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SLAB ON GROUND DESIGN & LESSONS LEARNED

By: Don Illingworth

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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

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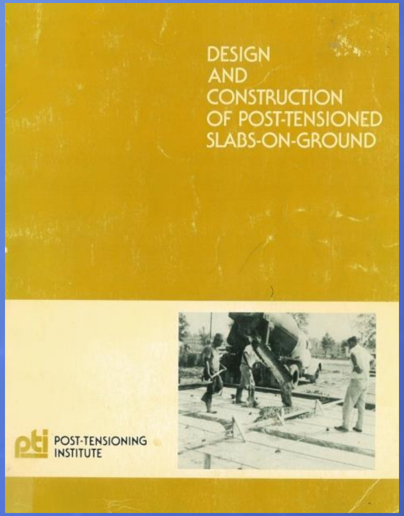
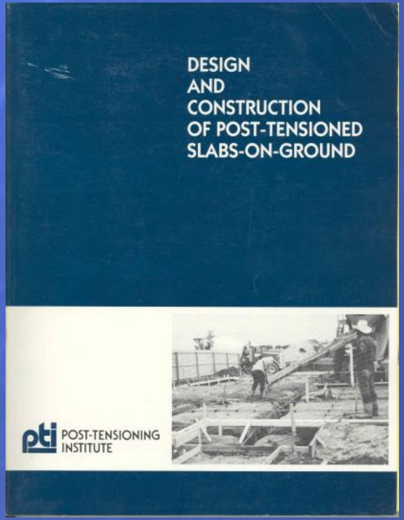
Post-Tensioning Institute's Slabs-On-Ground Design Publications

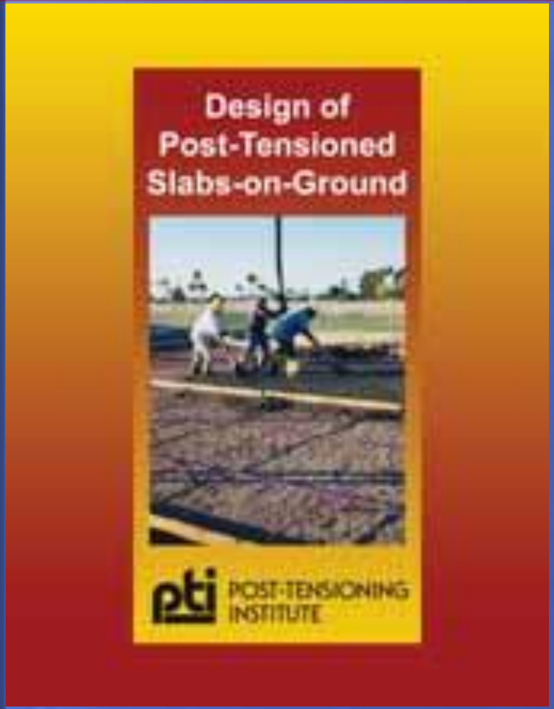


"1st Edition Manual"
Published in 1980



"2nd Edition Manual"
Published in 1996

PTI DESIGN PROCEDURE



3^{rd} Edition Manual and Standards

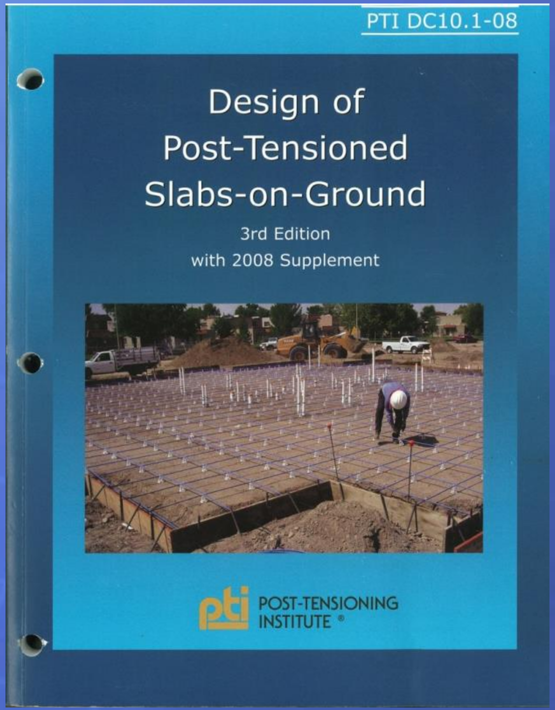
Addendum #1 (May 2007)

Addendum #2 (May 2008)

The Addenda generally reduced the conservatism of the 3^{rd} 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).

PTI DESIGN PROCEDURE

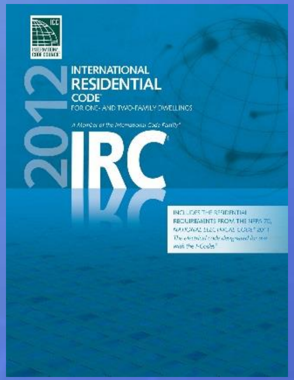


3rd Edition Manual with 2008 Supplement

Includes both addenda and errata

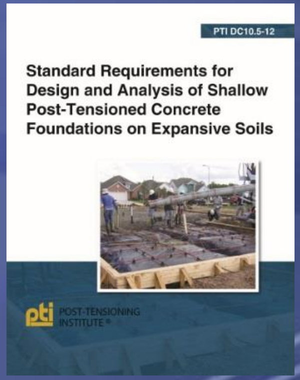
(three errata issued after publication of supplement)

Building code requirements



Addendum 1

Standards



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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

PTI DESIGN PROCEDURE

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

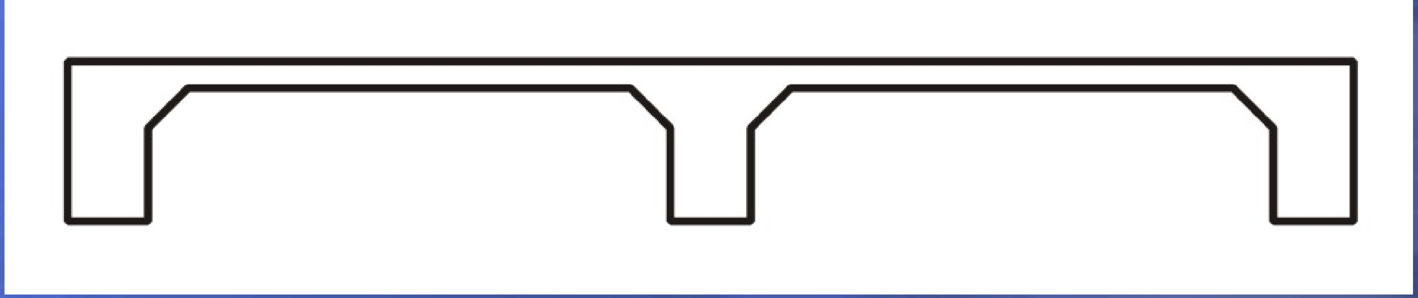
Type of Structure on Foundation

- Residential
  - Stiffness important
- Warehouse
  - Stiffness less important
  - Crack control
- Commercial
  - Stiffness important

- **Owner Expectations**

FOUNDATION TYPES

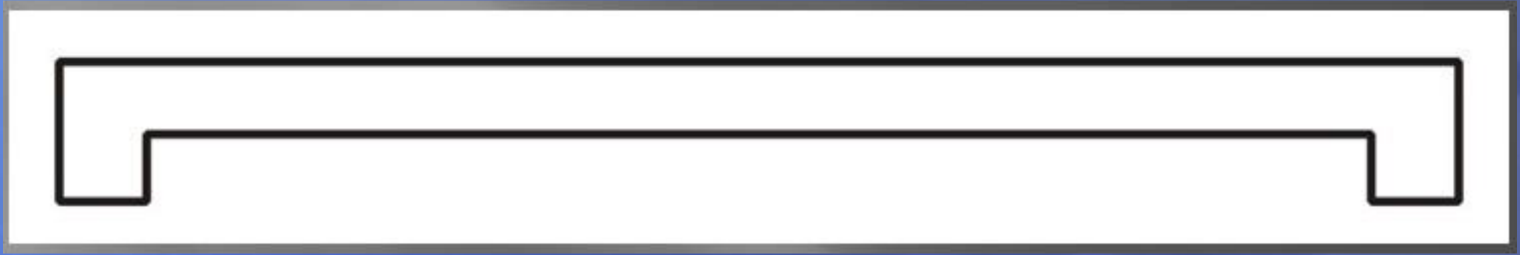
- **Ribbed Foundation**



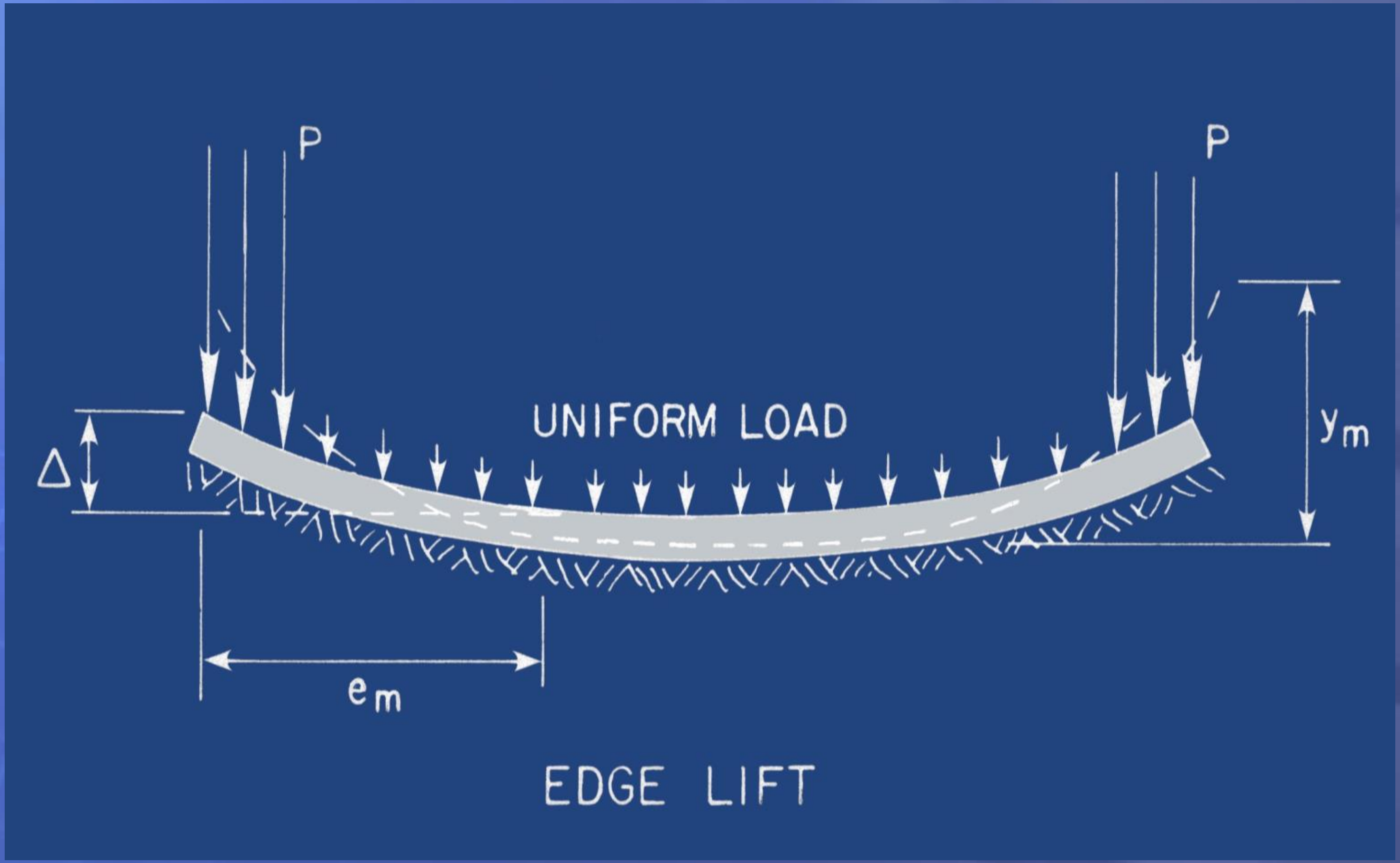
- **Pros**
  - Structurally efficient with less materials.
  - Does not rely on under slab fill for support (less earthwork).
- **Cons**
  - Labor intensive.
  - Requires trenching into grade or forming fill.

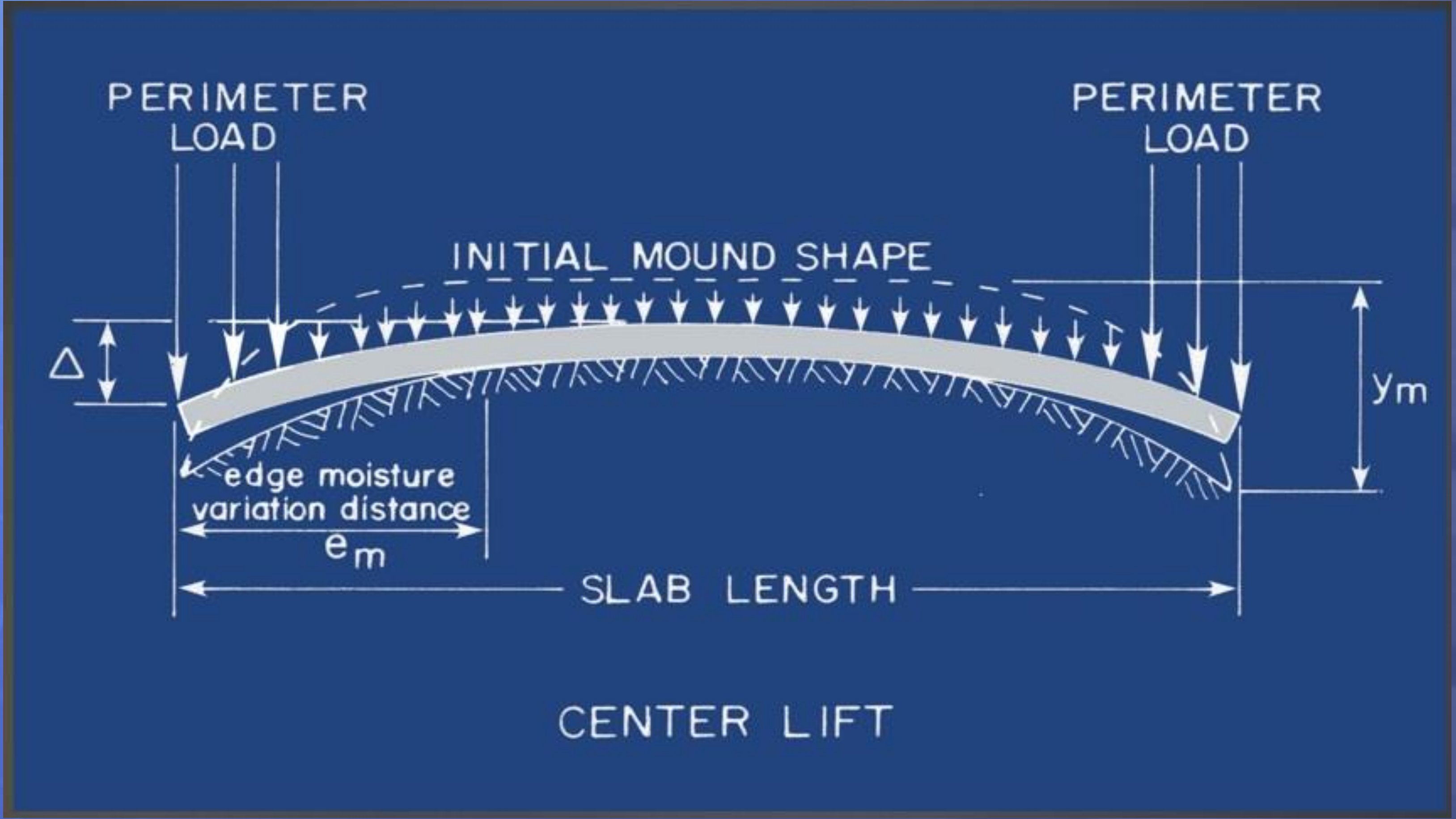
FOUNDATION TYPES

- 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.


