



Forensic Engineering = Causes of Distress in Concrete

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What is forensic engineering

- *Forensic engineering*—science concerned with the relations between engineering and the law.
- Forensic engineering is a specialized discipline which is a relatively new and unfamiliar field to the public.
- More common definition: *activities related to failure investigation*

- Forensic engineers perform “autopsies” on components and materials or full-sized buildings, bridges, foundations, and other engineered constructed works in order to determine the cause and extent of failure.
- A secondary purpose is to determine methods of repair/rehabilitation/replacement.

What are the qualifications of forensic engineers?

- ☐ Must be expert.
- ☐ Must be ethical
- ☐ Must like to be a detective
 - Must enjoy digging for the truth
 - Must think outside the box

So if you want to be an
engineering Sherlock Holmes,
let's go further.....



How is failure defined?

What is a failure?

- When a facility, structure or material does not perform in the manner it was intended.
- It does not have to collapse or cause people to be injured or killed in order that it be a failure

Failure Examples

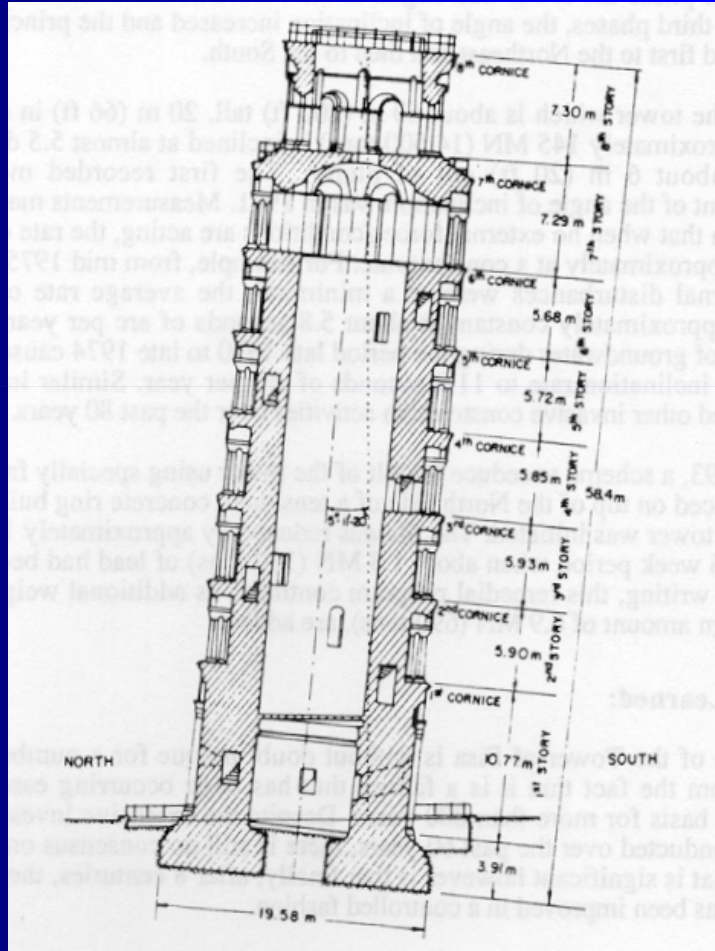
- A floor vibrates when people walk on it.
- One room in the building is not cooled by the air conditioning system
- A parking area ponds water when it rains
- A new concrete floor spalls
- The foundation moves differentially, causing cracking in the interior and exterior wall.

Famous Failures

- Tower of Pisa, Italy
- Tay Bridge, Scotland
- Hyatt Regency Hotel Walkway, Kansas City
- Big Dig (Boston) Tunnel Ceiling Panels

Famous Failures

Tower of Pisa (1173 to present)



- 200 ft (60 m) tall
- Inclined 5.5°
- Extensive efforts to determine cause
- Many efforts to correct problem

