Slab-on-Ground Design

Using the PTI Method

by

Ken Bondy

Biggest Single U.S. Market for Post-Tensioning Tendons

- Over 40% of all P/T tendons sold in the USA are for residential foundations.
- 58,000 tons of tendons installed in residential foundations in the year 2000 alone.
- Represents about 220,000 homes in one year.

History

- First used the late 1960’s in Texas and California
- Widest usage has been in
    - Texas (50%)
    - California (32%)
    - Nevada (7%)
    - Louisiana (5%)
- Usage increasing (4%) in
    - Arizona
    - Colorado
    - Florida
    - Georgia

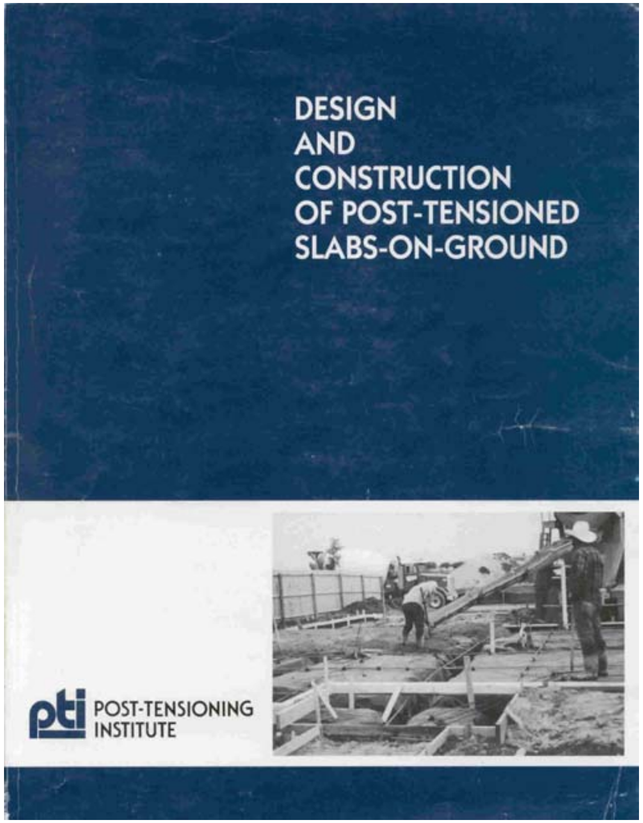
Evolution of Design Methods

- Earliest methods (±1965) were semi-empirical
  - Based upon simplified mathematical models
    - Assumed loss of support (Spanability)
  - Confirmed by actual performance
- PTI Method (1980) based upon rigorous mathematical study of soil/structure interaction
  - Most comprehensive design method ever developed for behavior of concrete foundations on expansive soils

The PTI Design Method

- Based upon a finite element computer model of soil/structure interaction, with research sponsored by PTI and executed at Texas A & M University in late 1970's
- 1st Edition published in 1980, 2nd Edition in 1996
- Incorporated into model building codes (UBC 1997, IBC 2000)
- Used to design millions of existing foundations

PTI Publications



DESIGN
AND
CONSTRUCTION
OF POST-TENSIONED
SLABS-ON-GROUND

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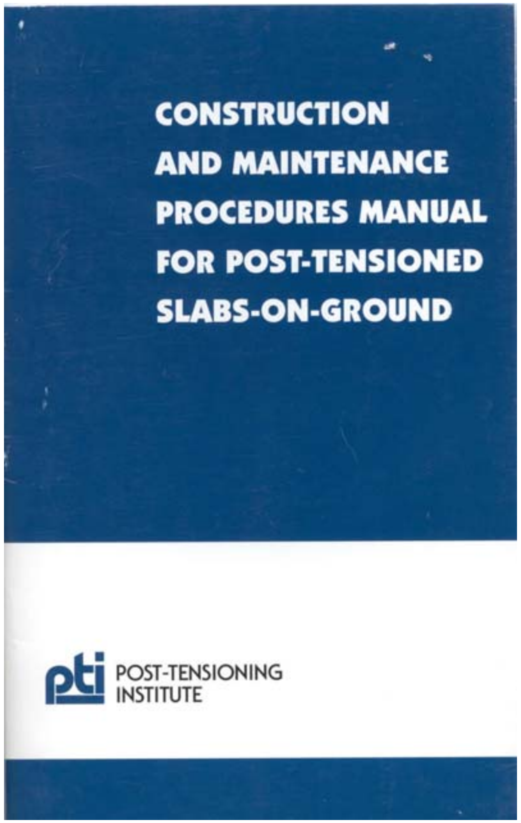
INSTITUTE



CONSTRUCTION
AND MAINTENANCE
PROCEDURES MANUAL
FOR POST-TENSIONED
SLABS-ON-GROUND

pti POST-TENSIONING
INSTITUTE

Technical Information Available

pti Technical Notes
1717 West Northern Avenue • Suite 114 • Phoenix, Arizona 85021
Dr. Bijan O. Aalami, Editor — For Professionals Engaged in Post-Tensioning Design — Issue 9 • July 2000

Performance Evaluation of Residential Concrete Foundations

By Kenneth B. Bondy[1]

INTRODUCTION

Many contemporary construction defect lawsuits involve light wood-framed residential buildings supported on post-tensioned concrete foundations built on expansive soils. Foundation performance is often an issue in these lawsuits. A primary tool for the evaluation of foundation performance in these cases is a level survey of the slab surface profile, typically made during the discovery phase of the lawsuit. Usually this survey is made using a water level, or "manometer", a simple and inexpensive instrument which can provide reasonable accuracy if the survey is properly executed. Forensic consultants often allege, on the basis of the level survey, that excessive foundation movement has occurred due to the effects of expansive soil volume changes, requiring expensive repairs to the foundation system. In some cases the consultants attribute ***all*** of the current slab surface elevation differentials to soil movement, thus completely ignoring construction effects and effectively assuming that the slab was built perfectly level. Those consultants who do recognize construction effects often use non-standard criteria for their evaluation, which vary wildly from consultant to consultant and are based largely on anecdotal personal opinions, unsupportable by any published, generally accepted study or work.

PURPOSE

The purpose of this Technical Note is to present a rational protocol for the performance evaluation of residential concrete foundations, focusing primarily on the estimation of as-built construction levelness using standardized, published criteria. The protocol developed is applicable to both post-tensioned and non-prestressed foundations.

TWO SURVEYS

The most reliable and certainly the easiest way to evaluate foundation performance, including construction effects, is by comparing two competently executed level surveys made on the slab surface, one current and one made immediately after the slab was built. If the current surface profile is very similar to the original profile it may be reasonably concluded that the slab was built in its current position. If the current surface profile is substantially different from the original profile, it may be reasonably concluded that foundation movement has caused the difference. Unfortunately, the earlier survey is rarely available, and diagnoses of foundation performance must generally be made with only one survey, made years after the slab was built.

