A Design Example for a Rectangular Concrete Tank
PCA Design Method

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The Portland Cement Association (PCA) has publications for designing rectangular and circular tanks. Some of the design provisions differ from that of the American Concrete Institute (ACI) specifications. Many in the industry use these PCA design concepts, so we will adapt them for our calculations as well. Much of the PCA publication is comprised of tables of coefficients for calculating moment and shear in two-way slabs. These tables should simplify the calculations. We will refer to the PCA Rectangular Concrete Tanks design manual as PCA-R, and the circular tank design manual as PCA-C.

An additional safety factor is used for the loads called the "Sanitation Coefficient", we will denote it with SC for brevity. Note that this notation is not an industry standard. The purpose of the sanitation coefficient is to indirectly reduce the stress, and thus the strain, in the steel reinforcing. The result is lower strain in the concrete, and thus less cracking. The ultimate load will be multiplied by SC, which has different values for different calculations:

$$SC = \begin{cases} 1.3 & \text{for flexure} \\ 1.65 & \text{for direct tension (hoop tensile stress in reinforcing)} \\ 1.0 & \text{shear provided by concrete} \\ 1.3 & \text{for shear beyond that provided by concrete} \end{cases}$$

Another change is the fluid load factor is 1.7 rather than 1.4 as stated in the ACI specification. For the purposes of this class, the following load combinations and factors will be used:

$M_u = 1.3(1.4D + 1.7F + 1.6H)$ for flexure

$P_u = 1.65(1.4D + 1.7F + 1.6H)$ for direct tension (hoop tensile stress in reinforcing)

$P_u = 1.0(1.4D + 1.7F + 1.6H)$ for direct compression (hoop compression stress in concrete)

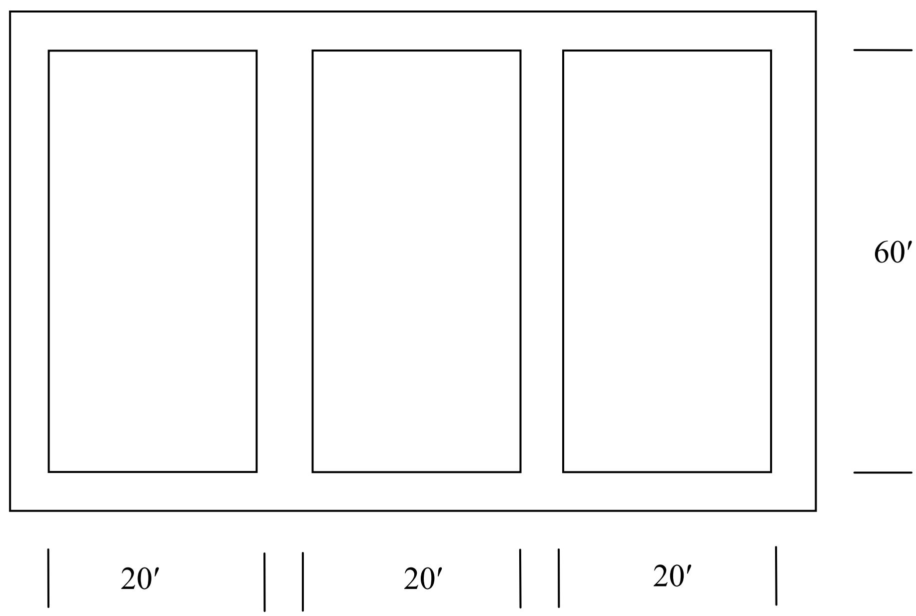
$V_u = 1.0(1.4D + 1.7F + 1.6H)$ shear provided by concrete

$V_u = 1.3(1.4D + 1.7F + 1.6H)$ for shear beyond that provided by concrete

D = dead load F = fluid pressure H = earth pressure

Rectangular Concrete Tank Design Example

An open top concrete tank is to have three chambers, each measuring 20′×60′ as shown. The wall height is 17′. The tank will be partially underground, the grade level is 10′ below the top of the tank. The highest groundwater table is expected to be 4′ below grade. The fluid level inside the tank is 15′.



