A Few Notes on the Design of Reinforced Concrete Tanks

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Load Cases

For Exterior Wall:

external earth pressure only
internal fluid pressure only
ACI 350.4R-04 section 4.1.1

For Interior Wall:

Fluid pressure on one side of wall only

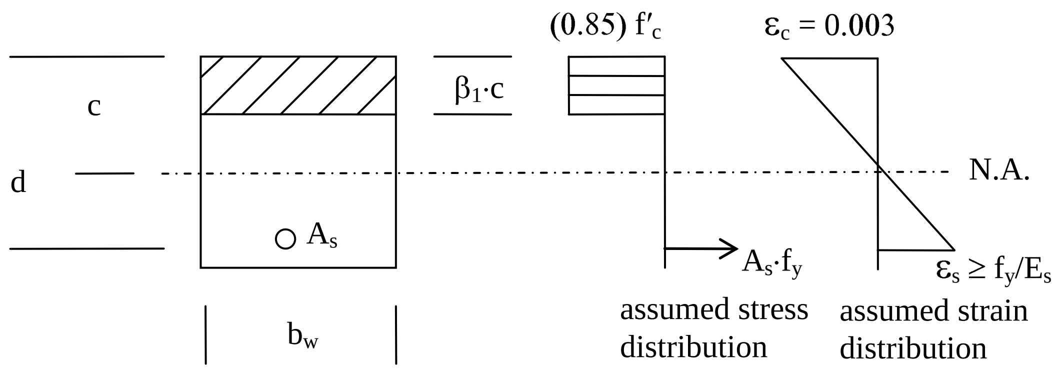
Tank Flotation:

1.25×Uplift ≤ Dead Load [ACI 350.4R-04 section 3.1.2]

Load Factors/Combinations:

1.4(D + F) [ACI 350-06 section 9.2]
D = dead load
F = fluid load

Flexural Analysis



compression = tension $\Rightarrow$ $\beta_1 \cdot c \cdot b_w \cdot (0.85 \cdot f'_c) = A_s \cdot f_y$

$$\Rightarrow \quad c = \frac{A_s \cdot f_y}{\beta_1 \cdot b_w \cdot (0.85 \cdot f'_c)}$$

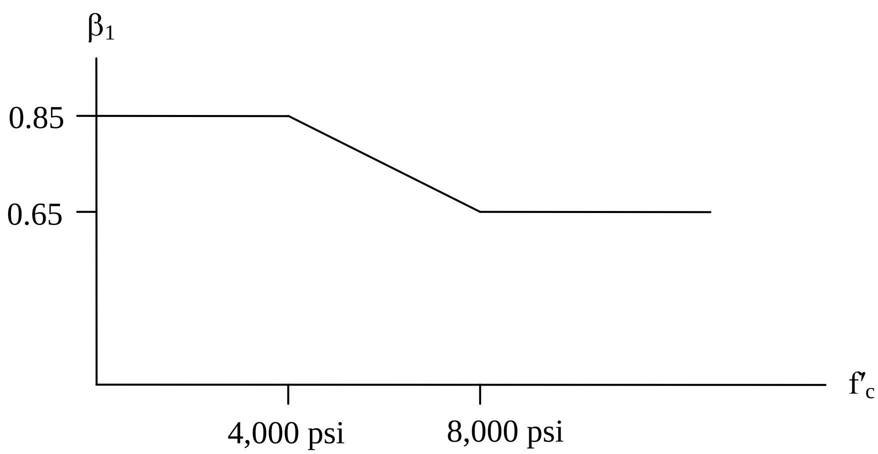
"nominal" moment capacity $M_n = A_s \cdot f_y \cdot \left(d - \frac{\beta_1 \cdot c}{2}\right)$

