Topics

- Define environmental concrete structure
- Pictorial examples
- Historical stroll down memory lane (NRCS based)
  - WSD/ASD Flexural Model
  - USD/LRFD Flexural Model
- The New Millennium (ACI 318, ACI 350, and NRCS concrete design criteria side-by-side)
What is an Environmental Concrete Structure?

- Conveys, contains, impounds water, and/or dissipates forces due to flowing water
- Secondary containment for the storage of hazardous wastes
- Designed to be watertight........or relatively so
- Serviceability limit states just as important as strength (maybe more so at times)
Grade Control Structure
In the Beginning

- SCS/NRCS National Engineering Handbook, Section 6, Chapter 4, Concrete, circa 1950’s
- Referenced Chp VIII of Joint Committee Report titled “Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete”
- $f_c = 0.40 f'_c$, $f_s = 20$ ksi, $v_c = 113$ psi
- $\rho_{ts} = 0.2\%$ exposed, $0.1\%$ unexposed
Working Stress Design Flexural Model

Stress Distribution In Straight-Line Theory

Flexural Equations Development.pdf
WORKING STRESS ANALYSIS

\[ T = C \]
\[ j d = d - \frac{kd}{3} \]
\[ T = A_s f_s \]
\[ C = \frac{1}{2} f_c b kd \]
\[ j = 1 - \frac{k}{3} \]

\[ A_s f_s = \frac{1}{2} f_c b kd \]
\[ f_s = \frac{1}{2 A_s} f_c b kd \]

\[ \frac{A_s}{b d} = \rho = \frac{1}{2} \frac{f_c}{f_s} \]

\[ M = T j d \]
\[ M = A_s f_s j d \]
\[ f_s = \frac{M}{A_s j d} \]

\[ M = \frac{1}{2} f_c b kd j d \]
\[ f_s = \frac{2M}{f_c b j k d^2} \]

\[ \frac{kd}{f_c} = \frac{d - kd}{E_c} \quad \frac{kd}{f_s} = \frac{E_c}{f_s} \]
\[ \frac{k}{1 - k} = n \frac{f_c}{f_s} \]
\[ k = n \frac{f_c}{f_s} - k \left( n \frac{f_c}{f_s} \right) \]
\[ k + k \left( n \frac{f_c}{f_s} \right) = n \frac{f_c}{f_s} \]
\[ k \left( 1 + n \frac{f_c}{f_s} \right) = n \frac{f_c}{f_s} \]
\[ k = \frac{n \frac{f_c}{f_s}}{1 + n \frac{f_c}{f_s}} = \frac{1}{n \frac{f_c}{f_s} + 1} \]
WORKING STRESS

BALANCED STEEL RATIO

$$\frac{A_s}{b \cdot d} = \rho = \frac{1}{2} \cdot \frac{f_c}{f_y} \cdot k = \frac{f_c}{2f_y} \cdot \frac{1}{\frac{f_y}{n \cdot f_c} + 1}$$

NRCS CRITERIA

$$f_c = 0.4f_c \quad f_s = \frac{f_y}{3} \quad \text{for grade 60 steel}$$

$$f_s = \frac{f_y}{2} \quad \text{for grade 40 steel}$$

TRANSFORMED SECTION ANALYSIS

Determining the neutral axis of the cracked transformed section of a rectangular, singly reinforced beam or slab:

Summing areas about the base of the neutral axil, c, yields

$$\frac{b \cdot c^2}{2} - n \cdot A_s \cdot (d - c) = 0$$

Substituting $$c = kd$$ and $$\rho = A_s / bd$$ results in

$$\frac{b \cdot (kd)^2}{2} - \rho \cdot n \cdot bd \cdot (d - kd) = 0$$

Dividing by $$bd^2$$ and solving for k gives

$$k = \sqrt{2 \cdot \rho \cdot n + (\rho \cdot n)^2 - \rho \cdot n}$$
The 1960’s

- SCS/NRCS National Engineering Handbook, Section 6, Chapter 4, Concrete, updated 1964
- Working Stress Design only
- References ACI 318-63
- $f_c = 0.40 f'_c$, $f_s = 20$ ksi, $v_c = 70$ psi
- $\rho_{ts} = 0.3\%$ exposed
- $\rho_{ts} = 0.2\%$ exposed face & < 30ft joints
- $\rho_{ts} = 0.1\%$ unexposed face & < 30ft joints
The 1970’s

- ACI 318-71 primarily uses SD, but allows an Alternate Design Method (ADM) based on WSD
- ACI 318-71 introduces z-values for crack control
- ACI 318-77 moves ADM to Appendix
- ACI 350R-77 “Concrete Sanitary Engr Structures” recommends WSD from ACI 318-64, but uses lower allowable stresses and z-values
\[ T = C \quad a = \beta_1 \cdot c \]

\[ \rho = \frac{A_s}{b \cdot d} \quad T = A_s f_y \quad C = 0.85 f'_c \cdot b \cdot a \quad a = \frac{A_s f_y}{0.85 f'_c \cdot b} \]

\[ A_s = \rho \cdot b \cdot d \]

\[ \frac{a}{d} = \frac{A_s f_y}{0.85 f'_c \cdot b \cdot d} \]

\[ \frac{a}{d} = \frac{\rho f_y}{0.85 f'_c} \]

\[ M_n = A_s f_y \left( d - \frac{a}{2} \right) \]

\[ M_n = A_s f_y d \left( 1 - \frac{a}{d \cdot 2} \right) \quad M_n = A_s f_y d \left( 1 - \frac{A_s f_y}{2 \cdot 0.85 f'_c \cdot b \cdot d} \right) \]

\[ M_n = \rho \cdot b \cdot d^2 f_y \left( 1 - \frac{\rho f_y}{1.7 f'_c} \right) \]

\[ \frac{M_n}{b \cdot d^2} = \rho f_y \left( 1 - \frac{\rho f_y}{1.7 f'_c} \right) \quad \frac{M_n}{f'_c b \cdot d^2} = \frac{f_y}{f'_c} \left( 1 - \frac{\rho f_y}{1.7 f'_c} \right) \quad \frac{M_n}{f'_c b \cdot d^2} = \omega \cdot (1 - 0.59 \cdot \omega) \]

