SLAB ON GROUND DESIGN & LESSONS LEARNED

By: Don Illingworth
IMPORTANT FACTORS IN SLAB ON GROUND DESIGN
History of SOG

- Became common in early 1950’s
- BRAB Report 1968
- PT Introduction Mid 1960’s
- HUD Approval 1968
- PTI Research 1975 @ Texas A&M
- 1st PTI Design Manual 1980
- 2nd ED 1996
- 3rd ED 2004
- PTI STD 2012
- Wire Reinforcement Institute (WRI) updated 1996
Post-Tensioning Institute’s Slabs-On-Ground Design Publications

“1st Edition Manual”
Published in 1980

Published in 1996
Addendum #1 (May 2007)

Addendum #2 (May 2008)

The Addenda generally reduced the conservatism of the 3rd Edition by:

- Providing clarification and guidance regarding new geotech provisions
- Modified boundary conditions of new geotechnical provisions.
- Changes to structural equations (Stiffness and Cracked Section).
Includes both addenda and errata

(three errata issued after publication of supplement)
Building code requirements

Addendum 1

Standards
**Building Codes**

- **ACI 318-05**
  - *R1.1.6* excludes residential post-tensioned SOG and refers their design to PTI 3rd Edition

- **IBC 2006**
  - For all practical purposes, only PTI and WRI methods are acceptable for foundations on expansive soils *(1805.8.2)*
  - Moments, shears, deflections calculated for one method can be used in the other

- **NFPA**
  - Will be rarely used, CA recently reversed original decision and will adopt I-codes
Since first publication of 3rd Edition, PTI also released 4 Frequently Asked Questions documents and 1 Technical Note applicable to slab-on-ground design and construction.

- FAQ No. 5 - Shrinkage and Temperature Reinforcement
- FAQ No. 6 - Field Elongation Measurements
- FAQ No. 7 - Soil Suction Profiles for Slab-on-Ground Applications
- FAQ No. 8 - Back-Up Bars for Slab-on-Ground Applications
- Tech Note 15 – Thicker is Weaker?
Foundation Based on Soil

- **Non Expansive PI<15-20 (Stable)**
  - Uniform thickness or shallow beams
  - Reinforced for crack control
  - PT average compression 50-75 psi

- **Moderate to High Expansive**
  - PI~20-50 PVR up to 4.5”
  - Uniform thickness
  - Waffle slab with beams
  - Both designed for expansive soil

- **Highly Expansive**
  - Treat soil to reduce movement or structurally suspended foundation
Type of Structure on Foundation

- Residential
  - Stiffness important

- Warehouse
  - Stiffness less important
  - Crack control

- Commercial
  - Stiffness important

Owner Expectations
Ribbed Foundation

**Pros**
- Structurally efficient with less materials.
- Does not rely on under slab fill for support (less earthwork).

**Cons**
- Labor intensive.
- Requires trenching into grade or forming fill.
FOUNDATION TYPES

- Uniform Thickness Foundation

  **Pros**
  - Does not require trenching into grade or forming fill (some parts of country use 7.5 inch thick slab with no turn down).

  **Cons**
  - Requires more concrete and post-tensioning cables.
  - Requires significant earthwork.
  - Sloping sites present problems.
PERIMETER LOAD

INITIAL MOUND SHAPE

edge moisture variation distance

PERIMETER LOAD

Δ

slab length

ym

center lift

em
Design Principles

- PTI Soil-Structure Interaction
  - Edge Lift
  - Center Lift

- Envelope Design for Cases in Between
Selection of Reinforcing System

Post-Tensioning
- Uniform size and shape with minimum elevation difference

Rebar
- Unusual shapes, large slabs, with multiple elevation changes
Important Items in Soils Report

- **PTI**
  - **Em**
    - Edge Lift
    - Center Lift
  - **Ym**
    - Edge Lift
    - Center Lift

- **Q Allowable Bearing Pressure**
Important Site Considerations

- Pre-Vegetation
  - Tree Lines
- Fence Lines
  - Roads, etc.
- Slopes
  - Cut Fill
- Drainage
- Time of Construction
- Landscaping
- Soil Modification
In PTI 2\textsuperscript{nd} and 3\textsuperscript{rd} Edition Manuals, $P_r$ is calculated at mid-slab. $P_{r \text{ mid slab}} < P_{r \text{ beta}}$

In “Combined Standard” $P_r$ is calculated at $\beta$
Slabs of Irregular Shapes

- **Shape Factor ~ 24**
- Overlapping Rectangles
- Beam Continuity
Shape Factor $\sim 24$

$$\frac{\text{Perimeter}^2}{\text{Area}}$$
SHAPE FACTOR (SF) = \frac{\text{Perimeter}^2}{\text{Area}}

