## Foundations on Expansive Clay Soil

# Part 3 - Investigation of Failed Foundations

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# Investigation of Foundation Failure

- Is structure moving?
- Where is movement occurring?
- Is structure experiencing heave, settlement or a combination?
- Is movement excessive?
- Why is movement occurring?
- What (if any) remedial measures are required?




# Investigation Steps

- Data Collection
- Testing
- Interpretation
- Recommendations




# Step 1 - Data Collection

# Review of Construction Documents

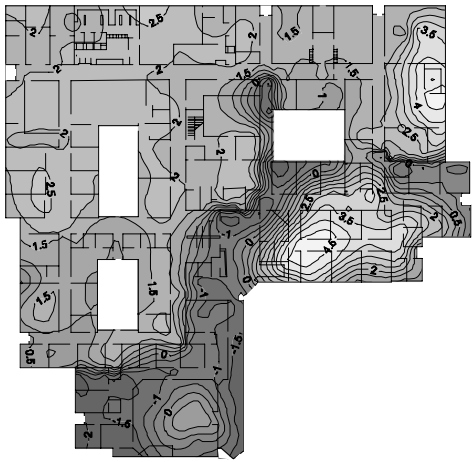
- Civil, structural and landscaping plans
- Original geotechnical report
- Compaction reports
- Fill testing
- Time of construction
- Reports by other consultants




# Field Investigation

- Elevation survey of slab
- Distress survey (interior and exterior)
- Leak testing of plumbing lines
- As-built structural documentation
- Geotechnical investigation
- Topographic/drainage survey
- Vegetation survey
- Owner interview



# Elevation Survey




# Elevation Survey

- Most important investigation tool.
- Normally done with digital water level.
- Adjust for thickness of floor coverings.
- Floors are not constructed flat. Differential elevation does not equal differential movement.
- Multiple surveys over time are useful where possible.

# Distress Survey - Interior

- Map locations and type of interior distress.
  - Separation vs. crack
  - Orientation & locations
  - Width & pattern
  - Photos
- Door alignment in frame & adjusted door strikes.
- Previous repairs to structure