\[ R_n = \rho f_y \left( 1 - \frac{\rho f_y}{1.7 f'_c} \right) \]
\[ R_n = \frac{M_n}{b \cdot d^2} \]

\[ \rho_b = \frac{0.85 \cdot f_c \cdot \beta_1}{f_y} \cdot \frac{\varepsilon_c}{\varepsilon_c + \varepsilon_y} \]

\[ \rho_b = \frac{0.85 \cdot f_c \cdot \beta_1}{f_y} \cdot \frac{87000}{87000 + f_y} \]

\[ \rho_{ccl} = \frac{0.85 \cdot f_c \cdot \beta_1}{f_y} \cdot \frac{\varepsilon_c}{\varepsilon_c + 0.002} \]

\[ \rho_{ccl} = \frac{0.85 \cdot f_c \cdot \beta_1}{f_y} \cdot \frac{0.003}{0.003 + 0.002} \]

\[ \rho_{tcl} = \frac{0.85 \cdot f_c \cdot \beta_1}{f_y} \cdot \frac{\varepsilon_c}{\varepsilon_c + 0.005} \]

\[ \rho_{tcl} = \frac{0.85 \cdot f_c \cdot \beta_1}{f_y} \cdot \frac{0.003}{0.003 + 0.005} \]
The 1980’s

- Based on ACI 318-77 SD modified to produce similar design proportions as NEH 6 WSD
- Modifications include higher load factors, limited design yield strengths, lower z-values, and lower maximum reinforcing steel ratio
- SCS NEH-6 revised 1980 to include z-value criteria
The 1980’s

- ACI 350R-83 adopts SD modified to produce similar design proportions as ACI 350R-77 WSD
- Modification is mainly sanitary durability factor (load factor multiplier)
- ACI 350 reorganized and renamed “Environmental Engineering Concrete Structures”
- ACI 350 starts drafting a Code document based on previous Report and dependent on ACI 318 Code
The 1990’s

- ACI 318 deletes ADM from the Code, but allows use of ADM as published in previous Codes
- ACI 350 continues to redraft and reballot a Code document
- ACI 350 defines Environmental Engineering Concrete Structures as including “…ancillary structures for dams, spillways, and channels.”
Evolution of SCS/NRCS
Concrete Design
The New Millennium
New Millennium
Comparison of ACI 318-99, ACI 350-01, and NRCS TR 67

- ACI 318-99 replaced z-value with direct calculation for steel spacing
- ACI 350-01 was an update to ACI 318-95 nomenclature
  - Placed lower limits on z-values
  - Introduced service durability factors to be applied to factored load effects
- NRCS TR 67 – no change

ACI 350-06 Concrete Protection for Reinforcement.pptx
ACI 350-06 Concrete Protection for Reinforcement

7.7 — Concrete protection for reinforcement

7.7.1 — Cast-in-place concrete (nonprestressed)

The following minimum concrete cover shall be provided for reinforcement, but shall not be less than required by 7.7.6:

(a) Concrete cast against and permanently exposed to earth ............................................................ 3

(b) Concrete exposed to earth, liquid, weather, or bearing on work mat or slabs supporting earth cover:
   Slabs and joists ................................................................. 2
   Beams and columns:
   Stirrups, spirals, and ties .............................................. 2
<table>
<thead>
<tr>
<th></th>
<th>ACI 318-99</th>
<th>ACI 350-01</th>
<th>NRCS TR-67 1980</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load Factor</strong></td>
<td>$1.4(D+F) + 1.7(L+H)$</td>
<td>$1.4(D) + 1.7(F+L+H)$</td>
<td>$1.8(D) + 1.8(L+H)$</td>
</tr>
<tr>
<td><strong>Durability Factor</strong></td>
<td>N/A</td>
<td>1.3 – flexure &amp; shear</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.65 – axial tension</td>
<td></td>
</tr>
<tr>
<td><strong>Crack control, normal exposure</strong></td>
<td>$s = \left( \frac{540}{f_s} \right) - 2.5c_c$</td>
<td>$Z = 115 \text{ kips/in}$</td>
<td>$Z = 130 \text{ kips/in}$</td>
</tr>
<tr>
<td><strong>Crack control, severe exposure</strong></td>
<td>N/A</td>
<td>$Z = 95 \text{ kips/in}$</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Max spacing, s</strong></td>
<td>18 inches</td>
<td>12 inches</td>
<td>18 inches</td>
</tr>
<tr>
<td><strong>f_c</strong></td>
<td>3,000 psi</td>
<td>4,000 psi</td>
<td>4,000 psi</td>
</tr>
<tr>
<td><strong>f_y</strong></td>
<td>60,000 psi</td>
<td>60,000 psi</td>
<td>40,000 psi</td>
</tr>
<tr>
<td><strong>f_s</strong></td>
<td>as high as 36,000 psi</td>
<td>27,000 psi</td>
<td>20,000 psi</td>
</tr>
<tr>
<td><strong>(\rho_{\text{design}})</strong></td>
<td>only upper limit of 0.75(\rho_b)</td>
<td>only upper limit of 0.75(\rho_b)</td>
<td>(\rho_{\text{shy}} = 0.31\rho_b)</td>
</tr>
<tr>
<td><strong>(\rho_{\text{min}})</strong></td>
<td>0.00333</td>
<td>0.00333</td>
<td>0.00500</td>
</tr>
<tr>
<td><strong>Min T &amp; S ratio</strong></td>
<td>0.0018</td>
<td>0.0030</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

**ACI 350-01&06 Exposure Definitions.pptx**
10.6.4.5 — For liquid retention, normal environmental exposure is defined as exposure to liquids with a pH greater than 5, or exposure to sulfate solutions of 1000 ppm or less. Severe environmental exposures are conditions in which the limits defining normal environmental exposure are exceeded.
New Millennium
Comparison of ACI 318-02, ACI 350-01, and NRCS TR 67