f'_c = 3,500 psi $\quad$ f_y = 60,000 psi

soil bearing capacity = 2,700 psf

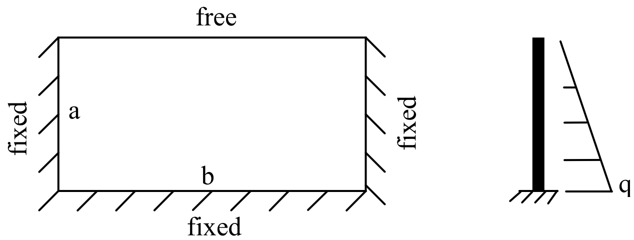
Walls above the groundwater table should be designed using a lateral earth pressure equivalent to that developed by a fluid weighing 45 pcf, below the groundwater table use 95 pcf.

Due to the settlement characteristics of the soil, it is recommended that the bearing pressure be kept as constant as possible for the full tank loading scenario.

Assume the density of the fluid in the tank is 63 pcf.

Interior Wall Design

Boundary condition case 3 in chapter 2 of PCA-R will be used for determining the applied moments to the tank walls (pages 2-17 thru 2-22). Consider the 15′ water depth to be the height of the wall.



a = 15′ b = 60′ b/a = 4.0 q = (15′)(63 pcf) = 945 psf

From page 2-18 of PCA-R, the maximum vertical moment coefficient is 149, looking at the M_x table. This moment occurs at the center-bottom of the wall. Similarly, the M_y table gives a maximum horizontal moment coefficient of 99, located at the top ends of the wall.

For the moment calculations $q_u = (1.3)(1.7)(945\text{ pcf}) = 2{,}089\text{ psf}$

$M_u = \text{moment coefficient} \times q_u \times a^2/1000$

Vertical Moment: coef = 149 $M_u = 70{,}034$ lb-ft/ft
Horizontal Moment: coef = 99 $M_u = 46{,}533$ lb-ft/ft

The maximum shear in the wall is obtained from the maximum shear coefficient from page 2-17 of PCA-R, in this case $C_s = 0.50$. The wall will be designed for the concrete to resist the entire shear force.

For the shear calculation $q_u = (1.0)(1.7)(945\text{ pcf}) = 1{,}607\text{ psf}$

$V_u = C_s \times q_u \times a = (0.50)(1{,}607\text{ psf})(15') = 12{,}053\text{ lb/ft}$

Note:
The moment in the wall varies considerably for different locations in the wall. The reinforcing could differ at several locations for a highly efficient design. The thickness of the wall could also vary, either tapering the wall or stepping the wall. However, for the sake of time, the reinforcing will be kept consistent for the entire wall. One design for the vertical moments, and the other for the horizontal moments. This is a common practice in engineering. Time is not only saved for the design engineer, but also the detailers and construction crew saves time as compared to a more complicated design. This design philosophy is entitled to change if substantial material savings could be realized and if time permits.

Vertical Flexure Design of Interior Wall:

try a 14″ thick wall with 2″ clear concrete cover and #8 bars @ 6″
(design a 1′ wide vertical strip of wall)

$b_w = 12''$ $d = 14'' - 2'' - \text{bar dia}/2 = 11.5''$ $A_g = 168 \text{ in}^2$

$f'_c = 3{,}500 \text{ psi}$ $f_y = 60{,}000 \text{ psi}$ $A_s = 1.58 \text{ in}^2$

$$c = \frac{A_s \cdot f_y}{\beta_1 \cdot b_w \cdot (0.85 \cdot f'_c)} = 3.124 \text{ in}$$

$$\phi M_n = (0.9) \cdot A_s \cdot f_y \cdot \left(d - \frac{\beta_1 \cdot c}{2}\right) = 867{,}898 \text{ lb-in/ft} = 72{,}325 \text{ lb-ft/ft}$$

$M_u = 70{,}034$ lb-ft/ft $\phi M_n = 72{,}325$ lb-ft/ft

minimum flexural steel

ACI 350-06 § 10.5.1 $\frac{200 \cdot b_w \cdot d}{f_y} \le A_s$ $\Rightarrow$ $A_{s.min} = 0.46 \text{ in}^2$ [flexure steel $A_s = 1.58 \text{ in}^2$]

