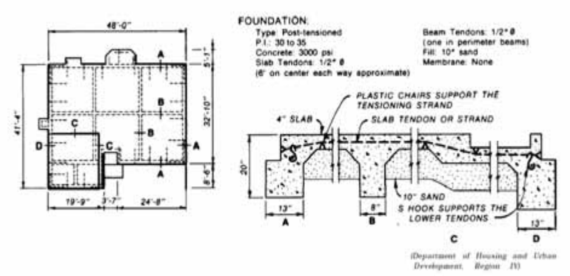
Foundations on Expansive Clay Soil
Part 2 – Design of Foundations



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The Philosophy of Foundation Design on Expansive Clay Soil

Real knowledge is to know the extent of one's ignorance (Confucius).

Philosophy of Foundation Design

- The design of foundations on expansive clay soils requires a significantly different design philosophy relative to the design of superstructure elements.
- Understanding these differences is critical to achieving a successful project.

Design Loads

- In general, structural engineering involves the calculation of loads and the design of members to resist the calculated loads (strength and deflection limit states).
- The deflections (and associated forces) imposed by expansive clay are unknown and (currently) unknowable.

Probabilistic Design

- Most structural elements are effectively designed for a zero probability of failure.
- Foundations on expansive soils are designed based on an acceptable probability of failure.
- Probability of failures is relatively high. Many structures will experience failure in their lifetime.

Definition of Failure

- Failure of traditional structures is based on accepted limit states (such as yield, rupture and deflection).
- There is no generally accepted definition of failure of foundations on expansive clay.

Design Codes

- Design codes exist for some types of stiffened slab-on-grade foundations (floatings mats).
- There are no design codes or design guidelines for many types of foundation systems used on expansive clay soils.
- Foundation for commercial systems have the least guidance.

Material Properties

- Material properties for steel, concrete and wood are well understood and relatively consistent.
- Soil properties vary widely even within the same project, and there is no accurate way to predict many of the soil parameters that control foundation design.

IBC 2000 Requirements

IBC 2000 requires design of foundations on expansive soil to comply with requirements of section 1805.8:

- Removal of expansive soil to depth of active zone.
- Stabilization of soil (chemical, dewatering, presaturation, etc).
- Use of slab-on-grade (WRI/CRSI or PTI)
- Compliance with 1805.8.1

ICB 2000 Section 1805.8.1

Foundations placed below where volume change occurs or below expansive soil shall comply with the following provisions:

- Foundations extending into or penetrating expansive soils shall be designed to prevent uplift of the supported structure.
- Foundations penetrating expansive soils shall be designed to resist forces exerted on the foundation due to volume change or shall be isolated from the expansive soil.

Building Code Requirements IRC 2000

R403.1.8 Foundations on Expansive soils. Foundations and floor slabs for buildings located on expansive soils shall be designed in accordance with Section 1805.8 of the *International Building Code*.

Building Code Requirements IRC 2000

Exception: Slab-on-ground and other foundation systems which have performed adequately in soil conditions similar to those encountered at the building site are permitted subject to the approval of the building official.

Building Code Requirements ACI 318

- ACI 318 minimum steel requirements (0.18%) are not applicable to slabs-on-grade.
- Refer to ACI 224 “Control of Cracking”
- Cracking is controlled with a combination of steel and control joints.
- Normally 0.50%-0.60% to control cracking with steel alone.

General Design Considerations

- Soil movement is caused by changes in soil moisture. Design and construction should maintain constant soil moisture.
- Distress to structures is a result of differential movement, not absolute movement.

General Design Considerations

- Lightly loaded structures are the most susceptible to damage. If possible, concentrate bearing loads to decreases potential swell.
- Do not use different types foundation systems to support different parts of the structure, unless separated by an expansion joint.

General Design Considerations

- Caution must be exercised when construction occurs during periods of unusual dryness or wetness.
- Consider the effect of tree removal in the foundation design.
- Avoid irregular shapes where possible. Use independently supported rectangular sections separated by expansion joints instead.

Selection of Foundation System

- Informed Consent
- Type of superstructure (maximum tolerable distortion)
- PVR
- Climate (wet, arid, semi-arid)
- Economics (residential, industrial, institutional, etc).

Informed Consent

- There is no one "right" type of foundation for expansive clay. Different systems provide different levels of performance at different cost.
- Selection is controlled by economics and performance expectations.
- Owner, architect, civil engineer and geotechnical engineer must be involved in selection of structural system.

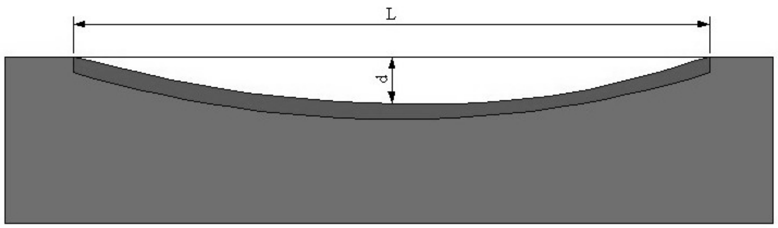
Informed Consent

- Document decision-making process.
- When litigation occurs, if it is not documented in writing, it did not occur.