- ACI 318-02 introduced major changes
  - Unified Design and net tensile strain
  - Introduced ASCE 7 Load Factors
  - Phi-factor revisions
- ACI 350-01 – no change
- NRCS TR 67 – no change
ACI LOAD FACTORS & DESIGN LOADS, U

\[ U = 1.4(D + F) \]  \hspace{1cm} (9-1)
\[ U = 1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R) \]  \hspace{1cm} (9-2)
\[ U = 1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (1.0L \text{ or } 0.8W) \]  \hspace{1cm} (9-3)
\[ U = 1.2D + 1.6W + 1.0L + 0.5(L_r \text{ or } S \text{ or } R) \]  \hspace{1cm} (9-4)
\[ U = 1.2D + 1.0E + 1.0L + 0.2S \]  \hspace{1cm} (9-5)
\[ U = 0.9D \pm 1.6W + 1.6H \]  \hspace{1cm} (9-6)
\[ U = 0.9D \pm 1.0E + 1.6H \]  \hspace{1cm} (9-7)

\textbf{D} = \text{dead load}; \quad \textbf{E} = \text{earthquake load}; \quad \textbf{F} = \text{lateral fluid pressure load}
\textbf{H} = \text{load due to the weight and lateral pressure of soil and water in soil}
\textbf{L} = \text{live load}; \quad \textbf{L}_{r} = \text{roof load}; \quad \textbf{R} = \text{rain load}; \quad \textbf{S} = \text{snow load}
\textbf{T} = \text{self-straining force such as creep, shrinkage, and temperature effects}
\textbf{W} = \text{wind load}
### STRENGTH REDUCTION FACTOR, $\phi$

<table>
<thead>
<tr>
<th>Condition</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension controlled sections</td>
<td>0.9</td>
</tr>
<tr>
<td>Compression controlled sections with ties</td>
<td>0.65</td>
</tr>
<tr>
<td>Compression controlled sections with spirals</td>
<td>0.70</td>
</tr>
<tr>
<td>Columns with small axial loads</td>
<td>0.65 – 0.9 or 0.70 – 0.9</td>
</tr>
<tr>
<td>Shear and Torsion</td>
<td>0.75</td>
</tr>
<tr>
<td>Bearing on concrete</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Unified Design Definitions

\[ \varepsilon_T = \text{Net Tensile Strain} \]

\[ d_t = \text{Depth to Extreme Tension Steel} \]

Note: \( d = d_t \) for single layer of tension steel
10.3.3-4 - STRAIN CONDITIONS

Compression Controlled
\[ c \geq 0.6d_t \]

Transition

Tension-Controlled
\[ c \leq 0.375d_t \]
## Comparison of ACI 318-02, ACI 350-01, and NRCS TR 67

<table>
<thead>
<tr>
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<th>ACI 318-02</th>
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<td></td>
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### TABLE 7.12.2.1—MINIMUM SHRINKAGE AND TEMPERATURE REINFORCEMENT

<table>
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<tr>
<th>Length between movement joints, ft</th>
<th>Minimum shrinkage and temperature reinforcement ratio</th>
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<tbody>
<tr>
<td></td>
<td>Grade 40</td>
</tr>
<tr>
<td>Less than 20</td>
<td>0.0030</td>
</tr>
<tr>
<td>20 to less than 30</td>
<td>0.0040</td>
</tr>
<tr>
<td>30 to less than 40</td>
<td>0.0050</td>
</tr>
<tr>
<td>40 and greater</td>
<td>0.0060*</td>
</tr>
<tr>
<td></td>
<td>Grade 60</td>
</tr>
<tr>
<td></td>
<td>0.0030</td>
</tr>
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</table>

*Maximum shrinkage and temperature reinforcement where movement joints are not provided.

Note: This table applies to spacing between expansion joints and full contraction joints. When used with partial contraction joints, the minimum reinforcement ratio shall be determined by multiplying the actual length between partial contraction joints by 1.5.
New Millennium
Comparison of ACI 318-05, ACI 350-01, and NRCS TR 67

- ACI 318-05 introduced minor changes
  - Unified the notations and definitions
  - Revised service level stress for flexure to 40,000 psi
- ACI 350-01 – no change
- NRCS TR 67 – no change
## Comparison of ACI 318-05, ACI 350-01, and NRCS TR 67

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New Millennium
Comparison of ACI 318-05, ACI 350-06, and NRCS TR 67

- ACI 318-05 – no change
- ACI 350-06 updated to ACI 318-02 nomenclature
  - Durability factor as a function of steel yield and service level stresses
  - Maximum bar spacing a function of steel stress, bar size, allowable crack width, and 2 inch max. clear cover
- NRCS TR 67 – no change
ACI 350-06 Durability Factor

\[ S_d = \frac{\phi f_y}{\gamma f_s} \geq 1.0 \quad (9-8) \]

where \( \gamma = \frac{\text{factored load}}{\text{unfactored load}} \)
10.6.4.1 — In normal environmental exposure areas as defined in 10.6.4.5

\[
 f_{s,max} = \frac{320}{\beta \sqrt{s^2 + 4(2 + d_b/2)^2}} \quad (10-4)
\]

but need not be less than 20,000 psi for one-way and 24,000 psi for two-way members.

10.6.4.2 — In severe environmental exposure areas as defined in 10.6.4.5

\[
 f_{s,max} = \frac{260}{\beta \sqrt{s^2 + 4(2 + d_b/2)^2}} \quad (10-5)
\]

but need not be less than 17,000 psi for one-way and 20,000 psi for two-way members.
## Comparison of ACI 318-05, ACI 350-06, and NRCS TR 67