P
P
UNIFORM LOAD
Δ
y_m
e_m
EDGE LIFT


PERIMETER LOAD
PERIMETER LOAD
INITIAL MOUND SHAPE
Δ
y_m
edge moisture variation distance
e_m
SLAB LENGTH
CENTER LIFT

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

?
PI
PVR
% Swell

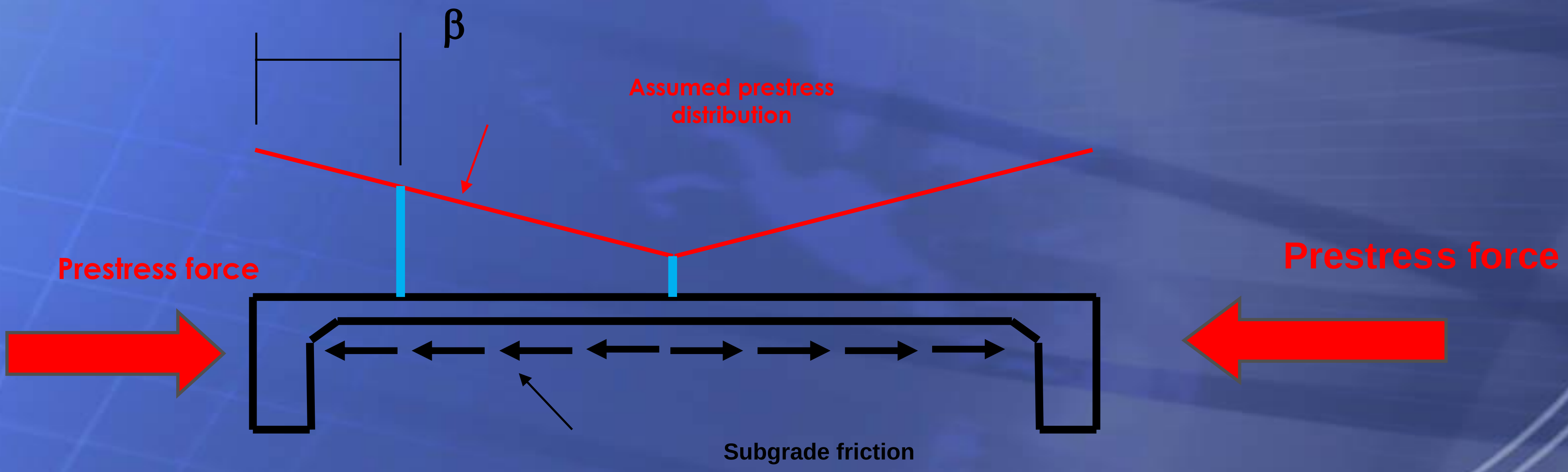
- Q Allowable Bearing Pressure

Important Site Considerations

- Pre-Vegetation
  - Tree Lines
- Fence Lines
  - Roads, etc.
- Slopes
  - Cut Fill
- Drainage
- Time of Construction
- Landscaping
- Soil Modification

PRESTRESS AT BETA

In PTI 2nd and 3rd Edition Manuals, P_r is calculated at mid-slab. $P_{r\ mid\ slab} < P_{r\ beta}$



In "Combined Standard" P_r is calculated at β

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Slabs of Irregular Shapes

- Shape Factor ~ 24
- Overlapping Rectangles
- Beam Continuity

Slabs of Irregular Shapes

- Shape Factor ~ 24

$$\frac{\text{Perimeter}^2}{\text{Area}}$$

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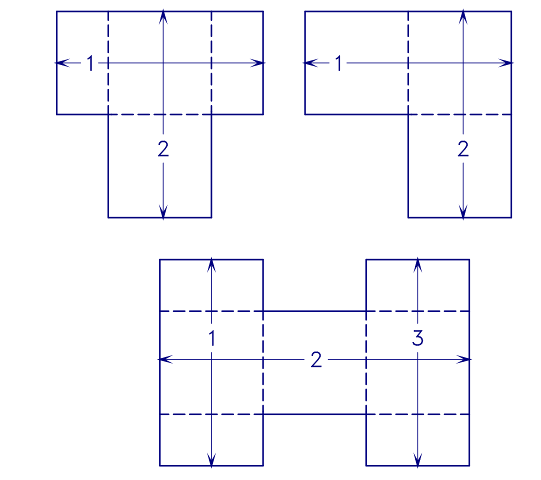
SHAPE FACTOR (SF)= $\frac{\text{Perimeter}^2}{\text{Area}}$

(defined as perimeter^2/area)

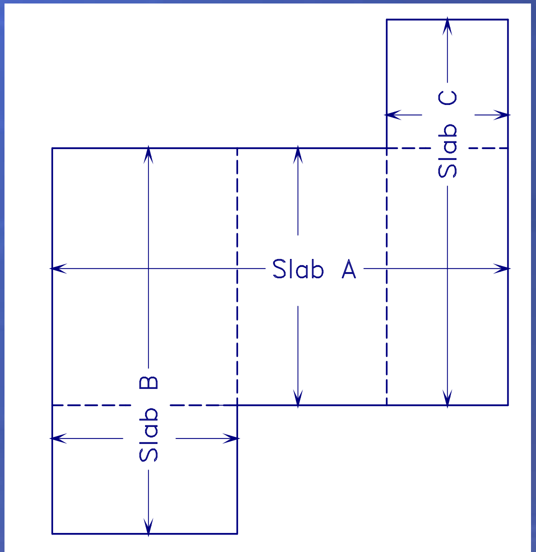
If the SF is greater than 24 then the designer should consider:

- ❖ Modifications to the foundation footprint
- ❖ Use strengthened foundation system
- ❖ Soil treatment to reduce shrink / swell potential
- ❖ Use additional non-prestressed reinforcement
- ❖ Provide additional beams

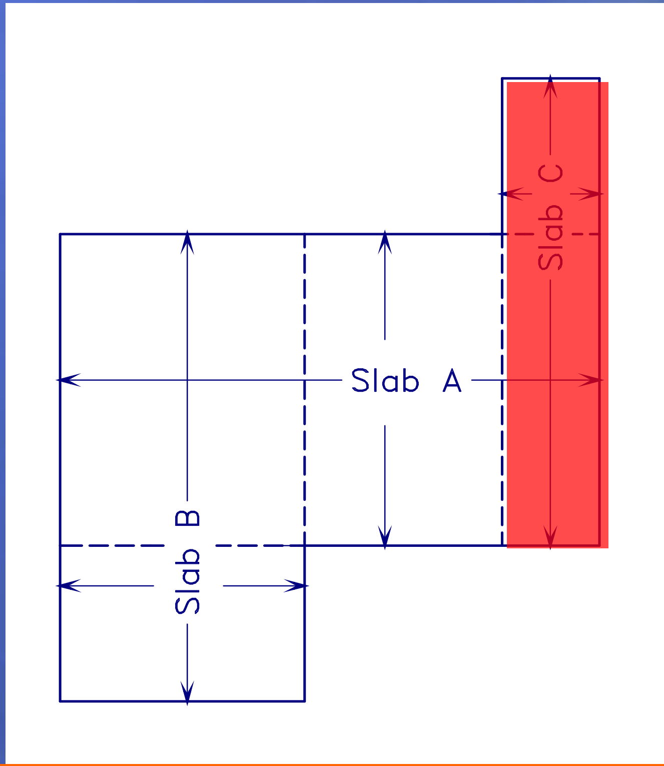
BRAB & 1st & 2nd Ed of PTI



Slabs of irregular shapes should be divided into overlapping rectangles and a separate design made for each rectangle.



3rd Ed of PTI



Primary attention is given to the rectangle that most reasonably represents the majority of the actual foundation.

Long, narrow rectangles are NOT representative.

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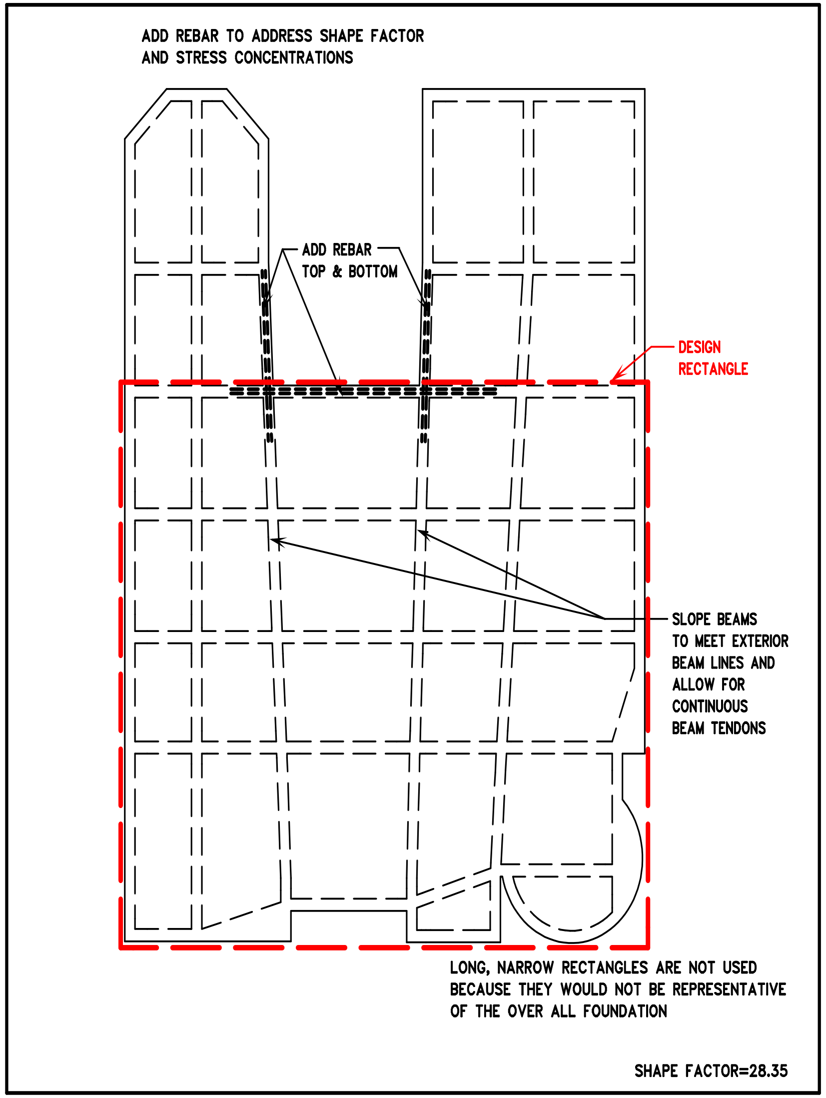

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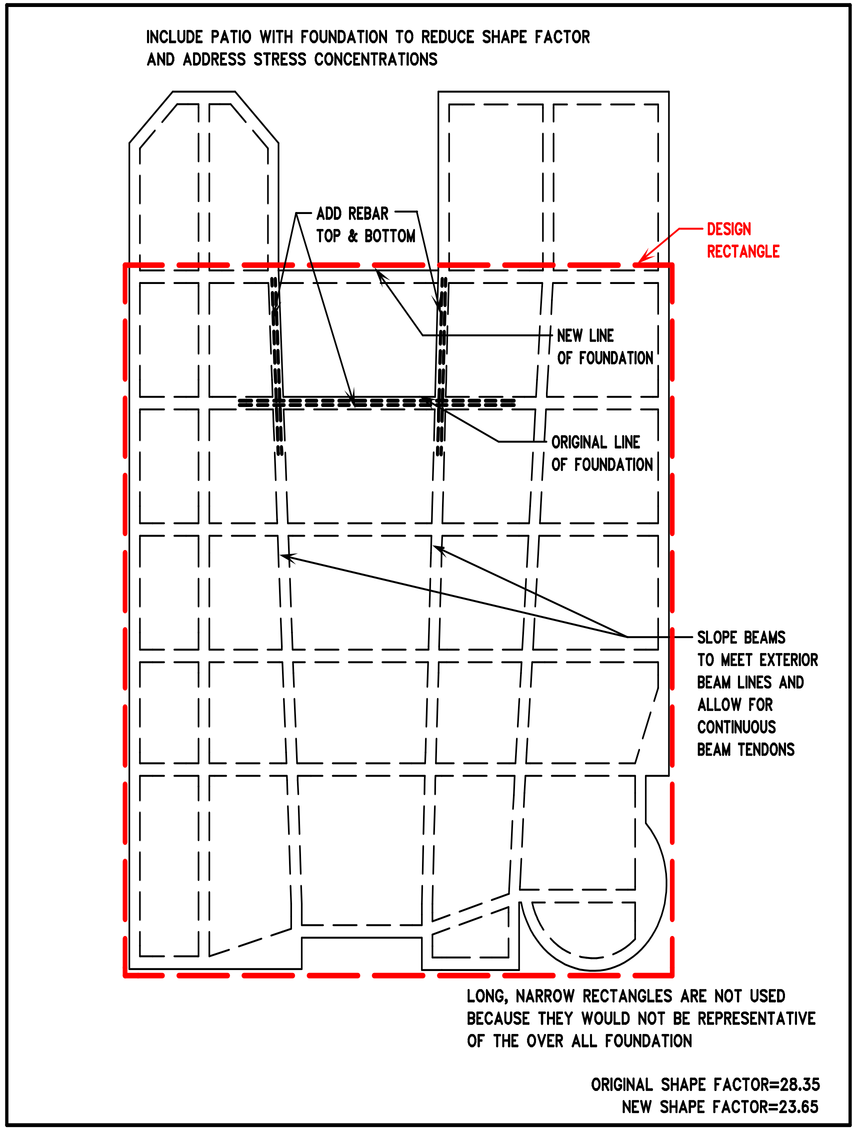

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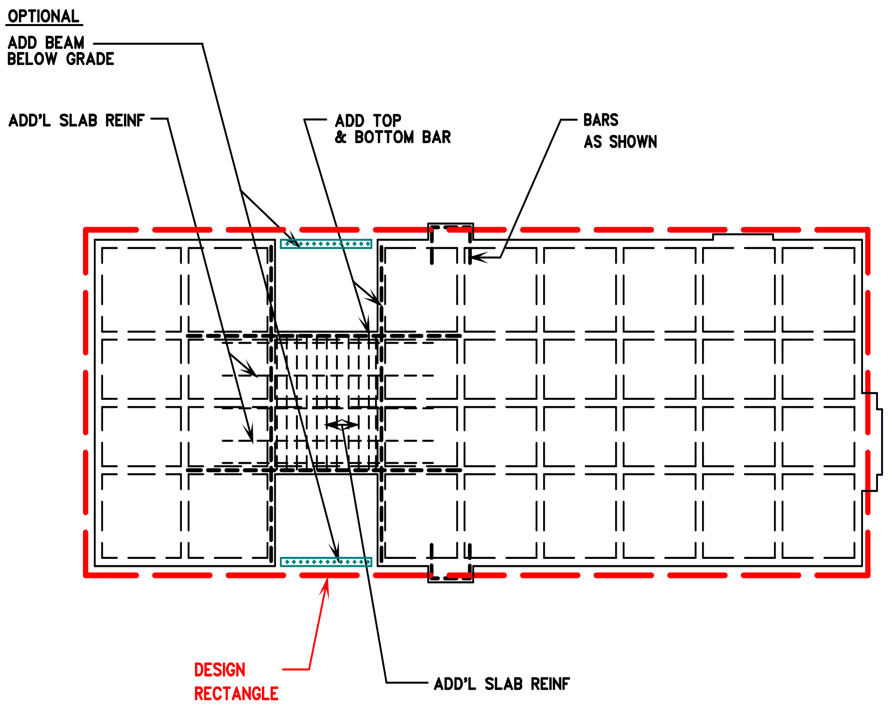


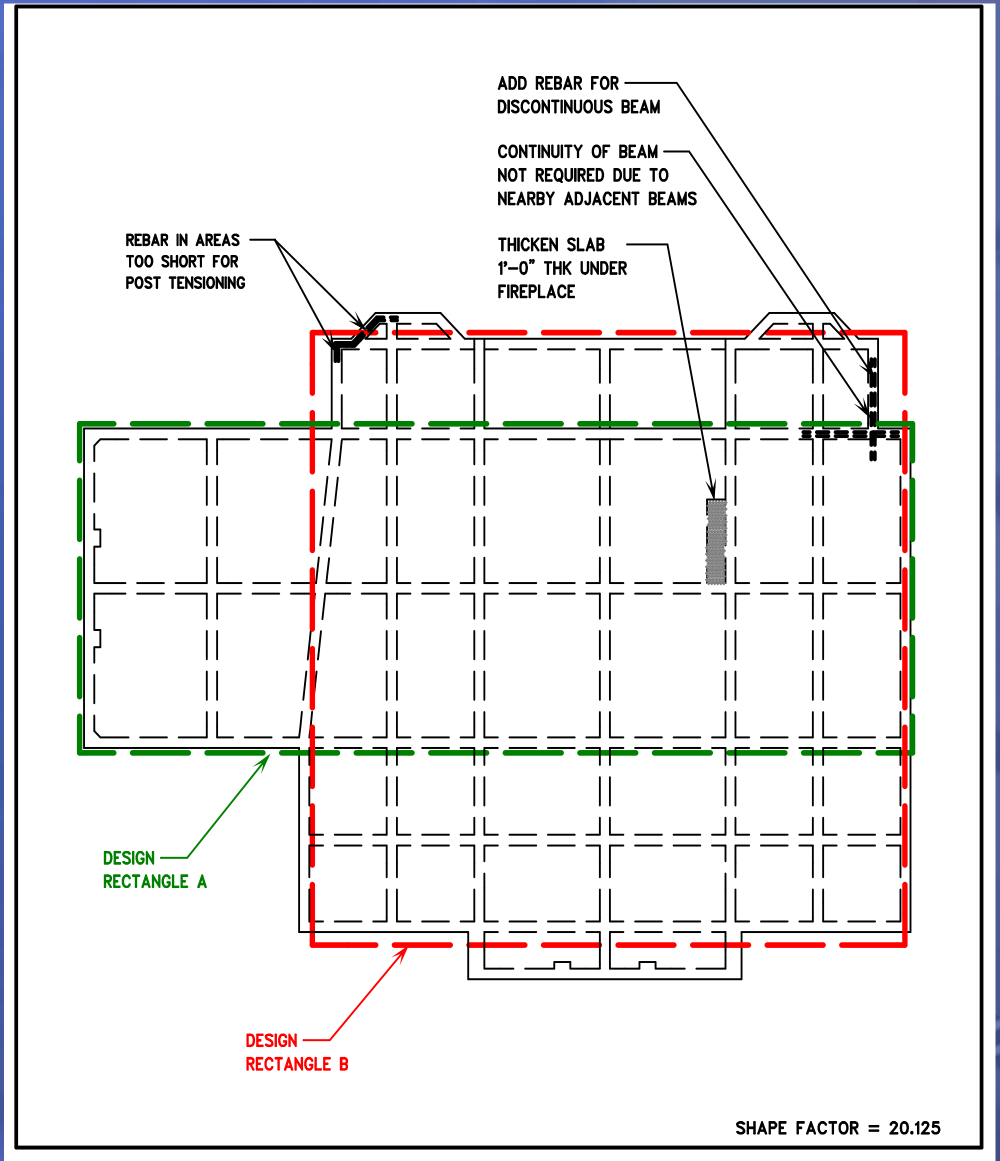
ADD REBAR DUE TO SHAPE FACTOR.