Lacking an initial survey it is impossible to determine with certainty whether the slab 1) was built with its current surface profile, 2) was built with a completely different surface profile and deformed into its current shape, or 3) attained its current surface profile by some combination of 1) and 2). However with the use of the protocol proposed herein a reasonable diagnosis of the presence or absence of ***significant*** soil and foundation movement is possible.

PROTOCOL FOR SINGLE-SURVEY EVALUATION

In the absence of survey information about the as-built slab surface profile, the subsequent diagnosis of excessive expansive soil movement requires, in the author's opinion, three related and concurrent conditions, all of which must be carefully evaluated, and all of which must be present to establish a reasonably certain diagnosis of excessive soil and foundation movement:

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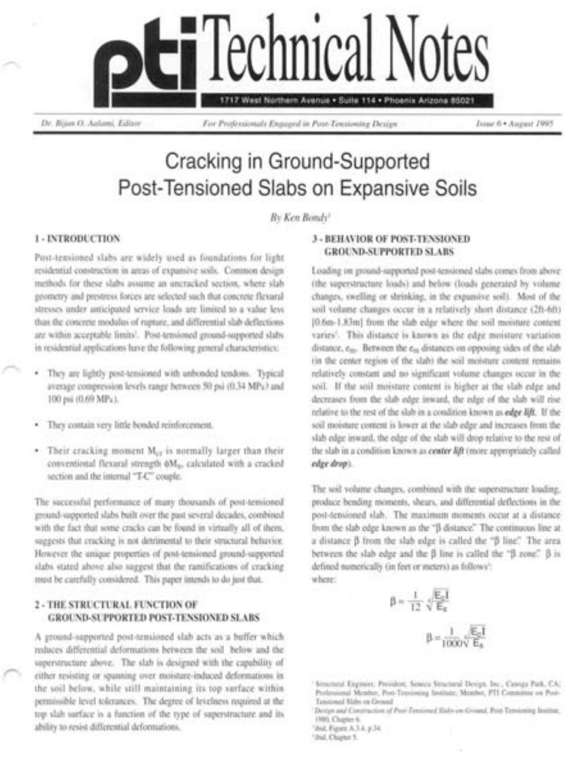

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Cracking in Ground-Supported Post-Tensioned Slabs on Expansive Soils

By Ken Bondy[1]

1 - INTRODUCTION

Post-tensioned slabs are widely used as foundations for light residential construction in areas of expansive soils. Common design methods for these slabs assume an uncracked section, where slab geometry and prestress forces are selected such that concrete flexural stresses under anticipated service loads are limited to a value less than the concrete modulus of rupture, and differential slab deflections are within acceptable limits[2]. Post-tensioned ground-supported slabs in residential applications have the following general characteristics:

- They are lightly post-tensioned with unbonded tendons. Typical average compression levels range between 50 psi (0.34 MPa) and 100 psi (0.69 MPa).
- They contain very little bonded reinforcement.
- Their cracking moment M_{cr} is normally larger than their conventional flexural strength ϕM_n, calculated with a cracked section and the internal "T-C" couple.

The successful performance of many thousands of post-tensioned ground-supported slabs built over the past several decades, combined with the fact that some cracks can be found in virtually all of them, suggests that cracking is not detrimental to their structural behavior. However the unique properties of post-tensioned ground-supported slabs stated above also suggest that the ramifications of cracking must be carefully considered. This paper intends to do just that.

2 - THE STRUCTURAL FUNCTION OF GROUND-SUPPORTED POST-TENSIONED SLABS

A ground-supported post-tensioned slab acts as a buffer which reduces differential deformations between the soil below and the superstructure above. The slab is designed with the capability of either resisting or spanning over moisture-induced deformations in the soil below, while still maintaining its top surface within permissible level tolerances. The degree of levelness required at the top slab surface is a function of the type of superstructure and its ability to resist differential deformations.

3 - BEHAVIOR OF POST-TENSIONED GROUND-SUPPORTED SLABS

Loading on ground-supported post-tensioned slabs comes from above (the superstructure loads) and below (loads generated by volume changes, swelling or shrinking, in the expansive soil). Most of the soil volume changes occur in a relatively short distance (2ft-6ft) [0.6m-1.83m] from the slab edge where the soil moisture content varies[3]. This distance is known as the edge moisture variation distance, e_m. Between the e_m distances on opposing sides of the slab (in the center region of the slab) the soil moisture content remains relatively constant and no significant volume changes occur in the soil. If the soil moisture content is higher at the slab edge and decreases from the slab edge inward, the edge of the slab will rise relative to the rest of the slab in a condition known as ***edge lift***. If the soil moisture content is lower at the slab edge and increases from the slab edge inward, the edge of the slab will drop relative to the rest of the slab in a condition known as ***center lift*** (more appropriately called ***edge drop***).

The soil volume changes, combined with the superstructure loading, produce bending moments, shears, and differential deflections in the post-tensioned slab. The maximum moments occur at a distance from the slab edge known as the "β distance." The continuous line at a distance β from the slab edge is called the "β line." The area between the slab edge and the β line is called the "β zone." β is defined numerically (in feet or meters) as follows[4]:

where:

$$\beta = \frac{1}{12}\sqrt[4]{\frac{E_c I}{E_s}}$$

$$\beta = \frac{1}{1000}\sqrt[4]{\frac{E_c I}{E_s}}$$

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[2] *Design and Construction of Post-Tensioned Slabs-on-Ground*, Post-Tensioning Institute, 1980, Chapter 6.

[3] Ibid, Figure A.3.4, p.34

[4] Ibid, Chapter 5.

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Frequently Asked Questions
Slab-on-Ground Construction
Answers from the PTI Slab-on-Ground Committee — *July 2001 • Issue No. 3*

QUESTION: Is the placement of a vapor retarder recommended beneath a post-tensioned slab-on-ground foundation and, if it is, should it be placed on top of or below the leveling sand?

ANSWER: There have been several articles[1] published concerning the use of vapor retarders (often incorrectly referred to as "vapor barriers"), with a range of conclusions from "absolutely no" to "yes, without exception," and different opinions as to its placement on top of or below the leveling sand. There is no clear-cut answer to this often-asked question.

This is not a question that has a definitive consensus recommendation from regulatory and/or advisory organizations. The International Residential Code (IRC) 2000 (with exceptions) requires a vapor retarder ". . . *placed between the concrete floor slab and the base course or the prepared subgrade where no base course exists.*" (R506.2.3). The use of vapor retarders is also addressed in several ACI committee reports (including committees 302, 311, 332 and 360). ACI has modified its position, previously expressed in 302.1R-96, Section 4.1.5, that vapor retarders be placed ***under*** granular fill, pointing out problems that have occurred with such placement and recommending instead that each proposed installation be independently evaluated based upon project conditions and the potential effects of slab curling and cracking (*Concrete International*, April 2001, p. 72–73). ACI Committee 302 is revising 302.1R-96, addressing the various factors that may affect vapor retarder placement, but the current draft of this document (March, 2001) makes no definitive recommendation as to a universal placement; instead, it provides guidance for designers based on the specifics of the slab under consideration. In light of the above, comments were solicited from PTI Slab-on-Ground committee members, as well as consultants and associates of these committee members. Of the responses received, the clear majority recommended the use of a vapor retarder and its placement directly beneath the concrete.