multiply M_n by a safety factor $\phi = 0.9$

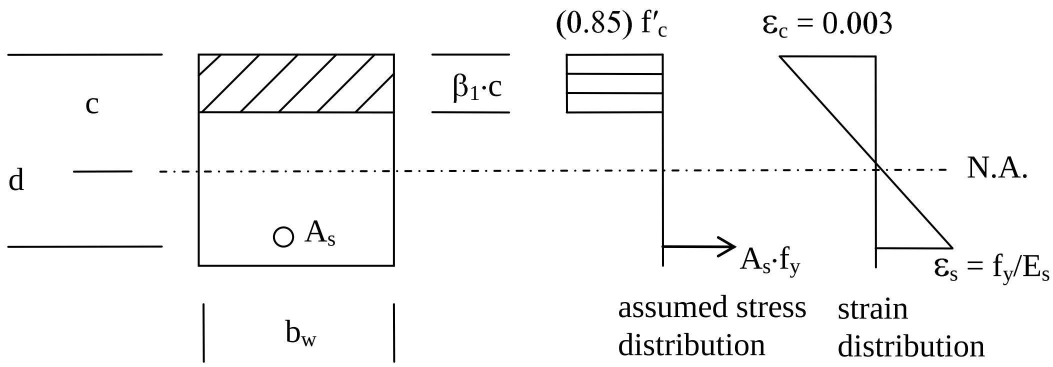
"design" moment capacity $\phi M_n = (0.9) A_s \cdot f_y \cdot \left(d - \frac{\beta_1 \cdot c}{2}\right)$

ACI 350-06 section 10.2.7.3:

$$\beta_1 = \begin{cases} 0.85 & \text{if} \quad f'_c \le 4{,}000 \text{ psi} \\ 1.05 - \dfrac{f'_c}{20{,}000} & \text{if} \quad 4{,}000 \text{ psi} < f'_c < 8{,}000 \text{ psi} \\ 0.65 & \text{if} \quad 8{,}000 \text{ psi} \le f'_c \end{cases}$$



Balanced Section



similar triangles from the strain distribution: $\frac{0.003}{c} = \frac{f_y / E_s}{d - c} \quad \Rightarrow \quad c = \frac{0.003 \cdot d}{0.003 + \frac{f_y}{E_s}}$

equilibrium: compression = tension $\quad \Rightarrow \quad \beta_1 \cdot c \cdot b_w \cdot (0.85 \cdot f'_c) = A_{s,b} \cdot f_y$

$$\Rightarrow \quad \beta_1 \cdot \frac{0.003 \cdot d}{0.003 + \frac{f_y}{E_s}} \cdot b_w \cdot (0.85 \cdot f'_c) = A_{s,b} \cdot f_y$$

$$\Rightarrow \quad A_{s,b} = \frac{(0.003)(0.85)\beta_1 \cdot b_w \cdot d \cdot f'_c}{\left(0.003 + \frac{f_y}{E_s}\right) \cdot f_y}$$

Shear

The shear strength provided by concrete is $V_c = 2\sqrt{f'_c} b_w d$ as per ACI 350-06 section 11.3.1.1. Walls, slabs and footings should be designed so that the concrete is capable of resisting the ultimate shear load at the same section that the ultimate moment is calculated:

$V_u \leq \phi V_c$, where $\phi = 0.75$

Minimum and Maximum Reinforcing

for flexure members in general ACI 350-06 section 10.5.1:

$$\frac{200 \cdot b_w \cdot d}{f_y} \le A_s \qquad \text{and} \qquad \frac{3 \cdot \sqrt{f_c'}}{f_y} \cdot b_w \cdot d \le A_s$$

walls have an additional criteria to meet, ACI 350-06 section 14.3.2:

$0.003 \times A_g \le A_s$ (A_g = gross area of the section)

Also, see ACI 350-06 section 7.12.2.1 for minimum steel requirements for shrinkage and temperature.