(defined as perimeter$^2$/area)

If the SF is greater than 24 then the designer should consider:

- Modifications to the foundation footprint
- Use strengthened foundation system
- Soil treatment to reduce shrink / swell potential
- Use additional non-prestressed reinforcement
- Provide additional beams
Slabs of irregular shapes should be divided into overlapping rectangles and a separate design made for each rectangle.
Primary attention is given to the rectangle that most reasonably represents the majority of the actual foundation. Long, narrow rectangles are NOT representative.
ADD REBAR TO ADDRESS SHAPE FACTOR AND STRESS CONCENTRATIONS

ADD REBAR TO MITT ENTRANCE BEAM LINES AND ALLOW FOR CONNECTED BEAM TENSIONS

LONG, NARROW RECTANGLES ARE NOT USED BECAUSE THEY WOULD NOT BE REPRESENTATIVE OF THE OVERALL FOUNDATION

SHAPE FACTOR = 0.38
INCLUDE PATIO WITH FOUNDATION TO REDUCE SHAPE FACTOR AND ADDRESS STRESS CONCENTRATIONS.

LONG, NARROW RECTANGLES ARE NOT USED BECAUSE THEY WOULD NOT BE REPRESENTATIVE OF THE OVERALL FOUNDATION.

ORIGINAL SHAPE FACTOR: 0.58
NEW SHAPE FACTOR: 25.85
OPTIMAL
ADD REBAR
BELOW GRADE

ADD SLAB REINF
ADD TOP & BOTTOM BAR
BASE AS SHOWN

DESIGN RECTANGLE
ADD REBAR DUE TO SHAPE FACTOR.
POSSIBLY ADD MORE DEPENDS ON SOIL CONDITIONS.
DOUBLE REBAR TENSIONS IN LOAD BEAMS FOR ADDED COMPRESSION THRU NARROW AREA.
ADD CONTROL JOINT IN SLAB.

SHAPE FACTOR = 30.834
• Rectangle that is most representative

• Watch shape factor, especially over 30

• Add rebar if weird shape

• Avoid discontinuous beam

• Okay to slope beams
Live Loads
  - Uniform 40 + ADD’ L

Dead Loads
  - Actual

Line Loads & Concentrated

Residential vs. Warehouse
• Dead + Live load from superstructure only (no concrete)

• If $P$ varies and ratio of largest to smallest $\leq 1.25$
  use largest for design

• If $P$ varies and ratio of largest to smallest $> 1.25$
  use largest for center lift and smallest for edge lift
RIB Design

■ Spacing
  ❖ Max 15’-0
  ❖ Typically 10’-12’
  ❖ Align with heavy loads
    - Normally independent of wall layout

■ Depth (MOST IMPORTANT)
  ❖ Typ 24”-30”
  ❖ May vary, must be 7” below slab
  ❖ Deep Exterior for frost or moisture barrier

■ Width
  ❖ 8”-14”
  ❖ Most common 10”-12”
  ❖ Bearing Area B +6t or 16t
USE SOME COMMON SENSE
(Good engineering judgment)
Beams are not required to be parallel or perpendicular or evenly spaced (Max. 15’ +/-)
In analysis, ratio of deepest to shallowest rib depth cannot exceed 1.2 (not new in combined standard but misunderstood).

The difference in the constructed ribs are not limited to the 1.2 ratio.
Max Moment @ Beta
Allowables

Shear @ Beta
Allowables

Deflection
- Allowables
- 3rd edition change from deflection to stiffness

ALLOWABLES FOR DESIGN ONLY AND NOT FOR ANALYSIS
Moment vs Slab Length

\[ y_m = 1.0 \text{ IN} \]
\[ e_m = 2.0 \text{ FT} \]
Allowable Concrete Stresses

- **Flexural**
  - Tension $6\sqrt{f'_c}$
  - Compression $0.45f'_c$

- **Shear**
  - $v_c = 1.7\sqrt{f'_c} + 0.2f_p$
  - Shear should NOT control
15 KSI (Long Term Loss)

- Strand ULT = 41.3K
- Stress 80% MAX = 33K
- Final After Losses = 27K
- 10% Elongation Variance
- Designed as uncracked section
- Minor cracking not uncommon and expected
Design Based on Uncracked Section

- Similar to working-stress design of elevated prestressed concrete members
- Effects of cracking studied in detail in original research (Ch. 5) and subsequent publications available through PTI (Technical Note #6).
- Effects of cracking generally inconsequential due to
  - Location of shrinkage cracks.
  - Increased soil support after flexural cracking.
Design as ribbed foundation. Convert to uniform thickness with same I.

