Contrasting Design Approaches for Slab-on-Ground and Raised Floor Foundations on Expansive Soils

Robert L. Lytton

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Houston, Texas
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Outline

• Elements of design
• Site conditions
• Slabs-on-ground
• Raised floor foundations
• Costs
Elements of Design

- Structural requirements
  - Moments
  - Shear
  - Deflection
  As determined by site conditions

- Costs
Site Conditions

• Soils

• Site hazards
  ➢ Trees
  ➢ Slopes
  ➢ Drainage

• Building geometry
Slabs-on-Ground: Soils

• $y_m$: differential movement of soil
  ➢ Perimeter swelling
  ➢ Perimeter shrinking
  ➢ Center swelling
  ➢ Center shrinking
Slabs-on-Ground: Soils

• $e_m$: edge moisture variation distance
  - Not a cantilever distance
  - A property of the soil mass
  - Depends on soil activity and cracking
Slabs-on-Ground: Soils

- $z_m$: depth of the moisture active zone
  - Depth of shrinkage cracks created by roots (log for root fibers)
  - No deeper than soil at the wilting point of plants
LOG (SUCTION, mm)

- Depth of the Moisture Active Zone
- Deepest Recorded Root Fiber
- Wet Suction Limit for Clay
- Equilibrium Suction for Non-Cemented Soils*
- Wilting Point for Vegetation

* From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russam and Coleman, 1961)
Slabs-on-Ground: Soils

- \( z_A \): depth of the movement active zone
  - Always shallower than \( z_m \)
  - Large factor in \( y_m \)
Raised Floor Foundations: Soils

- $y_m$: differential movement
  - Center drying, total shrinkage
  - Perimeter total swelling
    - Drainage
    - Flower beds
  - Perimeter total shrinking: trees
  - Downhill creep
NOTE
AMOUNT OF SHRINKAGE DEPENDS ON THE LEVEL OF RELATIVE HUMIDITY IN THE AIR BENEATH THE FLOOR. THE LOWER THE RELATIVE HUMIDITY, THE GREATER WILL BE THE AMOUNT OF SHRINKAGE. INITIALLY, THE SOIL WILL BE AT OR ABOVE 98% RELATIVE HUMIDITY. e_m IS THE EDGE MOISTURE VARIATION DISTANCE WHICH VARIES TYPICALLY BETWEEN 3 AND 9 FEET DEPENDING ON THE TYPE OF SOIL.
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Amount of shrinkage depends on the depth of the tree root zone, how far the roots penetrate beneath the building, and the type of soil.
NOTE
DOWNHILL CREEP OCCURS ON SLOPES THAT ARE STEEPER THAN 1 FOOT RISE IN 10 HORIZONTAL FEET. CREEP RATE IS GREATER THE STEEPER THE SLOPE AND THE WETTER THE SOIL IS.
Raised Floor Foundations: Soils

- $e_m$: edge moisture variation distance
  - Not as important as with slabs on ground except around the perimeter
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Raised Floor Foundations: Soils

- $z_m$: depth of the moisture active zone
  - Same factors as with slab on ground
  - Interest is in the total movement
Raised Floor Foundations: Soils

- $z_A$: depth of movement active zone
  - Important to determine movement of supports
    - Pads
    - Spread footings
    - Posts
    - Piers

Objective:
- design for expected movement
- small support movement

- Which to use? Determined by costs
Slab-on-Ground: Site Hazards

- **Trees**
  - Shrinkage
  - Affects $z_m$, $z_A$, $e_m$, $y_m$
- **Slopes**
  - Like differential shrinkage
  - Rate depends on moisture
  - Affects $z_m$, $y_m$
- **Drainage**
  - Swelling
  - Affects $e_m$, $y_m$
Raised Floor Foundations:
Site Hazards

- Trees: shrinkage reduces total differential movement
- Slopes
  - Like differential shrinkage
  - Rate depends on moisture
  - Affects $z_m$, $y_m$
- Drainage
  - Swelling
  - Increases total differential movement
  - Affects $y_m$
Slab-on-Ground: Building Geometry

• Shape factor affects structural design quantities
  - Moment
  - Shear
  - Differential deflection

• Shape factor

\[
\frac{(\text{Perimeter})^2}{\text{Area}} \leq 24
\]

- Circle = 12.56
- Square = 16
- Rectangle = 3.7 \sim 1 \quad \text{SF} = 24
Raised Floor Foundations: Building Geometry

With adjustable floor elevation, does not matter
This is a soil-structure interaction problem.