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<td>1.2 (D+F) + 1.6(L+H)</td>
<td></td>
</tr>
<tr>
<td><strong>Durability Factor</strong></td>
<td>N/A</td>
<td>$S_d = \frac{fy}{fs} \geq 1.0$</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Crack control, normal exposure</strong></td>
<td>$s = 15 \left( \frac{40,000}{f_s} \right) - 2.5c_c$</td>
<td>$f_{s,\text{max}} = \frac{20 \text{kpsi}}{\beta \sqrt{s^2 + 4(2+d_b/2)^2}} \leq 36 \text{kpsi}$</td>
<td>Z = 130 kips/in</td>
</tr>
<tr>
<td><strong>Crack control, severe exposure</strong></td>
<td>N/A</td>
<td>$f_{s,\text{max}} = \frac{17 \text{kpsi}}{\beta \sqrt{s^2 + 4(2+d_b/2)^2}} \leq 36 \text{kpsi}$</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Max spacing, s</strong></td>
<td>18 inches</td>
<td>12 inches</td>
<td>18 inches</td>
</tr>
<tr>
<td><strong>f'c</strong></td>
<td>4,000 psi</td>
<td>4,000 psi</td>
<td>4,000 psi</td>
</tr>
<tr>
<td><strong>f_y</strong></td>
<td>60,000 psi</td>
<td>60,000 psi</td>
<td>40,000 psi</td>
</tr>
<tr>
<td><strong>f_a</strong></td>
<td>as high as 40,000 psi</td>
<td>based on bar spacing as above</td>
<td>20,000 psi</td>
</tr>
<tr>
<td><strong>\rho_{design}</strong></td>
<td>only upper limit of \rho_t</td>
<td>only the upper limit of \rho_t</td>
<td>$\rho_{shy} = 0.31 \rho_b$</td>
</tr>
<tr>
<td><strong>\rho_{min}</strong></td>
<td>0.00333</td>
<td>0.00333</td>
<td>0.0050</td>
</tr>
<tr>
<td><strong>Min T &amp; S ratio</strong></td>
<td>0.00180</td>
<td>0.0030</td>
<td>0.0030</td>
</tr>
</tbody>
</table>
New Millennium

Comparison of ACI 318-08, ACI 350-06, and NEH 636.30

- ACI 318-08 – changes to combined bending and axial force design procedure
- ACI 350-06 – no change
- NRCS NEH 636, Chapter 30 – draft 2008
  - Incorporates ACI 350-06 and ACI 318-08
  - Tensile steel stress of 20,000 psi
  - Max. steel ratio of $0.546 \rho_{bal}$
  - $f_y = 60,000$ psi
Comparison of ACI 318-08, ACI 350-06, and NEH 636.30

<table>
<thead>
<tr>
<th></th>
<th>ACI 318-08</th>
<th>ACI 350-06</th>
<th>NEH 636.30 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load Factor</strong></td>
<td>1.4(D+F) 1.2(D+F)+1.6(L+H)</td>
<td>1.4(D+F) 1.2(D+F)+1.6(L+H)</td>
<td>1.4(D+F) 1.2(D+F)+1.6(L+H)</td>
</tr>
<tr>
<td><strong>Durability Factor</strong></td>
<td>N/A</td>
<td>$S_d = \frac{\phi f_y}{f_s} \geq 1.0$</td>
<td>$S_d = \frac{\phi f_y}{f_s} \geq 1.0$</td>
</tr>
<tr>
<td><strong>Crack control, normal exposure</strong></td>
<td>$s = 18 \left( \frac{40,000}{f_s} \right) - 2.5c_c$</td>
<td>$f_{s,\text{max}} = \frac{320}{\beta \sqrt{s^2 + 4(2 + d_s/2)^2}} \leq 36ksi$</td>
<td>$s = \sqrt{\left( \frac{320}{f_y \beta} \right)^2 - 4 \left( 2 + \frac{d_s}{2} \right)^2}$</td>
</tr>
<tr>
<td><strong>Crack control, severe exposure</strong></td>
<td>N/A</td>
<td>$f_{s,\text{max}} = \frac{260}{\beta \sqrt{s^2 + 4(2 + d_s/2)^2}} \leq 36ksi$</td>
<td>Special Design required</td>
</tr>
<tr>
<td><strong>Max spacing, s</strong></td>
<td>18 inches</td>
<td>12 inches</td>
<td>12 inches</td>
</tr>
<tr>
<td><strong>$f_c$</strong></td>
<td>4,000 psi</td>
<td>4,000 psi</td>
<td>4,000 psi</td>
</tr>
<tr>
<td><strong>$f_y$</strong></td>
<td>60,000 psi</td>
<td>60,000 psi</td>
<td>60,000 psi</td>
</tr>
<tr>
<td><strong>$f_x$</strong></td>
<td>as high as 40,000 psi</td>
<td>based on bar spacing as above</td>
<td>20,000 psi</td>
</tr>
<tr>
<td><strong>$\rho_{\text{design}}$</strong></td>
<td>only upper limit of $\rho_t$</td>
<td>only the upper limit of $\rho_t$</td>
<td>$\rho_{\text{shy}} = 0.546 \rho_b$</td>
</tr>
<tr>
<td><strong>$\rho_{\text{min}}$</strong></td>
<td>0.00333</td>
<td>0.00333</td>
<td>0.00333</td>
</tr>
<tr>
<td><strong>Min T&amp;S ratio</strong></td>
<td>0.00180</td>
<td>0.0030</td>
<td>0.0030</td>
</tr>
</tbody>
</table>
### Table 4.2.1.a Exposure Category F – Freezing and thawing exposure

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>Not applicable</td>
<td>Concrete not exposed to freezing and thawing cycles</td>
</tr>
<tr>
<td>F1</td>
<td>Moderate</td>
<td>Concrete exposed to freezing and thawing cycles and occasional exposure to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>moisture</td>
</tr>
<tr>
<td>F2</td>
<td>Severe</td>
<td>Concrete exposed to freezing and thawing cycles and in continuous contact</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with moisture</td>
</tr>
<tr>
<td>F3</td>
<td>Very Severe</td>
<td>Concrete exposed to freezing and thawing cycles that will be in continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>contact with moisture and exposure to deicing chemicals</td>
</tr>
</tbody>
</table>

### Table 4.2.1.b Exposure Category S – Sulfate exposure

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Water-soluble sulfate (SO₄) in soil, percent by weight</th>
<th>Sulfate (SO₄) in water, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>Not applicable</td>
<td>SO₄ &lt;0.10</td>
<td>SO₄ &lt;150</td>
</tr>
<tr>
<td>S1</td>
<td>Moderate</td>
<td>0.10 ≤ SO₄ &lt;0.20</td>
<td>150 ≤ SO₄ &lt;1500 Seawater</td>
</tr>
<tr>
<td>S2</td>
<td>Severe</td>
<td>0.20 ≤ SO₄ ≤ 2.00</td>
<td>1500 ≤ SO₄ ≤10,000</td>
</tr>
<tr>
<td>S3</td>
<td>Very severe</td>
<td>SO₄ &gt;2.00</td>
<td>SO₄ &gt;10,000</td>
</tr>
</tbody>
</table>
ACI 318-08, Chapter 4 (cont’d)