Allowable Distortion

- Superstructure distress is a result of curvature, not rigid rotation.
- Fully rigid slabs can experience large rigid body rotations (tilt) without damage to superstructure.
- Compliant slabs can experience distress to superstructure under small differential vertical movements.

Measurement of Curvature



Superstructure system	Tolerable vertical angular deflection/ span length ratios, Δ/ℓ	Description
Rigid	1/600 to 1/1000	Precast concrete block, unreinforced brick, masonry or plaster walls, slab-on-grade.
Semirigid	1/360 to 1/600	Reinforced masonry or brick reinforced with horizontal and vertical tie bars or bands made of steel bars or reinforced concrete beams vertical reinforcement located on sides of doors and windows; slab-on-grade isolated from walls.
Flexible*	1/150 to 1/360	Steel, wood framing; brick veneer with articulated joints; metal, vinyl, or wood panels; gypsum board on metal or wood studs; vertically oriented construction joints; strip windows or metal panels separating rigid wall sections with 25-ft spacing or less to allow differential movement; all water pipes and drains into structure with flexible joints; suspended floor or slab-on-grade isolated from walls (heaving and cracking of slab-on-grade probable and accounted for in design).
Split construction*	1/150 to 1/360	Walls or rectangular sections heave as a unit (modular construction); joints at 25-ft spacing or less between units and in walls; suspended floor or slab-on-grade isolated from walls (probable cracking of slab-on-grade); all water pipes and drains equipped with flexible joints; construction joints in reinforced and stiffened slabs at 150-ft spacing or less and cold joints at 65-ft spacing or less.

* A Δ/ℓ value exceeding 1/250 is not recommended for normal practice, and a Δ/ℓ exceeding 1/150 often leads to structural damage.

Allowable Curvature

Foundation Types - Structurally Supported

- PdVM > 3-4 inches
- Construction
  - Conventionally formed
  - Void forms (Slab and grade beams)
- Support
  - Piers
  - Footings
  - Grade beams

Foundation Types - Floating (Slab-on-Grade)

- Rigid (PdVM < 3 to 4 inches)
  - Stiffened slab-on-grade
  - Stiffened slab-on-grade with piers
  - Mat foundation
- Compliant (PdVM < 1 inch)

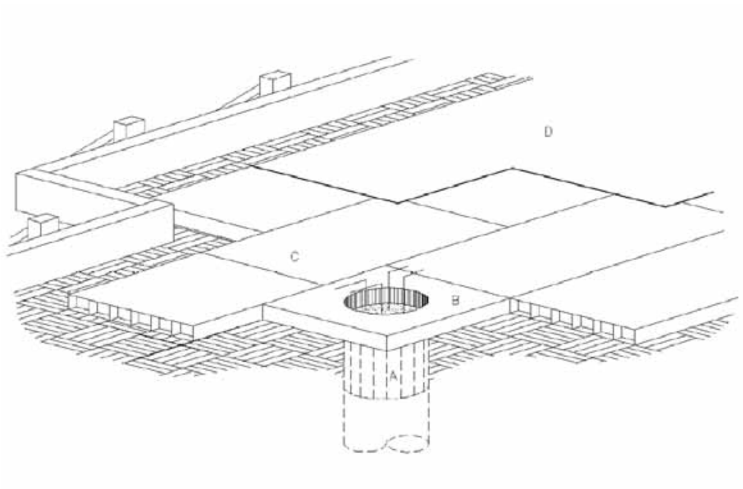
Elevated Structural Slab on Deep Piers

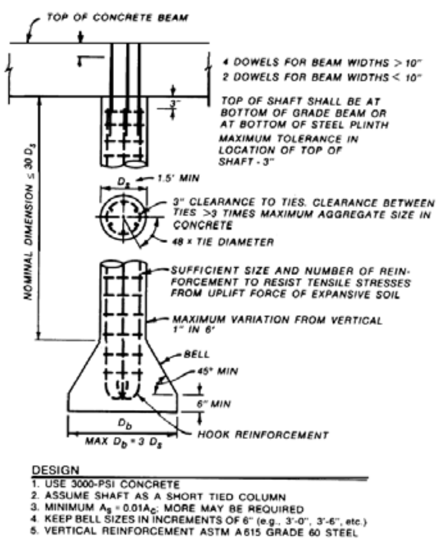
- Best performing foundation system for expansive clay soil. Generally preferred if expected differential movement exceeds 4 inches.
- Slab is isolated from expansive soil.
- Under-slab void can be formed conventionally or using void forms.