- Soil is not a uniform pressure
- $e_m$ is not a cantilever distance
- Structural properties of slab and soil are creep (long-term) properties
Slab-on-Ground: Structural Requirements

- Ground pressures never come close to bearing capacity
- $z_m$ is dictated by site conditions and not by regional conditions
- $y_m$ for both edge shrinking and edge swelling (> 1 inch) must be estimated accurately
Slab-on-Ground: Structural Requirements

• $e_m$: for both edge shrinking and edge swelling is the most sensitive predictor of design moments, shears, and required stiffness, EI.

• $z_A$: is smaller than $z_m$ and is dictated by site conditions and not by regional conditions.
EXAGGERATED EXAMPLE OF DAMAGE TO A HOME AS A RESULT OF SHRINKING OR SWELLING SOILS
Example 1: Center Lift (em=5.5ft, ym=3.608in.), Moment, Mx (kips ft/ft)
Example 1: Center Lift (em=5.5ft, ym=3.608in.), Shear Force, Qx (kips/ft)
Example 1: Edge Lift, \((em=2.5\text{ft}, \ ym=0.752\text{in.})\), Displacements (in.), (CT)
Example 1: Edge Lift (em=2.5ft, ym=0.752in.), Moment, Mx (kips ft/ft)
Example 1: Edge Lift ($em=2.5\text{ft}$, $ym=0.752\text{in}$.), Shear Force, $Q_x$ (kips/ft)
Example 1: Edge Lift (em=2.5ft, ym=0.752in.), Moment, Mxy (kips ft/ft)
**Slab-on-Ground: Structural Requirements**

- $\beta$ – length = relative stiffness length
  
  \[ \frac{1}{12} \frac{4 \sqrt{E_c I}}{E_s} \]  
  
  $E_c = \text{creep stiffness of concrete}$  
  $E_s = \text{creep stiffness of soil}$

- Dictates what is a long- and short-slab (> 6$\beta$ is long)

- Controls design quantities for long slabs
Design Criteria: Deflections / Tolerance

- Sensitivity of foundation and super structure ($\Delta/L$)
- Differential ($\Delta_c + \Delta_s$)
  - As built ($\Delta_c$)
  - Soil movement ($\Delta_s$)
- Total
- Twisting
Design Criteria: Stiffness

- Substitute for deflection tolerance
- Enough concrete section to handle soil movement
Raised Floor Foundations: Structural Requirements

This is NOT a soil-structure interaction problem.

- Moment
- Shear
- Deflection

are the same as for column-supported structures.
Raised Floor Foundations: Structural Requirements

• Allowable deflections before adjusting support elevations dictate the design quantities of the floor supports

• Design of supporting footings, posts or piers is to make rough estimate of total movement
  - Vertical
  - Rotation
Movement Patterns

Exterior  Interior
Footing

Exterior  Interior
Post
Movement Patterns

Exterior (Swelling)  Interior (Shrinkage)

Pier

$z_A$
DRILLED PIER
DRILLED PIER

Shear Stress

Horizontal Stress Distribution

Shear Stress

Horizontal Stress Distribution
DRILLED PIER

Axial Tension

Deflection

Moment
DRILLED PIER REINFORCEMENT

Temperature and Shrinkage Reinforcement

Concrete Tensile Strength Governs

Steel Yield Stress Governs

Percent of Steel due to Side Friction Stress

Side Friction Stress, $\alpha_c$, (psf)
THORNTHWAITE MOISTURE INDEX
(20 Year Average, 1955–1974)
Physical Meaning of Scales

- Oven Dry
- Airdry (R.H. = 50%)
- Tensile Strength of Confined Water
- Wilting Point
- Clay Plastic Limit
- Clay Wet Limit
- Field Capacity
- Liquid Limit

\[ pF = \text{pF} - 8 \]

\[ pG = \text{pG} - 2 \]
Empirically Measured Suctions
BCI 2002 to 2008 = 26,000+ Data Points

Soil Suction, pF
Reasonable Suction Change Range

2003 Total Soil Suction Data (4776 Observations)
Unsaturated Soil Mechanics
Typical Suction Envelope

Typical “Trumpet” shape based on Mitchell and Lytton.
Exponential Suction Profile for Extreme Wetting and Drying Condition

\[ U(Z, t) = U_c + U_o \exp \left( -\sqrt{\frac{n\pi}{\alpha}} Z \right) \cos \left( 2\pi nt - \sqrt{\frac{n\pi}{\alpha}} Z \right) \]

\[ U(Z) = U_c + U_o \exp \left( -\sqrt{\frac{n\pi}{\alpha}} Z \right) \]

