$




where

$z$ = quantity limiting distribution of flexural reinforcement

$w$ = maximum crack width (unit of 1/1,000 mm)

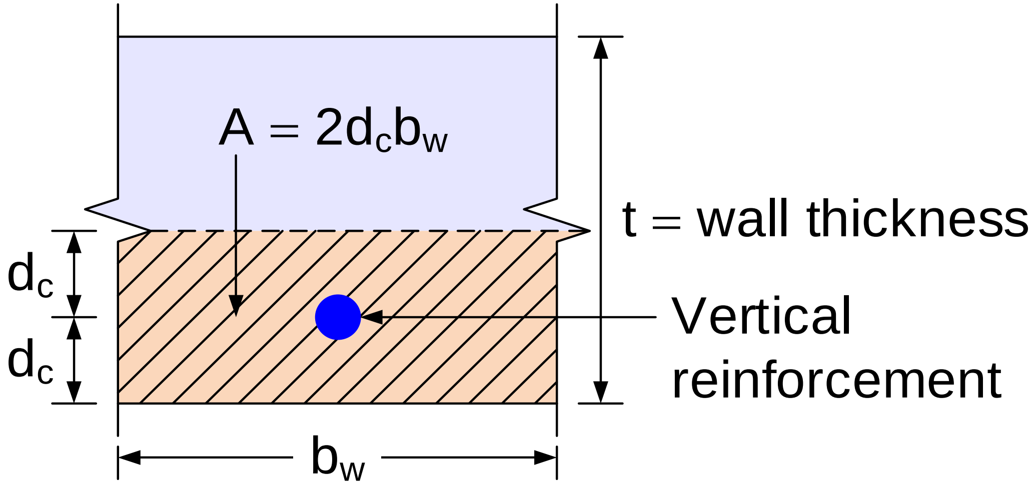
$f_s$ = calculated stress in reinforcement at service loads

$d_c$ = concrete covering measures from extreme fiber to center of bar.

$A$ = effective tension area of concrete surrounding the flexural tension reinforcement divided by the number of bars, $cm^2$

# Crack Control

In ACI 350, the cover $d_c = 5$ cm. For $d_c > 5$ cm, rearranging Gergery-Lutz equation and solving for the maximum bar spacing for a given value of z :




$$\max\ b_w = \frac{z^3}{2 \times d_c^2 \times f_s^3}$$

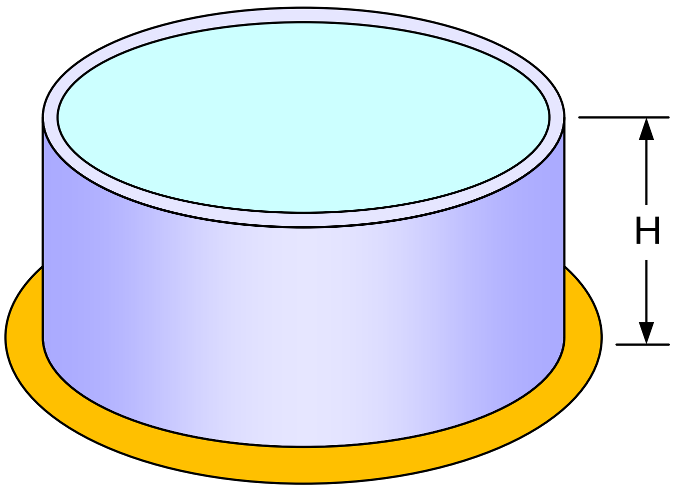
**ACI 318** For interior $z \le 31{,}000$ kg/cm → crack width $w = 0.41$ mm