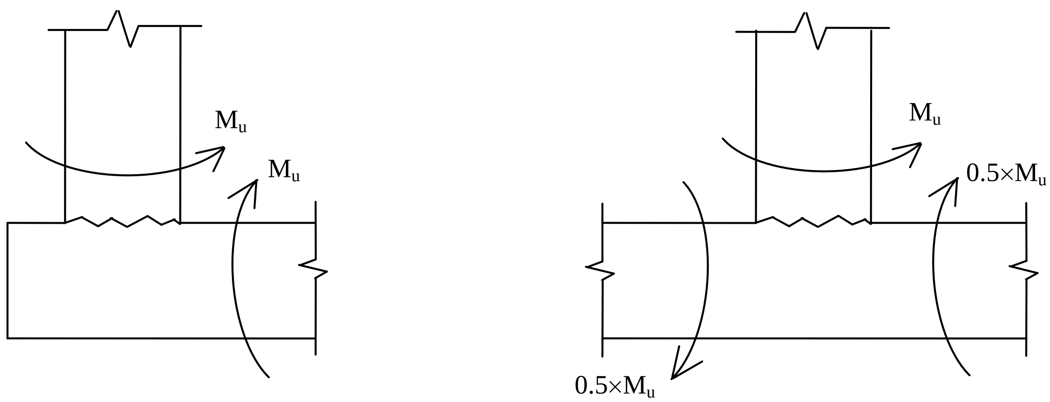
There does not appear to be a maximum steel limit in ACI 350-06, as there is in ACI 318. However, it may be good to include it in the design.

ACI 318-89 section 10.3.3:

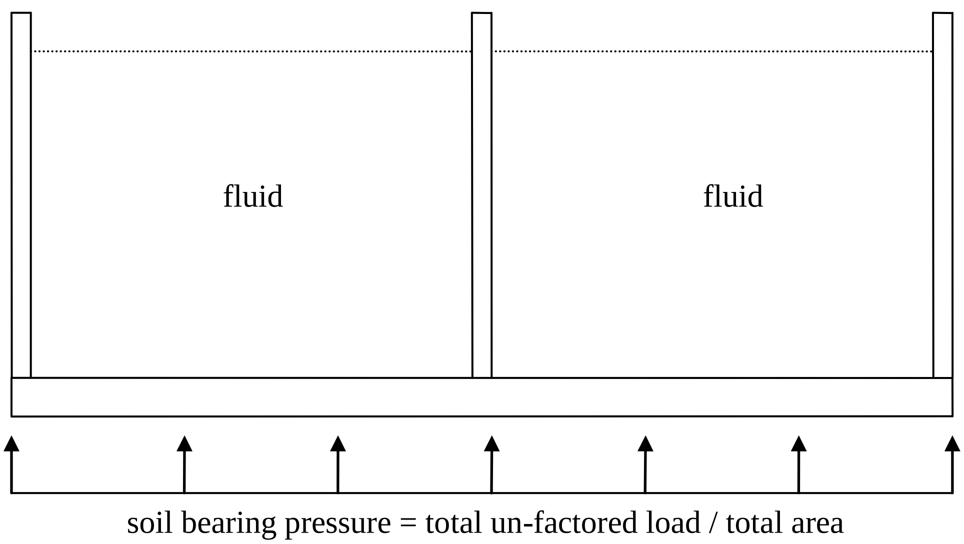
$$A_{s,max} = 0.75 \cdot A_{s,b} = \frac{(0.75)(0.003)(0.85)\beta_1 \cdot b_w \cdot d \cdot f_c'}{\left(0.003 + \frac{f_y}{E_s}\right) \cdot f_y} = \frac{(0.0019125)\beta_1 \cdot b_w \cdot d \cdot f_c'}{\left(0.003 + \frac{f_y}{E_s}\right) \cdot f_y}$$