### Table 4.2.1.c Exposure Category P – In contact with water requiring low permeability concrete

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>Not applicable</td>
<td>Concrete where low permeability to water is not required</td>
</tr>
<tr>
<td>P1</td>
<td>Required</td>
<td>Concrete required to have low permeability to water</td>
</tr>
</tbody>
</table>

### Table 4.2.1.d Exposure Category C – Conditions requiring corrosion protection of reinforcement

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>Not applicable</td>
<td>Concrete that will be dry or protected from moisture in service</td>
</tr>
<tr>
<td>C1</td>
<td>Moderate</td>
<td>Concrete exposed to moisture but not to external source of chlorides in service</td>
</tr>
<tr>
<td>C2</td>
<td>Severe</td>
<td>Concrete exposed to moisture and an external source of chlorides in service – from deicing chemicals, salt, brackish water, seawater, or spray from these sources</td>
</tr>
</tbody>
</table>
### Table 4.3.1.a For Exposure Category F – Freezing and thawing exposure

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Max w/cm</th>
<th>Min psi</th>
<th>Additional Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F1</td>
<td>0.45</td>
<td>4500</td>
<td>Table 4.4.1</td>
</tr>
<tr>
<td>F2</td>
<td>0.45</td>
<td>4500</td>
<td>Table 4.4.1</td>
</tr>
<tr>
<td>F3</td>
<td>0.45</td>
<td>4500</td>
<td>Table 4.4.1</td>
</tr>
</tbody>
</table>

### Table 4.3.1.b For Exposure Category S – Sulfate exposure

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Max w/cm</th>
<th>Min psi</th>
<th>Required Cementitious Materials* - Types</th>
<th>Additional Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S1</td>
<td>0.50</td>
<td>4000</td>
<td>III** IP(MS), IS(&lt;70)(MS)</td>
<td>MS</td>
</tr>
<tr>
<td>S2</td>
<td>0.45</td>
<td>4500</td>
<td>V** -</td>
<td>HS</td>
</tr>
<tr>
<td>S3</td>
<td>0.45</td>
<td>4500</td>
<td>V + pozzolan or slag†</td>
<td>HS + pozzolan or slag†</td>
</tr>
</tbody>
</table>
### Table 4.3.1.c For Exposure Category P – In contact with water requiring low permeability concrete

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Max w/cm</th>
<th>Min psi</th>
<th>Additional Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>0.50</td>
<td>4000</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.3.1.d For Exposure Category C – Conditions requiring corrosion protection of reinforcement

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Max w/cm</th>
<th>Min psi</th>
<th>Max water-soluble chloride ion (Cl(^{-})) content in concrete, percent by weight of cement</th>
<th>Additional Minimum Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C0</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>-</td>
<td>-</td>
<td>0.30</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>0.40</td>
<td>5000</td>
<td>0.15</td>
<td>Cover(^{+})</td>
</tr>
<tr>
<td>Prestressed Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C0</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>0.40</td>
<td>5000</td>
<td>0.06</td>
<td>Cover(^{+})</td>
</tr>
</tbody>
</table>
### TABLE 4.4.1—TOTAL AIR CONTENT FOR CONCRETE EXPOSED TO CYCLES OF FREEZING AND THAWING

<table>
<thead>
<tr>
<th>Nominal maximum aggregate size, in.</th>
<th>Air content, percent</th>
<th>Exposure Class F2 and F3</th>
<th>Exposure Class F1</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8</td>
<td>7.5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>1/2</td>
<td>7</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td>3/4</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>1-1/2</td>
<td>5.5</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>2†</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3†</td>
<td>4.5</td>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 4.4.2—REQUIREMENTS FOR CONCRETE SUBJECT TO EXPOSURE CLASS F3

<table>
<thead>
<tr>
<th>Cementitious materials</th>
<th>Maximum percent of total cementitious materials by weight*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash or other pozzolans conforming to ASTM C 618</td>
<td>25</td>
</tr>
<tr>
<td>Slag conforming to ASTM C 989</td>
<td>50</td>
</tr>
<tr>
<td>Silica fume conforming to ASTM C 1240</td>
<td>10</td>
</tr>
<tr>
<td>Total of fly ash or other pozzolans, slag, and silica fume</td>
<td>50†</td>
</tr>
<tr>
<td>Total of fly ash or other pozzolans and silica fume</td>
<td>35†</td>
</tr>
</tbody>
</table>
### TABLE 4.1.2.1 — MINIMUM CEMENTITIOUS MATERIAL CONTENT

<table>
<thead>
<tr>
<th>Nominal maximum aggregate size, in.</th>
<th>Coarse aggregate (ASTM C 33) size no.</th>
<th>Minimum cementitious materials (lb/yd^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1/2</td>
<td>467</td>
<td>515</td>
</tr>
<tr>
<td>1</td>
<td>57</td>
<td>535</td>
</tr>
<tr>
<td>3/4</td>
<td>67</td>
<td>560</td>
</tr>
<tr>
<td>1/2</td>
<td>7</td>
<td>580</td>
</tr>
<tr>
<td>3/8</td>
<td>8</td>
<td>600</td>
</tr>
</tbody>
</table>

*For nominal maximum coarse aggregate size not indicated, interpolate the minimum cementitious material content between nominal sizes shown.