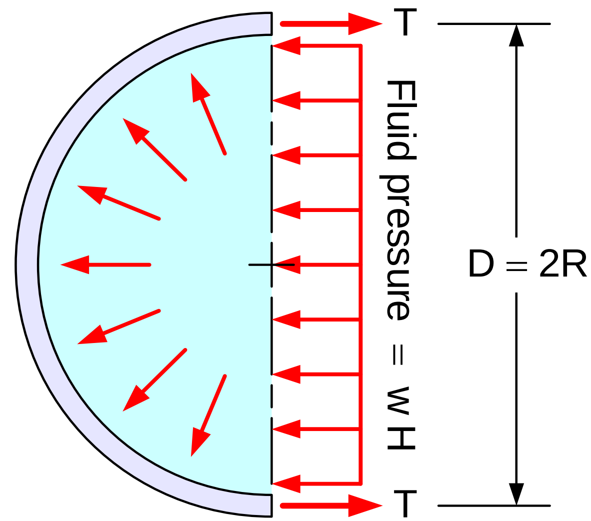
For Exterior $z \le 26{,}000$ kg/cm → crack width $w = 0.34$ mm

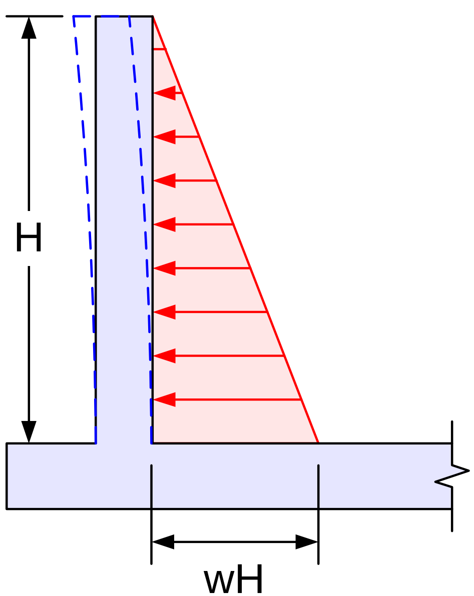
**ACI 350** Stricter than ACI 318, since cracking is more important in tank

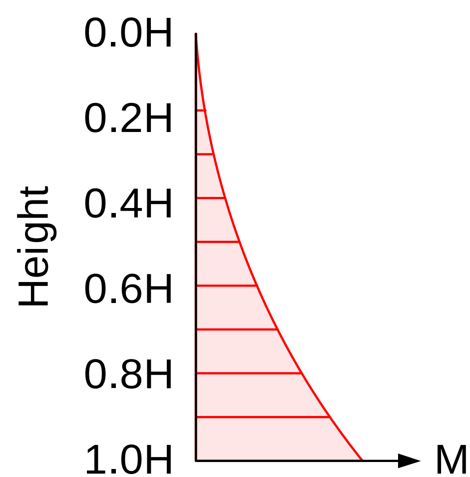
$z \le 20{,}600$ kg/cm, for severe environment $z \le 17{,}000$ kg/cm

# Cylindrical Tank



# Carpenter's Method

For cylinder tank of height H and diameter D

Maximum moment : $M = F w H^3$

Maximum tension ring : $T = \frac{1}{2} w H D (1 - K)$

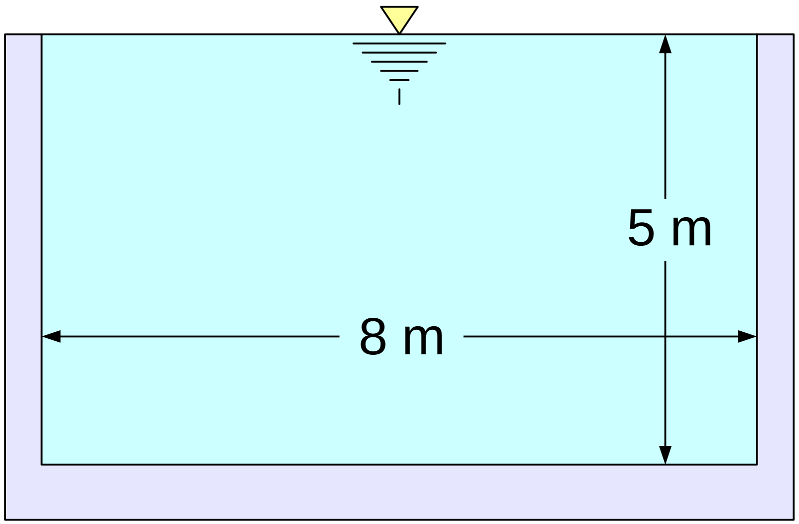
Maximum tension ring position at KH from base