Elevated Structural Slab on Deep Piers

- Full load of structure is carried on piers.
- Slab spans structurally between piers.
- Piers bear below the active zone.
- Piers must be designed to resist uplift from skin friction caused by swelling soil (use surcharge where possible).

Void Form System



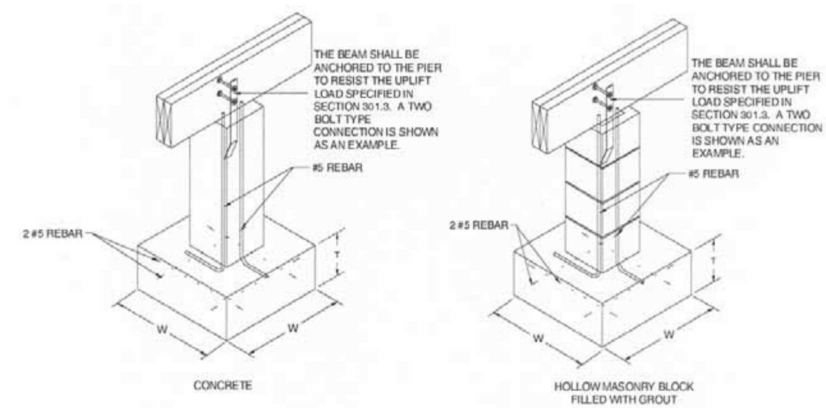


Typical Deep Pier Detail

Elevated Structural Slab Pier and Beam

- Framed floor supported by piers on shallow footings. Perimeter is sometimes supported by perimeter strip footing.
- This system has little resistance to soil movement but is easily adjusted.
- This system is not commonly used today, as it is more expensive than a concrete slab-on-grade.

Typical Pier and Beam Detail



Design of Structural Foundation - General

- Superstructure is designed using conventional reinforced concrete, steel and/or wood design methods.
- Concentrate loads on supports to increase surcharge pressure.
- Maintain constant pressure under piers/footing to minimize differential consolidation.

Stiffened Slab-on-Grade with Piers

- Primarily used in areas where the expected mode of movement is settlement.
- Slab is constructed as stiffened slab-on-grade for purposes of heave.
- System must be designed to act as structural supported slab between piers (soil settlement removes soil support).

Stiffened Slab-on-Grade with Piers

- If the piers and slab are not designed to resist uplift, connection to piers must be sleeved.
- Commonly designed without consideration for loss of structural support from soil settlement. This is a violation of good engineering design principles and requirements of IBC/IRC.

Stiffened Slab-on-Grade (Waffle Slab)

- Widely used for light structures without concentrated superstructure loads (columns).
- Commonly used in residences, schools, and commercial facilities.
- No size limitation, but effective stiffness increases with decreasing size of slab.

Stiffened Slab-on-Grade

- A stiffened slab-on-grade does not prevent movement, but limits curvature to control structural distress.
- Expected differential movement, not total soil movement, controls design.
- Two types of stiffened SOG's:
  - Thin stiffened slab (waffle slab)
  - Thick slab w/perimeter grade beam.

Stiffened Slab-on-Grade

- US practice mainly uses thin stiffened slab.
- Thick slabs with perimeter grade beams are commonly used in Britain, Australia and California.
- Generally useful for predicted differential movement of up to 4 inches.

General Design of Stiffened SOG

- Three rational design methods exist (all incorporated into IBC):
  - BRAB
  - WRI/CRSI
  - PTI
- Methods provide maximum moment, shear and deflection.
- Design is conventional based on provided design forces.

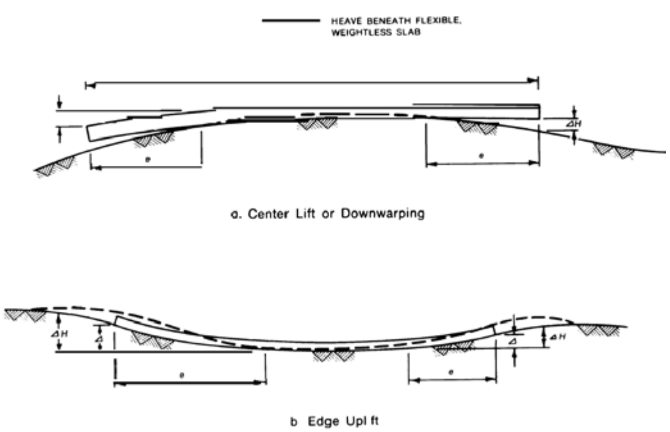
General Design of Stiffened SOG

- Allowable curvature is based on superstructure system.
- Use select fill as needed to reduce PVR to acceptable limits.

Uniform Thickness SOG

- Uniform thickness slabs are designed using the same procedures as a stiffened slab.
- The perimeter of the slab is normally turned down to form a perimeter grade beam.
- Turned down beam keys slab into soil and can result in restraint to shrinkage and associated cracking.