Uniformly, the consistent positive comment was the benefit that the vapor retarder provided in minimizing vapor transmission through the concrete. The placement of the vapor retarder on top of the leveling sand also provided a better base for the support of the tendons and eliminated the possibility for field problems that occur when the leveling sand is on top. When the sand is on top of the vapor retarder, displacement of the sand during concrete placement can result in reduced slab thickness and/or beam properties, mixing of sand with concrete, and an uneven underside surface of the concrete slab, increasing the effects of subgrade friction.

Uniformly, the consistent negative comment was that the vapor retarder caused the retention of moisture in the bottom of the slab, allowing the top (exposed to the air) to cure differentially. This caused the slab edges to curl and, in some cases, shrinkage cracks to form. Curling and cracking could be minimized by placing the sand layer on top of the vapor retarder; however, this causes greater concerns for the performance of the foundation, as listed above. As recommended in Section 4.5 of PTI's "*Construction and Maintenance Procedures Manual for Post-Tensioned Slab-on-Ground Construction*," 2nd Edition, cutting the vapor retarder in the bottom of the ribs will aid in water egress from the bottom of the concrete during curing. The major concern for the placement of the sand layer on top of the vapor barrier is the displacement of the sand during concrete placement.

Based on comments that were received, the consensus opinion of specialists in the design and construction of post-tensioned slabs-on-ground is that a vapor retarder be placed beneath all post-tensioned slab-on-ground foundations used for residential applications and that the vapor retarder be placed on top of the leveling sand. Designers should evaluate each installation on a case-by-case basis and make their own decisions about vapor retarder use and placement as they see fit, based upon the information available to them and the conditions and history that exist in their geographic area.

For industrial floors and special-use foundations, the use of a vapor retarder may reduce slab subgrade friction; however, the negative effect of slab curling due to differential curing rates must be anticipated.

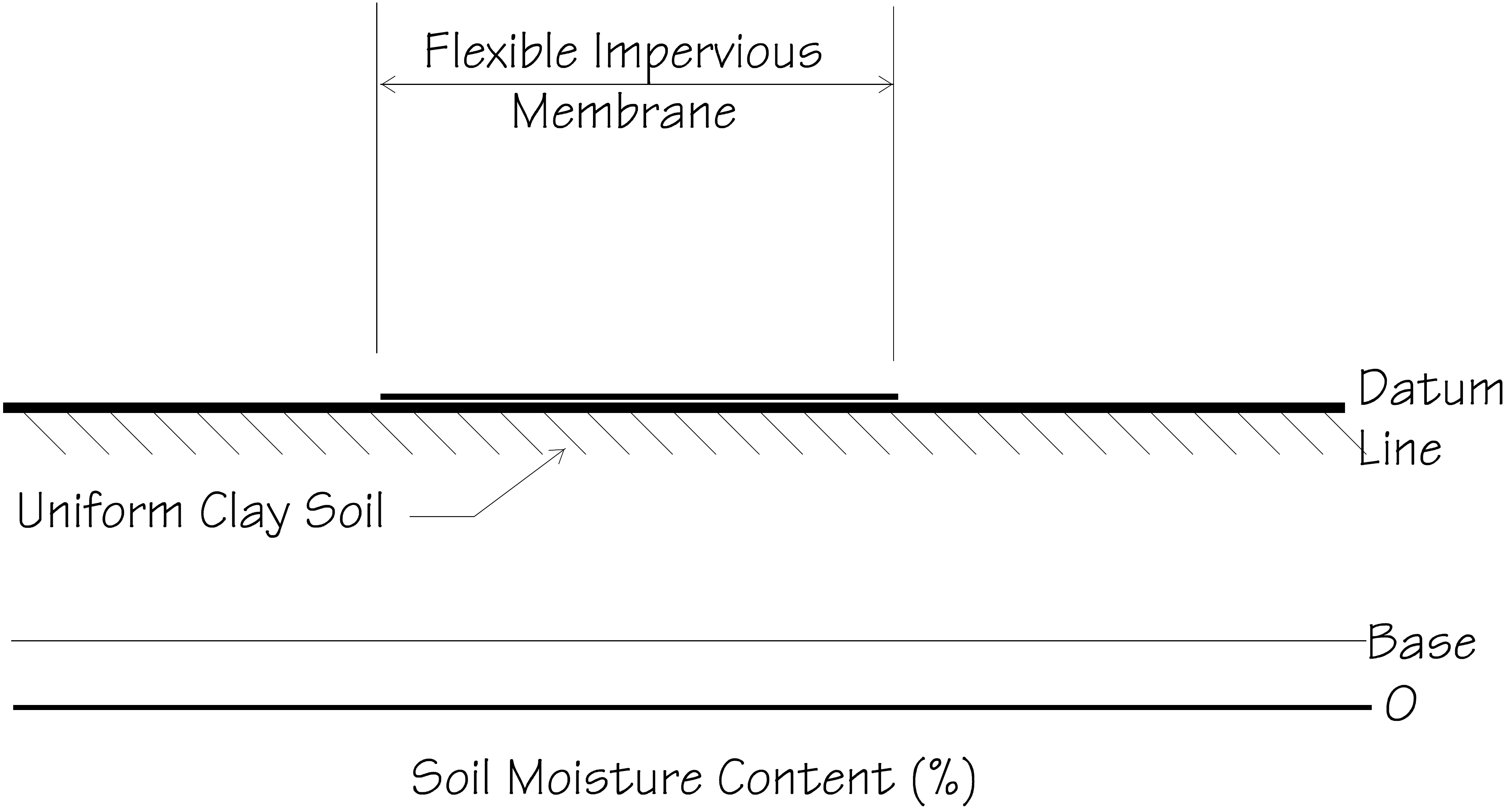
Structural Function of P/T Foundation

- Acts as a buffer between the soil below and the superstructure above to prevent unacceptable deformations in superstructure.
- Foundation is designed to resist or span over moisture-induced deformations in the soil below, while still maintaining its top surface within permissible level tolerances.