POSSIBLY ADD PIERS DEPENDING ON SOIL CONDITIONS.

DOUBLE BEAM TENDONS IN LONG BEAMS FOR ADDED COMPRESSION THRU NARROW AREA.

ADD CONTROL JOINT IN BRICK.

SHAPE FACTOR = 30.834



ADD REBAR FOR DISCONTINUOUS BEAM
CONTINUITY OF BEAM NOT REQUIRED DUE TO NEARBY ADJACENT BEAMS
REBAR IN AREAS TOO SHORT FOR POST TENSIONING
THICKEN SLAB 1'-0" THK UNDER FIREPLACE
DESIGN RECTANGLE A
DESIGN RECTANGLE B
SHAPE FACTOR = 20.125

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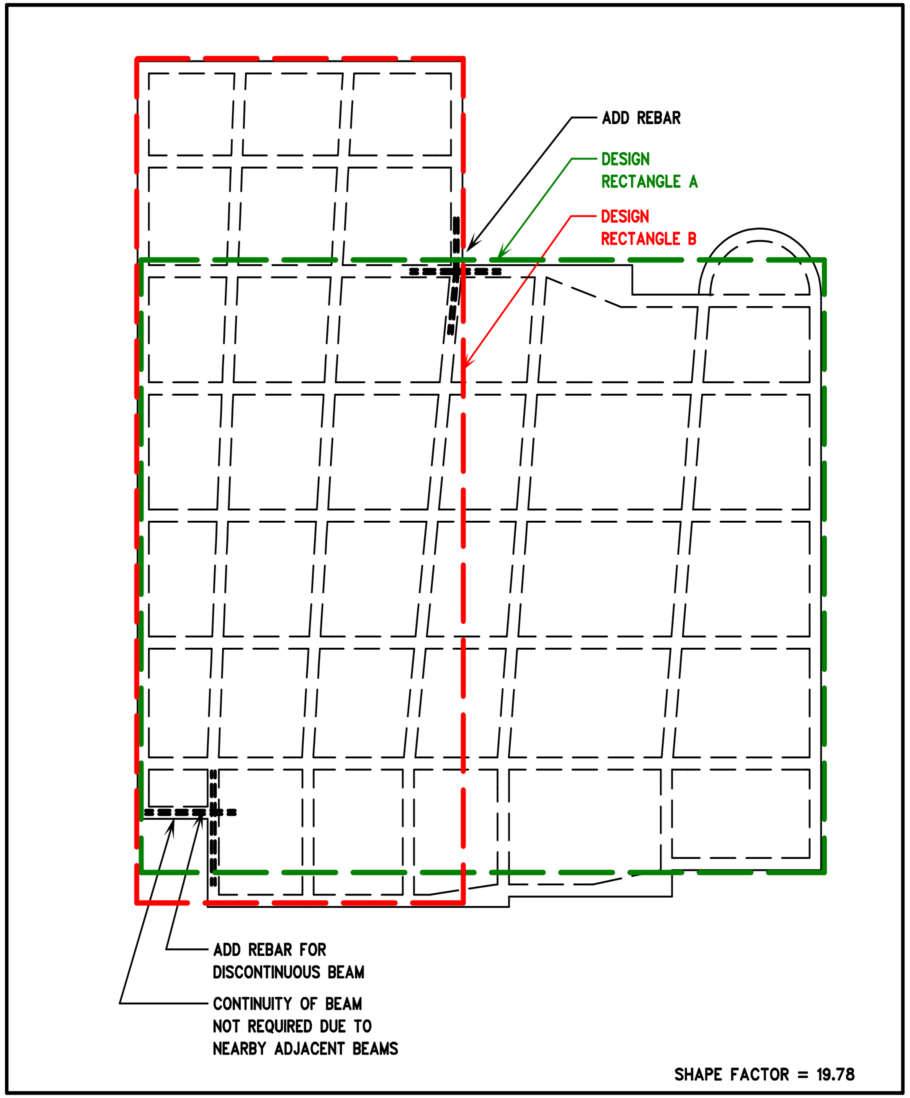

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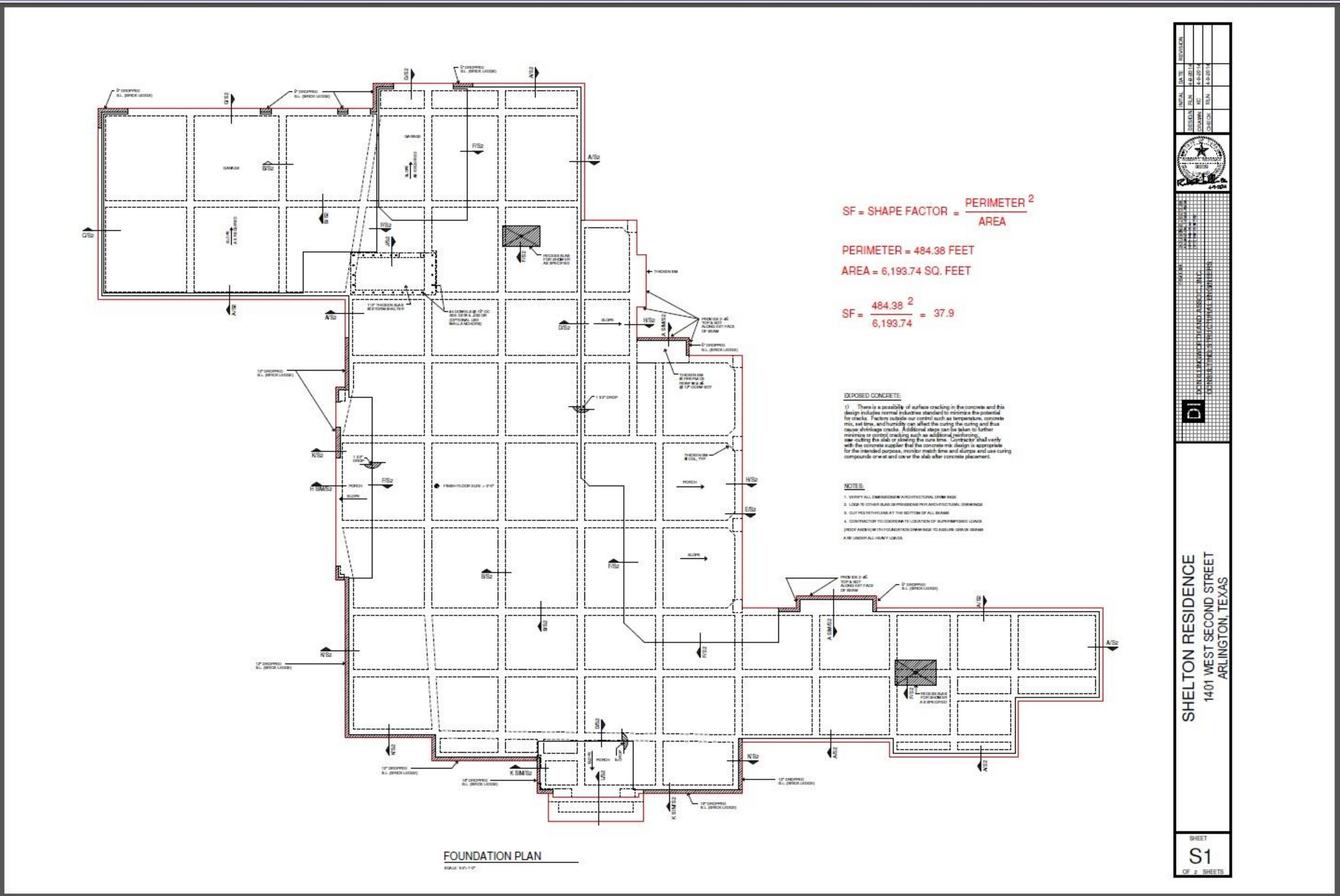

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Summary

- Rectangle that is most representative
- Watch shape factor, especially over 30
- Add rebar if weird shape
- Avoid discontinuous beam
- Okay to slope beams

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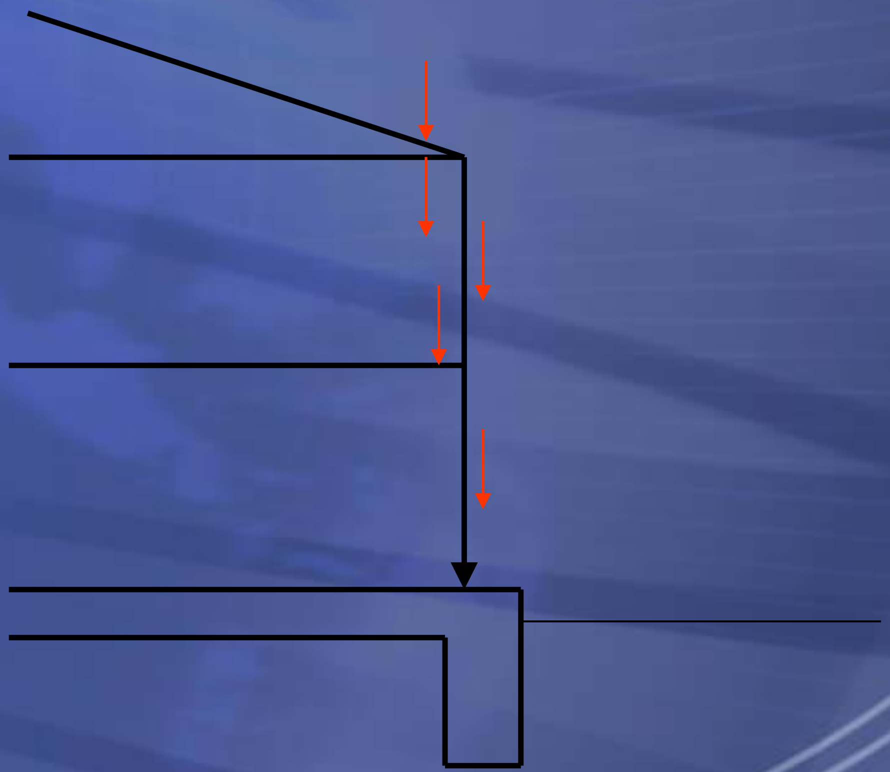
Loading

- Live Loads
  - Uniform 40 + ADD’L
- Dead Loads
  - Actual
- Line Loads & Concentrated

- Residential vs. Warehouse

Edge Load *P* (4.5.4.3)(6.1.4)

- Dead + Live load from superstructure only (no concrete)
- If P varies and ratio of largest to smallest ≤ 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)

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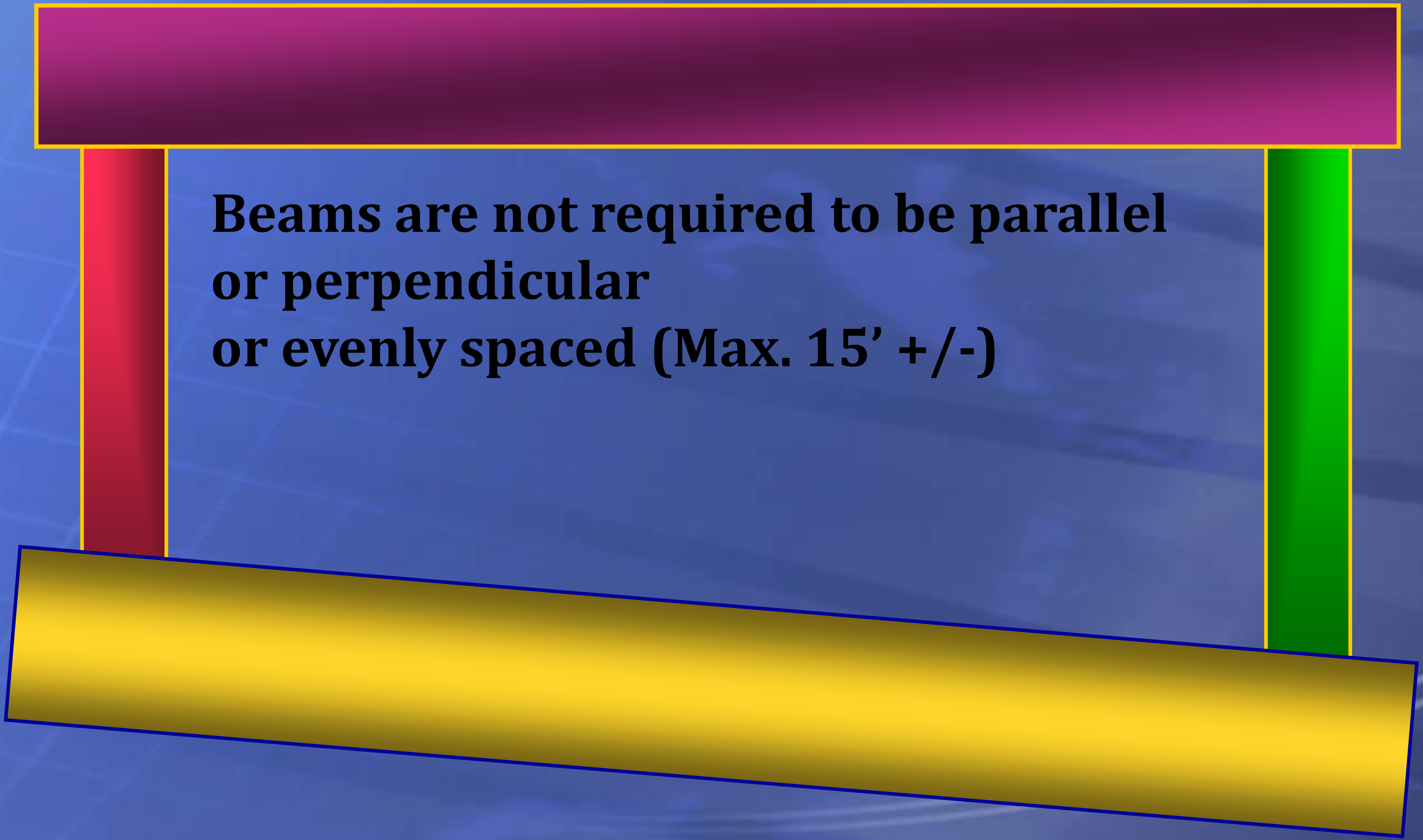
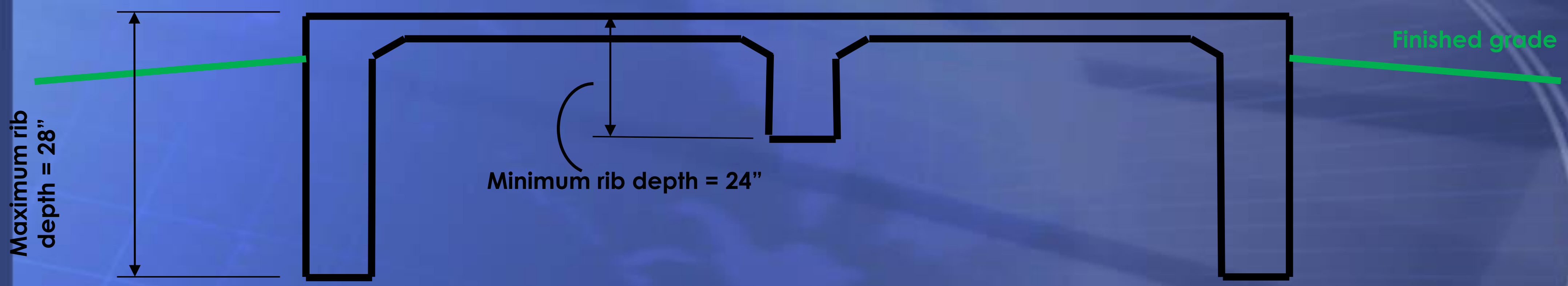
BE FLEXIBLE