Slab Design

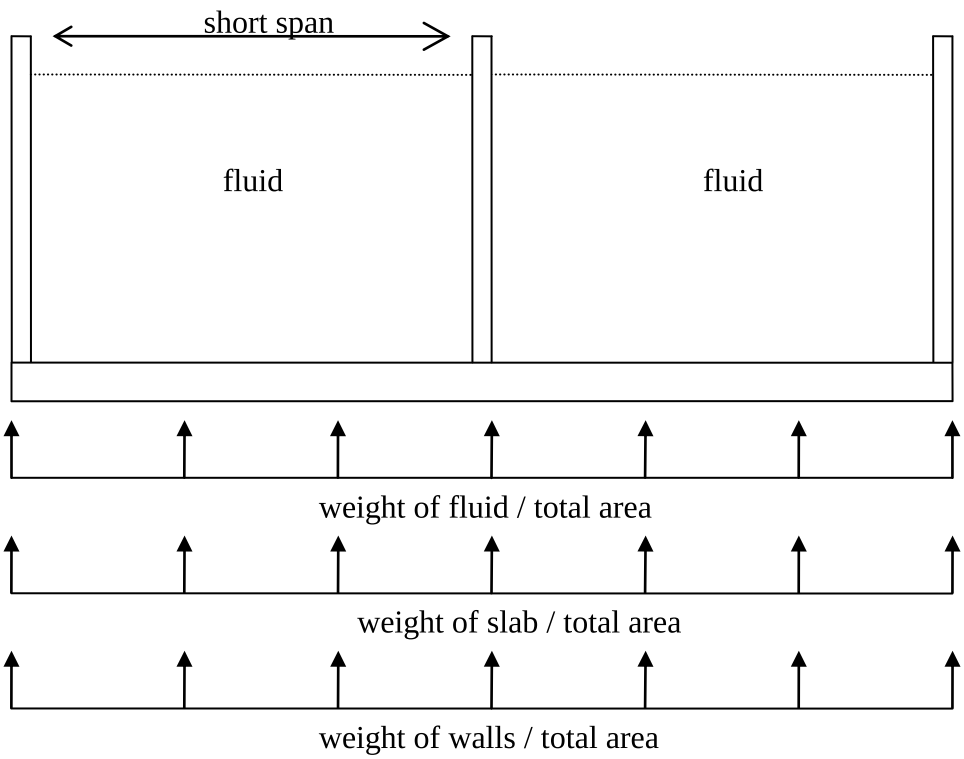
One criteria for the design of the slab is that it must be able to resist the moment supplied by the [cantilever] walls. This may or may not govern the design of the slab, but it needs to be checked.



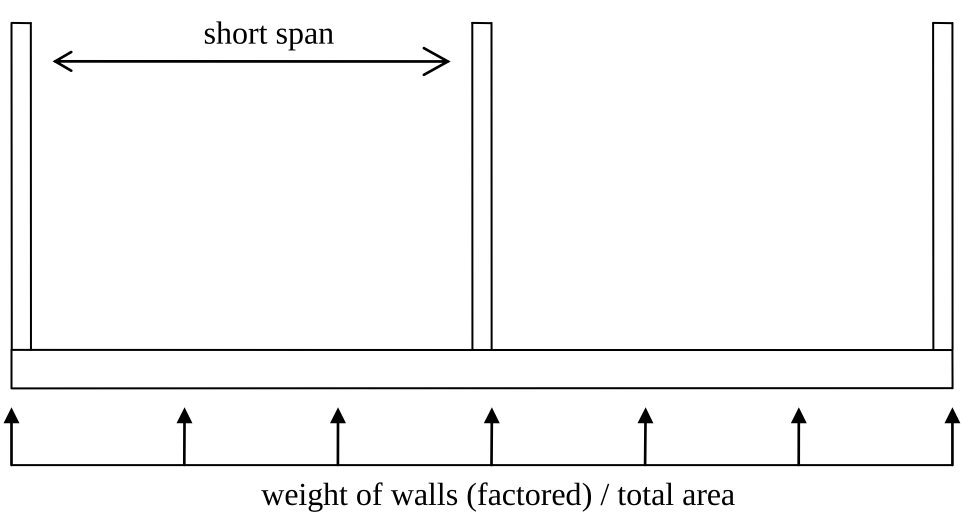
The slab is designed as a large mat foundation for the tank walls and fluid. The bearing pressure on the soil is approximated as a constant pressure obtained from the total load (un-factored) divided by the total area. This bearing pressure must be less than the soil bearing capacity.