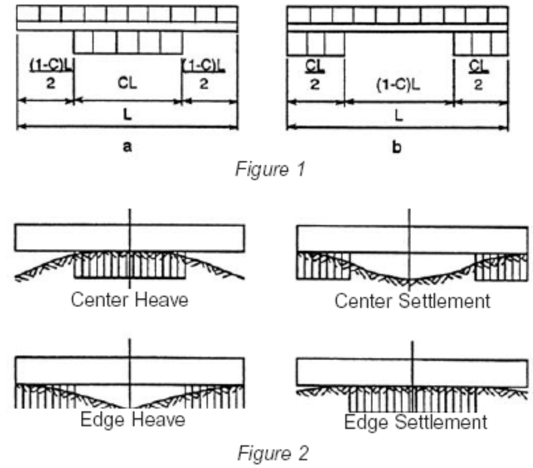
Design Modes



BRAB Design Method

- Original rational design method for slabs-on-grade for expansive soil.
- Developed by the Building Research Advisory Board in 1968.
- Developed primarily for residential structures.
- Based on semi-empirical support conditions.

BRAB Support Conditions



BRAB Support Index

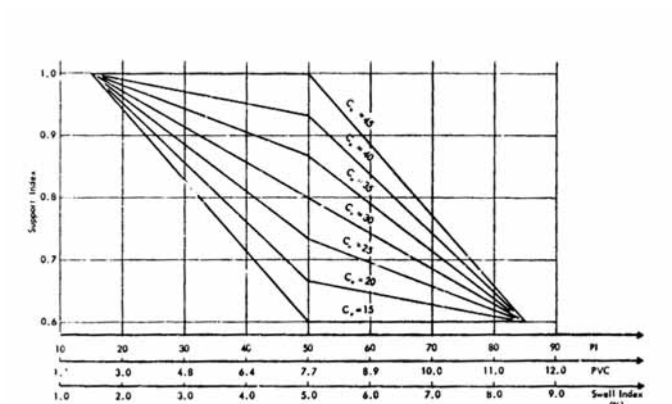
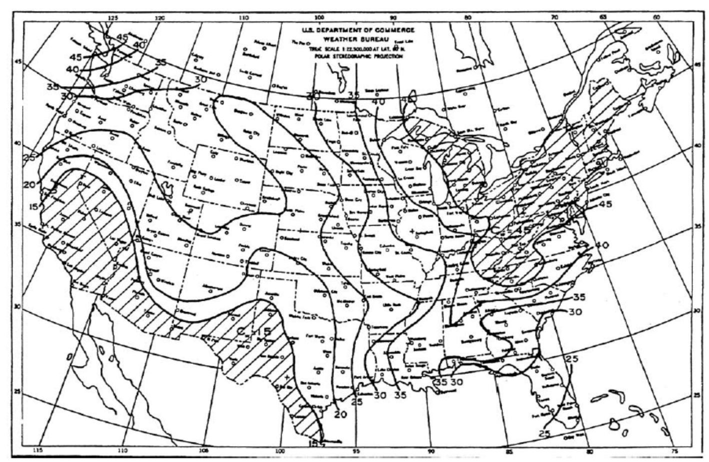


FIG. 6 Support Index (C) Based on Criterion for Soil Sensitivity and Climatic Rating (C_w)

BRAB – Climatic Rating



Climatic Ratings (C_W) for Continental United States

BRAB - Design Forces

$$M_{\max} = \frac{\omega L^2 L'(1-C)}{8}$$

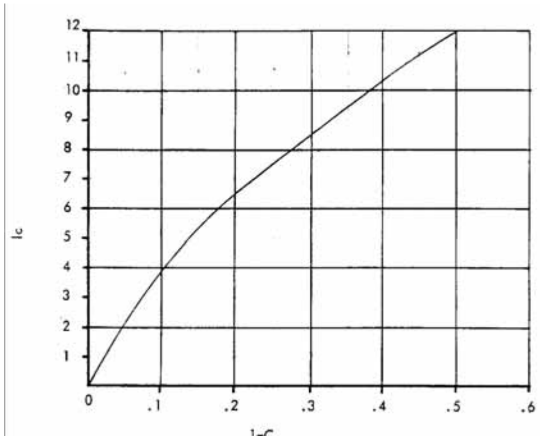
$$V_{\max} = \frac{\omega L L'(1-C)}{2}$$

$$\Delta_{\max} = \frac{\omega L^4 L'(1-C)}{96\,EI}$$

WRI/CRSI Design Method

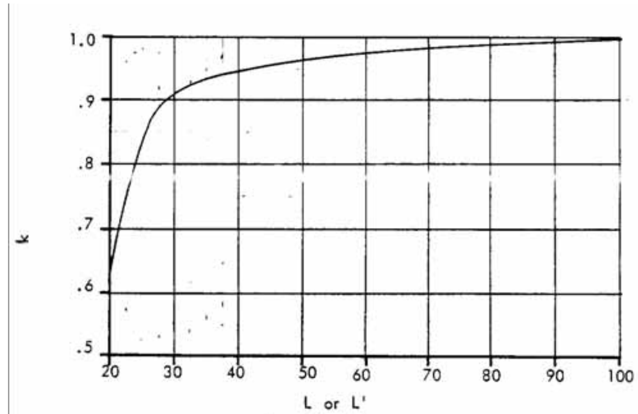
- Empirical modification of the BRAB method.
- Essentially the same method, modified to provide a lower design cantilever.
- Design method is part of IBC, but is not a peer reviewed or consensus standard.