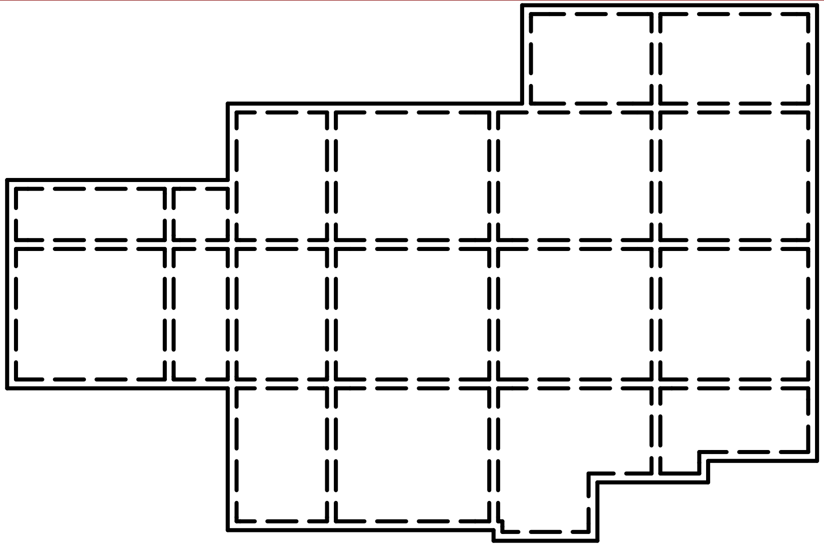


VARIABLE RIB DEPTHS

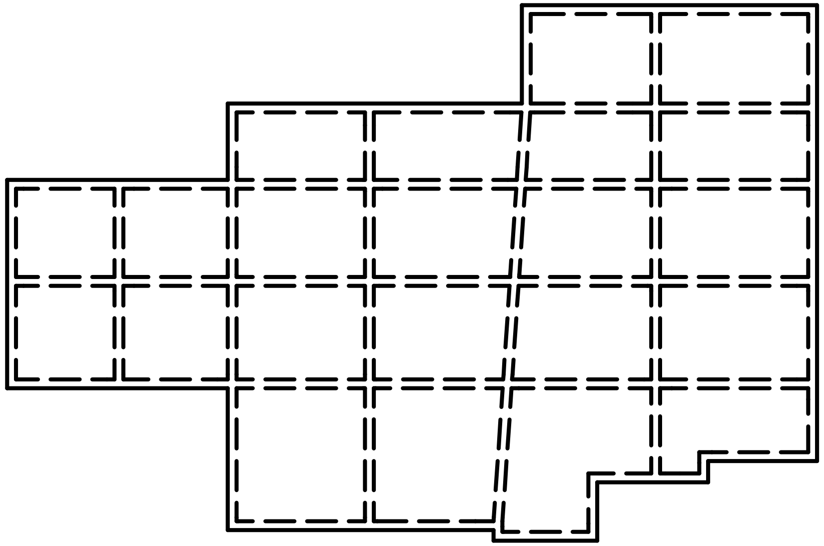


In analysis, ratio of deepest to shallowest rib depth cannot exceed 1.2 (not new in combined standard but misunderstood).

The difference in the constructed ribs are not limited to the 1.2 ratio



BEFORE



AFTER

Bending Moments PTI

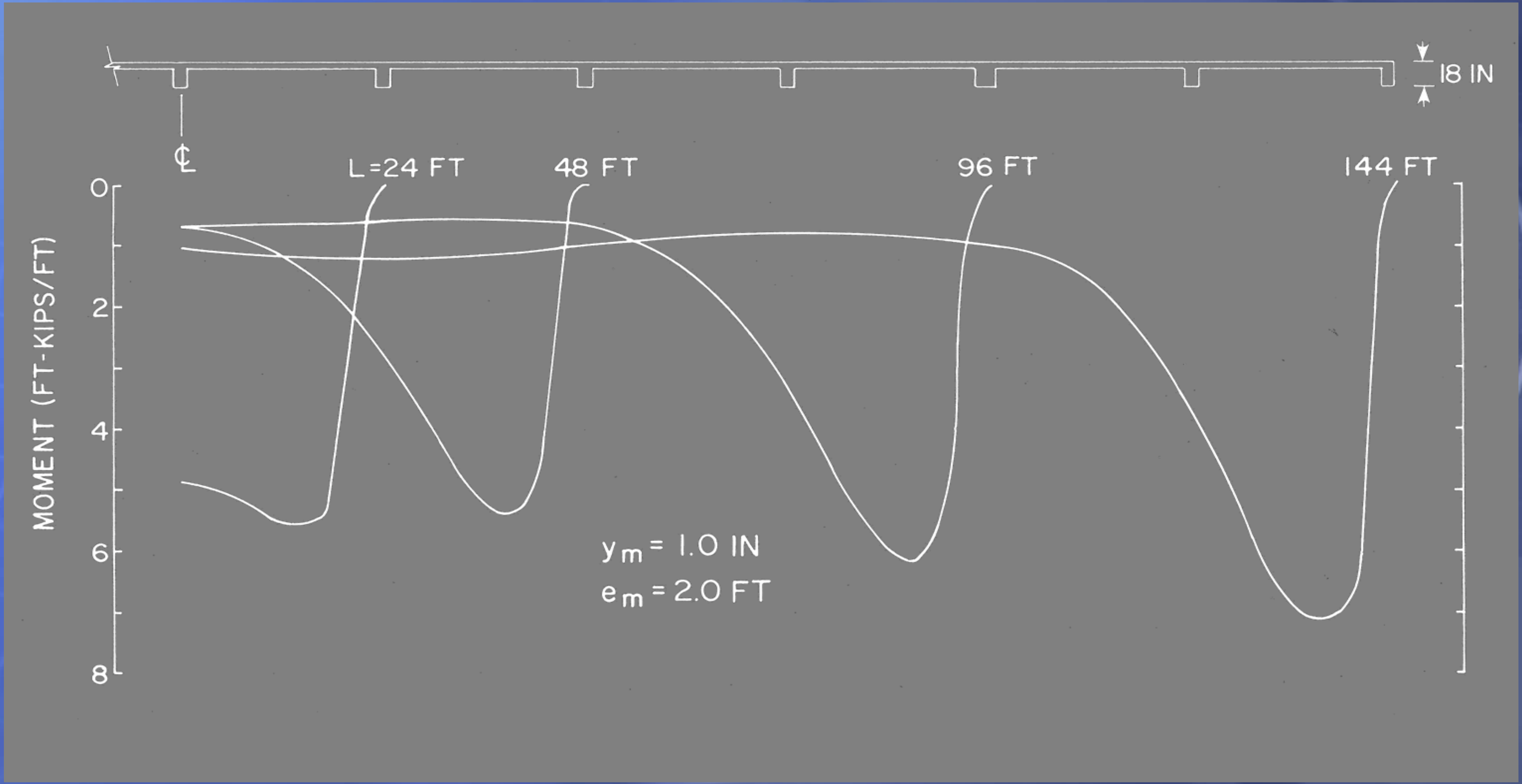
- Max Moment @ Beta

  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



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

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Pre-stress Losses

- 15 KSI (Long Term Loss)
  - Strand ULT = 41.3K
  - Stress 80% MAX = 33K
  - Final After Losses = 27K

  - 10 % Elongation Variance

Cracked Section Consideration

- 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.

Uniform Slab Conversion

- 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

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A.2.1 Center Lift Design

A. Moment in the Long Direction

$$M_L = A_o\left[B(e_m)^{1.238} + C\right]$$

where:

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

and for:

$$0 \le e_m \le 5 \qquad B = 1,\ C = 0$$

$$e_m > 5 \qquad B = \left(\frac{y_m - 1}{3}\right) \le 1.0$$

$$C = \left[8 - \frac{P - 613}{255}\right]\left[\frac{4 - y_m}{3}\right] \ge 0$$

B. Moment in the Short Direction

For $L_L / L_S \ge 1.1$:

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

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

$$M_L = \frac{(S)^{0.10}(he_m)^{0.78}(y_m)^{0.66}}{7.2(L)^{0.0065}(P)^{0.04}}$$

B. Moment in the Short Direction

For $L_L / L_S \ge 1.1$:

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

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

$$\Delta_o = \frac{(L)^{0.35}(S)^{0.88}(e_m)^{0.74}(y_m)^{0.76}}{15.9(h)^{0.85}(P)^{0.01}}$$

$$\Delta_p = \frac{P_e e \beta^2}{2E_c I}$$

$$\Delta = \Delta_o + \Delta_p$$

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PTI SOG COMMITTEE VERSION - Build 082706

PTISlab 3.0 SOG

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Geostructural Tool Kit, Inc.

Registered To : Don Illingworth

Serial Number : 199-399-009

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	829,614	LB
Bearing Area	4,305	FT^2
Applied Pressure on Soil	193	PSF
Soil Pressure Safety Factor	6.49	

Prestress Summary

Subgrade Friction calculated by method prescribed in PTI Manual

	Short Direction	Long Direction
Number of Slab Tendons	26	24
Number of Beam Tendons	14	18
Spacing of Slab Tendons (Feet)	2.90	2.82
Center of Gravity of Concrete (from top of slab) (Inch)	8.58	9.54
Center of Gravity of Tendons (from top of slab) (Inch)	11.71	13.89
Eccentricity of Prestressing (Inch)	-3.13	-4.35
Minimum Effective Prestress Force (K)	832.9	886.1
Beta Distance Effective Prestress Force (K)	968.8	1,030.2
Minimum Effective Prestress (PSI)	136	145
Beta Distance Effective Prestress (PSI)	159	169

Moment Analysis - Center Lift Mode

Maximum Moment, Short Direction	11.16	FT-K/FT
Maximum Moment, Long Direction	10.62	FT-K/FT

	Tension in Top Fiber (KSI) Short Direction	Tension in Top Fiber (KSI) Long Direction		Compression in Bottom Fiber (KSI) Short Direction	Compression in Bottom Fiber (KSI) Long Direction
Allowable Stress	-0.329	-0.329	Allowable Stress	1.350	1.350
Actual Stress	-0.056	-0.052	Actual Stress	0.683	0.631

Stiffness Analysis - Center Lift Mode

Based on a Stiffness Coefficient of 480

	Short Direction	Long Direction
Available Moment of Inertia ($Inch^4$)	574,321	611,101
Required Moment of Inertia ($Inch^4$)	225,858 (338,786)	215,102 (322,654)
Required Moment of Inertia controlled by	Width	Length

Shear Analysis - Center Lift Mode

Maximum Shear, Short Direction.	1.88	K/FT
Maximum Shear, Long Direction	1.78	K/FT

	Short Direction	Long Direction
Allowable Shear Stress (PSI)	164 (120)	166 (122)
Actual Shear Stress (PSI)	52	39

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RIBBED FOUNDATION - RESULTS OF ANALYSIS continued

Cracked Section Analysis - Center Lift Mode

	Short Direction	Long Direction
Cracked Section Capacity (FT-K)	1,694.9	1,581.1
0.9 Moment (FT-K)	768.1	659.0

Moment Analysis - Edge Lift Mode

Maximum Moment, Short Direction 18.08 FT-K/FT (122)
Maximum Moment, Long Direction 12.79 FT-K/FT

	Tension in Bottom Fiber (KSI) Short Direction	Long Direction		Compression in Top Fiber (KSI) Short Direction	Long Direction
Allowable Stress	-0.329	-0.329	Allowable Stress	1.350	1.350
Actual Stress	-0.458	-0.113	Actual Stress	0.345	0.25

Stiffness Analysis - Edge Lift Mode

Based on a Stiffness Coefficient of 960

	Short Direction	Long Direction
Available Moment of Inertia (Inch^4)	574,321	611,101
Required Moment of Inertia (Inch^4)	732,033 (1,098,050)	518,074 (777,111)
Required Moment of Inertia controlled by	Width	Length

Shear Analysis - Edge Lift Mode

Maximum Shear, Short Direction 5.09 K/FT
Maximum Shear, Long Direction 5.15 K/FT

	Short Direction	Long Direction
Allowable Shear Stress (PSI)	164 (120)	166 (122)
Actual Shear Stress (PSI)	141	112

Cracked Section Analysis - Edge Lift Mode

	Short Direction	Long Direction
Cracked Section Capacity (FT-K)	921.5	1,183.5
0.9 Moment (FT-K)	1,244.7	793.6

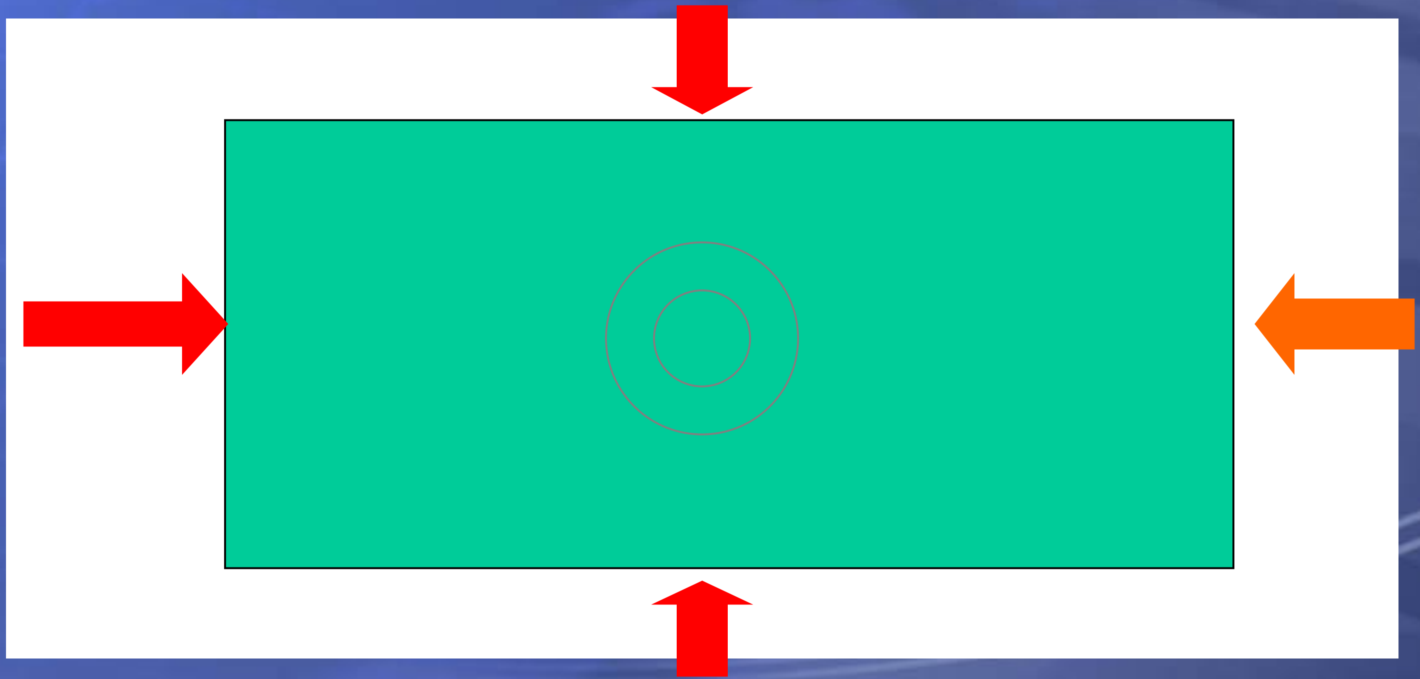
Numbers in parenthesis calculated using original equations