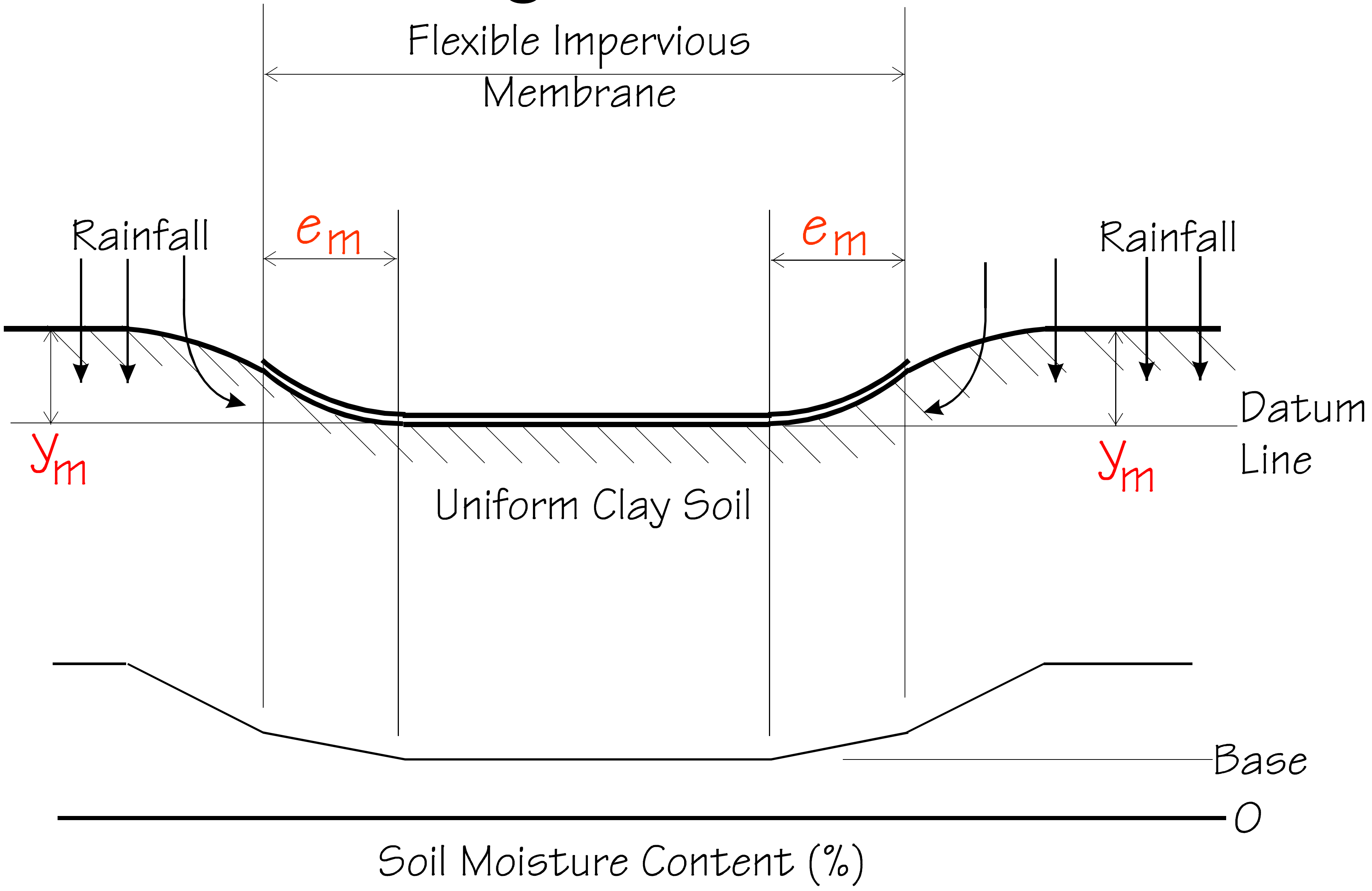
Expansive Soil Swell Modes

- Edge Lift
  - Soils are wetter at slab edge than at any point inside slab edge.
- Center Lift
  - Soils are drier at slab edge than at any point inside slab edge.

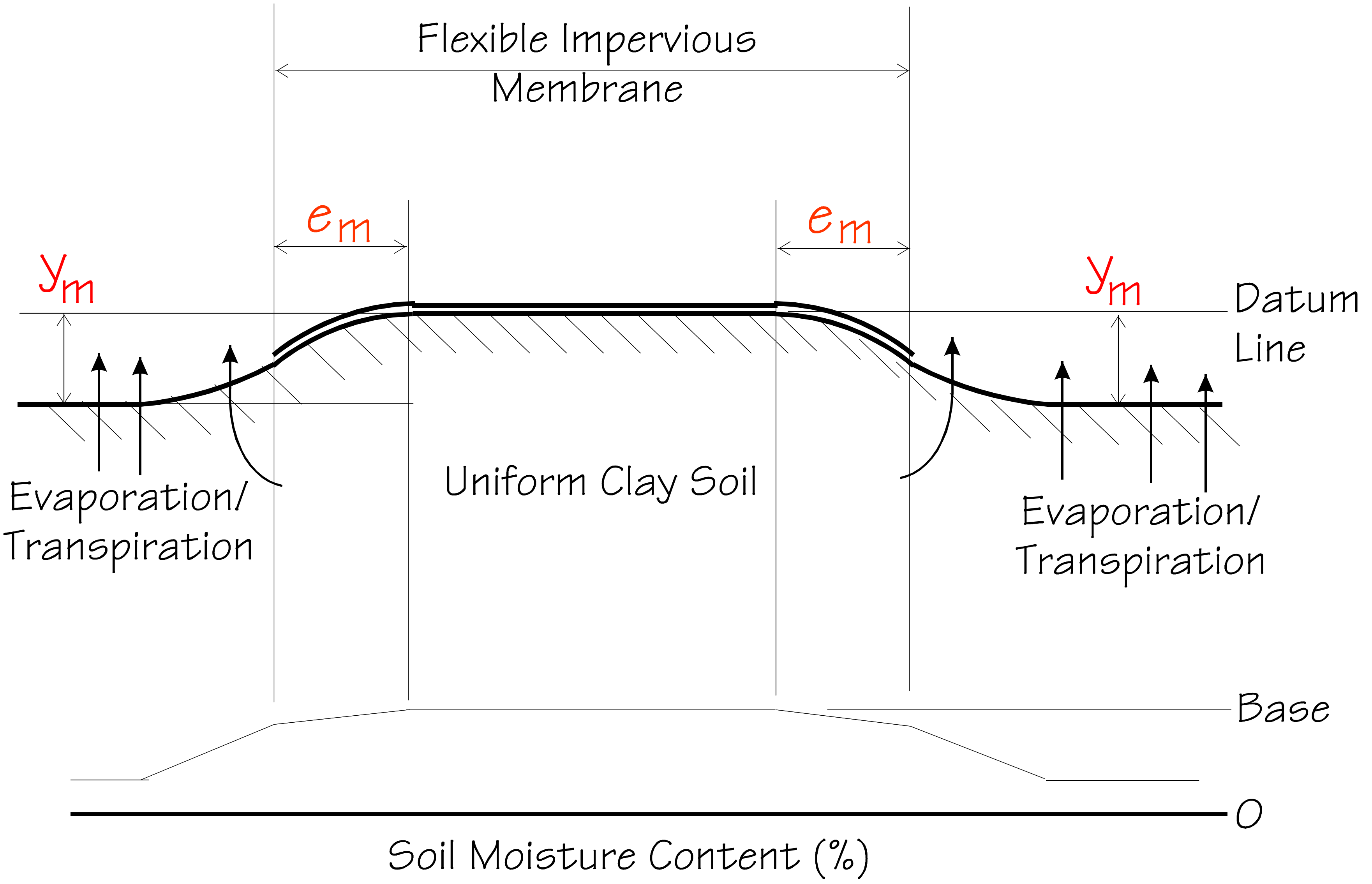
Soil Model


Flexible Impervious Membrane
Datum Line
Uniform Clay Soil
Base
0
Soil Moisture Content (%)