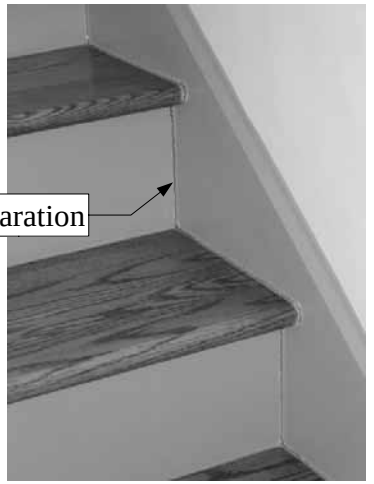

# Finish crack




# Finish Cracks




# Finish Separations



# Door Alignment





# Door Alignment

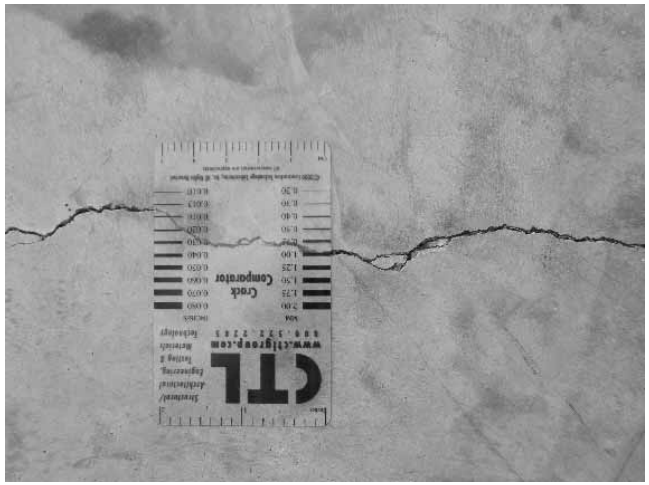



# Prior Repairs to Finishes




# Interior Underpinning

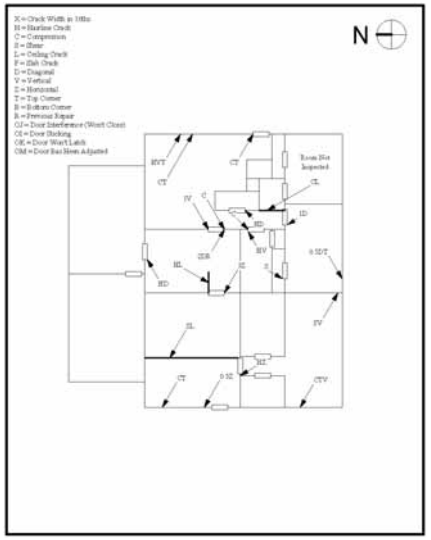
# Slab & Tile Cracks







# Interior Distress Map





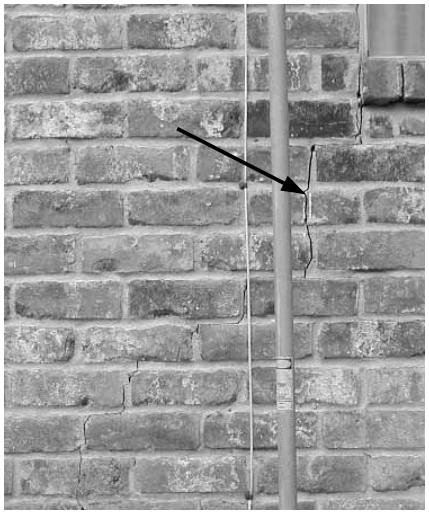


# Distress Survey - Exterior

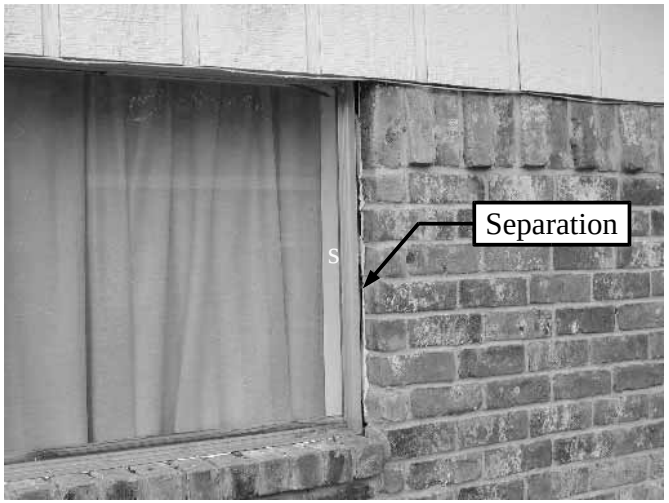
- Map location and type of exterior distress.
  - Crack vs separation
  - Orientation
  - Width & pattern
  - Photos
- Movement in adjacent flat work.
- Age