WRI/CRSI Support Index



(1-C) vs. Cantilever Length (lc)

WRI/CRSI Support Index



L or L' vs k
Figure 13

WRI/CRSI - Design Forces

$$M = \frac{wL' (l_c)^2}{2}$$

$$\Delta = \frac{w (l_c)^4 L'}{4E_c I}$$

$$V = wL' l_c$$

PTI Design Method

- Design manual for post-tensioned slabs-on-grade. With modification, can also be used for conventionally reinforced foundations.
- Based on regression analysis of the results of finite element models of slab-on-grade on elastic foundation.

Typical PTI Design Equations

- Method is practically implemented via software application.

$$M_L = \frac{1}{727}\left[L^{0.013} \cdot S^{0.306} \cdot h^{0.688} \cdot P^{0.534} \cdot y_m^{0.193}\right] \cdot \left[B \cdot e_m^{1.238} + C\right]$$

$$V_L = \frac{L^{0.07} \cdot h^{0.4} \cdot P^{0.03} \cdot e_m^{0.16} \cdot y_m^{0.67}}{3 \cdot S^{0.15}}$$

PTI Design Method

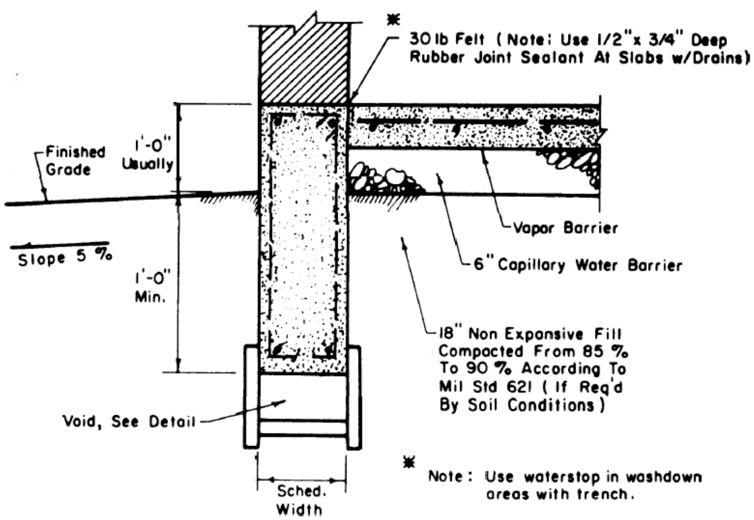
- Primary design values are y_m and e_m.
- These values represent the expected differential movement and the expected distance over which the movement will occur.
- Determination of these values is also the most controversial part of the design method

PTI Design Method

- Stiffened slabs-on-grade suffer from restraint to shortening (RTS).
- Mechanical interlock between grade beams and soil can prevent slab shortening and development of compressive stress in slab.

Compliant Foundation

- Most common system for medium and large commercial buildings with column loads
- Typically uses a perimeter grade beam on piers with an unstiffened interior slab-on-grade.
- Perimeter grade beams and piers must be designed to resist heave.



Compliant Foundation

- The interior slab will move.
- Movement is minimized by the use of select fill, good drainage and proper landscaping.
- Do not tie floating slab to structural elements (grade beams or interior columns). Provide isolation joints.

Compliant Foundation

- Do not tie interior walls to compliant slab at both the base of wall and to the structural frame.
- Do not tie suspended ceiling to roof frame and walls.

Mat/Raft Foundation
(Large multi-story buildings)

- Weight of building is equal to or greater than expected swell pressure.
- Typically 3 feet or more thick, with continuous two-way reinforcing top and bottom. Typically contains about 1% total steel.
- Placed near or below the depth of seasonal moisture variation.

Deep Footings

- Design intent for deep spread footings is similar to mat foundations.
- Used when weight of building is equal to or greater than expected swell pressure.
- Typically placed near or below the depth of seasonal moisture variation.

Basements

- Underground walls must be designed for lateral pressure from swelling soils.
- Consider use of non-expansive backfill.
- Seal surface of backfill to prevent entry of surface water.
- Consider installation of footing drains with high water tables.

Basements

- Basement walls are normally designed as deep beams supported on piers.
- Basement floor should use floating slab that is not connected to the walls. No columns should bear on the floor slab.