Edge Lift


Flexible Impervious
Membrane
Rainfall
e_m
e_m
Rainfall
Datum
Line
y_m
y_m
Uniform Clay Soil
Base
0
Soil Moisture Content (%)

Center Lift (Edge Drop)



Geotechnical Engineer Provides Critical Soil Design Parameters

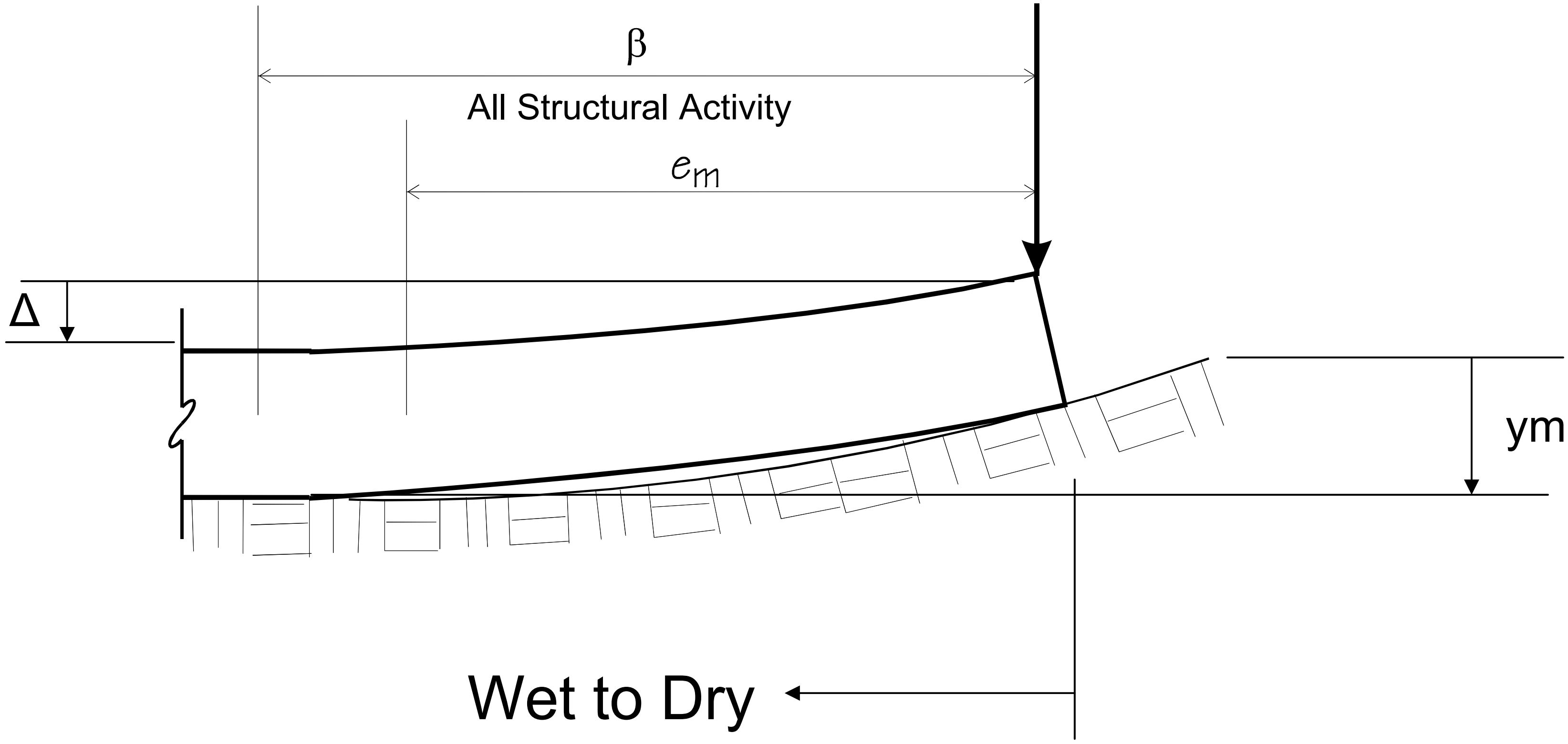
- Edge Moisture Variation Distance e_m
  - Thornthwaite Moisture Index (climate)
  - Soil Permeability
  - Vegetation
- Unrestrained Differential Swell y_m
  - Properties (activity) of clay
  - Depth of clay (active zone)
  - Soil suction
- One set of e_m & y_m values established for each swell mode (edge and center lift)
- Design cannot be done without these parameters