# Finish Cracks



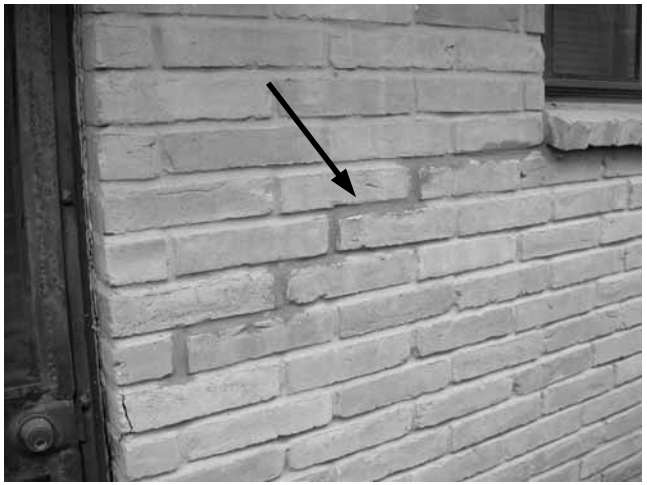
# Finish Separations







# Previous Repairs to Finishes






# Previous Repairs to Finishes



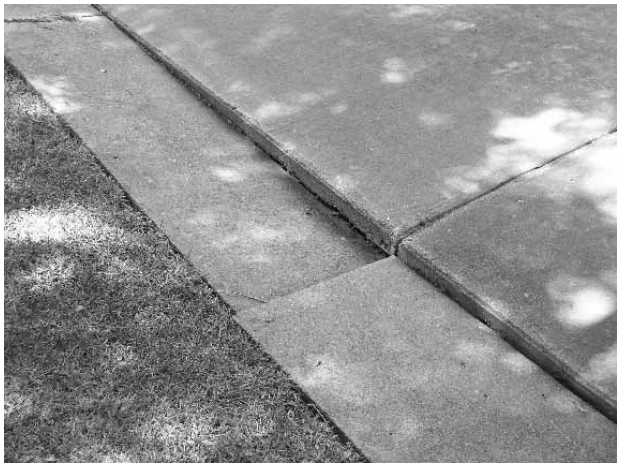

# Differential Movement at Pier Caps

# Movement of Flat Work





# Movement of Flat Work






# Previous Underpinning

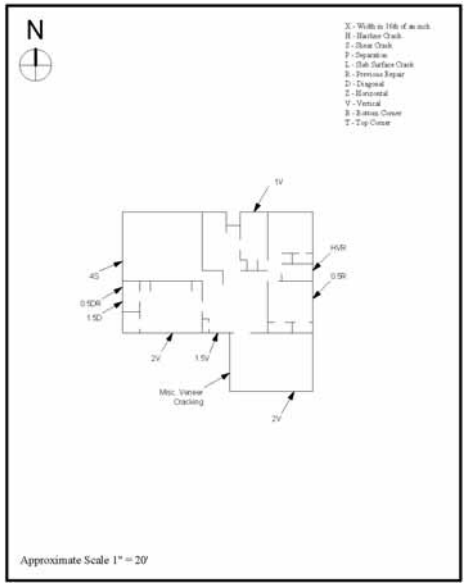



# A/C Condensate Drain

# Cracking of Exposed Slab




# Exterior Distress Map





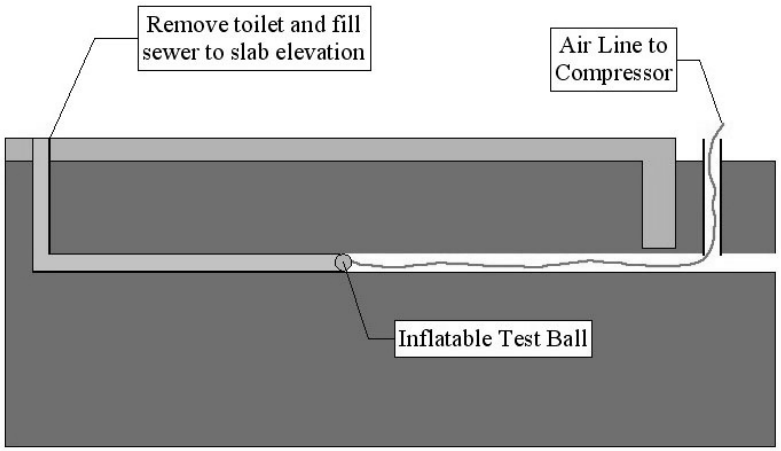


# Sewer Line Leak Testing

- Tested for leaks under hydrostatic pressure using inflatable plugs to isolate lines. Water level is observed from toilet or other fixture.
- Leakage under operational conditions can be determined using flow test.
- Video cameras can be used to examine condition of sewer lines and geometry of leaks.




# Hydrostatic Leak Testing



# Leak Test Limitations

- Systems which leak under hydrostatic pressure may not leak in operation.
- Testing cannot reliably locate multiple leaks in the same branch. Some areas cannot be tested due to lack of access.
- Flow test results may not match hydrostatic test results.

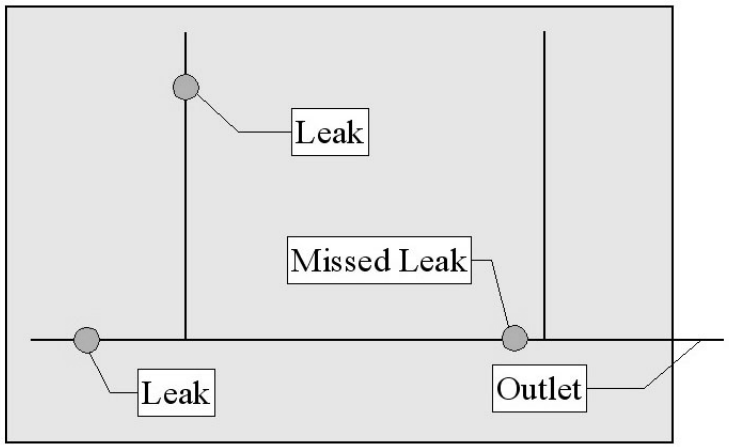



# Leak Test Limitations

- Small leaks may not be detected in flow testing.
- Flow testing may not replicate actual flow conditions during operation.
- Soil saturation from hydrostatic test may affect flow test results.