Not common in this area or highly expansive soils. Has perimeter beam and typically 8”-10” thick.

Used in California and Arizona
PTI Design Equations

A.2.1 Center Lift Design

A. Moment in the Long Direction

\[ M_L = A_0(B(e_m))^{1238} + C \]

where:

\[ A_0 = \frac{1}{727} \left[(L)^{0.013}(S)^{0.306}(h)^{0.688}(P)^{0.534}(y_m)^{0.193}\right] \]

and for:

\[ 0 \leq e_m \leq 5 \quad B = 1, \ C = 0 \]

\[ e_m > 5 \quad B = \left(\frac{y_m - 1}{3}\right) \leq 1.0 \]

\[ C = \left[8 - \frac{P - 613}{255}\left(4 - y_m\right)\right] \geq 0 \]

B. Moment in the Short Direction

For \( L_L / L_S \geq 1.1 \):

\[ M_S = \left[\frac{58 + e_m}{60}\right] M_L \]

For \( L_L / L_S < 1.1 \):

\[ M_S = M_L \]

C. Shear in the Long Direction

\[ V_L = \frac{(L)^{0.09}(S)^{0.71}(h)^{0.43}(P)^{0.44}(y_m)^{0.16}(e_m)^{0.93}}{1940} \]

A.2.2 Edge Lift Design

A. Moment in the Long Direction

\[ M_L = \frac{(S)^{0.10}(e_m)^{0.78}(y_m)^{0.66}}{7.2(L)^{0.00065}(P)^{0.9}} \]

B. Moment in the Short Direction

For \( L_L / L_S \geq 1.1 \):

\[ M_S = h^{0.35}\left[\frac{19 + e_m}{57.75}\right] M_L \]

For \( L_L / L_S < 1.1 \):

\[ M_S = M_L \]

C. Shear in Both Directions

\[ V_L \text{ or } V_S = \frac{(L)^{0.07}(h)^{0.4}(P)^{0.03}(e_m)^{0.16}(y_m)^{0.67}}{3.0(S)^{0.015}} \]

D. Differential Deflection

\[ \Delta_L = \frac{(L)^{0.35}(S)^{0.88}(e_m)^{0.74}(y_m)^{0.76}}{15.9(h)^{0.89}(P)^{0.01}} \]

\[ \Delta_P = \frac{P_0 e_0^2}{2E_0 I} \]

\[ \Delta = \Delta_L + \Delta_P \]
PTISlab 3.0 SOG

Project Title: Sample
Project Engineer: 
Geotechnical Report: 

Project Number: 
Project Date: April 9, 2014
Report Date: 
Report Number: 

RIBBED FOUNDATION - RESULTS OF ANALYSIS

Soil Bearing Analysis
- Total Applied Load: 629,614 LB
- Bearing Area: 4,305 FT²
- Applied Pressure on Soil: 193 PSF
- Soil Pressure Safety Factor: 6.49

 Prestress Summary
- Subgrade Friction calculated by method prescribed in PTI Manual

<table>
<thead>
<tr>
<th>Short Direction</th>
<th>Long Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Slab Tendons</td>
<td>26</td>
</tr>
<tr>
<td>Number of Beam Tendons</td>
<td>14</td>
</tr>
<tr>
<td>Spacing of Slab Tendons (Feet)</td>
<td>2.50</td>
</tr>
<tr>
<td>Center of Gravity of Concrete (from top of slab) (Inch)</td>
<td>8.68</td>
</tr>
<tr>
<td>Center of Gravity of Tendons (from top of slab) (Inch)</td>
<td>11.71</td>
</tr>
<tr>
<td>Eccentricity of Prestressing (Inch)</td>
<td>-3.13</td>
</tr>
<tr>
<td>Minimum Effective Prestress Force (K)</td>
<td>852.9</td>
</tr>
<tr>
<td>Beta Distance Effective Prestress Force (K)</td>
<td>980.8</td>
</tr>
<tr>
<td>Minimum Effective Prestress (PSI)</td>
<td>150</td>
</tr>
<tr>
<td>Beta Distance Effective Prestress (PSI)</td>
<td>159</td>
</tr>
</tbody>
</table>

Moment Analysis - Center Lift Mode
- Maximum Moment, Short Direction: 11.16 FT-KFT
- Tension in Top Fiber (KSI) - Compression in Bottom Fiber (KSI)
  | Short | Long |
  | Direction | Direction | Direction | Direction |
  | Allowable Stress | 1.350 | 1.356 | 0.683 | 0.631 |
  | Actual Stress | -0.329 | -0.056 | -0.052 | -0.052 |