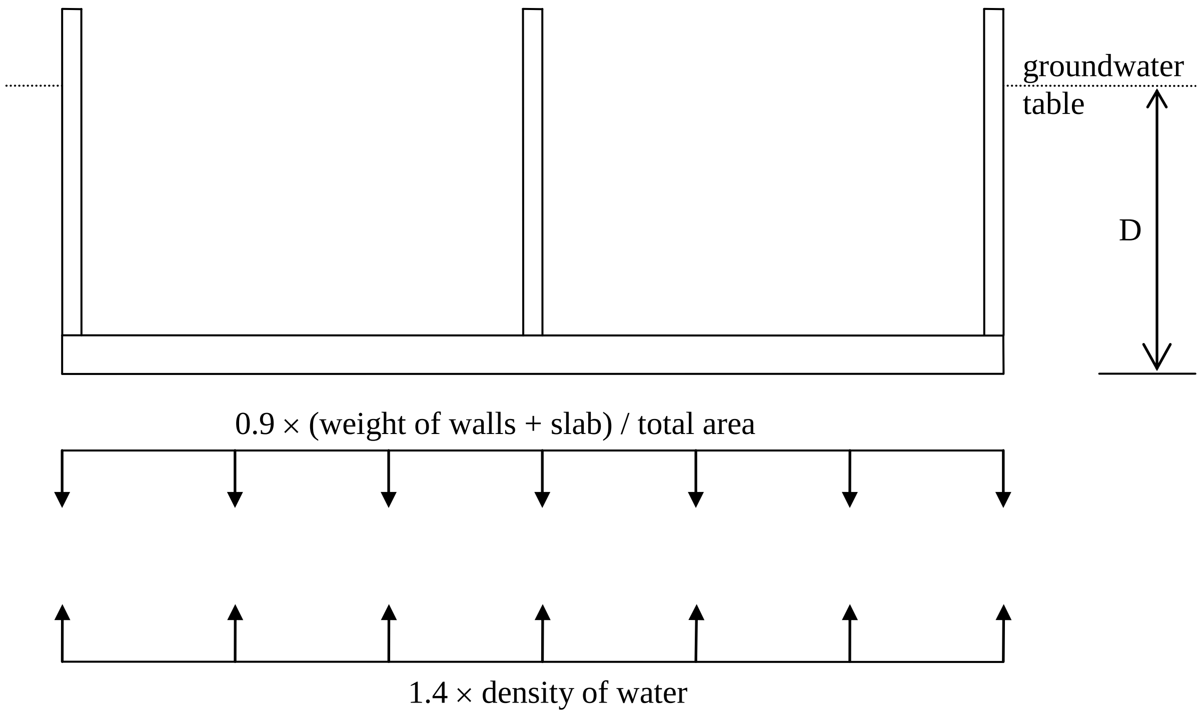
Two loading scenarios are considered. The first involves soil which is not saturated, so there is no water pressure uplift. In this case the soil supports the fluid, walls, and slab. However, for the design of the flexural steel, the weight of the fluid and slab are resisted by equal soil pressures, leaving only the weight of the walls.



Design for slab flexure:



The second load scenario to consider is that of an empty tank, with the groundwater table at it’s highest elevation. The loads for flexural design of the slab are the weight of the slab and walls (factored) pushing down, and the water pressure (factored) pushing up.