Mitchell (1979)

Fort Worth Interstate 820
NOTE

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# Raised Floor Foundation Boundary Conditions

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<thead>
<tr>
<th>OUTSIDE</th>
<th>pF WET</th>
<th>pF DRY</th>
<th>R.H.</th>
<th>BENEATH, %</th>
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<tr>
<td>FLOWER BED</td>
<td>2.9</td>
<td>6.50</td>
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<td>6.22</td>
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The amount of shrinkage depends on the depth of the tree root zone, how far the roots penetrate beneath the building, and the type of soil.
Laboratory Tests

- Atterberg limits
- Hydrometer
- Water content
- Dry density
- Sieve analysis
LOG (SUCTION, mm)

- **Depth of the Moisture Active Zone**
- **Total Suction**
- **Matric Suction**

**DEPTH, m**

- Depth of the Deepest Recorded Root Fiber
- Wet Suction Limit for Clay
- Equilibrium Suction for Non-Cemented Soils*
- Wilting Point for Vegetation

* From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russam and Coleman, 1961)
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<th>Area</th>
<th>Percentage</th>
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<td>838.7</td>
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<td>Zac fine sandy loam, 1 to 5 percent slopes</td>
<td>11,762.7</td>
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<td>1,729.5</td>
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<td><strong>377,977.9</strong></td>
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Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.
## Typical Clay Properties

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<th>Range</th>
<th>Example</th>
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<tr>
<td>Liquid Limit</td>
<td>55-90</td>
<td>86</td>
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<tr>
<td>Plasticity</td>
<td>30-60</td>
<td>59</td>
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<td>Plastic Limit</td>
<td>25-30</td>
<td>27</td>
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<tr>
<td>Percent Passing #200</td>
<td>80-99</td>
<td>97</td>
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<tr>
<td>Percent Passing 0.002mm</td>
<td>-</td>
<td>65</td>
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Effects of Flower Beds

Graph showing the relationship between surface heave and depth of flower bed.
Effects of Flower Beds

15 ft - Depth to Constant Suction

Depth of Vertical Moisture Barrier, ft.

At Edge of Foundation
3 ft from edge
Depth of Flower Bed, ft

Surface Heave, inches
NOTE

VERTICAL AND HORIZONTAL MOISTURE BARRIERS DECREASE THE AMOUNT OF MOISTURE THAT GETS BENEATH THE WALLS OF THE BUILDING. EFFECTIVE DEPTHS OF VERTICAL MOISTURE BARRIERS ARE BETWEEN 2.5 AND 4 FEET. EFFECTIVE WIDTHS OF HORIZONTAL MOISTURE BARRIERS ARE BETWEEN 4 FEET AND \( e_m \), THE EDGE MOISTURE VARIATION DISTANCE.
Effects of Trees

Diagram showing the depth of root zones and surface shrinkage movement in relation to tree roots at the edge of a foundation.
Effects of Trees

Tree Roots at the Edge of the Foundation

Depth of Root / Moisture Barrier, ft.

Depth of Root Zone, ft.

Surface Shrinkage Movement, in.
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Figure 8 - $e_m$ Selection Chart

- Center lift
- Edge lift

Thornthwaite Moisture Index ($l_m$)
see Post-Tensioning Institute Figure A.3.2

Edge Moisture Variation Distance, $e_m$ in feet
Use higher value of $e_m$ as found by $l_m$ and $\alpha'$

$e_m$ should not exceed 9 feet

$\alpha'$, Weighted Average of Modified Unsaturated Diffusion Coefficient
Downhill creep occurs on slopes that are steeper than 1 foot rise in 10 horizontal feet. Creep rate is greater the steeper the slope and the wetter the soil is.
During dry periods roots extract water from the soil and cause shrinkage cracks.
Crack Spacing Gets Larger with Depth
RUNOFF WATER

WATER SOAKS INTO SOIL

SUCTION RANGE BETWEEN CRACKS

pF

DRY LIMIT

WET LIMIT

2.0

4.0

2.5

2.0

4.0
Foundation soil properties

Moisture Conditions
- Beside Raised Floors
- Beneath Raised Floors

Differential Movements

Soil Properties

Site Investigation
## Raised Floor Foundation Boundary Conditions

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