### TABLE 4.2.1 — TOTAL AIR CONTENT FOR FROST-RESISTANT CONCRETE

<table>
<thead>
<tr>
<th>Nominal maximum aggregate size, in.</th>
<th>Air content, percent</th>
<th>Severe exposure</th>
<th>Moderate exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8</td>
<td>7-1/2</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td></td>
<td>5-1/2</td>
</tr>
<tr>
<td>3/4</td>
<td>6</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td></td>
<td>4-1/2</td>
</tr>
<tr>
<td>1-1/2</td>
<td>5-1/2</td>
<td></td>
<td>4-1/2</td>
</tr>
<tr>
<td>2†</td>
<td>5</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3†</td>
<td>4-1/2</td>
<td></td>
<td>3-1/2</td>
</tr>
</tbody>
</table>

*See ASTM C 33 for tolerance on oversize for various nominal maximum size designations.
†These air contents apply to total mixture, as for the preceding nominal maximum aggregate sizes. When testing these concretes, however, aggregate larger than 1-1/2 in. is removed by handpicking or sieving and air content is determined on the minus 1-1/2 in. fraction of mixture (tolerance on air content as delivered applies to this value). Air content of total mixture is computed from the value determined on the minus 1-1/2 in. fraction.
TABLE 4.2.2—REQUIREMENTS FOR SPECIAL EXPOSURE CONDITIONS

<table>
<thead>
<tr>
<th>Exposure condition</th>
<th>Maximum water-cementitious materials ratio, by weight*</th>
<th>Minimum $f'_c$, psi*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete intended to have low permeability when exposed to water, wastewater, and corrosive gasses</td>
<td>0.45</td>
<td>4000</td>
</tr>
<tr>
<td>Concrete exposed to freezing and thawing in a saturated condition or to deicing chemicals</td>
<td>0.42</td>
<td>4500</td>
</tr>
<tr>
<td>Concrete exposed to corrosive chemicals other than deicing chemicals</td>
<td>0.42</td>
<td>4500</td>
</tr>
<tr>
<td>For corrosion protection of reinforcement in concrete exposed to chlorides in tanks containing brackish water and concrete exposed to deicing chemicals, seawater, or spray from seawater</td>
<td>0.40</td>
<td>5000</td>
</tr>
</tbody>
</table>

*A lower water-cementitious material ratio or higher strength may be required for durability of concrete exposed to sulfates (Table 4.3.1).*
### TABLE 4.2.3 — REQUIREMENTS FOR CONCRETE EXPOSED TO DEICING CHEMICALS

<table>
<thead>
<tr>
<th>Cementitious materials</th>
<th>Maximum percent of total cementitious materials by weight*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash or other pozzolans conforming to ASTM C 618</td>
<td>25</td>
</tr>
<tr>
<td>Slag conforming to ASTM C 989</td>
<td>50</td>
</tr>
<tr>
<td>Silica fume conforming to ASTM C 1240</td>
<td>10</td>
</tr>
<tr>
<td>Total of fly ash or other pozzolans, slag, and silica fume</td>
<td>50†</td>
</tr>
<tr>
<td>Total of fly ash or other pozzolans and silica fume</td>
<td>35†</td>
</tr>
</tbody>
</table>

*The total cementitious material also includes ASTM C 150, C 595, and C 845 cement. The maximum percentages above shall include:
(a) Fly ash or other pozzolans present in Type IP or I(PM) blended cement, ASTM C 595;
(b) Slag used in the manufacture of a IS or I(SM) blended cement, ASTM C 595;
(c) Silica fume, ASTM C 1240, present in a blended cement
†Fly ash or other pozzolans and silica fume shall constitute no more than 25 and 10 percent, respectively, of the total weight of the cementitious materials.
### TABLE 4.3.1—REQUIREMENTS FOR CONCRETE EXPOSED TO SULFATE-CONTAINING SOLUTIONS

<table>
<thead>
<tr>
<th>Sulfate exposure</th>
<th>Water soluble sulfate (SO₄) in soil, percent by weight</th>
<th>Sulfate (SO₄) in water, ppm</th>
<th>Cement type</th>
<th>Maximum water-cementitious ratio, by weight*</th>
<th>Minimum specified compressive strength $f'_{c}$, psi*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>0.00-0.10</td>
<td>0-150</td>
<td>—</td>
<td>0.45</td>
<td>—</td>
</tr>
<tr>
<td>Moderate†</td>
<td>0.10-0.20</td>
<td>150-1500</td>
<td>II, IP(MS), IS(MS), I(PM)(MS), IS(MS)</td>
<td>0.42</td>
<td>4500</td>
</tr>
<tr>
<td>Severe</td>
<td>0.20-2.00</td>
<td>1500-10,000</td>
<td>V</td>
<td>0.40</td>
<td>5000</td>
</tr>
<tr>
<td>Very severe‡</td>
<td>Over 2.00</td>
<td>Over 10,000</td>
<td>V plus pozzolan§</td>
<td>0.40</td>
<td>5000</td>
</tr>
</tbody>
</table>

* A lower water-cementitious materials ratio or higher strength may be required for corrosion protection for concrete exposed to chlorides (Table 4.2.2).
†Seawater.
‡Additional corrosion barriers such as coatings or liners shall be required for very severe exposure.
§Pozzolan that has been determined by test or service record to improve sulfate resistance when used in concrete containing Type V cement.
## ACI 350-06 Chapter 4

### TABLE 4.4.1—MAXIMUM CHLORIDE ION CONTENT FOR CORROSION PROTECTION OF REINFORCEMENT

<table>
<thead>
<tr>
<th>Type of member</th>
<th>Maximum water soluble chloride ion (Cl⁻) in concrete, percent by weight of cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestressed concrete</td>
<td>0.06</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Environmental Engineering Concrete Structures

Flexural Design Eq’ns
Design Strength Curves for Grade 60 Steel
Basic Design Equations

New NRCS NEH 636.30: For $f'_c = 4$ ksi and $f_y = 60$ ksi

Hydraulic Structures: $L.F._{\text{effective}} = 2.7$

- $f_s = 20$ ksi
- $\rho_{\text{max}} = 0.01556$

$$d_{\text{min}} := \sqrt{\frac{15.721 \cdot M_u}{b}}$$

$$A_s := \frac{M_u}{3.843d_{\text{min}}}$$

$M_u$ is in k-ft; $b$ and $d$ are in inches
Basic Design Equations

Environmental Structure: For $f_c = 4$ ksi and $f_y = 60$ ksi

Normal Exposure: $L.F_{\text{effective}} = 2.25$

- $f_s = 24$ ksi
- $\rho_{\text{max}} = 0.01402$

\[
d_{\text{min}} := \sqrt{\frac{18.09 \cdot M_u}{b}}
\]

\[
A_s := \frac{M_u}{3.943d_{\text{min}}}
\]