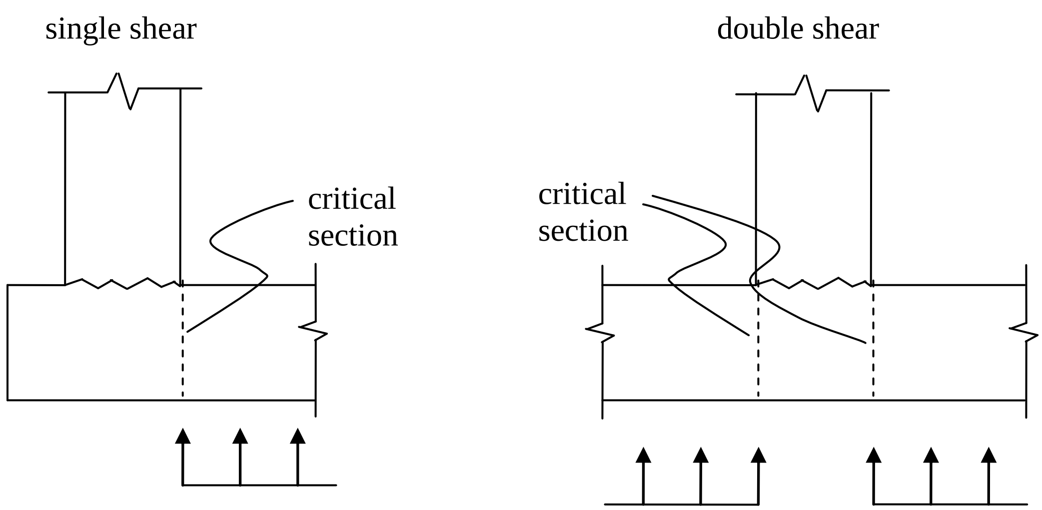
The larger of the two load scenarios governs the design of the slab. A 1′ wide strip of slab is considered as a continuous beam for the flexural steel design.

Shear:

The shear in a slab (or wall) should be resisted by the concrete only. ACI 350-06 section 11.3.1.1 gives the shear strength of a concrete section as:

$$V_c = 2\sqrt{f_c'}\,b_w d$$

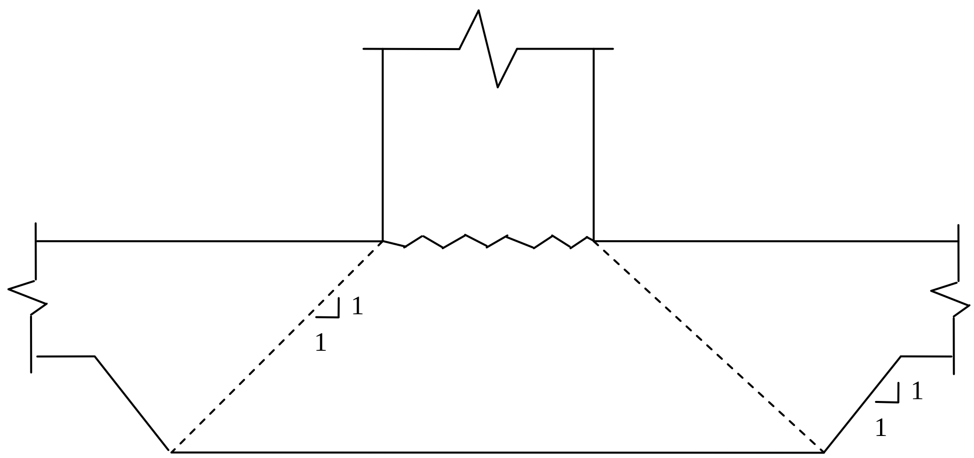
Single or double shear conditions should be considered, as seen below.