ACI 350-06 § 10.5.1 $\frac{3 \cdot \sqrt{f'_c}}{f_y} \cdot b_w \cdot d \le A_s$ $\Rightarrow$ $A_{s.min} = 0.408 \text{ in}^2$ [flexure steel $A_s = 1.58 \text{ in}^2$]

minimum vertical wall steel

ACI 350-06 § 14.3.2 $0.003 \times A_g \le A_s$ $\Rightarrow$ $A_{s.min} = 0.504 \text{ in}^2$ [total steel $A_s = 3.16 \text{ in}^2$]

minimum steel for temperature and shrinkage

ACI 350-06 § 14.3.2 $0.005 \times A_g \le A_s$ $\Rightarrow$ $A_{s.min} = 0.84 \text{ in}^2$ [total steel $A_s = 3.16 \text{ in}^2$]

maximum flexural steel

ACI 318 § 10.3.3 $A_{s,max} = \frac{(0.0019125) \cdot \beta_1 \cdot b_w \cdot d \cdot f'_c}{\left(0.003 + \frac{f_y}{E_s}\right) \cdot f_y} = 2.58 \text{ in}^2$ [flexure steel $A_s = 1.58 \text{ in}^2$]

Horizontal Flexure Design of Interior Wall:

The wall is 14″ thick, place the horizontal bars inside of the vertical bars. Try #8 bars @ 8″

b_w = 12″   d = 14″ - 2″ - vertical bar dia - bar dia/2 = 10.5″ A_g = 168 in^2

f'_c = 3,500 psi f_y = 60,000 psi A_s = 1.185 in^2

$$c = \frac{A_s \cdot f_y}{\beta_1 \cdot b_w \cdot (0.85 \cdot f'_c)} = 2.343 \text{ in}$$

$$\phi M_n = (0.9) \cdot A_s \cdot f_y \cdot \left(d - \frac{\beta_1 \cdot c}{2}\right) = 608{,}174 \text{ lb-in/ft} = 50{,}681 \text{ lb-ft/ft}$$

M_u = 46,533 lb-ft/ft ϕM_n = 50,681 lb-ft/ft

minimum flexural steel

ACI 350-06 § 10.5.1 $\frac{200 \cdot b_w \cdot d}{f_y} \le A_s$ ⇒ $A_{s.min}$ = 0.42 in^2 [flexure steel A_s = 1.185 in^2]

ACI 350-06 § 10.5.1 $\frac{3 \cdot \sqrt{f'_c}}{f_y} \cdot b_w \cdot d \le A_s$ ⇒ $A_{s.min}$ = 0.248 in^2 [flexure steel A_s = 1.185 in^2]

minimum vertical wall steel

ACI 350-06 § 14.3.2 $0.003 \times A_g \le A_s$ ⇒ $A_{s.min}$ = 0.504 in^2 [total steel A_s = 2.37 in^2]

minimum steel for temperature and shrinkage

ACI 350-06 § 14.3.2 $0.005 \times A_g \le A_s$ ⇒ $A_{s.min}$ = 0.84 in^2 [total steel A_s = 2.37 in^2]

maximum flexural steel

ACI 318 § 10.3.3 $A_{s,max} = \frac{(0.0019125) \cdot \beta_1 \cdot b_w \cdot d \cdot f'_c}{\left(0.003 + \frac{f_y}{E_s}\right) \cdot f_y}$ = 2.357 in^2 [flexure steel A_s = 1.185 in^2]

Shear Capacity (1′ wide strip either way):