$M_u$ is in k-ft; $b$ and $d$ are in inches
Basic Design Equations

Environmental Structure: For $f'_c = 4$ ksi and $f_y = 60$ ksi

Normal Exposure: $L.F_{effective} = 1.6$

$\rho_{max} = 0.00852$

$f_s = 36$ ksi

$28.22 \cdot M_u$

$d_{min} := \sqrt{\frac{28.22 \cdot M_u}{b}}$

$A_s := \frac{M_u}{4.16d_{min}}$

$M_u$ is in k-ft; $b$ and $d$ are in inches

Reinforced Concrete Wall Design-EECS ACI 350-06 with $f_{smax} = 24$ksi
Reinforced Concrete Wall or Beam Design - ACI 350-06 \( f_s = 24 \text{ ksi} \)

The design moment is the moment at the base of the stem. The moment is factored and is caused by lateral earth pressure, water, or surcharge loads. The design shear is at wall base. It is also factored and due to lateral earth and surcharge pressures. The 1.6 single load factor has been included in the moment, shear force, and uniform load.

\[
\begin{align*}
    f_c & := 4.0 \text{ksi} & f_y & := 60 \text{ksi} & f_s_{\text{max}} & := 24 \text{ksi} & f_c_{\text{max}} & := 1.8 \text{ksi} & f_{yv} & := 60 \text{ksi} & \phi & := 0.9 & \phi_v & := 0.75 & b & := 12 \text{in} \\
    w_u & := 6.07 \frac{\text{kip}}{\text{ft}} & L_n & := 7 \text{ft} & M_u & := 5.49 \text{kip-ft} & M_s & := 3.43 \text{kip-ft} & V_u & := 2.15 \text{kip} & d_{bs} & := \frac{0}{8} \text{in} & c_c & := 2 \text{in}
\end{align*}
\]

\[
\beta_1 := \begin{cases} 
    (f_c \geq 4 \cdot \text{ksi}) \cdot (f_c \leq 8 \cdot \text{ksi}) \cdot 0.85 - 0.05 \cdot \frac{f_c - 4 \cdot \text{ksi}}{\text{ksi}}, & \text{if} \left[ (f_c \leq 4 \cdot \text{ksi}), 0.85, 0.65 \right] \\
    \beta_1 = 0.85 & 
\end{cases}
\]
\[ E_s := 29000 \text{ksi} \quad E_c := 145 \cdot 1.5 \cdot \sqrt{f_c} \cdot \text{psi} = 3644 \cdot \text{ksi} \]
\[ n := \frac{E_s}{E_c} = 8 \]
\[ \gamma := \frac{M_u}{M_s} = 1.601 \quad S_d := \max \left( \frac{\phi f_y}{\gamma f_{s\_max}}, 1.0 \right) = 1.406 \quad S_d \cdot M_u = 7.72 \cdot \text{kip}\cdot\text{ft} \]
\[ \rho_b := \left( 0.85 \cdot \beta_1 \cdot \frac{f_c}{f_y} \right) \cdot \frac{87 \text{ksi}}{87 \text{ksi} + f_y} \quad \rho_b = 0.0285 \]
\[ \rho_{\text{max}} := \frac{f_{c\_max}}{2 \cdot f_{s\_max}} \left( \frac{1}{1 + \frac{f_{s\_max}}{n \cdot f_{c\_max}}} \right) \quad \rho_{\text{max}} = 0.01402 \quad \frac{\rho_{\text{max}}}{\rho_b} = 0.492 \]
\[ R_n := \rho_{\text{max}} f_y \left[ 1 - \left( 0.5 \cdot \rho_{\text{max}} \cdot \frac{f_y}{0.85 \cdot f_c} \right) \right] \quad R_n = 0.737 \cdot \text{ksi} \]
\[ d_{\text{min}} := \sqrt{S_d \cdot M_u \cdot \frac{1}{\phi \cdot R_n \cdot b}} \quad d_{\text{min}} = 3.41 \text{ in} \]
\[ h_{\text{min}} := d_{\text{min}} + c_c + \frac{5}{16} \text{ in} \quad h_{\text{min}} = 5.724 \text{ in} \]
\[ h := 6.0 \text{in} \quad d := h - c_c - \frac{5}{16} \text{in} \quad d = 3.687 \cdot \text{in} \]

\[ R_n := S_d \cdot M_u \cdot \frac{1}{\phi \cdot b \cdot d^2} \quad R_n = 0.631 \cdot \text{ksi} \]

\[ f_c \left( 1 - \sqrt{1 - 2 \cdot \frac{R_n}{0.85 \cdot f_c}} \right) \]

\[ \rho := 0.85 \cdot \frac{f_c}{f_y} \quad \rho = 0.011723 \]

\[ A_{s_{req}} := \rho \cdot b \cdot d \quad A_{s_{req}} = 0.519 \cdot \text{in}^2 \]

\[ R_{nu} := M_u \cdot \frac{1}{\phi \cdot b \cdot d^2} = 0.449 \cdot \text{ksi} \]

\[ f_c \left( 1 - \sqrt{1 - 2 \cdot \frac{R_{nu}}{0.85 \cdot f_c}} \right) \]

\[ \rho_u := 0.85 \cdot \frac{f_c}{f_y} \quad \rho_u = 0.00805 \]

\[ A_{s_{u_{req}}} := \rho_u \cdot b \cdot d = 0.36 \cdot \text{in}^2 \quad \text{Area of steel required for } M_u \text{ only, w/o the durability factor.} \]