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

Sub-Grade Design

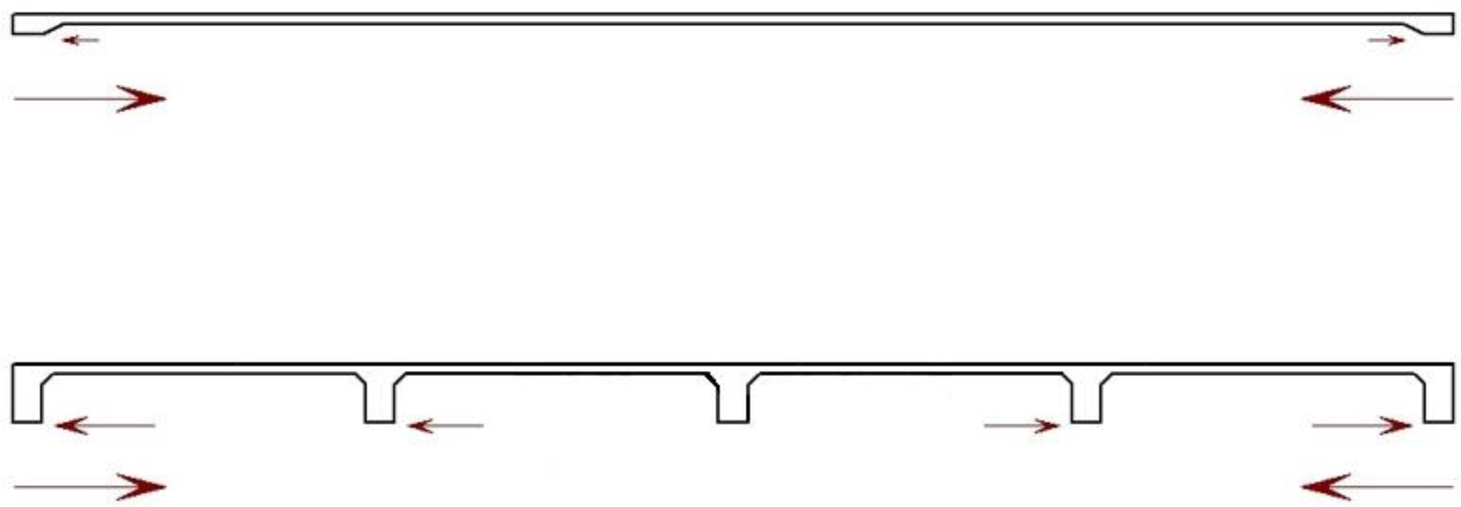
- WEIGHT OF THE SLAB “SLIDING” OVER SUBGRADE
- EDGES MOVE TOWARD THE CENTER
- MIDDLE IS POINT OF FIXITY



Design

- 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



TOO LITTLE P/A

- INADEQUAATE AVERAGE COMPRESSION (TOO LITTLE P/A) WILL ALLOW CRACKS TO FORM

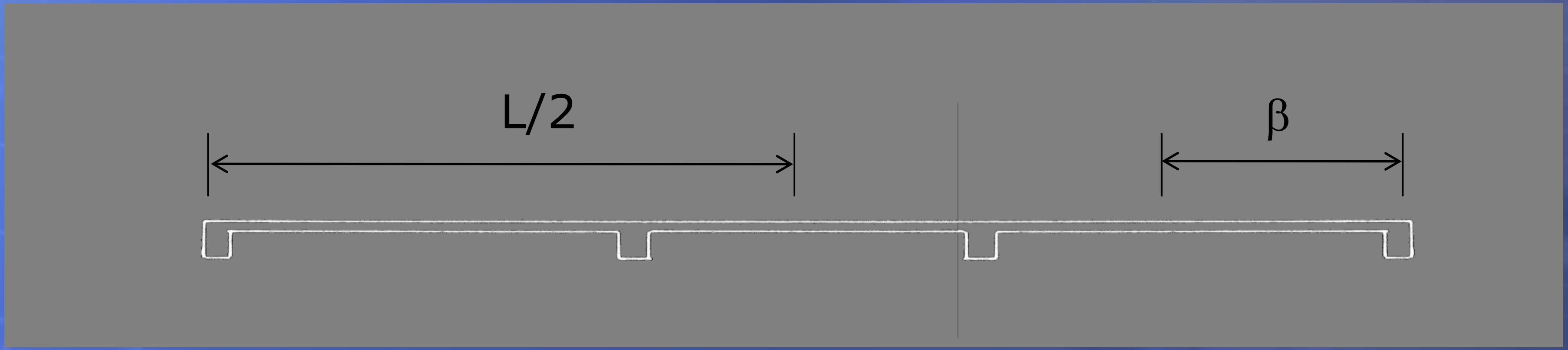
ADEQUATE P/A

- ADEQUATE AVERAGE COMPRESSION (P/A) WILL RESIST CRACKING AND CLOSE SHRINKAGE AND TEMPERATURE CRACKS.

PRESTRESS FORCE

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)

The prestress force in the concrete (Pr) at Beta should be used to determine the bending and shear stresses.



$$P_r = P_e - \mu W_{slab}$$

Where: P_e is the prestress force in the tendon after losses
μ is the subgrade friction coefficient
W_{slab} is the weight of slab from perimeter to β or midslab


RED RAIDERS
4

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CRACKS (NOT ENOUGH P/A)

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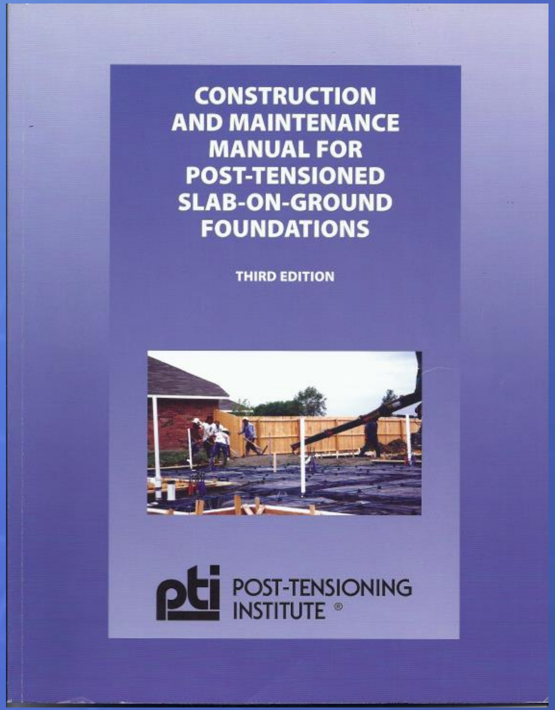
PTI FIELD MANUAL



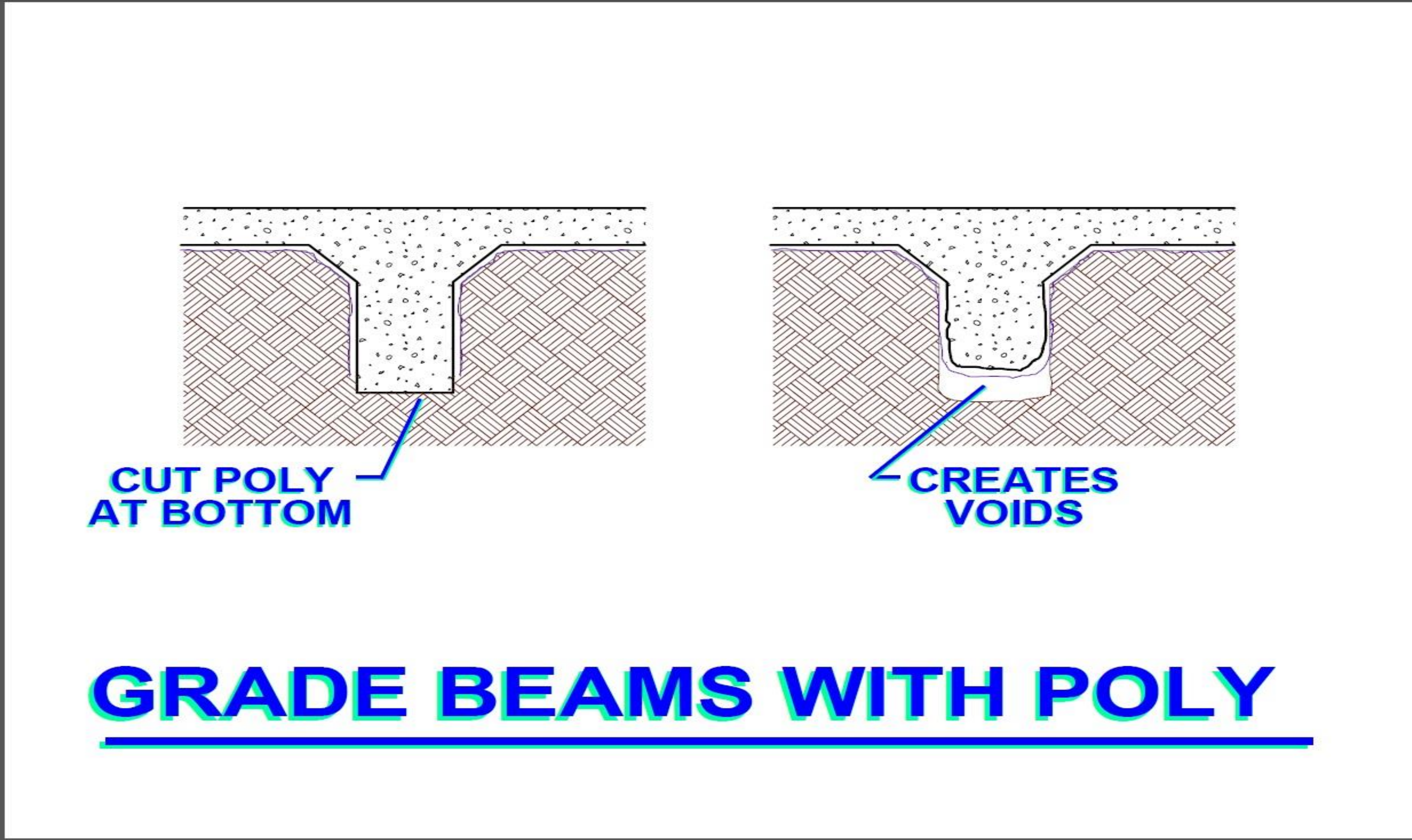
CONSTRUCTION AND MAINTENANCE MANUAL FOR POST-TENSIONED SLAB-ON-GROUND FOUNDATIONS

Beams, Slabs (Tolerances)

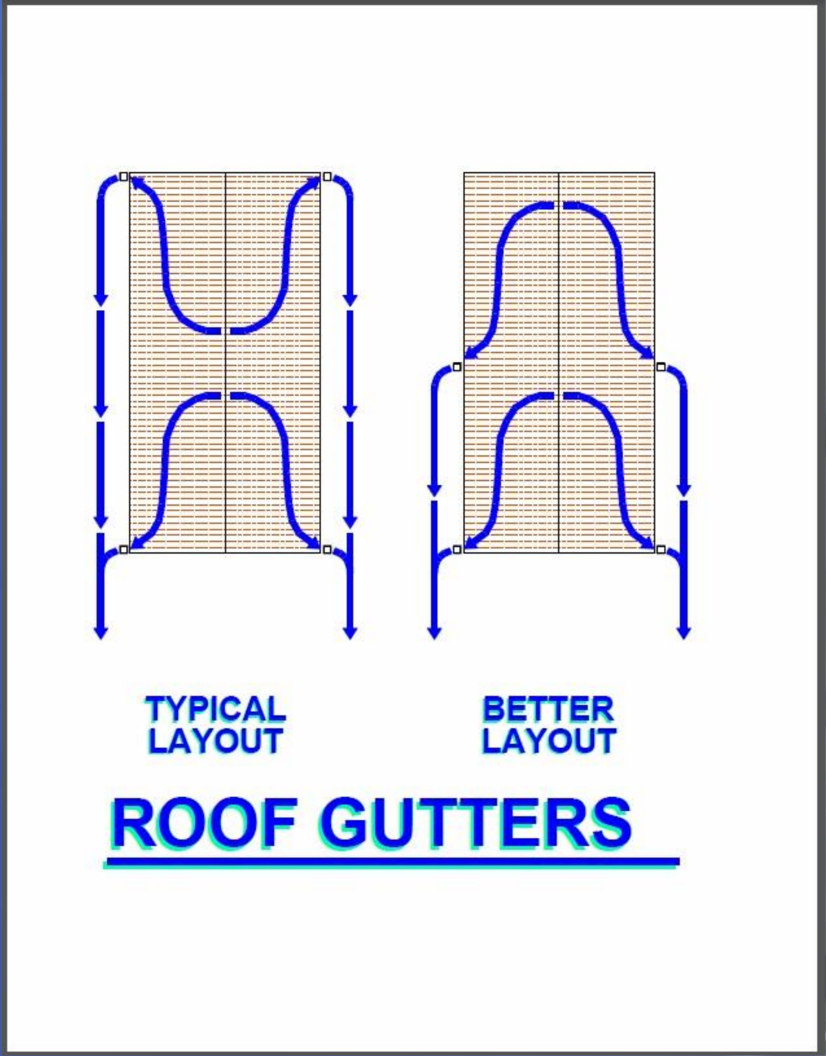
- 8.3.1.a- Ribbed Foundations
  - Rib Depth h: -1 in.; + 0.2h
  - Rib Width: -1 in.; + 2 in.
  - Slab Thickness:
    - Individual Location: -1/2 in. + 2 in.
    - Average Thickness: -1/4 in. + 1 in.

LESSONS LEARNED

Poly/Cut Poly

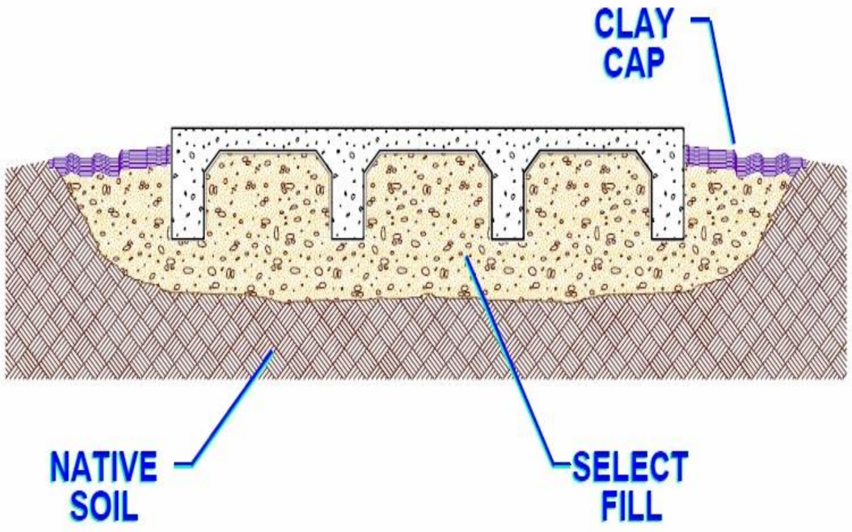


Roof Gutters and Downspout Placement

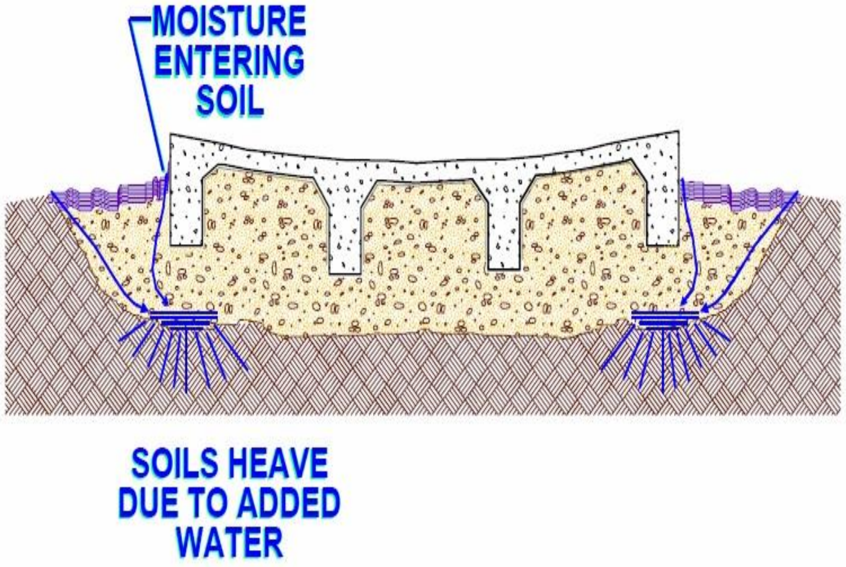


Undrained Bathtub

Over Excavation and Backfill with Select fill "BATH TUB"