# Multiple Leaks







# As-Built Construction

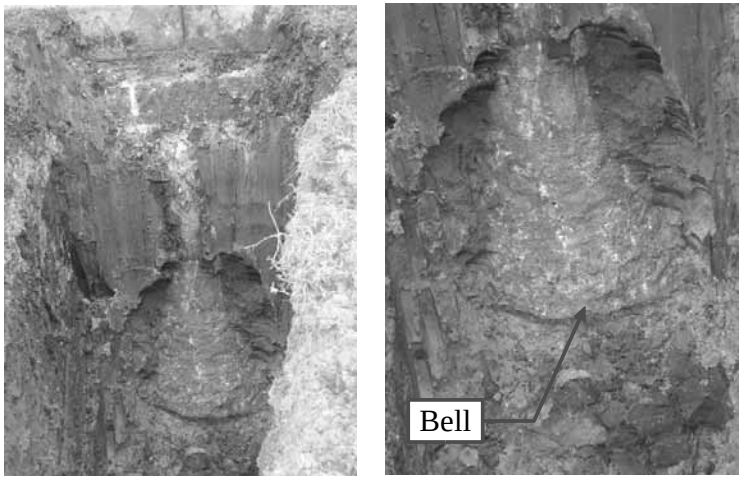
- Check for piers using soil probe. If piers are present, excavate to determine if piers are original or remedial.
- Check pier depth and bell size.
- Check for voids and void boxes under grade beams and slab.
- Check depth of grade beam.
- Locations of expansion joints.

# As-Built Construction

- Concrete compressive strength
- Slab reinforcing (size, spacing and depth).



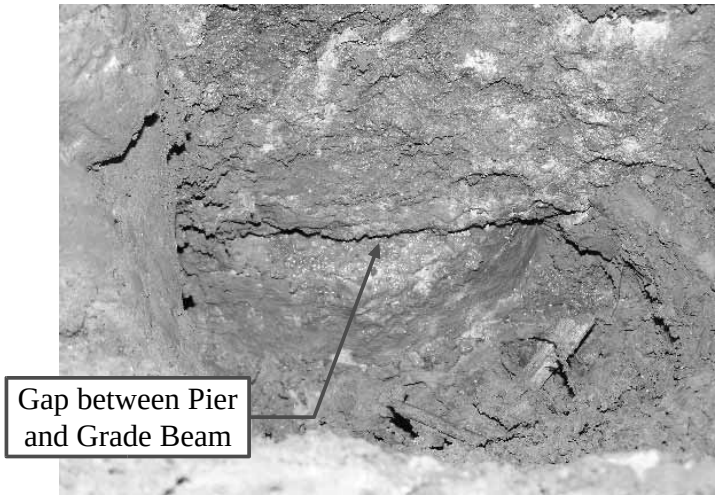

# Pier Excavation







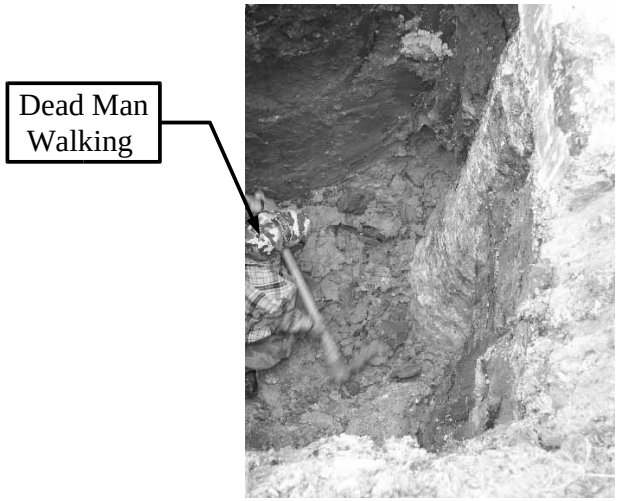
# Gap at Pier Cap







# The Wrong Way



# Test Pits

Test pits dug along grade beams can reveal significant information:

- Depth of grade beam.
- Presence/absence of void boxes.
- Voids grade beams.
- Presence of piers.
- Separation between pier and grade beam.
- Water under slab.
- Type of fill at perimeter (clay vs loam).




# Geotechnical Investigation

- Soil moisture profile (water content, liquidity index and/or suction).
- Soil classification.
- Depth and type of fill.
- Swell potential/plasticity index.
- Depth to water table.
- Interior, adjacent and remote (baseline) borings.




# Geotechnical Investigation

- Design data
  - Allowable bearing pressure for piers
  - Potential vertical rise
  - Expected consolidation under design loads.




# Petrography

- Testing conducted on cores recovered in interior geotechnical borings.
- Shrinkage vs stress crack
- Plastic shrinkage cracking
- w/c ratio

# Test Pits

- Depth of grade beams.
- Presence of voids or void boxed under grade beams.
- Water under foundation.
- Presence of piers.
- Separations between piers and grade beams.




# Drainage Survey

- Micro slope adjacent to building.
- Locations of downspouts and splash blocks.
- Drainage of flower and shrub beds, including drainage plane.
- Areas of negative drainage.