Minimizing Shrinkage Cracking

- Limit water-to-cement (w/c) ratio.
- Minimize cement content.
- Require curing compounds or wet curing.
- Use hot-weather concreting practices.
- Double vapor barrier in critical applicaitons.
- Smooth sub-grade.

Bonded Slab Reinforcement and Slab Cracking

- Design of bonded slab reinforcement should consider requirements of the owner and architect.
- Do not use temperature and shrinkage steel requirements from ACI-318 for slabs-on-grade:

  The provisions of this section are intended for structural slabs only; they are not intended for soil supported slabs-on-grade.

ACI 224R-01 – Control of Cracking in Concrete Structures

The minimum amount and spacing of reinforcement to be used in structural floors, roof slabs and walls for control of temperature and shrinkage cracking is given in ACI 318 or ACI 350R. The minimum reinforcing percentage, which is between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracking to a more acceptable level, the percentage requirements needs to exceed about 0.60%.

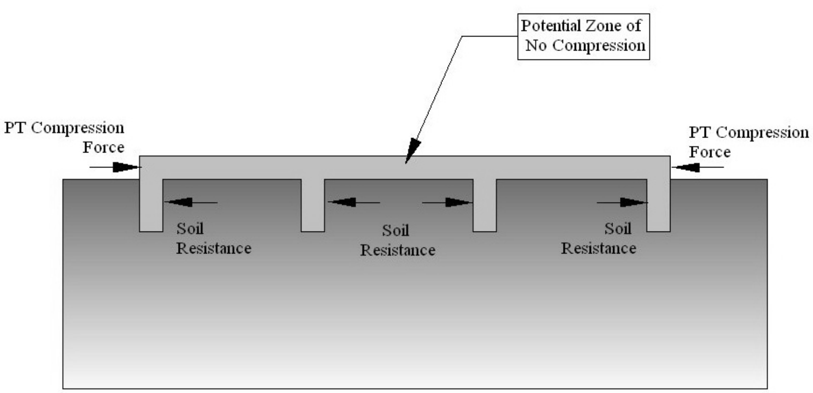
Control Joints (ACI 224.3R-95)

- Use of control joints in slab in order to minimize shrinkage cracking.
- Panel aspect ratio should not exceed 1.25 to 1.5.
- Joints should be spaced at 24 to 36 times the slab thickness.
- Place mid-way between grade beams.
- Additional slab steel may be required if no control joints are installed.

Restraint to Shortening (RTS)

- RTS affects post-tensioned slabs only.
- Subgrade friction or keying action between foundation and soil can prevent development of pre-compression in central potion of slab.
- Lack of precompression allows formation of shrinkage cracks in non-compressed areas.

Restraint to Shortening (RTS) Cracking



Sand Bed

- Sand bed is commonly installed under the slab to allow for leveling prior to pouring of concrete.
- Sand bed can allow movement of moisture under slab.
- Leveling bed is not needed. Sand bed is already prohibited by Walter P Moore standard specifications under pavements.

Select Fill

- Select fill is added to reduce the potential vertical heave of the soil.
- Fill must be fully compacted, non-swelling and impermeable. Permeable fill will allow water to move to the underlying expansive soils.
- Exercise caution if depth of select fill is not constant.

Select Fill

- Amount of select fill should be deferred to geotechnical engineer.

"Install select fill as required by geotechnical engineer to reduce potential vertical movement to 1 inch."

- Incorporate the geotechnical report into construction documents (include in project manual).

Typical Select Fill Properties

- 10 < PI < 20.
- LL < 40.
- Clay to sandy clay. Minimal sand or silt.
- Refer to geotechnical report for specific recommendations.
- Require periodic testing of select fill properties during construction, similar to compaction testing.

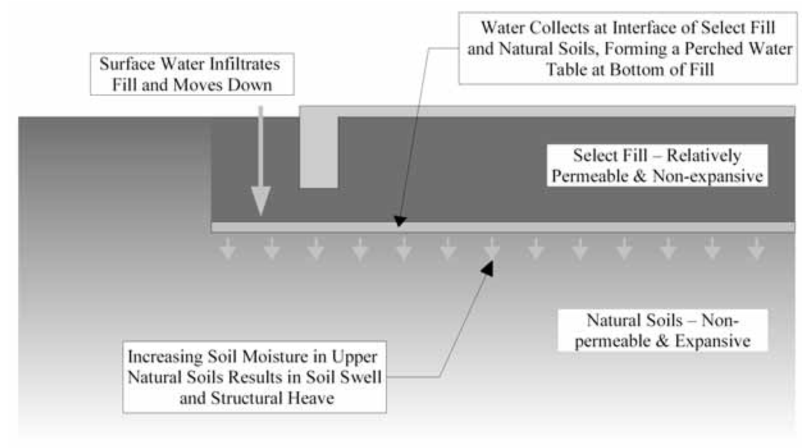
Select Fill - Surcharge or Replacement

- PVR calculations considering effect of select fill may assume fill to be placed on top of existing grade or as replacement for existing soil.
- PVR calculation will vary significantly depending on which assumption is made.