	Edge Lift	Center Lift
e_m	2.0 ft	5.0 ft
y_m	0.75 in	3.0 in

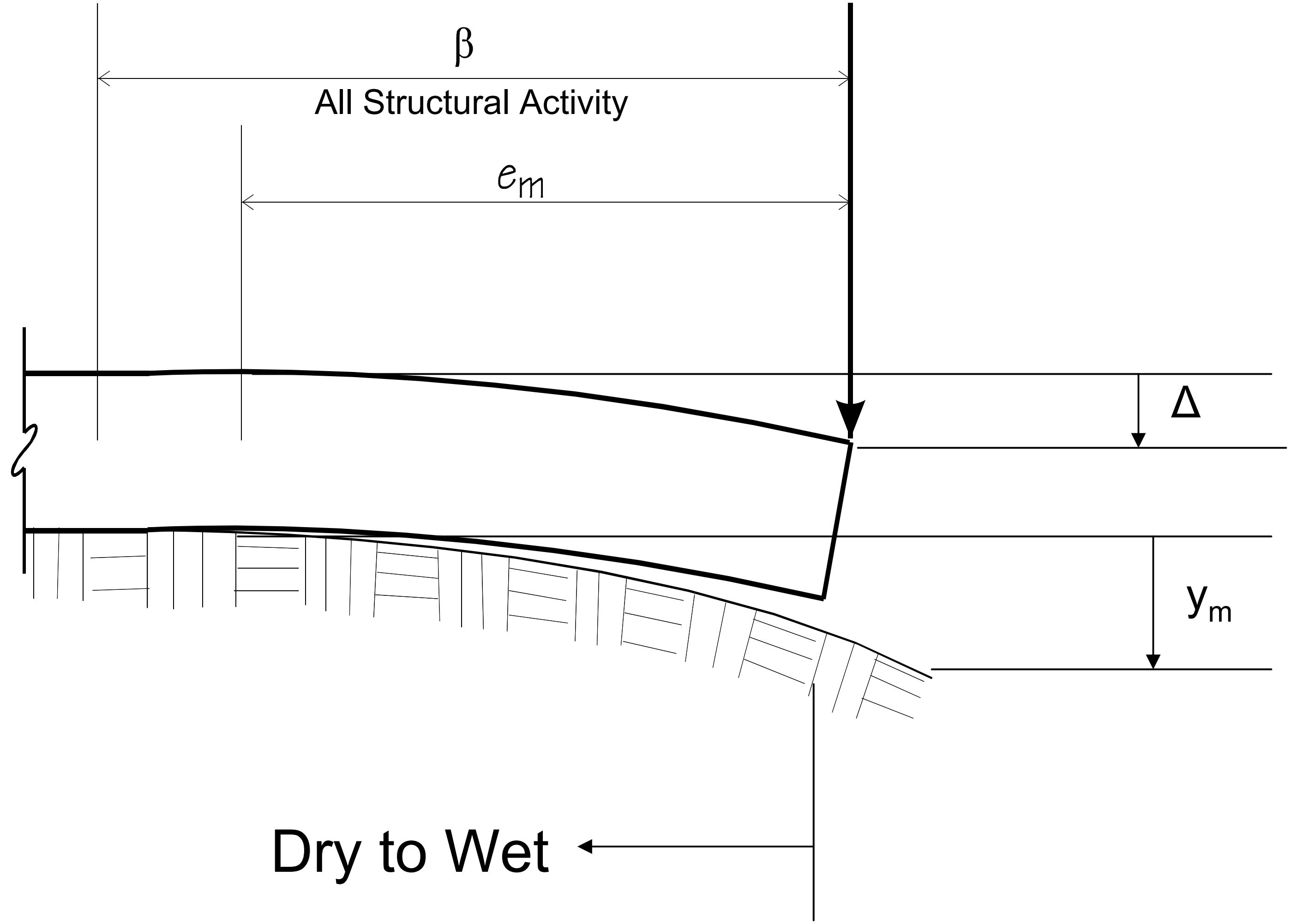
New Method For Determining e_m & y_m

- Under review by PTI Slab-on-Ground Committee.
- e_m based upon soil properties:
  - Unsaturated diffusion coefficient α
    - Soil suction.
    - Soil permeability.
    - Cracks and roots.
      - Soil Fabric Factor (roots, cracks, layers).
- Simplified method for determining y_m based primarily on soil suction profiles.
- Considers effect of vertical barriers (cutoff walls).

Edge Lift



Center Lift

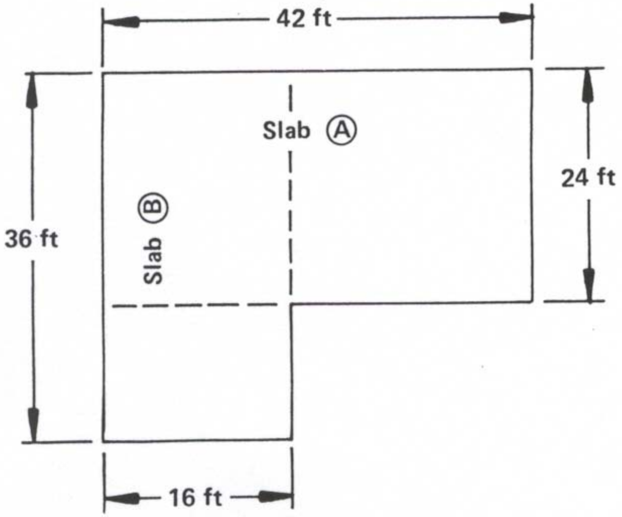


Ribbed and Uniform Thickness Foundations

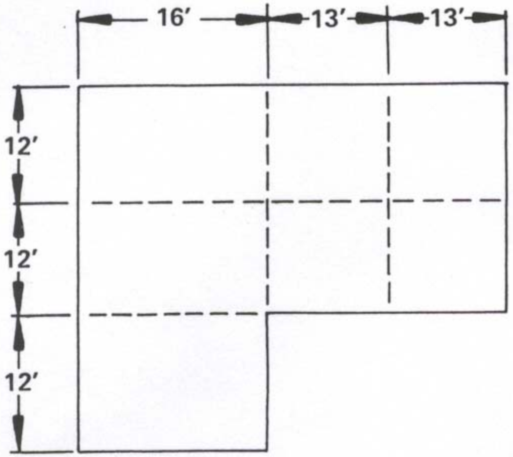
- PTI Design Method based on “ribbed” foundation system
  - Slab thickness t=4” minimum
  - Ribs=Grade Beams
    - h=t+7” with 12” minimum depth.
    - b=8-14”
  - Rib spacing S=6’ minimum, 17’ maximum.
- Can be converted to uniform (solid) thickness slab

Overlapping Rectangles

- Determine preliminary geometry and layout:
  - Rib spacing
  - Rib size
  - Slab thickness
- Divide slab into overlapping rectangles congruent with slab perimeter.



a. Divide Plan Area Into Two Overlapping Rectangles.