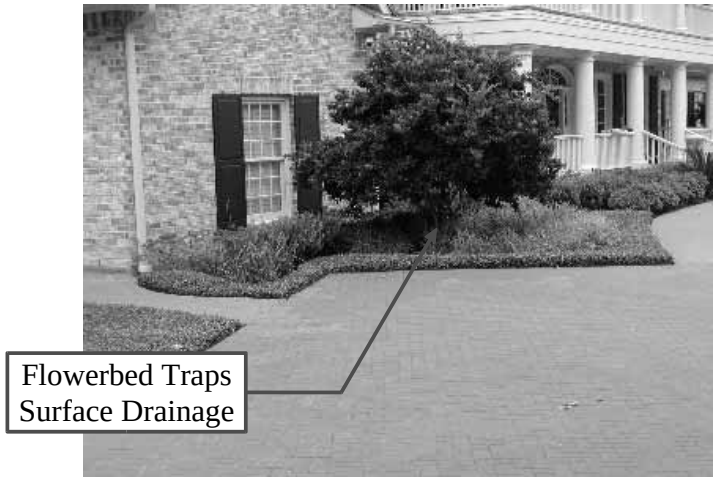

# Improper Surface Drains





# Trapped Drainage

# Trapped Drainage



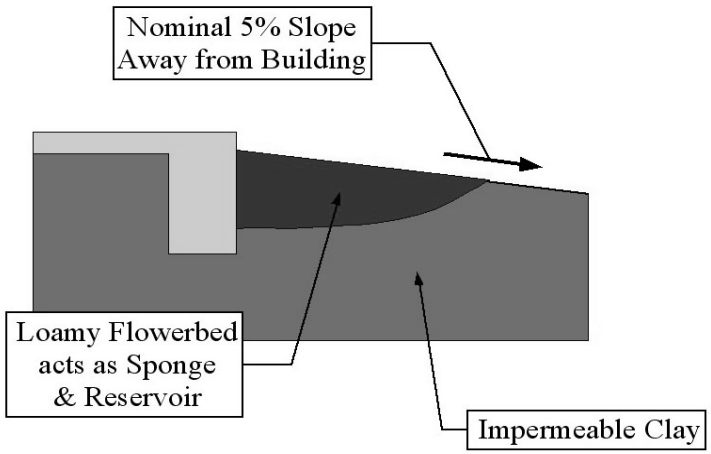




# Pool MEP




# Perched Drainage Plane







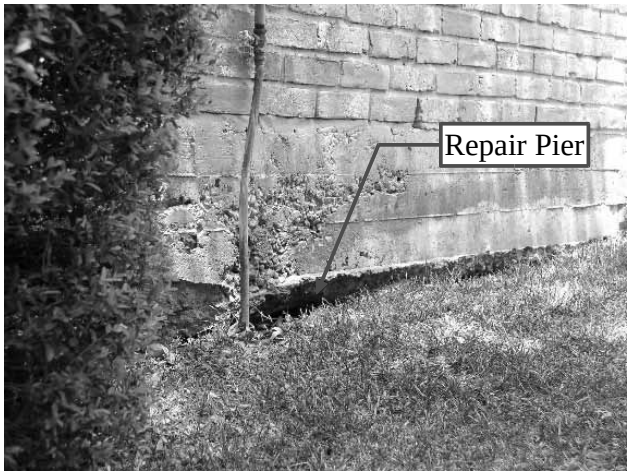
# Landscaping Survey

- Location, type and sizes of large trees.
- Extent of tree canopies.
- Gaps between soil and grade beams.
- Locations of shrub and flower beds.
- Locations of sprinkler heads.
- Location of concrete and impermeable flatwork.

# Soil Gaps at Grade Beam




# Gap Under Grade Beam







# Dessicated Soil




# Dessicated Soil

# Trees




# Owner Interview

- History of foundation movement.
- Timing of distress.
- Sequence of distress.
- Cyclical/seasonal movement of cracks.
- Plumbing problems.
- Irrigation practices.