Stiffness Analysis - Center Lift Mode
- Based on a Stiffness Coefficient of 480
  | Short | Long |
  | Direction | Direction |
  | Available Moment of Inertia (Inch²) | 574,321 | 611,101 |
  | Required Moment of Inertia (Inch²) | 226,656 | 215,102 |
  | Required Moment of Inertia controlled by Width | 338,766 | 322,654 |
  | Shear Analysis - Center Lift Mode | 1.68 KFT | 1.75 KFT |
  | Maximum Shear, Short Direction | 52 | 39 |
  | Allowable Shear Stress (PSI) | 164 (120) | 166 (122) |
  | Actual Shear Stress (PSI) | 52 | 39 |
## RIBBED FOUNDATION - RESULTS OF ANALYSIS continued

### Cracked Section Analysis - Center Lift Mode

<table>
<thead>
<tr>
<th>Description</th>
<th>Short Direction</th>
<th>Long Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked Section Capacity (FT-K)</td>
<td>1.654.9</td>
<td>1.581.1</td>
</tr>
<tr>
<td>0.9 Moment (FT-K)</td>
<td>768.1</td>
<td>659.0</td>
</tr>
</tbody>
</table>

### Moment Analysis - Edge Lift Mode

<table>
<thead>
<tr>
<th>Description</th>
<th>Short Direction</th>
<th>Long Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Moment, Short Direction</td>
<td>18.08 FT-KFT</td>
<td>12.70 FT-KFT</td>
</tr>
<tr>
<td>Maximum Moment, Long Direction</td>
<td>732,033 (1,008,050)</td>
<td>518,074 (777,111)</td>
</tr>
</tbody>
</table>

### Stiffness Analysis - Edge Lift Mode

<table>
<thead>
<tr>
<th>Description</th>
<th>Short Direction</th>
<th>Long Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Moment of Inertia (Inch^2)</td>
<td>674.321</td>
<td>611,101</td>
</tr>
<tr>
<td>Required Moment of Inertia (Inch^2)</td>
<td>732,033</td>
<td>518,074</td>
</tr>
</tbody>
</table>

### Shear Analysis - Edge Lift Mode

<table>
<thead>
<tr>
<th>Description</th>
<th>Short Direction</th>
<th>Long Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Shear, Short Direction</td>
<td>5.09 KF FT</td>
<td>6.16 KF FT</td>
</tr>
<tr>
<td>Maximum Shear, Long Direction</td>
<td>164 (120)</td>
<td>166 (122)</td>
</tr>
<tr>
<td>Allowable Shear Stress (PSI)</td>
<td>141</td>
<td>112</td>
</tr>
<tr>
<td>Actual Shear Stress (PSI)</td>
<td>104 (120)</td>
<td>106 (122)</td>
</tr>
</tbody>
</table>

### Cracked Section Analysis - Edge Lift Mode

<table>
<thead>
<tr>
<th>Description</th>
<th>Short Direction</th>
<th>Long Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked Section Capacity (FT-K)</td>
<td>921.6</td>
<td>1,163.5</td>
</tr>
<tr>
<td>0.9 Moment (FT-K)</td>
<td>1,244.7</td>
<td>793.6</td>
</tr>
</tbody>
</table>

Numbers in parenthesis calculated using original equations.
Sub-Grade Friction

- Depends on foundation type and surface material
- Extremely important for large slabs and some usages
- Crack Control
  - Very important for exposed concrete surfaces
WEIGHT OF THE SLAB “SLIDING” OVER SUBGRADE

EDGES MOVE TOWARD THE CENTER

MIDDLE IS POINT OF FIXITY
REQUIRED AVERAGE COMPRESSION (P/A)  
GENERALLY  50 – 150 psi

AVERAGE TENDON FORCE  
GENERALLY  27 kips

SLAB THICKNESS  
4” – 7”

COEFFICIENT OF FRICTION  
- Slabs cast on polyethylene sheeting - 0.75  
- Slabs cast directly on a sand layer - 1.0  
- Slabs cast on a granular sub-base - 1.75  
- Slabs cast directly on plastic soil - 2.0  
- Slabs cast directly on asphalt - 3.25
MINIMIZE SUBGRADE DRAG
INADEQUATE AVERAGE COMPRESSION (TOO LITTLE P/A) WILL ALLOW CRACKS TO FORM
ADEQUATE AVERAGE COMPRESSION (P/A) WILL RESIST CRACKING AND CLOSE SHRINKAGE AND TEMPERATURE CRACKS.
The prestress force in the concrete (Pr) at Beta should be used to determine the bending and shear stresses.