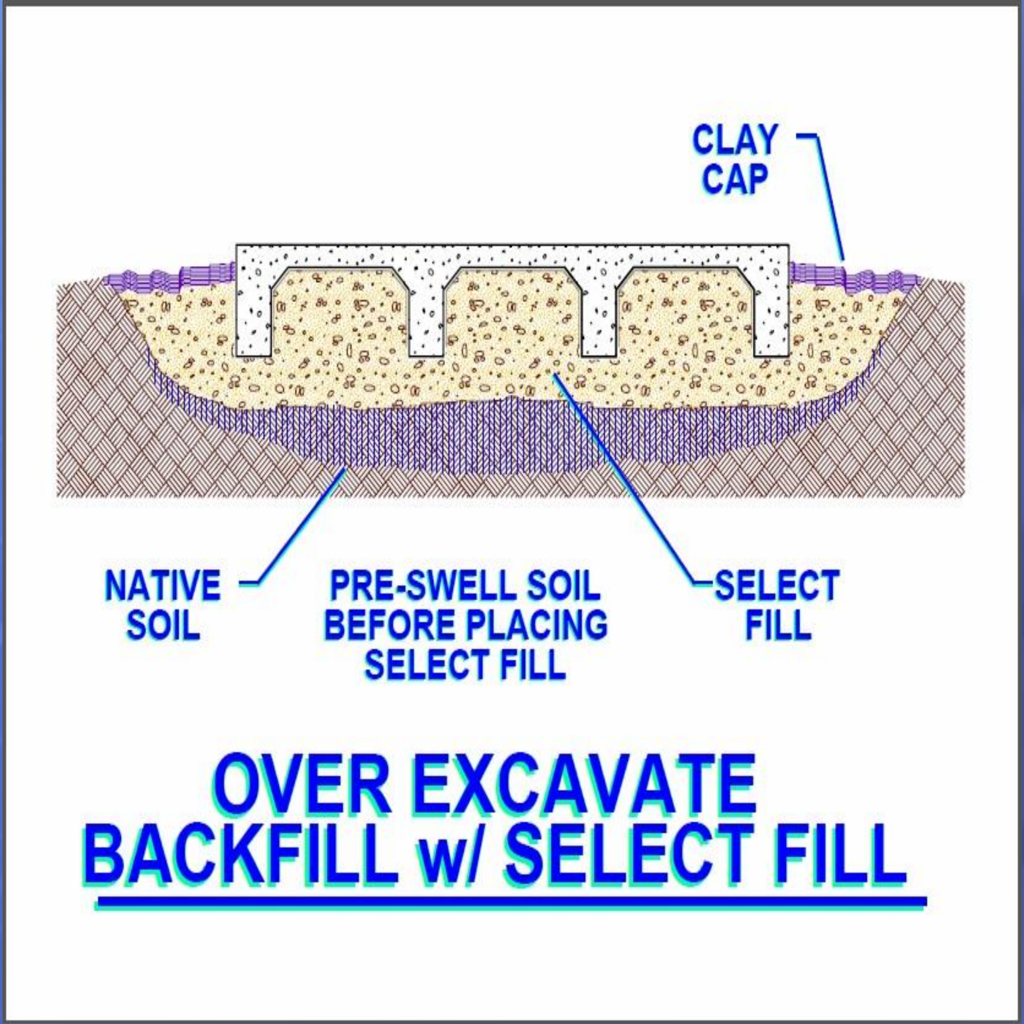


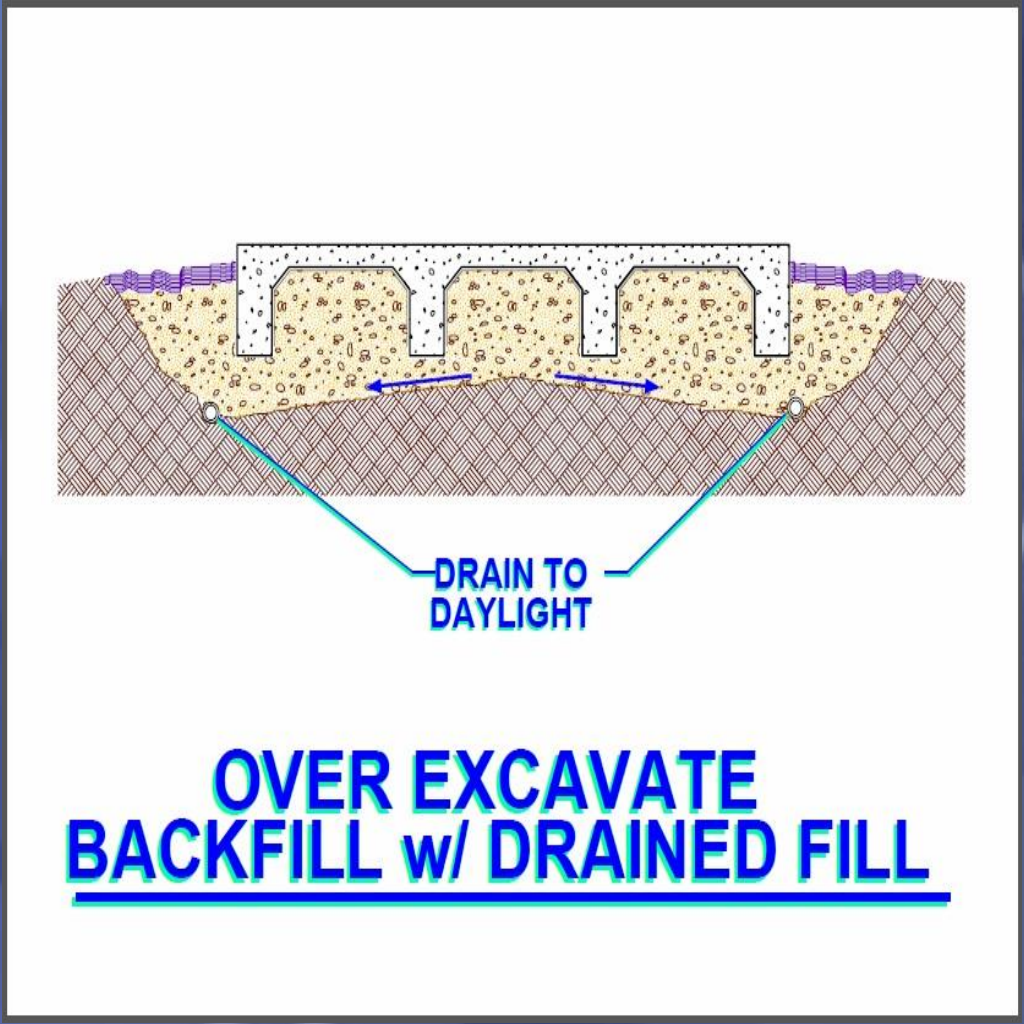
OVER EXCAVATE BACKFILL w/ SELECT FILL



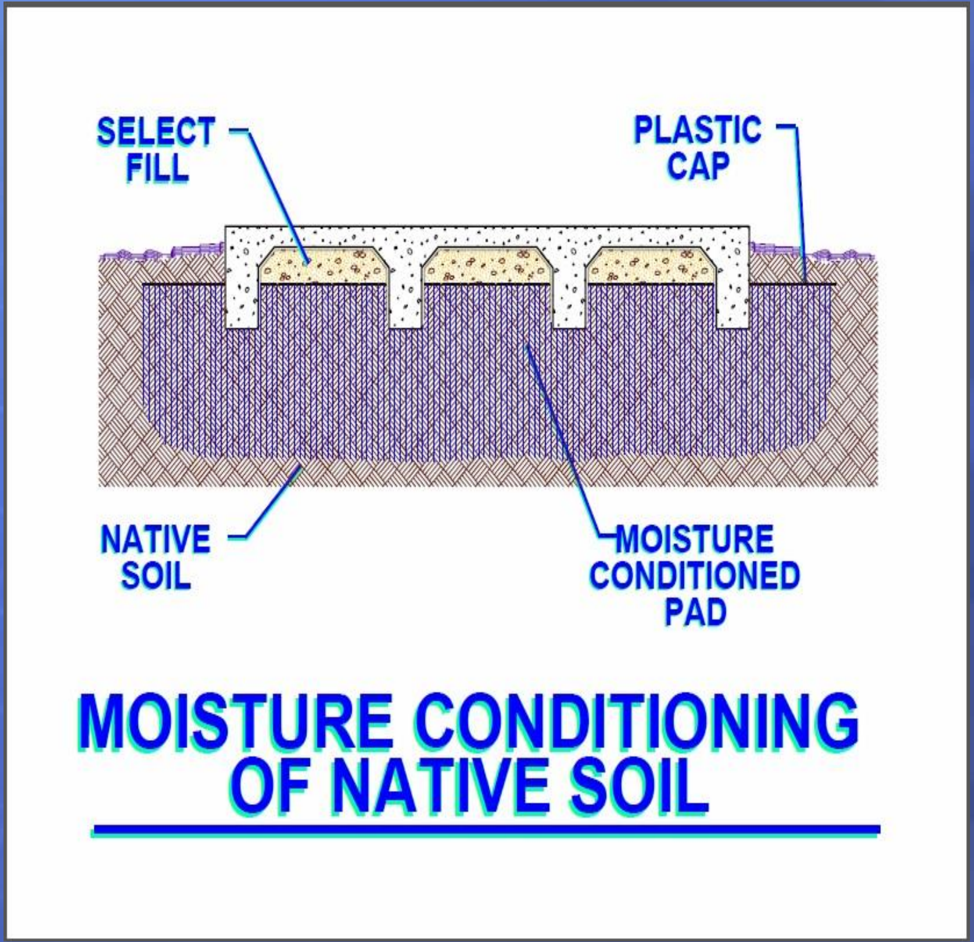
UNDRAINED BATH TUB

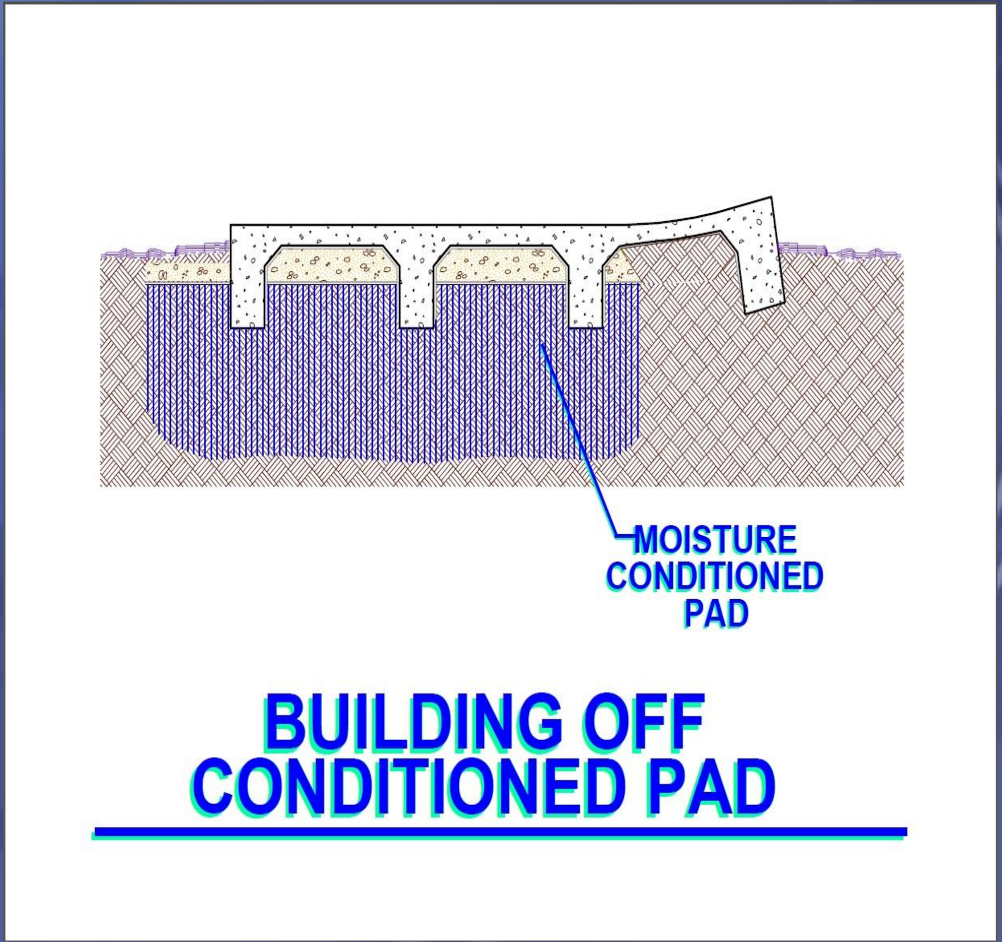
Over Excavation and Backfill with Select fill "BATH TUB"





Building Off of Moisture Conditioned Pad





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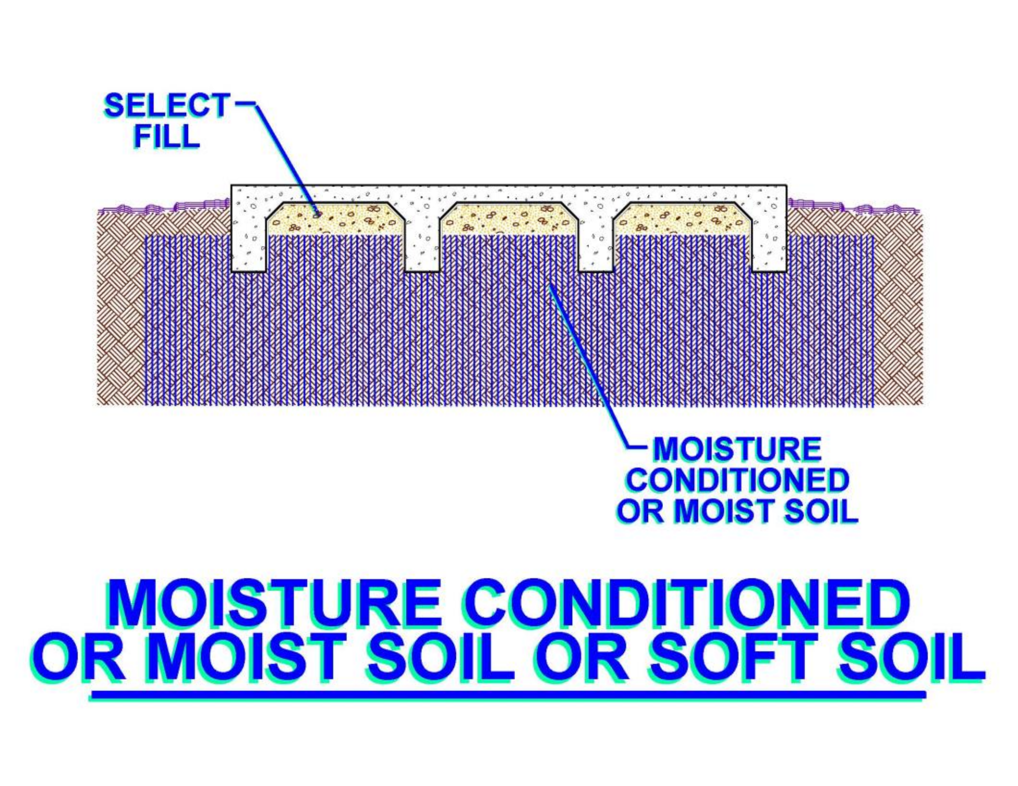
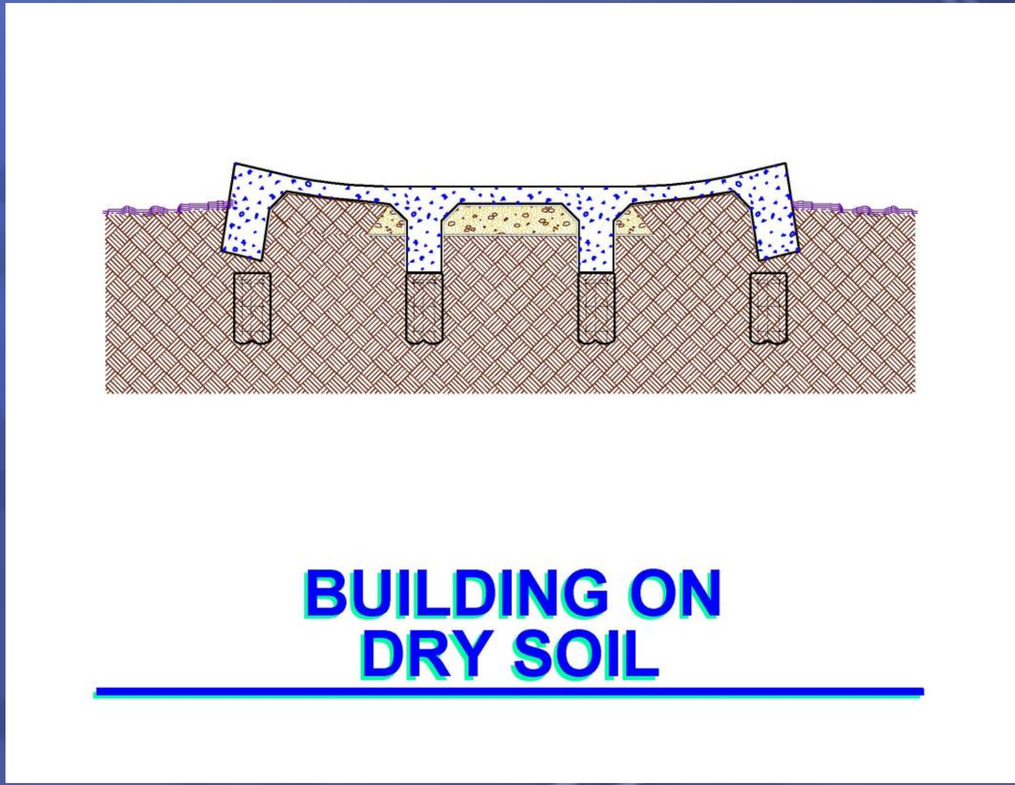
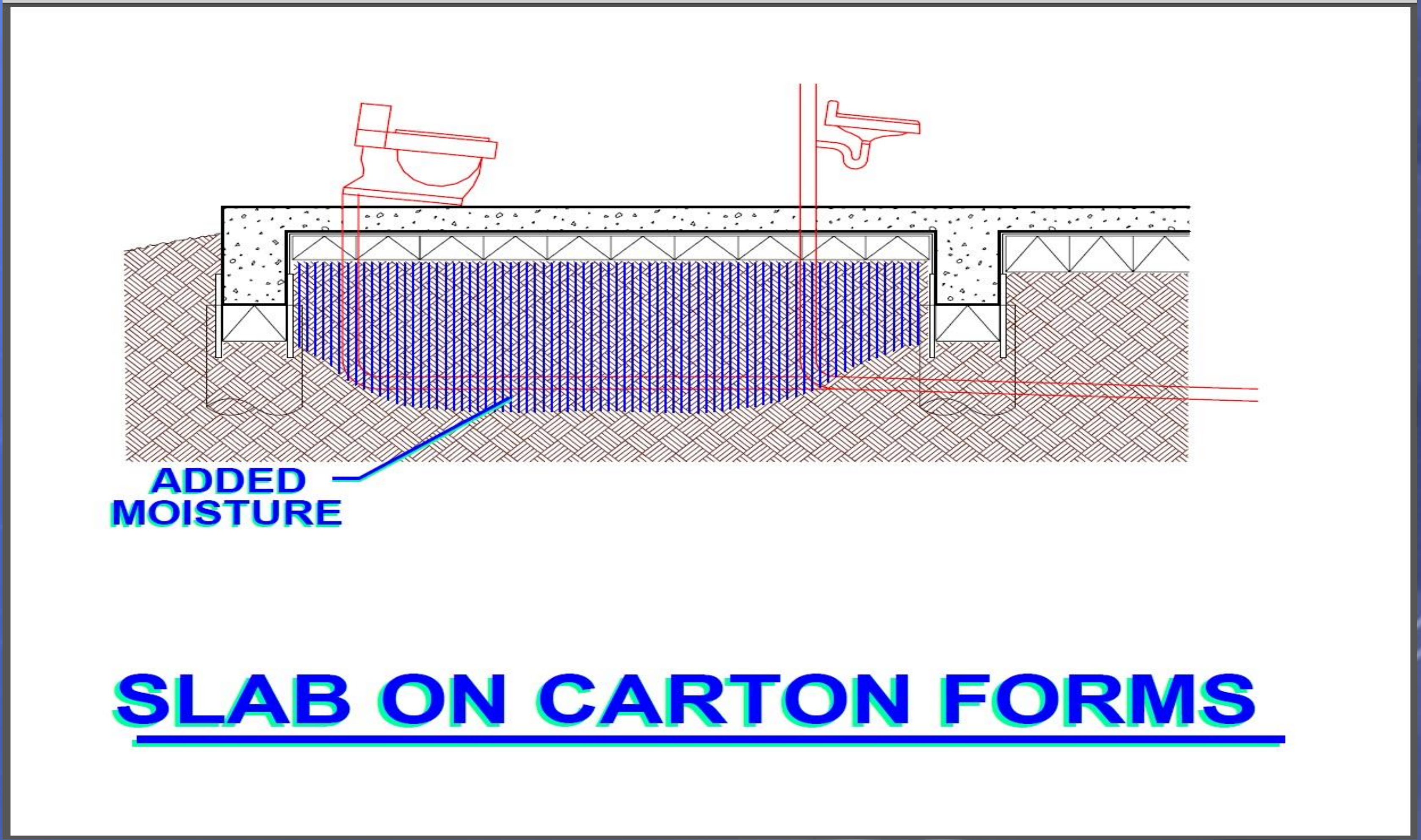
When to use piers