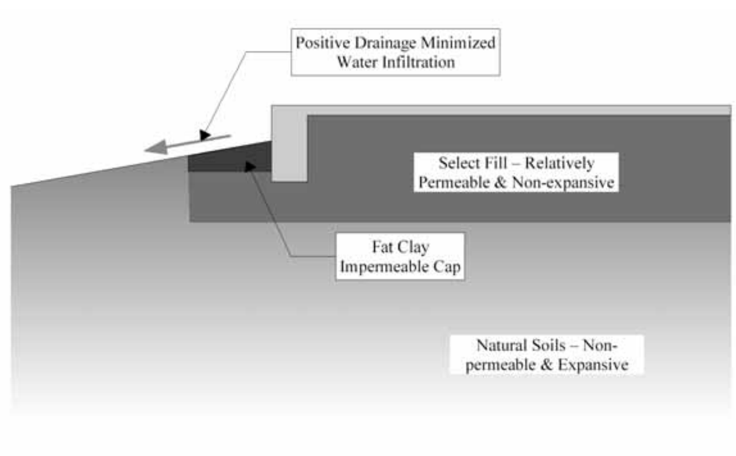
Select Fill – The Bathtub Effect

- The permeability of select fill can be significantly lower than that of the natural soils.
- This can lead to infiltration of water into and through the select fill, causing an increase in moisture of the underlying natural soils.

The Problem



The Solution



Excavation

- Cut areas reduce overburden pressure and may contribute to swell.
- Consider use of native soils for fill to reduce differential movement between cut and fill areas.
- Do not allow excavations to dry out or pond water during construction Consider use of sealing compounds.

Maintain Soil Moisture

Since shrink-swell is a result of <u>changes</u> in moisture content, all movement can be prevented by maintaining constant moisture content. Factors to consider include:

- Drainage
- Landscaping
- Irrigation
- Moisture barriers

Drainage

- Drainage must be adequate to move water away from the foundation.
- Drainage can be provided by surface grading or subsurface drains.
- Generally, a 5% slope within 10 feet of the foundation perimeter is required by code.
- Drainage must be coordinated among design team.

Drainage – 2000 IBC Code Requirements

1803.3 Site Grading. The ground immediately adjacent to the foundation shall be sloped away from the building at a slope of not less than one unit vertical in 20 units horizontal (5-percent slope) for a minimum distance of 10 feet measured perpendicular to the wall or an approved alternate method of diverting water away from the foundation shall be used.

Drainage – 2000 IBC Code Requirements

1805.3.4 Foundation elevations. On graded sites, the top of any exterior foundation shall extend above the elevation of the street gutter at point of discharge if the inlet of an approved drainage device a minimum of 12 inches plus 2 percent.

Drainage

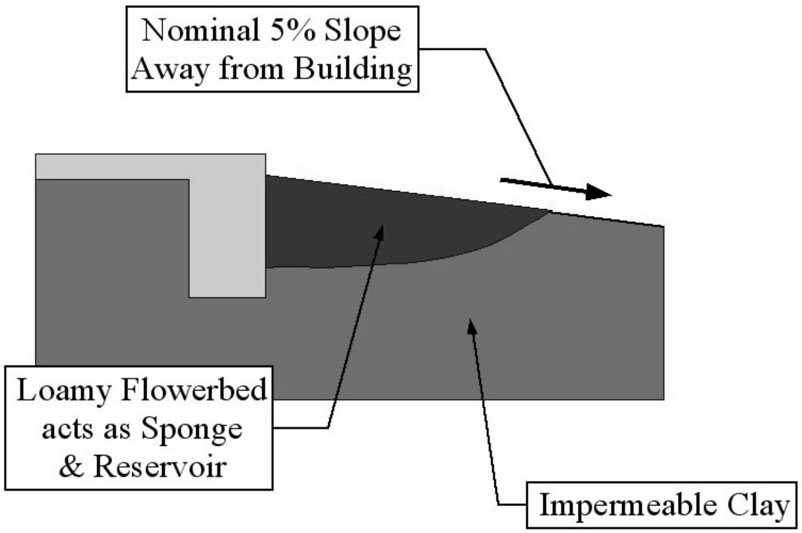
- Set finish floor high enough to allow proper drainage and landscaping bed construction
- Fine grading adjacent to structure must be done with impervious fill (fat clay)
- Install gutters and downspouts.
- Improper surface drainage has been blamed for mold ($$$).

Landscaping

- Generally, trees should be kept at 1.0 to 1.5 tree heights away from the building.
- Root barriers can be used to mitigate the effects of new trees.
- Buildings constructed near existing trees can experience problems if the tree dies.