The prestress force in the concrete (Pr) at mid-slab should be used to determine the minimum effective prestress stress (50 PSI) or force (0.05A).

\[
P_r = P_e - \mu W_{\text{slab}}
\]

Where:
- \(P_e\) is the prestress force in the tendon after losses
- \(\mu\) is the subgrade friction coefficient
- \(W_{\text{slab}}\) is the weight of slab from perimeter to \(\beta\) or midslab
CRACKS
(NOT ENOUGH P/A)
CONSTRUCTION AND MAINTENANCE MANUAL FOR POST-TENSIONED SLAB-ON-GROUND FOUNDATIONS
8.3.1.a - Ribbed Foundations

- Rib Depth $h$: -1 in.; + 0.2$h$
- Rib Width: -1 in.; + 2 in.
- Slab Thickness:
  - Individual Location: -1/2 in. + 2 in.
  - Average Thickness: -1/4 in. + 1 in.
GRADE BEAMS WITH POLY

CUT POLY AT BOTTOM

CREATE VOIDS
Roof Gutters and Downspout Placement
Undrained Bathtub
Over Excavation and Backfill with Select fill “BATH TUB”

OVER EXCAVATE BACKFILL w/ SELECT FILL

UNDRAINED BATH TUB
Over Excavation and Backfill with Select fill “BATH TUB”

OVER EXCAVATE BACKFILL w/ SELECT FILL

OVER EXCAVATE BACKFILL w/ DRAINED FILL
Building Off of Moisture Conditioned Pad

MOISTURE CONDITIONING OF NATIVE SOIL

BUILDING OFF CONDITIONED PAD
When to use piers

- MOISTURE CONDITIONED OR MOIST SOIL OR SOFT SOIL
- BUILDING ON DRY SOIL
Plumbing Problems and Moisture Problems with Foundation on Void Boxes

SLAB ON CARTON FORMS
Previous Tree Rows and Uneven Soil Moisture Conditions
Incompatible Foundation Systems

PIERS w/ SLAB-ON-GRADE

PIERS w/ SLAB-ON-GRADE
Incompatible Foundation Systems

PIERS w/ SLAB-ON-GRADE
- Metal Building Type: Slab-On-Grade
- P.I. = 20 – 30
- P.V.R. < 1”
- 4” S.O.G. Turned Down
- Exterior Grade Beam
Movement Where Partition Wall Meets Exterior Wall
Effect of Post-Tensioning

EFFECTS OF PT SHORTINING
Effect of Post-Tensioning cont.

EFFECTS OF PT SHORTNING
Tendon length

Tendons less than 15' 0 are generally too short to stress
Corner Cracks
FOUNDATION MAINTENANCE

Proper foundation maintenance will minimize differential soil movement. Because of heavy rains at certain times of the year, it is impossible to keep moisture away from the foundation. However, good drainage will control excessive moisture, and this is very important. Excessive drying of the soil can be prevented by controlled watering around the foundation during dry seasons. Trees and other large vegetation accelerate the drying process, and careful consideration should be given when planting. Proper landscaping and ground cover will help prevent drying. Some recommended steps for foundation maintenance and care are listed below:

- Maintain positive drainage away from the foundation with a suggested slope of four inches in the first six feet away from the foundation.
- Fill any depressions adjacent to or near the foundation with native soil. Do not use sand or other granular materials.
- Check gutters and downspouts to be sure that water is discharged away from the foundation area.
- Water liberally around the foundation during dry spells. This should be done in a uniform manner around the entire house to prevent uneven soil movement. This will include the areas of the yard where there is no grass or plants. Automatic lawn sprinkling or automatic foundation soaker hose systems may be installed and are very beneficial.
- Plant trees a distance away from the foundation equal to their anticipated height. If existing trees are near the foundation, they will draw added water from the foundation thus requiring more water within this area. Sometimes tree roots that go under the foundation will need to be cut and a barrier trench installed to prevent new roots from growing under the foundation.
- Cracks in the soil from drying should not be allowed to form. If they do, gradual watering should be applied adjacent to the cracks so they will close. Water should not be placed directly into the open cracks.

The object of a proper maintenance program is to attain as constant a moisture content as is possible for the soil under the foundation and the perimeter of the house. Special emphasis must be made in watering programs during dry seasons and the effect that trees have in the removal of soil moisture during these dry seasons.
Questions?