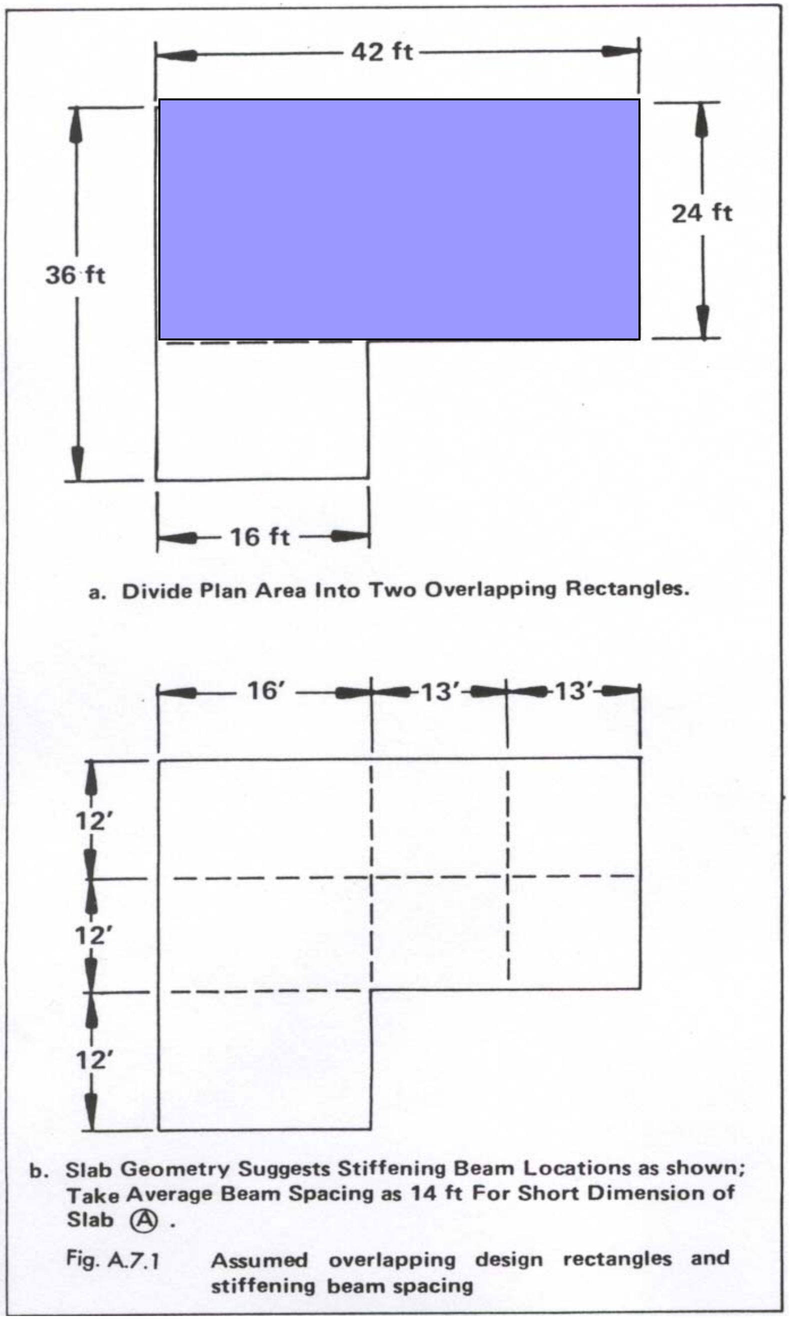


b. Slab Geometry Suggests Stiffening Beam Locations as shown; Take Average Beam Spacing as 14 ft For Short Dimension of Slab Ⓐ.

Fig. A.7.1 Assumed overlapping design rectangles and stiffening beam spacing

Rectangle A

24’ x 42’



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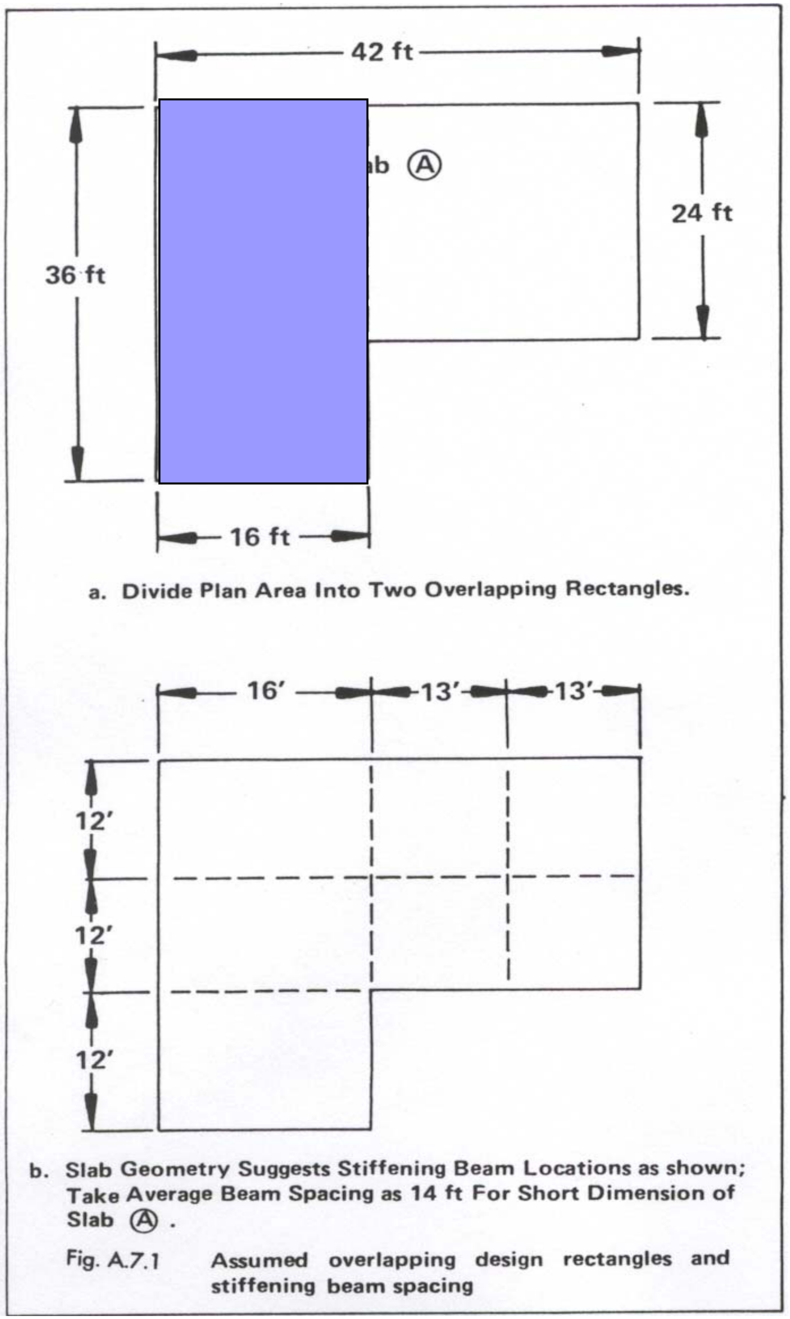
b. Slab Geometry Suggests Stiffening Beam Locations as shown; Take Average Beam Spacing as 14 ft For Short Dimension of Slab Ⓐ .

Fig. A.7.1 Assumed overlapping design rectangles and stiffening beam spacing

Rectangle B

16’ x 36’



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b. Slab Geometry Suggests Stiffening Beam Locations as shown; Take Average Beam Spacing as 14 ft For Short Dimension of Slab Ⓐ .

Fig. A.7.1 Assumed overlapping design rectangles and stiffening beam spacing

Design Equations

- For each swell mode (edge or center lift)
  - For each direction (Long or Short), use equations to determine:
    - Maximum Moment
    - Maximum Shear
    - Maximum Differential deflection