Minimum wall thickness : $t = (30H + 50)$ mm

| H/D | F | | | | K | | | |
|---|---|---|---|---|---|---|---|---|
| | H/t | | | | H/t | | | |
| | 10 | 20 | 30 | 40 | 10 | 20 | 30 | 40 |
| 0.1 | 0.075 | 0.047 | 0.036 | 0.028 | - | - | - | - |
| 0.2 | 0.046 | 0.028 | 0.022 | 0.015 | - | 0.50 | 0.45 | 0.40 |
| 0.3 | 0.032 | 0.019 | 0.014 | 0.010 | 0.55 | 0.43 | 0.38 | 0.33 |
| 0.4 | 0.024 | 0.014 | 0.010 | 0.007 | 0.50 | 0.39 | 0.35 | 0.30 |
| 0.5 | 0.020 | 0.012 | 0.009 | 0.006 | 0.45 | 0.37 | 0.32 | 0.27 |
| 1.0 | 0.012 | 0.006 | 0.005 | 0.003 | 0.37 | 0.28 | 0.24 | 0.21 |
| 2.0 | 0.006 | 0.003 | 0.002 | 0.002 | 0.30 | 0.22 | 0.19 | 0.16 |
| 4.0 | 0.004 | 0.002 | 0.002 | 0.001 | 0.27 | 0.20 | 0.17 | 0.14 |

## EXAMPLE-2 : Cylindrical Water Tank

The open cylindrical reinforced concrete tank is 5 m deep and 20 m in diameter. Concrete compressive strength is $f'_c$ = 280 kg/cm$^2$ and reinforcement $f_y$ = 4,000 kg/cm$^2$. water unit weight w = 1,000 kg/m$^3$, shrinkage coefficient $\varepsilon_{sh}$ = 0.0003




### (1) Wall thickness

Simple formula:

$$t = (30H + 50)$$
$$= 30 \times 5 + 50$$
$$= 200 < 300 \text{ mm}$$

**USE t = 30 cm**

ACI 350 :
$H \geq 3.0$ m

Tension ring : $T = \frac{1}{2} wHD(1-K)$

$$H/D = 5/8 = 0.625$$

$$H/t = 5/0.2 = 25$$

| | 20 | **25** | 30 |
|---|---|---|---|
| 0.5 | 0.37 | **0.345** | 0.32 |
| **0.625** | | **0.324** | |
| 1.0 | 0.28 | **0.26** | 0.24 |

→ **K**

$$T = \frac{1}{2} wHD(1-K) = \frac{1}{2} \times 1.0 \times 5 \times 8(1-0.324) = 13.52 \text{ tons}$$

**ACI 350 :**

$$n = \frac{E_s}{E_c} = \frac{2.04 \times 10^6}{15,100\sqrt{280}} \cong 8$$

$$t = \frac{\varepsilon_{sh} E_s + f_s - n f_{ct}}{100 f_s f_{ct}} T = \frac{0.0003 \times 2.04 \times 10^6 + 1,700 - 8 \times 33.47}{100 \times 1,700 \times 33.47} T$$

$$t = 0.000359 \text{ T} \quad \text{where T is in kg}$$

$$t = 0.359 \text{ T} \quad \text{where T is in tons} = 0.359 \times 13.52 = 4.85 < 30 \text{ cm}$$ **OK**