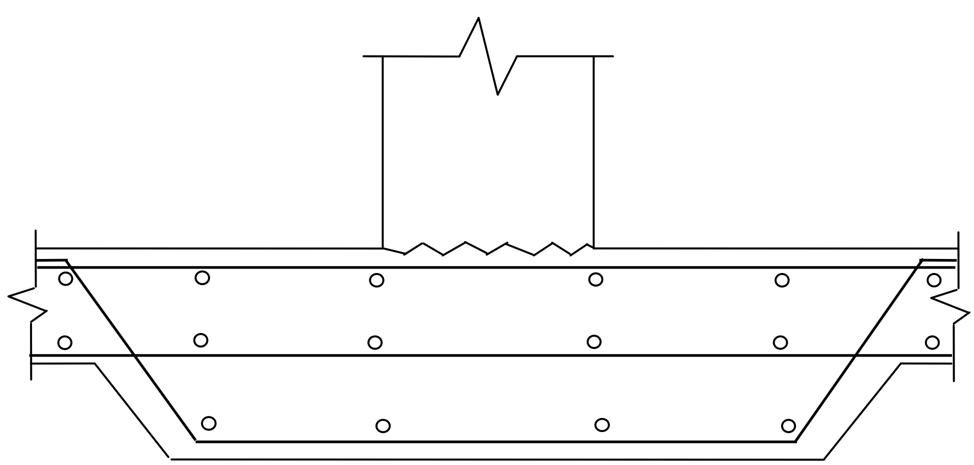
The critical sections to be checked for shear are at the face of the wall, as per ACI 350-06 section 15.5.2. The design strength is then $\varphi V_n = \varphi V_c$ where $\phi = 0.75$, as per ACI 350-06 section 9.3.2.3. Note that the loads causing the shear need to be factored.

Thickened Slabs

If the ultimate shear in the critical section is greater than the capacity, there are two options. The simplest solution is to thicken the slab, which is often done if the capacity is inadequate by only a small amount. Another option is to thicken the slab at the location of the wall. It is common practice to design the length of the thickened slab in the manner shown below. The critical sections remain at the face of the wall.



The reinforcing for the slab extends through the thickened portion, as illustrated below. Additional rebar will be needed at the bottom of the thickened slab. The rebar in the bottom of the thickened slab is mainly needed for the minimum reinforcing requirement in ACI 350-06 section 7.12.2.1 (temperature and shrinkage steel), this is due to the larger gross area of concrete.



Flotation

ACI 350.4R-04 section 3.1.2 requires the weight of the empty tank exceed the uplift from the highest groundwater level with a factor of safety of 1.25.

$$1.25 \le \frac{\text{Dead Load}}{\text{Uplift}}$$

No load factors for the dead load or the water pressure are used in this calculation.

A Few Provisions to be Considered (not an exhaustive list)

minimum steel for flexure section: ACI 350-06 section 10.5.1

minimum vertical steel in walls: ACI 350-06 section 14.3.2

minimum horizontal steel in walls: ACI 350-06 section 7.12.2.1

maximum spacing for vertical steel in walls: ACI 350-06 section 14.3.5

maximum spacing for horizontal steel in walls: ACI 350-06 section 14.3.5

walls more than 10″ thick must have two layers of rebar: ACI 350-06 section 14.3.4

minimum wall thickness: ACI 350-06 section 14.6

additional bars around wall openings: ACI 350-06 section 14.3.7

nominal shear strength: ACI 350-06 section 11.3.1.1

slab thickness: ACI 350-06 section H.3

concrete cover for slabs: ACI 350-06 section H.4.4 and section 7.7.1

minimum steel for shrinkage and temperature: ACI 350-06 section 7.12.2.1

strength reduction factors: ACI 350-06 section 9.3

[tensile] hoop stress in rebar for round tanks:
$f_s \leq 20{,}000$ psi for normal environmental exposures – ACI 350-06 section 9.2.6.2
$f_s \leq 17{,}000$ psi for severe environmental exposures – ACI 350-06 section 9.2.6.3

concrete cover: ACI 350-06 section 7.7.1

reinforcing details: ACI 350-06 chapter 12

waterstops:
waterstops must be incorporated into construction joints: ACI 350.4R-04 section 5.4 and ACI 350-06 section 4.8.2
(there is product information available on the internet, search for “waterstop”)

Area of Reinforcing

Bar	A_s (in^2)
#2	0.049
#3	0.11
#4	0.20
#5	0.31
#6	0.44
#7	0.60
#8	0.79
#9	1.00
#10	1.27