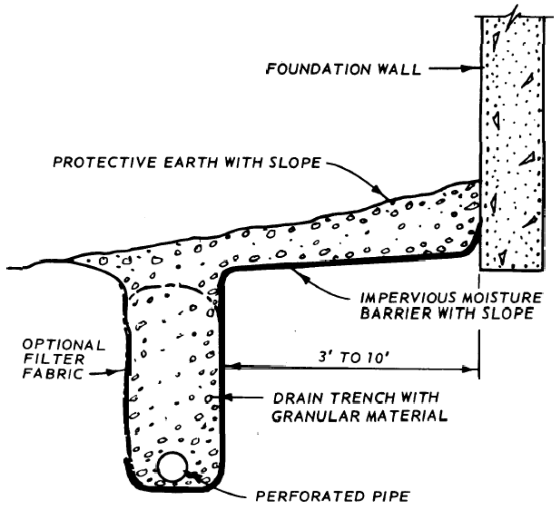
Landscaping

- Shrub beds and flowerbeds can result in heave if watered excessively.
- Shrub beds and flower beds will affect moisture balance due to irrigation.
- Installation of shrub beds and flowerbeds must not affect the drainage plane away from the structure.



Moisture Barriers

- Promotes uniform soil moisture by slowing seasonal moisture loss and gain.
- Moisture barriers slow but do not stop moisture movement.
- Can be horizontal or vertical.
- Efficacy of moisture barriers has been questioned.



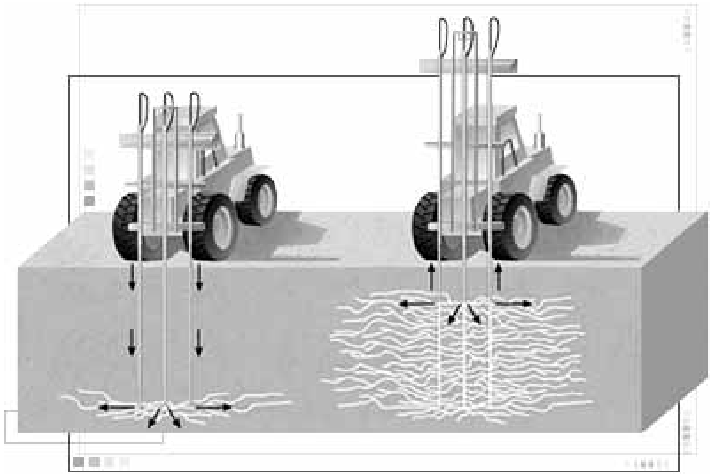
Concrete Flat work

- Adjacent concrete flat work (parking lots, driveways and sidewalks) can act as a vertical moisture barriers.
- Moisture barriers alter the soil moisture balance under the slab.
- Flat work should be installed with at least a 1% slope away from the structure.

Soil Treatment

- Various chemical compounds can be injected into clay soil in order to reduce activity of the clay particles and modify mechanical properties.
- These treatments have proved successful in laboratory testing.
- Low permeability of clay makes practical field application difficult.

Soil Treatment



Soil Treatment - Lime

- Lime or lime - fly ash can be pressure injected or mechanically mixed.
- Lime has three effects:
  - Reduces permeability
  - Replaces sodium ions with calcium ions reducing affinity for water
  - Increases strength due to pozzolanic reaction (this effect increases with use of fly ash).

Soil Treatment

- Potassium injection replaces sodium ions with potassium ions.
- Injection chemicals may be combined with surfactants to increases penetration (ammonium lignosulphonate).
- Various proprietary systems using organic chemicals are also on the market.

Presaturation

- Presaturation refers to increasing water content of the soil prior to construction so that it is fully swelled.
- Also referred to as ponding.
- Accomplished by ponding or water injection.
- Ponding is ineffective because of the impermeability of the clay.

Presaturation

- Water injection has worked effectively to presaturate soil.
- Drying of soil after construction can eventually result in settlement.
- Presaturation is most effective in semi-arid areas where soil is less likely to dry.

Utility Trenches

- Utility trenches with poorly compacted or improper fill can act as a conduit for water to move under structure.
- Use clay plug at exit of utility trench from under slab.
- Use compacted select fill in other locations.

Utility Penetrations

- Consider sleeved connections for utility lines (water, gas and sewer) entering into floating structure.
- If buried lines are sleeved, this will allow future adjustment of foundation without damaging utilities.
- Sleeved connections are most important for slab-on-grade with piers.

Owner Maintenance

Owners and property managers must be informed of maintenance requirements:

- Drainage including gutters.
- Vegetation (planting or removal of trees).
- Irrigation.
- Flower/shrub beds.

Foundation on Slopes

- Shrink-swell cycles on sloping terrain can lead to creep of the foundation downslope.
- Structures built on a cut-and-fill bench will experience differential lateral movement.
- Consider deep foundations.

Construction Considerations

- Test select fill for suitability of use on a regular basis, similar to testing for compaction.
- Require certification of grading and drainage by RLS. Specify tolerances for grading adjacent to building.
- Require inspection of utility trench backfill for compaction and suitability.