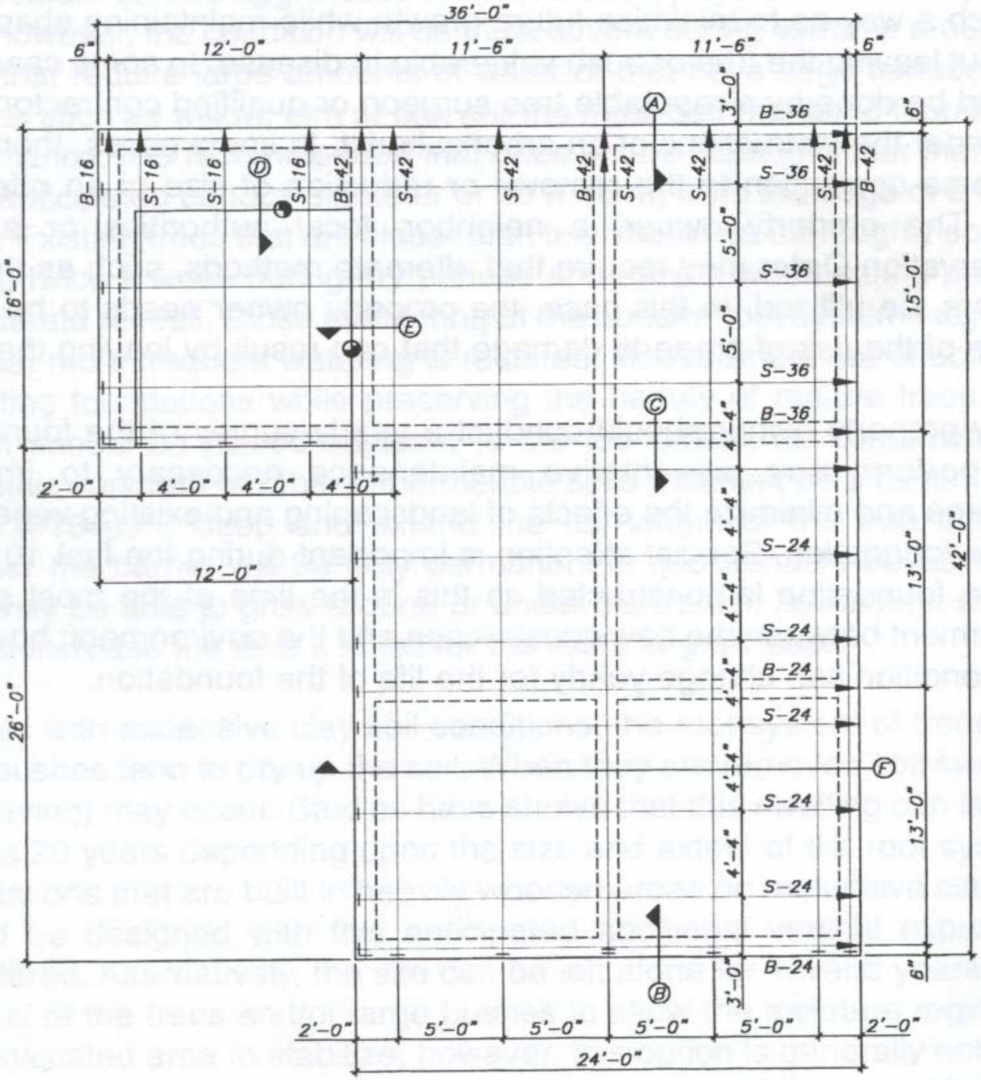
Design Based on Uncracked Section

- Effects of cracking studied in detail in original research and subsequent publications available through PTI.
- Effects of cracking generally inconsequential due to
  - Location of shrinkage cracks.
  - Increased soil support after flexural cracking.

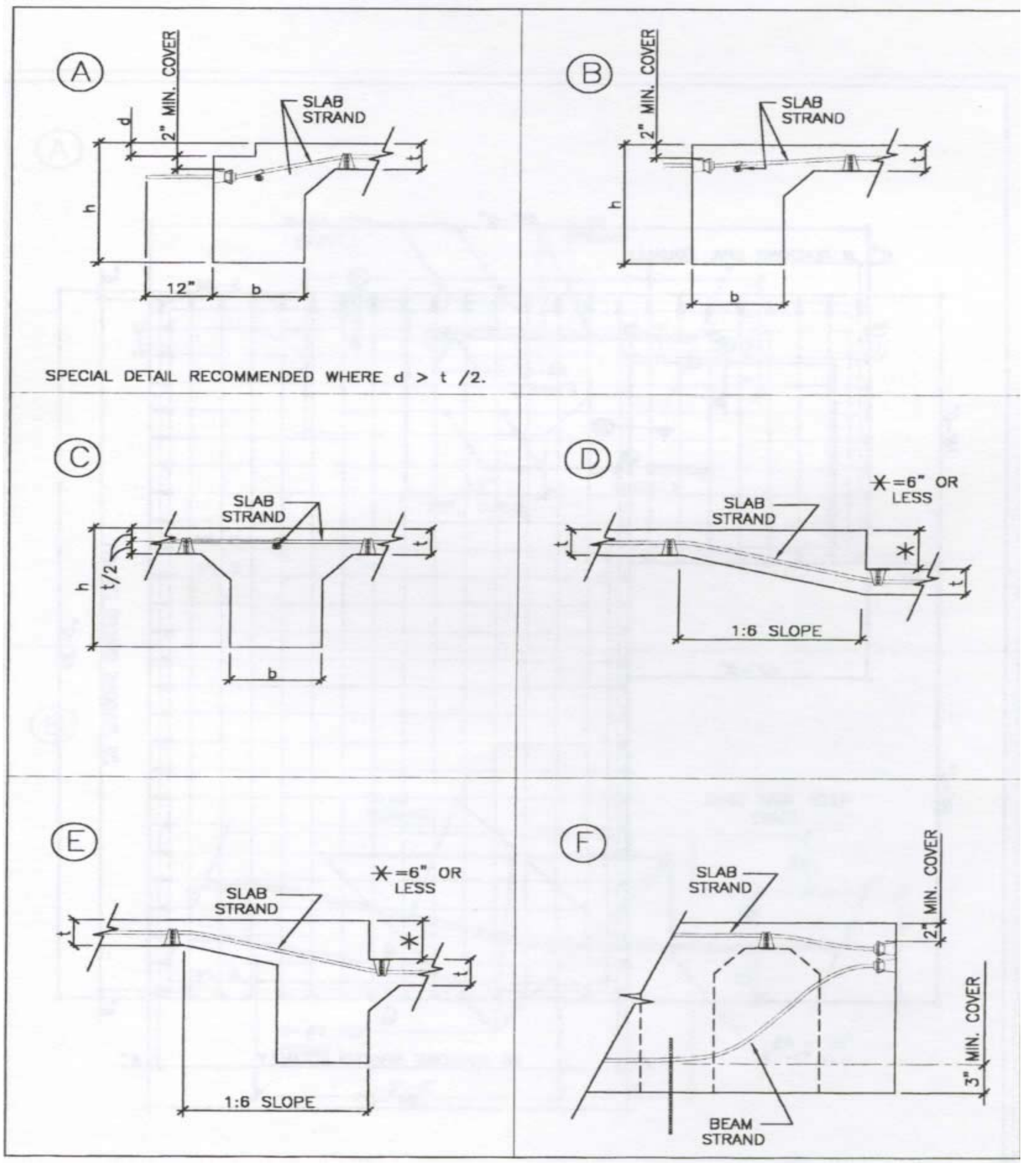
Allowable Concrete Stresses

- Flexural
  - Tension $6\sqrt{f'_c}$
  - Compression $0.45f'_c$
- Shear
  - $v_c = = 1.7\sqrt{f'_c} + 0.2f_p$
- Differential deflection
  - L/C_Δ
    - L=smaller of total slab length or 6β.
    - C_Δ = coefficient based on superstructure material.

Typical Slab Layout



Typical Details



Ribbed Foundation

Uniform Thickness Foundation

Thank You!