$b_w = 12''$ $d = 11.5''$ $f'_c = 3{,}500$ psi

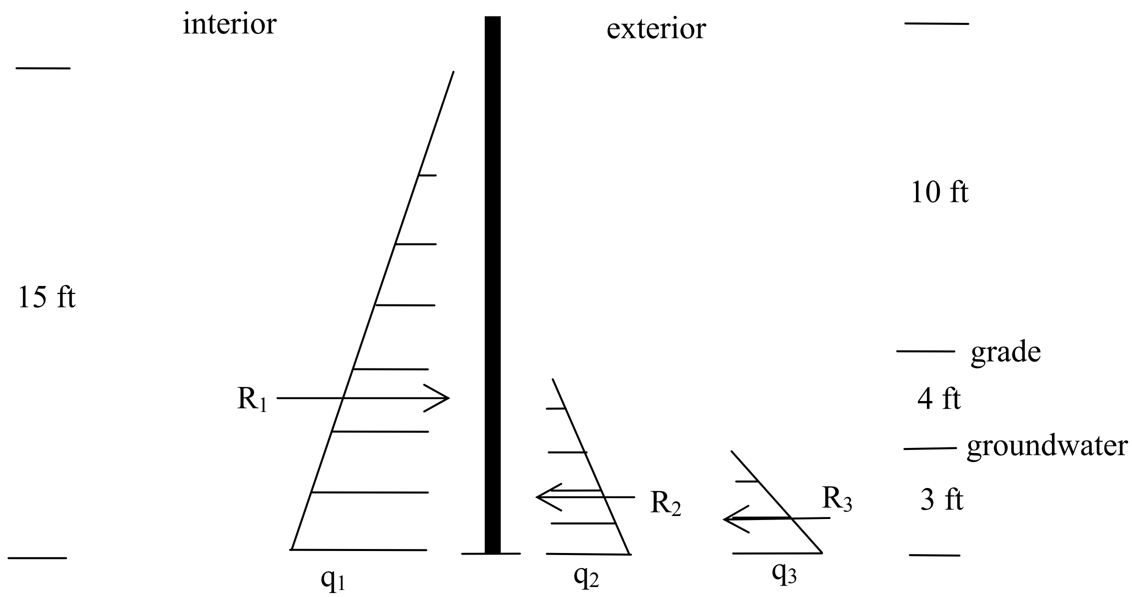
$$V_c = 2\sqrt{f'_c}\,b_w d = 16{,}328 \text{ lb/ft}$$

design shear strength = $\phi V_n = 0.75V_c = 12{,}246$ lb/ft

$V_u = 12{,}053$ lb/ft $\phi V_n = 12{,}246$ lb/ft

Long Exterior Wall

The Long exterior wall has the same geometry as the interior wall. A simple demonstration shows that the effect of the interior fluid is significantly greater than the exterior soil and groundwater. The long exterior wall will take the same design as the interior walls.



interior

$q_1 = (1.3)(1.7)(15')(63\ \text{pcf}) = 2{,}089$ psf $R_1 = 0.5(15')q_1 = 15{,}668$ lb/ft $d_1 = 15'/3 = 5'$

moment $= R_1 \times d_1 = 78{,}340$ lb-ft/ft

exterior

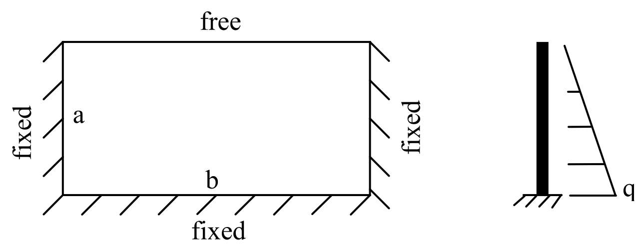
$q_2 = (1.3)(1.6)(7')(45\ \text{pcf}) = 656$ psf $R_2 = 0.5(7')q_2 = 2{,}296$ lb/ft $d_2 = 7'/3 = 2.334'$

$q_3 = (1.3)(1.7)(3')(50\ \text{pcf}) = 332$ psf $R_3 = 0.5(3')q_3 = 498$ lb/ft $d_3 = 3'/3 = 1'$

moment $= R_2 \times d_2 + R_3 \times d_3 = 5{,}857$ lb-ft/ft

<u>Short Exterior Wall Design</u>

As with the long exterior walls, the effect of the internal fluid pressure will be greater than that of the exterior soil and groundwater pressure. As a result the wall will be designed for the interior fluid pressure.



a = 15′ b = 20′ b/a = 1.33 q = (15′)(63 pcf) = 945 psf

The coefficients for b/a = 1.5 are larger than those for b/a = 1.25. Conservatively the tables for b/a = 1.5 will be used. From page 2-20 of PCA-R, the maximum vertical moment coefficient is 61. This moment occurs at the center-bottom of the wall. Similarly the maximum horizontal moment coefficient is 44, located near the top ends of the wall.