Plumbing Problems and Moisture Problems with Foundation on Void Boxes



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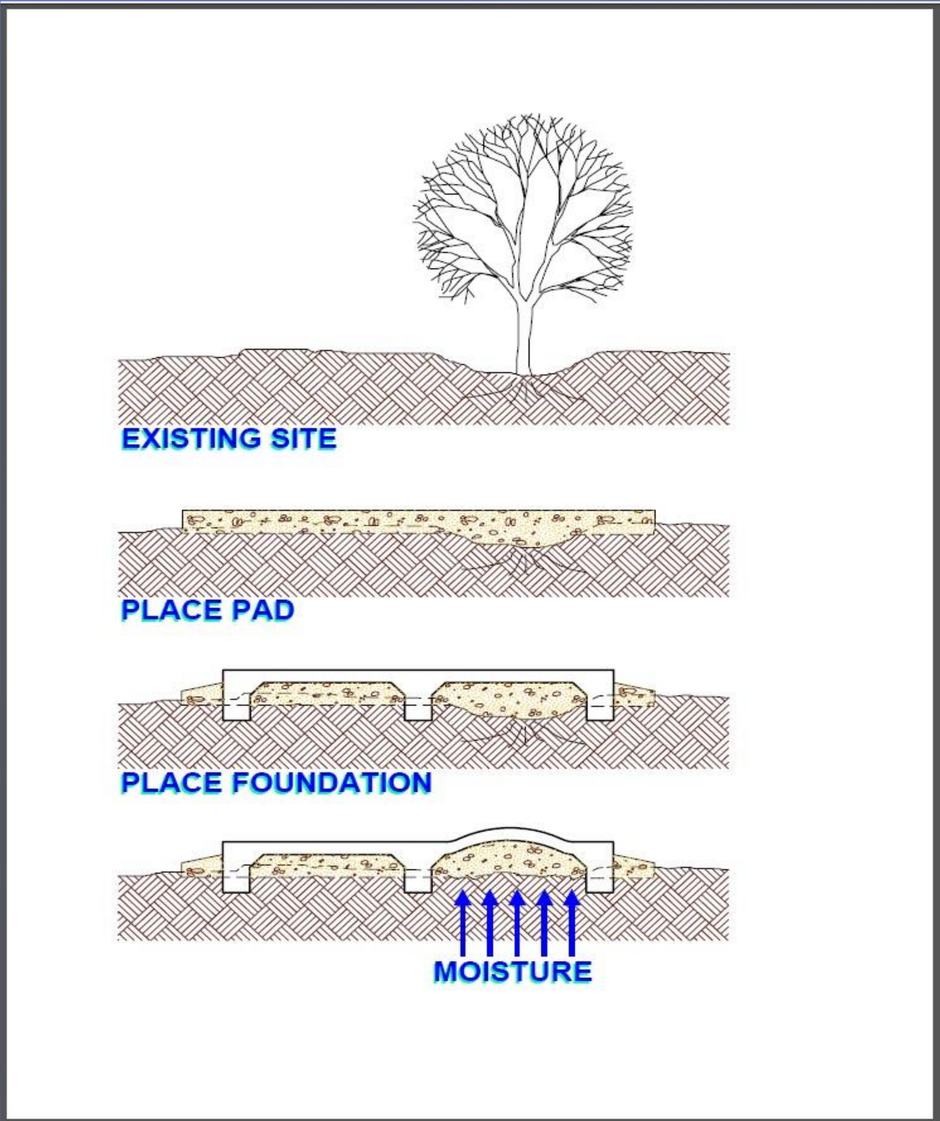
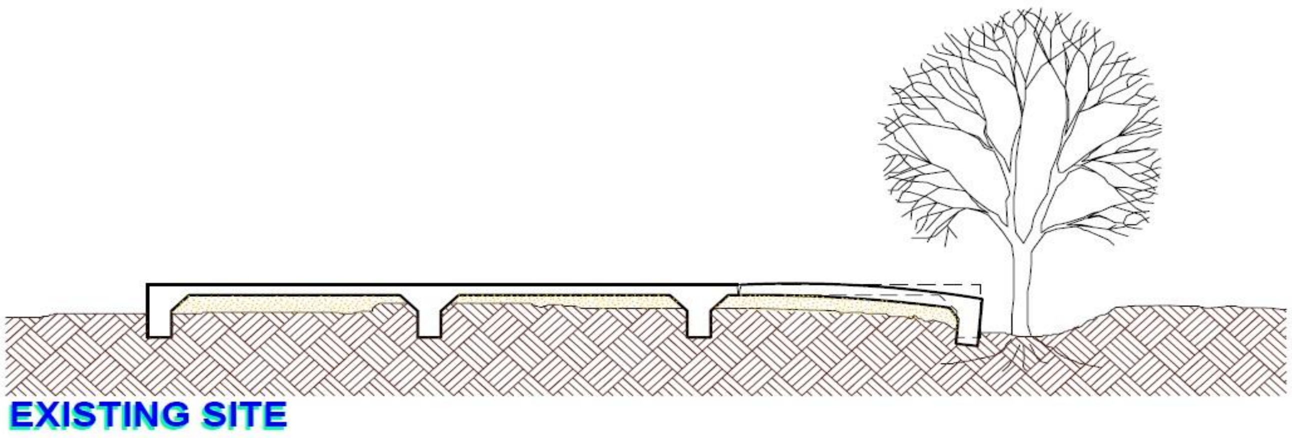
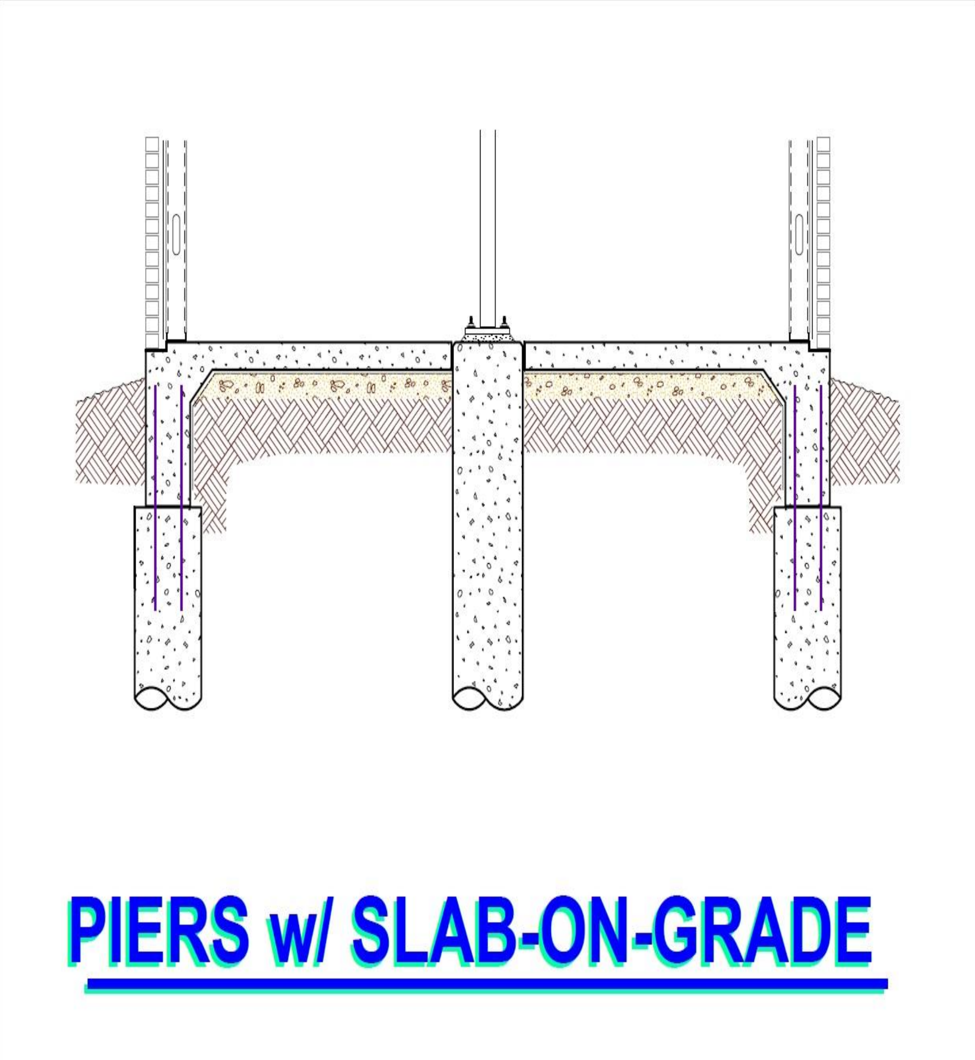
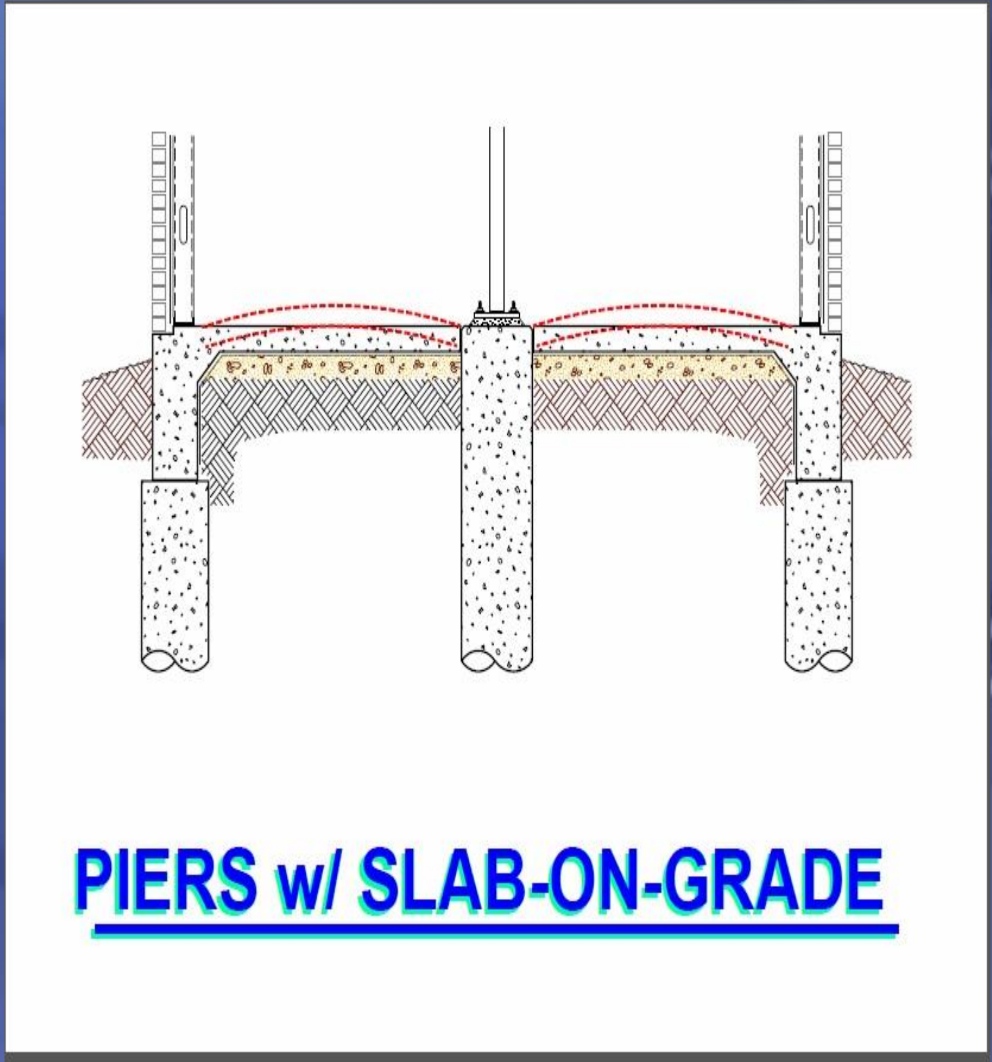
Previous Tree Rows and Uneven Soil Moisture Conditions