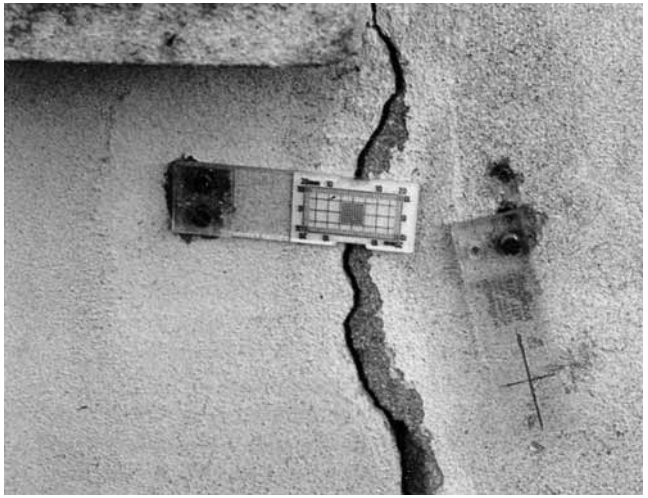



# Structural Monitoring

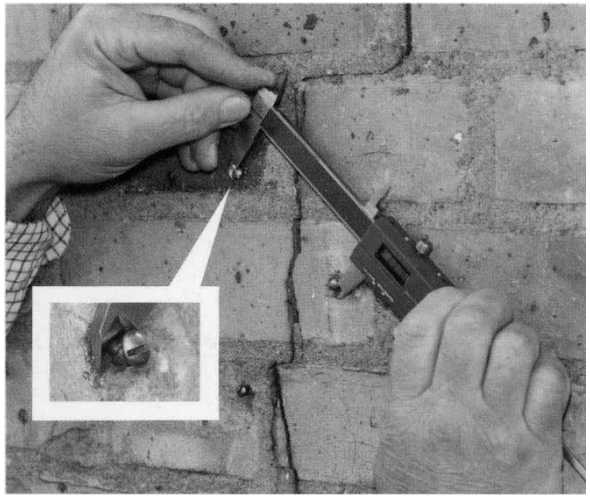
- Monitoring over time can help to determine cause of distress and appropriate repair methodology.
- Crack widths can be monitored with crack gage.
- Ensure elevation measurements are taken at the same locations.
- Use permanent external benchmark if possible




# Crack Gage



# Crack Measurement






# Step 2 - Data Analysis

- The information gathered in the data collection phase must tell a consistent story.
- No single source of data can be used to determine magnitude, mode or cause of movement.

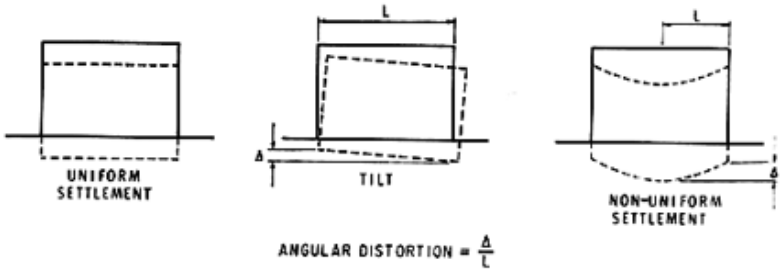



# Failure Patterns

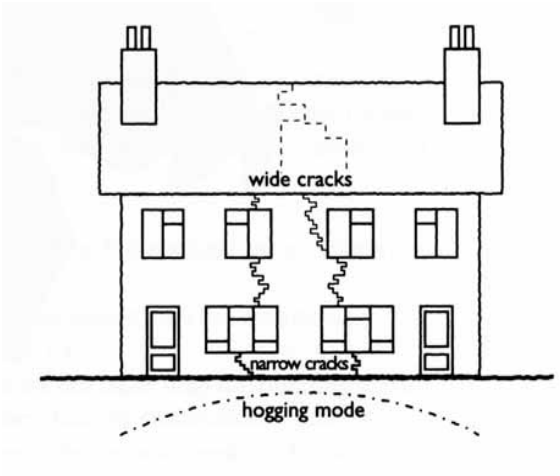
- Center heave (also called doming, hogging or center lift).
- Edge settlement
- Center settlement
- Edge heave (also called edge lift)
- Slope creep (typically on slopes greater than 5%)