For the moment calculations $q_u = (1.3)(1.7)(945 \text{ pcf}) = 2{,}089$ psf

$M_u = \text{moment coefficient} \times q_u \times a^2/1000$

Vertical Moment:	coef = 61	M_u = 28,672 lb-ft/ft
Horizontal Moment:	coef = 44	M_u = 20,682 lb-ft/ft

The maximum shear in the wall is obtained from the maximum shear coefficient from page 2-17 of PCA-R, in this case $C_s = 0.40$. The wall will be designed for the concrete to resist the entire shear force.

For the shear calculation $q_u = (1.0)(1.7)(945 \text{ pcf}) = 1{,}607$ psf

$V_u = C_s \times q_u \times a = (0.40)(1{,}607 \text{ psf})(15') = 9{,}642$ lb/ft

Vertical Flexure Design for the Short Exterior Wall:

Keep the wall thickness at 14″ with 2″ clear concrete cover and #6 bars @ 8″

$b_w = 12''$ $d = 14'' - 2'' - \text{bar dia}/2 = 11.625''$ $A_g = 168\ \text{in}^2$

$f'_c = 3{,}500$ psi $f_y = 60{,}000$ psi $A_s = 0.66\ \text{in}^2$

$$c = \frac{A_s \cdot f_y}{\beta_1 \cdot b_w \cdot (0.85 \cdot f'_c)} = 1.305 \text{ in}$$

$$\phi M_n = (0.9) \cdot A_s \cdot f_y \cdot \left(d - \frac{\beta_1 \cdot c}{2}\right) = 394{,}548 \text{ lb-in/ft} = 32{,}879 \text{ lb-ft/ft}$$

$M_u = 28{,}672$ lb-ft/ft $\phi M_n = 32{,}879$ lb-ft/ft

minimum flexural steel

ACI 350-06 § 10.5.1 $\frac{200 \cdot b_w \cdot d}{f_y} \le A_s$ $\Rightarrow$ $A_{s.min} = 0.465\ \text{in}^2$ [flexure steel $A_s = 0.66\ \text{in}^2$]

ACI 350-06 § 10.5.1 $\frac{3 \cdot \sqrt{f'_c}}{f_y} \cdot b_w \cdot d \le A_s$ $\Rightarrow$ $A_{s.min} = 0.413\ \text{in}^2$ [flexure steel $A_s = 0.66\ \text{in}^2$]

minimum vertical wall steel

ACI 350-06 § 14.3.2 $0.003 \times A_g \le A_s$ $\Rightarrow$ $A_{s.min} = 0.504\ \text{in}^2$ [total steel $A_s = 1.32\ \text{in}^2$]

minimum steel for temperature and shrinkage

ACI 350-06 § 14.3.2 $0.005 \times A_g \le A_s$ $\Rightarrow$ $A_{s.min} = 0.84\ \text{in}^2$ [total steel $A_s = 1.32\ \text{in}^2$]

maximum flexural steel

ACI 318 § 10.3.3 $A_{s,max} = \frac{(0.0019125) \cdot \beta_1 \cdot b_w \cdot d \cdot f'_c}{\left(0.003 + \frac{f_y}{E_s}\right) \cdot f_y} = 2.609\ \text{in}^2$ [flexure steel $A_s = 0.66\ \text{in}^2$]

Horizontal Flexure Design for the Short Exterior Wall:

The wall is 14″ thick, place the horizontal bars inside of the vertical bars. The interior walls and long exterior walls have horizontal a spacing of 8″. In order to accommodate rebar splices keep the spacing for the horizontal steel at 8″. Try #5 bars @ 8″

$b_w = 12''$ $\quad$ $d = 14'' - 2''$ - vertical bar dia - bar dia/2 = 10.6875″ $\quad$ $A_g = 168\ in^2$