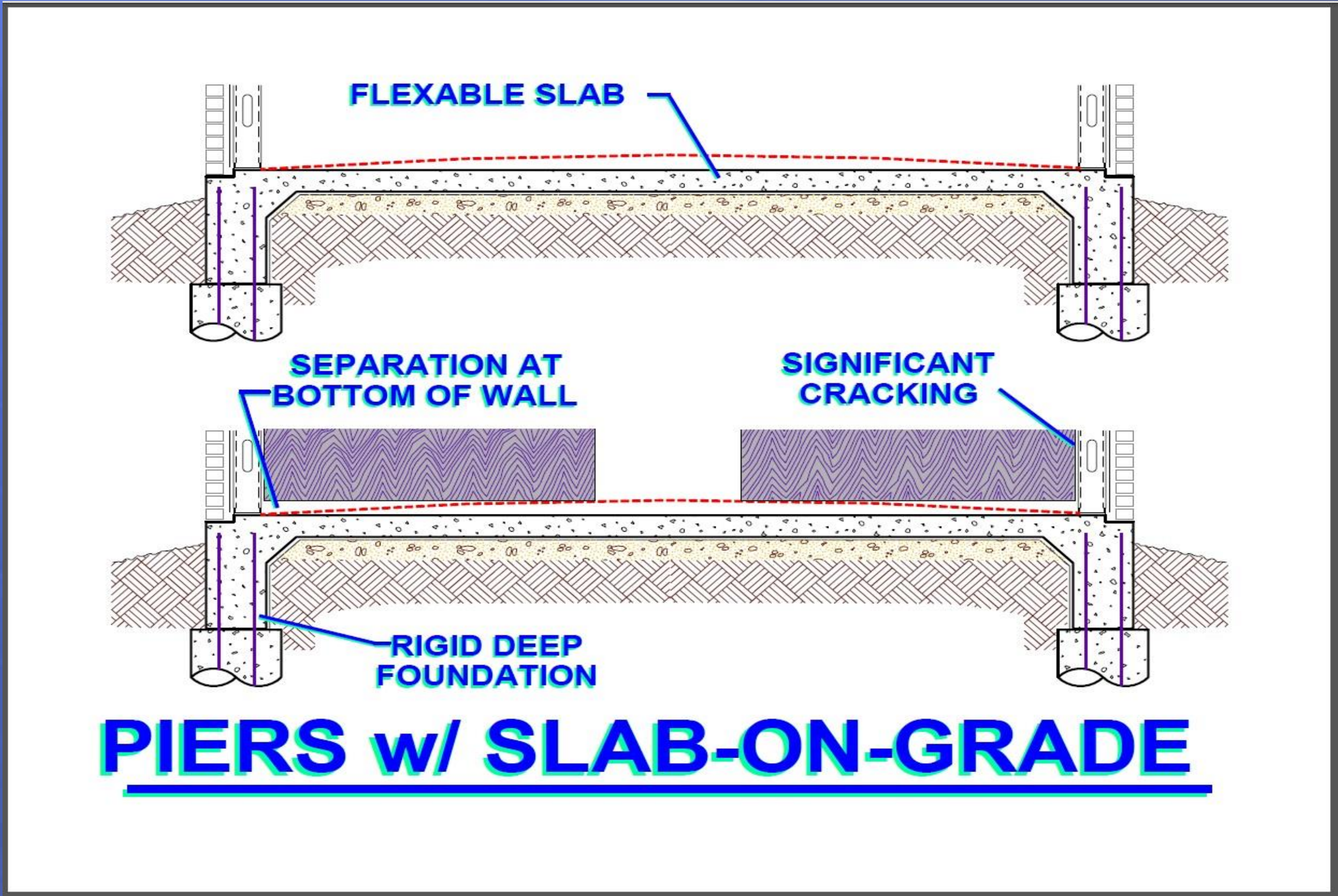

EXISTING SITE

Incompatible Foundation Systems

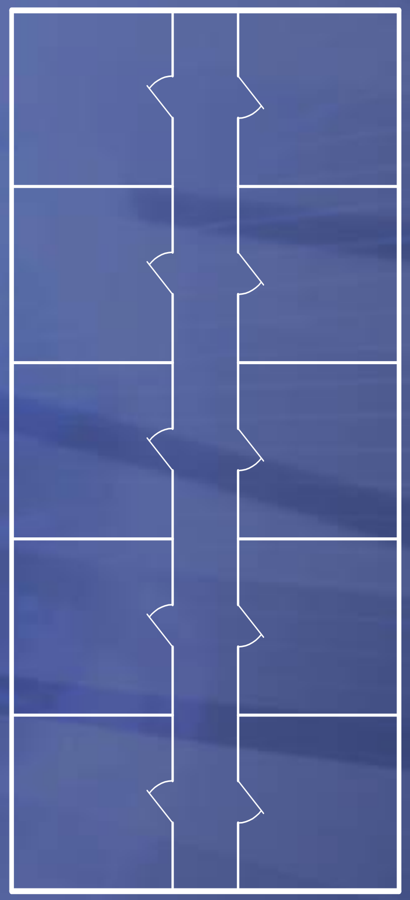




Incompatible Foundation Systems



SANCTUARY



CLASSROOM BUILDING

Heads Up "THINK"

- Metal Building Type: Slab-On-Grade
- P.I. = 20 – 30 4” S.O.G. Turned Down
- P.V.R. < 1” Exterior Grade Beam

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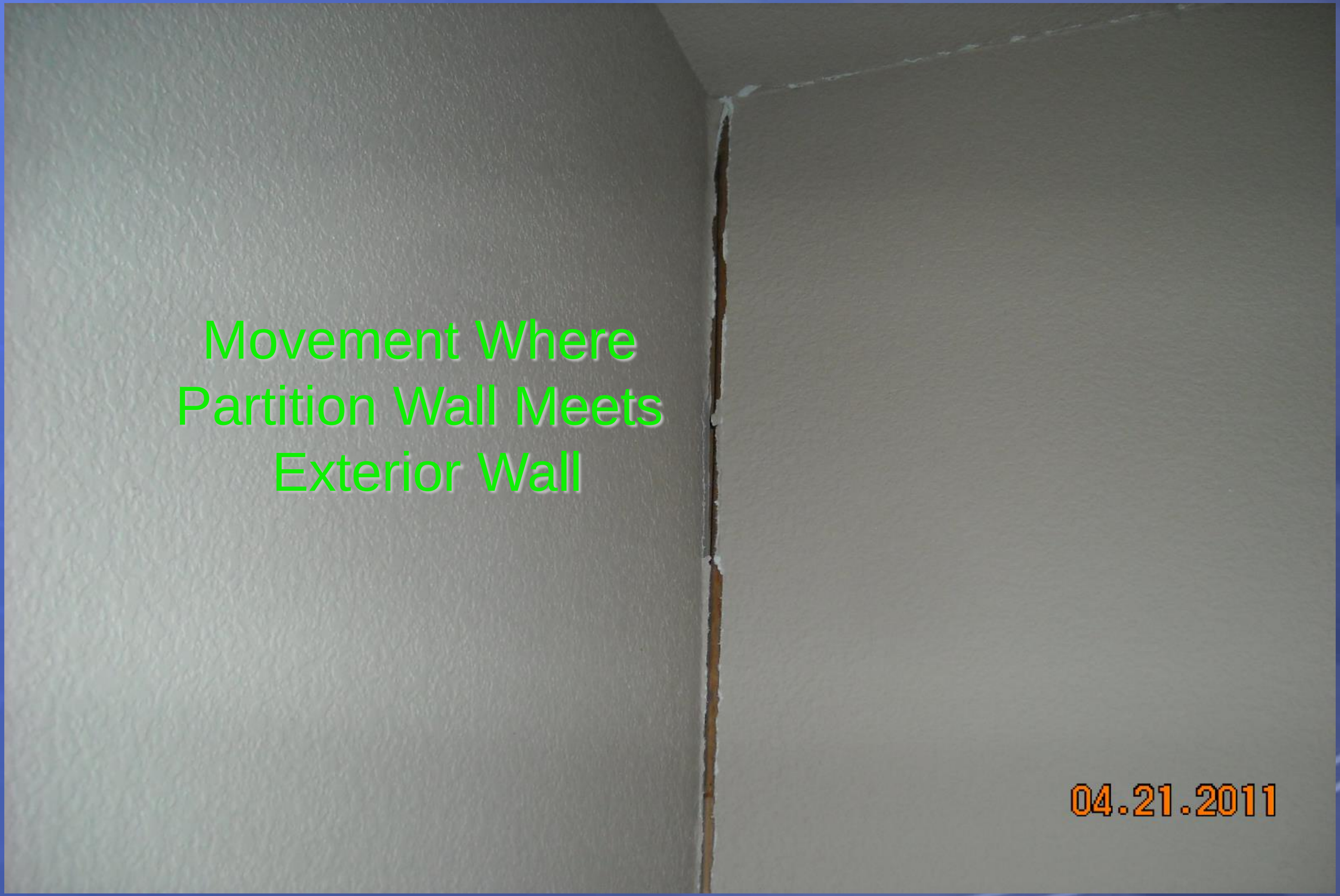
04.21.2011


Movement Where Partition Wall Meets Exterior Wall
04.21.2011

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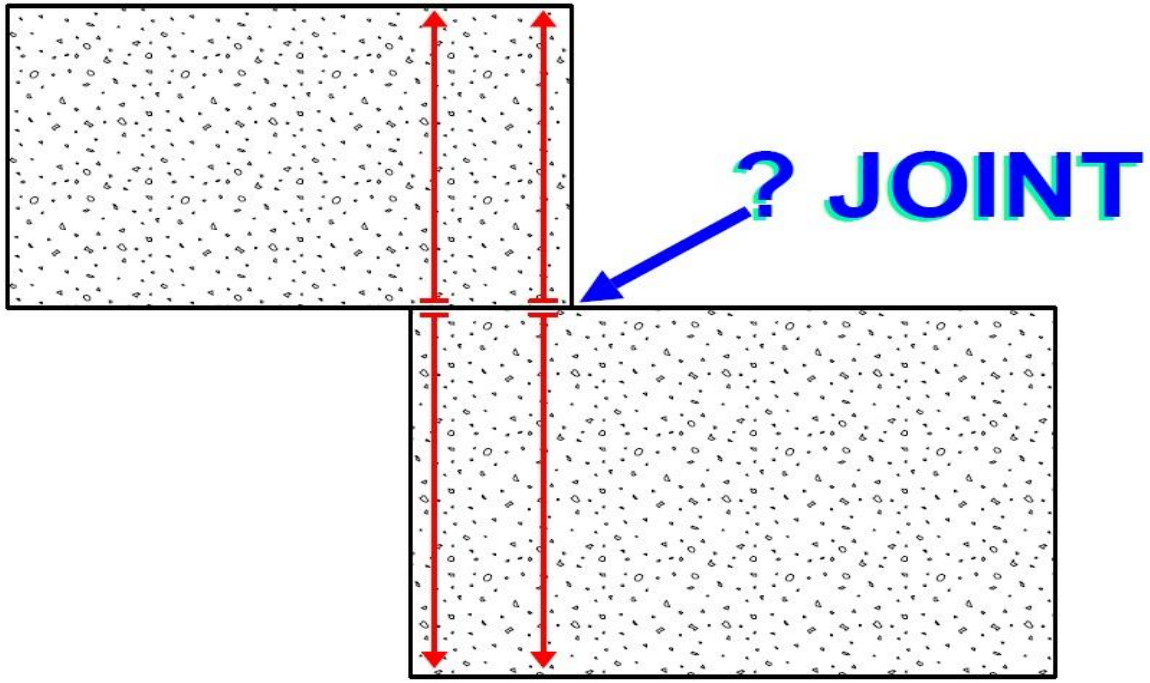
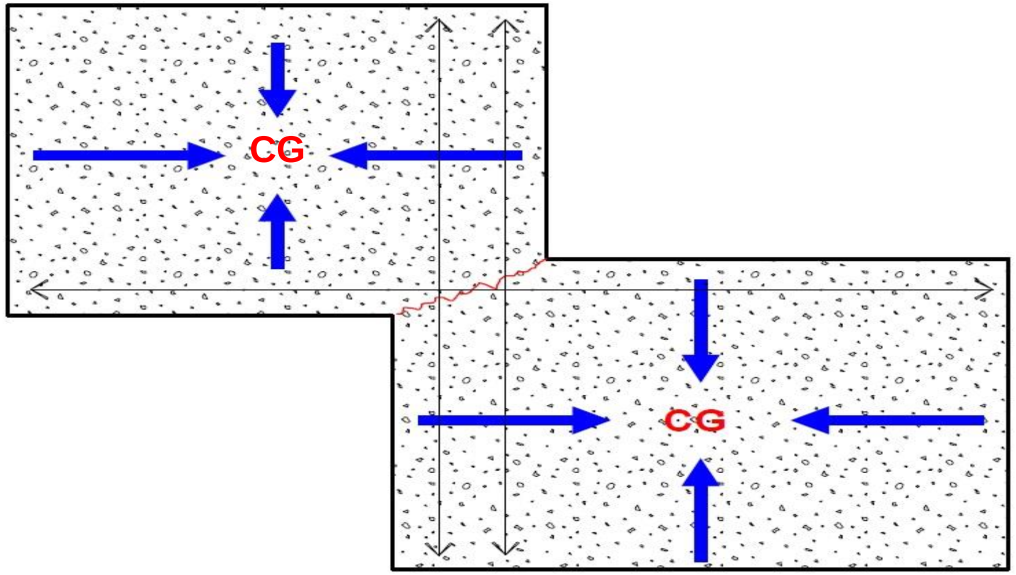
Effect of Post-Tensioning



EFFECTS OF PT SHORTINING

Effect of Post-Tensioning cont.



EFFECTS OF PT SHORTINING

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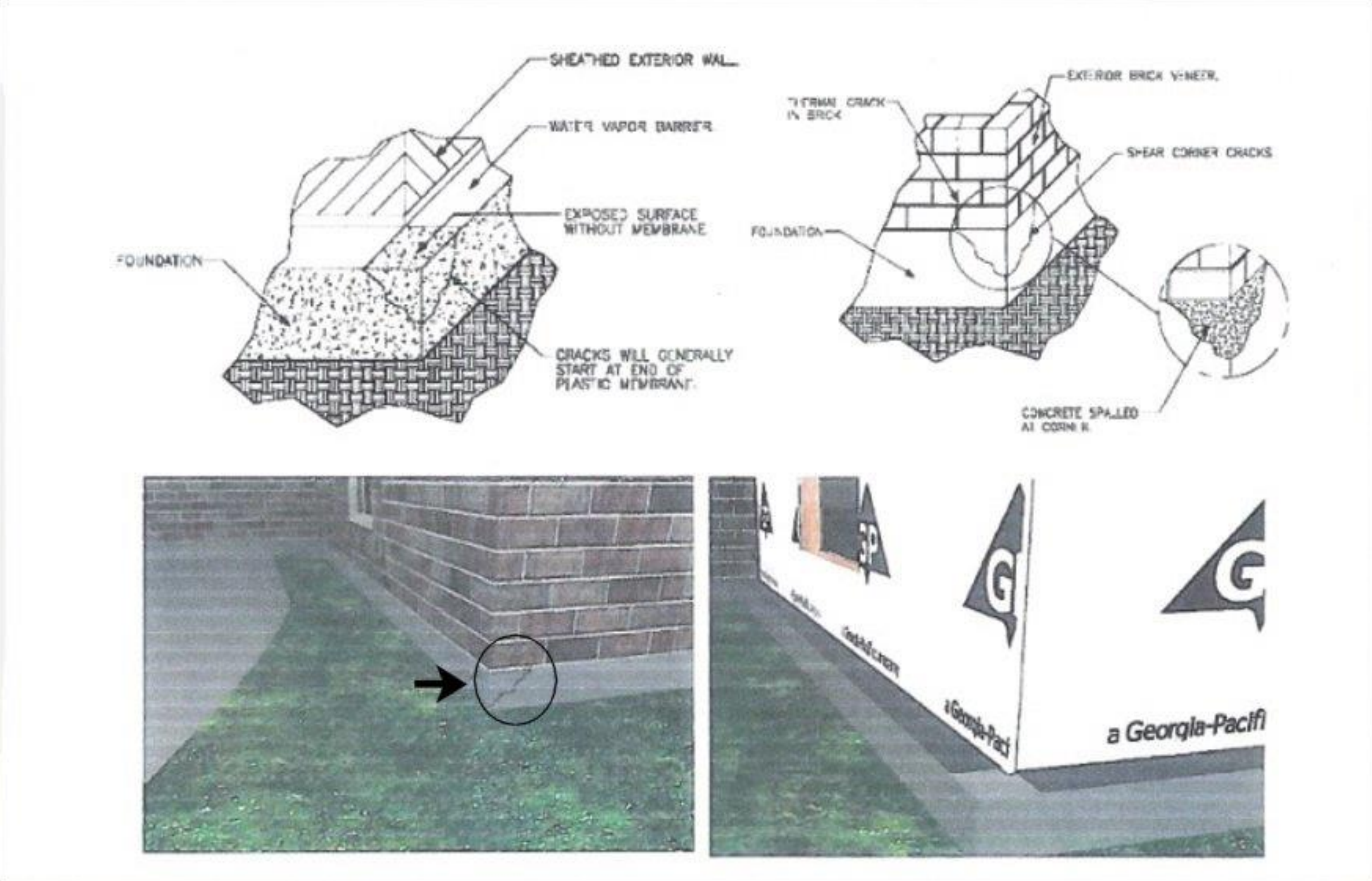
Tendon length

Tendons less than 15’-0 are generally too short to stress

Corner Cracks

Corner Cracks



FOUNDATION MAINTENANCE

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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 not 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 that 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?

THANK YOU