# Types of Movement



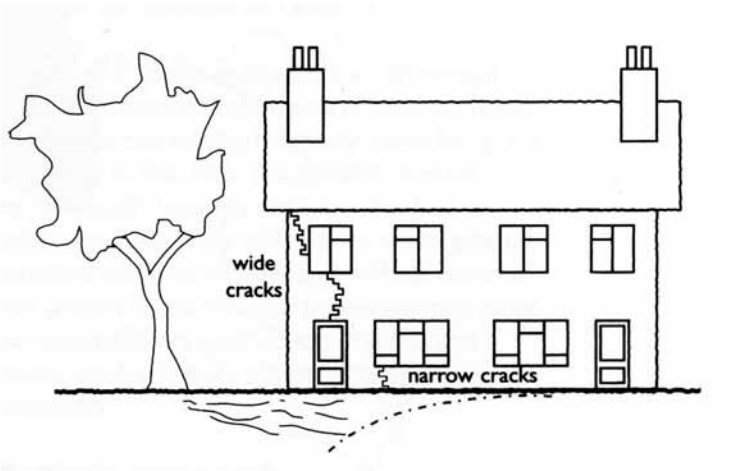
# Center Heave/Edge Settlement







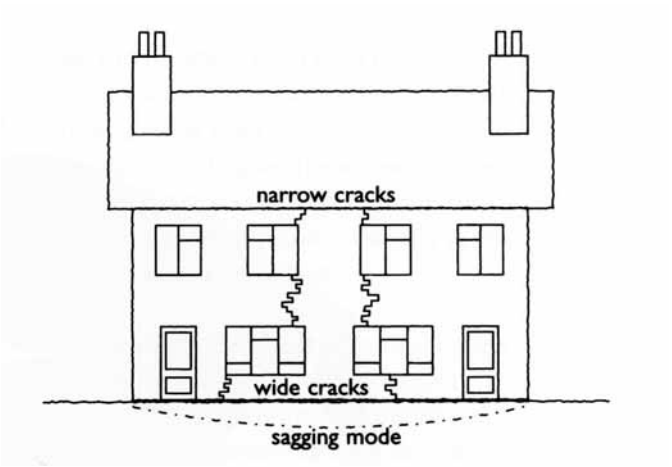
# Edge Settlement







# Edge Heave/Center Settlement







# Causes of Foundation Movement

- Variation in climate.
- Change in depth of water table.
- Removal of trees.
- Planting of trees
- Inadequate drainage.
- Seepage along construction interfaces.
- Irrigation

## Causes of Foundation Movement

- Leaking utility lines
- Drying of soil below heated rooms
- Seepage of moisture along utility trenches
- Poor compaction of fill.
- Improper fill material.




## Interpretation of Differential Elevation Survey

- Slabs are not poured perfectly level.
- Is differential elevation movement of as-built condition?
- ACI tolerance for slab on grade is ±¾" from nominal elevation.
- F-number gives allowable tilt. For bull-floated slab, maximimum local tilt ranges from 0.9% to 1.0%.




## Geotechnical Interpretation

- Existing vs pre-construction MC and LI .
- MC and LI at high and low areas.
- Existing vs pre-construction bearing strength.
- MC and LI at leak and remote.
- MC and LI at interior and perimeter.




## Interpretation of Field Data

- Are voids

# Design Review

- Soil shrink-swell or soil failure under loads?
- Design analysis vs. failure analysis.
- Service loads on piers vs. allowable loads.
- Bearing pressure under grade beams.
- Bearing pressure under full foundation area.



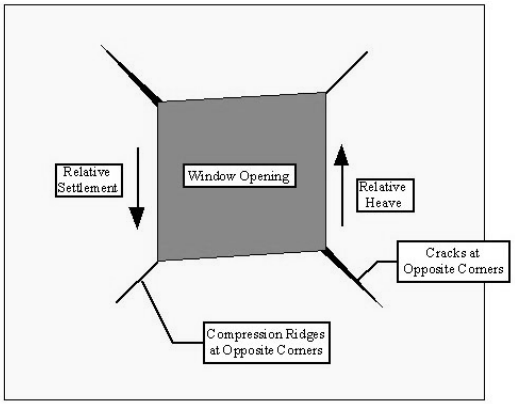

# Analysis of Cracks

- Not all cracks are caused by foundation movement.
  - Differential Movement (shear & flexural stress).
  - Thermal cracking (axial stress).
  - Moisture changes (axial stress).
- Rigid finishes are more susceptible to movement.
- Distress must be consistent with differential movement.




# Shear Cracks due to Differential Movement

- Diagonal cracks in walls are generally due to differential movement.
- Diagonal cracks form at location of maximum principle stress (tension).
- Vertical cracks in walls are generally due to thermal movement..
- Cracks due to expansive soil move generally show cyclical movement to some extent.
- Direction of diagonal crack can show direction of relative motion but not direction of absolute motion.







# Shear Cracks due to Differential Movement

# Flexural Cracks due to Differential Movement

- Flexure of the slab can result in vertically oriented cracking of finishes.
- These cracks will be tapered (wider at the top or bottom) depending on the mode of movement (center lift or edge lift).




# Thermal Cracking

- Can be mistaken for cracking caused by differential movement.
- Thermal movement in masonry (Brick and CMU) results in uniform width vertical cracks due to axial stresses.
- Cracks tend to occur at openings and changes in wall alignment.
- Absence of expansion joints will increase probability of thermal cracks.