$f'_c = 3{,}500$ psi $\quad$ $f_y = 60{,}000$ psi $\quad$ $A_s = 0.465\ in^2$

$$c = \frac{A_s \cdot f_y}{\beta_1 \cdot b_w \cdot (0.85 \cdot f'_c)} = 0.919 \text{ in}$$

$$\phi M_n = (0.9) \cdot A_s \cdot f_y \cdot \left(d - \frac{\beta_1 \cdot c}{2} \right) = 258{,}551 \text{ lb-in/ft} = 21{,}546 \text{ lb-ft/ft}$$

$M_u = 20{,}682$ lb-ft/ft $\quad$ $\phi M_n = 21{,}546$ lb-ft/ft

minimum flexural steel

ACI 350-06 § 10.5.1 $\quad \dfrac{200 \cdot b_w \cdot d}{f_y} \le A_s \quad \Rightarrow A_{s.min} = 0.428\ in^2$ [flexure steel $A_s = 0.465\ in^2$]

ACI 350-06 § 10.5.1 $\quad \dfrac{3 \cdot \sqrt{f'_c}}{f_y} \cdot b_w \cdot d \le A_s \quad \Rightarrow A_{s.min} = 0.374\ in^2$ [flexure steel $A_s = 0.465\ in^2$]

minimum vertical wall steel

ACI 350-06 § 14.3.2 $\quad 0.003 \times A_g \le A_s \quad \Rightarrow A_{s.min} = 0.504\ in^2$ [total steel $A_s = 0.93\ in^2$]

minimum steel for temperature and shrinkage

ACI 350-06 § 14.3.2 $\quad 0.005 \times A_g \le A_s \quad \Rightarrow A_{s.min} = 0.84\ in^2$ [total steel $A_s = 0.93\ in^2$]

maximum flexural steel

ACI 318 § 10.3.3 $\quad A_{s,max} = \dfrac{(0.0019125) \cdot \beta_1 \cdot b_w \cdot d \cdot f'_c}{\left(0.003 + \dfrac{f_y}{E_s}\right) \cdot f_y} = 2.357\ in^2$ [flexure steel $A_s = 0.465\ in^2$]

Shear Capacity (1′ wide strip either way):

b_w = 12″ d = 11.625″ f'_c = 3,500 psi

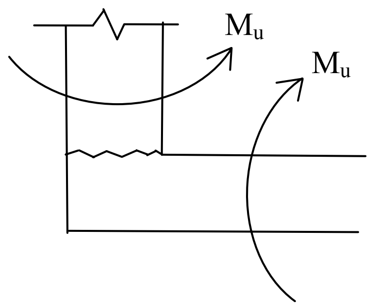
$$V_c = 2\sqrt{f'_c}\,b_w d = 16{,}505 \text{ lb/ft}$$

design shear strength = $\phi V_n = 0.75 V_c$ = 12,378 lb/ft

V_u = 9,642 lb/ft ϕV_n = 12,378 lb/ft

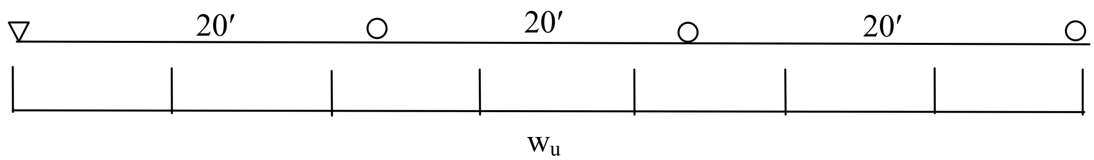
Slab Design

One of the criteria for slab design is that it must be able to resist the moment from the bottom of the wall. As a first approximation, assume the slab to be 14″ thick.



Another scenario is uplift from groundwater:

The tank in an empty state along with a high groundwater table can experience severe uplift on the floor slab. In this example the groundwater table is then 3′ + 1.17′ above the bottom of the 14″ thick slab. The approximate dimensions of the slab are 60′ × 20′. The slab will be designed as a one-way flexure member spanning in the short direction. Consider a 1′ wide strip of slab with an ultimate load w_u from the water pressure below the slab.



The water pressure pushing upward is reduced by the weight of the slab. The water pressure is multiplied by a factor of 1.7, and the dead weight of the concrete is multiplied by a factor of 0.9. The sanitation coefficient is 1.3 for flexure and 1/0 for shear, provided the concrete will resist all of the shear force.