**(2) Tension Ring**

$$T_u = \frac{1}{2} w_u H D (1 - K)$$

$$w_u = \text{Sanitary coefficient} \times (1.7 \times \text{Lateral force})$$

$$= 1.65 \times (1.7 \times 1.0) = 2.81 \text{ ton/m}$$

$$T_u = \frac{1}{2} \times 2.81 \times 5 \times 8 (1 - 0.324) = 37.99 \text{ tons}$$

$$A_s = T_u / (0.9 \times f_y) = 37.99 / (0.9 \times 4.0) = 10.55 \text{ cm}^2/\text{m}$$

**USE DB12 @ 0.20 m in 2 layers ($A_s = 11.3$ cm$^2$/m)**

Check tensile stress in concrete:

$$f_{ct} = \frac{T + \varepsilon_{sh} E_s A_s}{A_c + n A_s}$$

$$= \frac{37.99 \times 10^3 / (1.65 \times 1.7) + 0.0003 \times 2.04 \times 10^6 \times 11.3}{30 \times 100 + 8 \times 11.3}$$

$$= 6.62 \text{ kg/cm}^2 < [2\sqrt{f'_c} = 2\sqrt{280} = 33.47 \text{ kg/cm}^2] \quad \textbf{OK}$$

## (3) Bending Moment

$$M = F w H^3$$

$$w_u = \text{Sanitary coefficient} \times (1.7 \times \text{Lateral force})$$

$$= 1.3 \times (1.7 \times 1.0) = 2.21 \text{ ton/m}$$

$$H/D = 5/8 = 0.625$$

$$H/t = 5/0.2 = 25$$

| | 20 | **25** | 30 |
|---|---|---|---|
| 0.5 | 0.012 | **0.0105** | 0.009 |
| **0.625** | | **0.0093** | |
| 1.0 | 0.006 | **0.0055** | 0.005 |

→ F

$$M_u = 0.0093 \times 2.21 \times 5^3 = 2.57 \text{ t-m/m}$$

$$R_n = \frac{M_u}{\phi b d^2} = \frac{2,570 \times 100}{0.9 \times 100 \times 25^2} = 4.57 \text{ kg/cm}^2$$

$$\rho = \frac{0.85 f'_c}{f_y}\left(1 - \sqrt{1 - \frac{2R_n}{0.85 f'_c}}\right)$$

$$= \frac{0.85 \times 280}{4,000}\left(1 - \sqrt{1 - \frac{2 \times 4.57}{0.85 \times 280}}\right) = 0.00115 < [\,\rho_{max} = 0.0229\,]$$ **OK**

$$A_s = \rho\, b\, d = 0.00115 \times 100 \times 25 = 2.875 \text{ cm}^2/\text{m}$$

$$A_{s,min} = 0.0018\, b\, t = 0.0018 \times 100 \times 30 = 5.4 \text{ cm}^2/\text{m}$$ control

**USE DB12 @ 0.20 m ($A_s = 5.65$ cm²/m)** ($A_s = A_b$ (100/s))

**Check** max spacing $= \dfrac{z^3}{2 \times d_c^2 \times f_s^3} = \dfrac{20,600^3}{2 \times 5^2 \times 1,700^3}$

$$= 35.6 \text{ cm} > 20 \text{ cm}$$ **OK**

## (4) Shear Force

$$V = 0.5\, w\, H^2$$

$$w_u = \text{Sanitary coefficient} \times (1.7 \times \text{Lateral force})$$

$$= 1.0 \times (1.7 \times 1.0) = 1.70 \text{ ton/m}$$

$$V_u = 0.5 \times 1.70 \times 5^2 = 21.25 \text{ tons}$$

$$V_c = 0.53\sqrt{f'_c}\, b\, d = 0.53\sqrt{280} \times 100 \times 25 / 10^3 = 22.17 \text{ tons}$$

$$V_s = 1.3\,(V_u - \phi V_c)/\phi = 1.3\,(21.25 - 0.85 \times 22.17)/0.85$$

$$= 3.679 \text{ ton}$$

**Increase t = 35 cm → d = 30 cm → $V_s = 0$**

# (5) Detail Reinforcement