# Thermal Cracking Rates

**( No Differential Movement)**

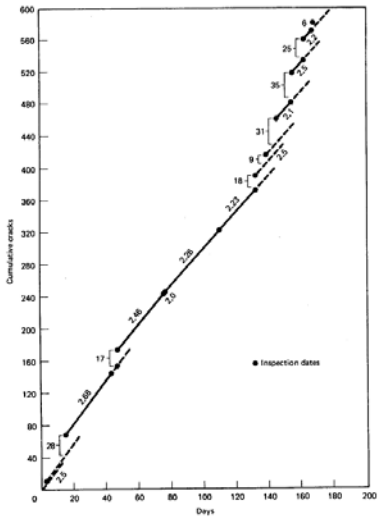



Figure 13-2 Cracking rates for masonry structures at Mercury, Nevada. Dots represent inspection dates. (From Wall, 1956.)




# Thermal Crack

# Thermal Crack




# Thermal Crack




# General Analysis of Cracks

- All structures have cracks.
- Distress should be worse in area exhibiting movement.
- Direction of relative movement should be consistent with differential elevation survey and cause of movement.




# Cracking of Slab

- Slab cracking without vertical displacement across the crack is rarely a result of differential movement.
- Common causes of slab cracks:
  - Drying shrinkage
  - Plastic shrinkage
  - Restraint to shrinkage
  - Excess w/c ratio
  - Inadequate control joints or slab steel

# Drying Separations

- Separations in wood trim and minor cracking of drywall finishes can be a result of drying of wood framing and/or trim.




# Drying Separations




# Timing of Failure

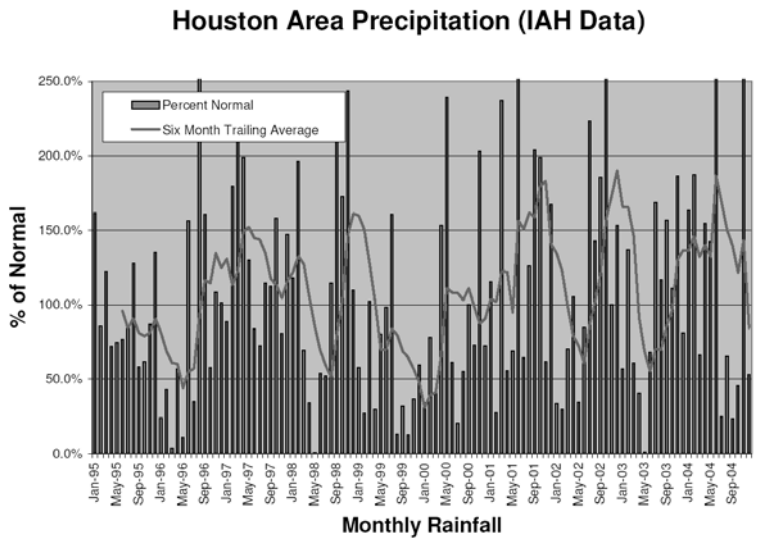
The probability of foundation failure increases with time:

- Vegetation increases in size.
- Probability of experiencing extreme drought or extreme precipitation increases.
- Probability of a failure in utility systems increases (water and sewer lines).




# Climate Review

- A review of the climate records is useful in determining the mode of movement (heave vs. settlement).
- Heave can be associate with periods with above average rainfall and/or below average temperatures.
- Settlement tends to be associated with periods of below average rainfall and above average temperature







# Plumbing Leaks

- Sewer leaks can result in localized heave of the foundation.
- Sewer leaks rarely cause significant movement.
  - Impermeability of clay prevents water migration over wide area.
  - Leaks are not pressurized.
- Leaks can be caused by movement; chicken and egg problem.




# Plumbing Leaks

- Leaks in riser can migrate through sand bed and/or plumbing trench.
- Grade beams act as barrier to migration through sand bed.




# Plumbing Leaks and Settlement

- Plumbing leaks can cause settlement via two mechanisms:
  - Liquification of soil (loss of bearing strength)
  - Erosion.
- These phenomena are rarely seen in practice.

# Need for Repairs

- There is no generally accepted criteria to determine when repairs to a foundation are needed.
- All slab-on-ground structures will experience some movement.
- All slab-on-ground structures will experience some cosmetic cracking of finishes.




# Need for Repairs

- Considerations for recommending repairs include:
  - The owners performance expectations.
  - The owners economic sensitivity (cost of repairs vs. cost of maintenance).
  - Potential for future movement.
  - Life safety (rarely an issue).
  - Effectiveness of repairs.