$w_u = 1.3[1.7(62 \text{ pcf})(4.17 \text{ ft})(1') - 0.9(150 \text{ pcf})(14''/12)(1')] = 367 \text{ lb/ft}$

$M_u = (0.1167)(367 \text{ lb/ft})(20 \text{ ft})^2 = 17{,}132 \text{ lb-ft/ft}$

$V_u = 1.0(1.7)(0.617)(367 \text{ lb/ft})(20') = 7{,}699 \text{ lb}$

} from continuous beam tables

Note that this moment is significantly smaller than the moment at the bottom of the long walls. The design of the slab in the short direction will be the same as that of the walls in the vertical direction, #8 bars @ 6″ top and bottom faces of the slab. Also note that the shear is considerably less than in the walls, thus the 14″ thick slab is adequate for the shear strength.

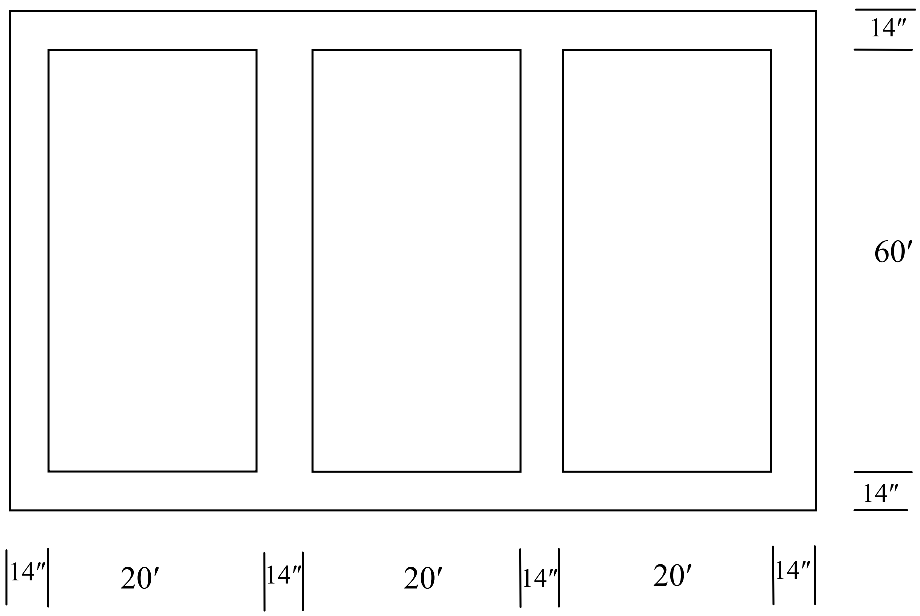
The slab in the long span direction is mainly taking moment from the bottom of the short exterior walls. The same design will be used in this direction as the vertical reinforcing for the short exterior walls, #6 bars @ 8″ top and bottom faces.

Flotation

ACI 350.R4-04 section 3.1.2 gives a criterion for flotation of the tank under high groundwater water conditions:

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

Total weight of tank:



slab $(64.66')(62.33')(1.166') = 4{,}699\ \text{ft}^3$

4 long walls $(4)(62.33')(17')(1.166') = 4{,}942\ \text{ft}^3$

6 short walls $(6)(20')(17')(1.166') = 2{,}378\ \text{ft}^3$

total volume = 12,019 ft^3

total weight of tank = $(12{,}019\ \text{ft}^3)(150\ \text{pcf}) = 1{,}802{,}850\ \text{lb}$

uplift pressure = (62 pcf)(4.17 ft) = 258.5 psf

uplift area = $(64.66')(62.33') = 4{,}031\ \text{ft}^3$

uplift force = 1,042,014 lb

$$\frac{\text{Dead Load}}{\text{Uplift}} = 1.73$$

Bearing on Soil

total weight of tank = 1,802,850 lb

weight of fluid = (3)(20′)(60′)(15′) (63 pcf) = 3,402,000 lb

total weight = 5,204,850 lb

footprint area = 4,031 ft^3

soil pressure = 1,291 psf

soil capacity = 2,700 psf