**FOR BEAM AND RETAINING WALL DESIGN**

\[ A_{s_{min}} := \max \left( 3 \cdot \frac{f_c}{f_y} \cdot \psi \cdot b \cdot \frac{d}{f_y}, 200 \frac{f_c}{f_y} \cdot b \cdot \frac{d}{f_y} \right) \quad A_{s_{min}} = 0.147 \cdot \text{in}^2 \quad \text{ACI 10.5.1} \]
\[ A_{sdes} := \begin{cases} A_{sreq} & \text{if } A_{sreq} \geq A_{smin} \\ \max \left( \left( \frac{4}{3} \right) \cdot A_{su\_req} - A_{sreq}, 0.002 \cdot b \cdot h \right) & \text{if } \left( \frac{4}{3} \right) \cdot A_{su\_req} \leq A_{smin} \\ A_{smin} & \text{otherwise} \end{cases} \]

\[ A_{sdes} = 0.519 \text{ in}^2 \quad A_{sreq} := A_{sdes} \]

**THE REQUIRED AREA OF STEEL:**

\[ A_{sreq} = 0.519 \text{ in}^2 \]

**SELECT BAR SIZES/SPACING:**

**TRY #5 BARS:**

\[ A_b := 0.31 \text{ in}^2 \quad \text{spacing}_{req} := \frac{A_b}{A_{sreq}} \cdot 12 \text{ in} \quad \text{spacing}_{req} = 7.17 \text{ in} \]

Try #5 bars:

\[ A_b = 0.31 \text{ in}^2 \quad \text{bar spacing} := 6.0 \text{ in} \quad A_s := \frac{A_b}{\text{bar spacing}} \cdot 12 \text{ in} \quad A_s = 0.62 \text{ in}^2 \]

\[ d_b := \frac{5}{8} \text{ in} \quad d := h - c_c - \frac{d_b}{2} \quad d = 3.69 \text{ in} \]
CHECK CRACK CONTROL:

\[ M_{\text{service}} := M_s = 3.43 \text{-kip-ft} \]

\[ \begin{align*}
kd & := \sqrt{\frac{\left(2 \cdot \frac{b}{n \cdot A_s}\right) + 1 - 1}{\left(\frac{b}{n \cdot A_s}\right)}} \\
kd & = 1.38 \text{-in} \quad \text{depth to neutral axis}
\end{align*} \]

\[ j_d := d - \frac{kd}{3} \]

\[ j_d = 3.2 \text{-in} \]

\[ k := \frac{kd}{d} \]

\[ k = 0.374 \]

\[ f_s := \frac{M_{\text{service}}}{j_d \cdot A_s} \]

\[ f_s = 20.6 \text{-ksi} \]

\[ f_c := \frac{f_s}{n \cdot \frac{k}{1 - k}} \]

\[ f_c = 1.542 \text{-ksi} \]

\[ \frac{f_c}{f_c'} = 0.386 \]
CHECK Zcrack (an ACI 350-01 requirement):

\[ d_t := d + 0\text{in} \] depth to bottom layer of tension steel; \( d \) and \( d_t \) are equal for a single layer of reinforcing.

\[ A_{bL} := 0.31\text{in}^2 \] Area of largest diameter bar in group

\[ d_c := h - d_t \quad d_c = 2.31\cdot\text{in} \quad A := \frac{[2\cdot(h - d)\cdot b]}{A_s} \quad A = 27.8\cdot\text{in}^2 \]

\[ z_{\text{crack}} := f_s \cdot \sqrt[3]{d_c \cdot A} \quad z_{\text{crack}} = 82.3\cdot\frac{\text{kip}}{\text{in}} \]

Average crack width per the Gergeley-Lutz equation, (inches):

\[ \beta := \frac{(h - kd)}{(d - kd)} \quad \beta = 2.001 \quad h = 6\cdot\text{in} \quad d = 3.69\cdot\text{in} \]

\[ \omega := 0.076 \cdot \frac{\text{in}^2}{\text{kip}} \cdot \beta \cdot z_{\text{crack}} \cdot 0.001 \quad \omega = 0.01252\cdot\text{in} \]
MAXIMUM BAR SPACING ALLOWED with calculated bar stress per ACI 350-06:

\[ f_s = 20.6 \text{ ksi} \quad f_c = 1.542 \text{ ksi} \quad \beta = 2.001 \]

As per ACI 350-06 10.6.4.4, when \( h < 16 \) inches, \( \beta = 1.35 \).

\[ \text{bar spacing} = 6 \text{ in} \quad d_b = 0.625 \text{ in} \]

\[ \text{clear spacing} := \text{bar spacing} - d_b = 5.375 \text{ in} \]

OKAY. Clear spacing shall be not less than the larger of the bar diameter or 1 inch.

\[ s_{\text{max}1} := \sqrt{\frac{\left(320 \text{ kip/in} \right)^2}{\beta^2 f_s^2}} - 4 \left(2 \text{ in} + \frac{d_b}{2}\right)^2 \]

\[ s_{\text{max}1} = 6.25 \text{ in} \]

ACI 350 - 10.6.4.1

\[ s_{\text{max}} := \min(s_{\text{max}1}, 12 \text{ in}) \]

\[ s_{\text{max}} = 6.25 \text{ in} \quad \text{bar spacing} = 6 \text{ in} \]
When the appearance of the concrete surface is of concern and the clear cover to the bottom most layer of tension steel exceed 3 inches, the following must be met:

$$s_{\text{max\_appearance}} := \min \left[ \left( \frac{540 \text{ kip}}{\text{in}} \right) \frac{\text{in}}{f_s} - 2.5 \cdot c_e, 12 \text{ in} \cdot \frac{\text{36 ksi}}{f_s}, 12 \text{ in} \right]$$  \hspace{1cm} \text{ACI 350 10.6.5}

$$s_{\text{max\_appearance}} = 12 \cdot \text{in}$$

**USE - #5's @ 6 inches:**

$$A_b = 0.31 \cdot \text{in}^2$$  \hspace{1cm} \text{bar spacing} = 6 \cdot \text{in}

$$\frac{A_s}{b} = 0.62 \frac{1}{\text{ft}} \cdot \text{in}^2$$  \hspace{1cm} h = 6 \cdot \text{in}
CODE REQUIREMENTS FOR ENVIRONMENTAL ENGINEERING CONCRETE STRUCTURES AND COMMENTARY (ACI 350-06)

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THANKS FOR PARTICIPATING!

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