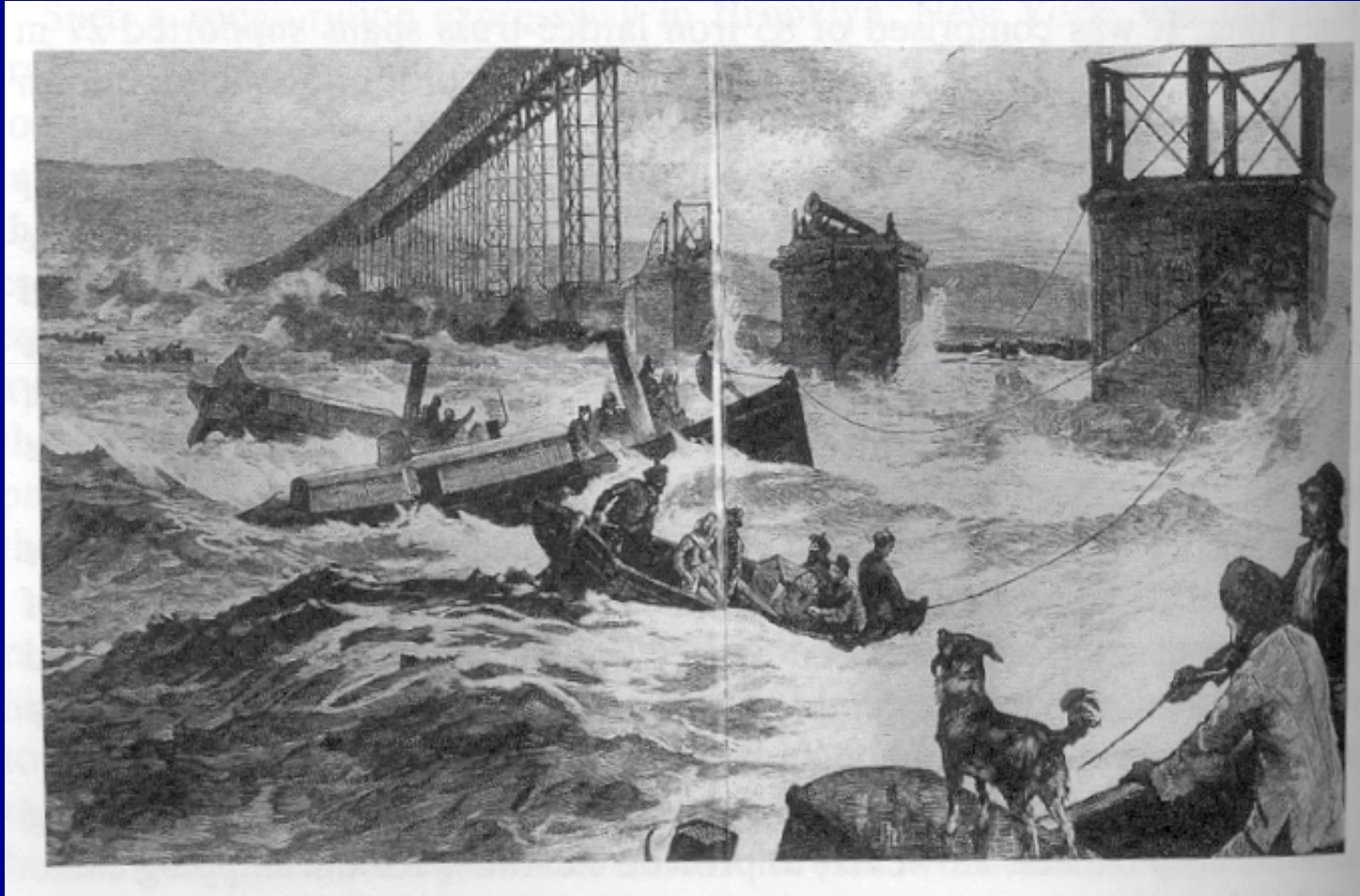
Famous Failures

Tay Bridge, Scotland (1879)

- Completed in 1828
- Length: 10,321 ft. (3146 m)
- 85 simply supported iron lattice-truss spans
- Failure occurred during a major storm
- Train was passing over bridge
- 75 people died
- Cause of failure: improper estimation of wind force in design
 - 10 psf (0.5 kPa) instead of 50 psf (2.5 kPa)

Famous Failures

Tay Bridge, Scotland (1879)



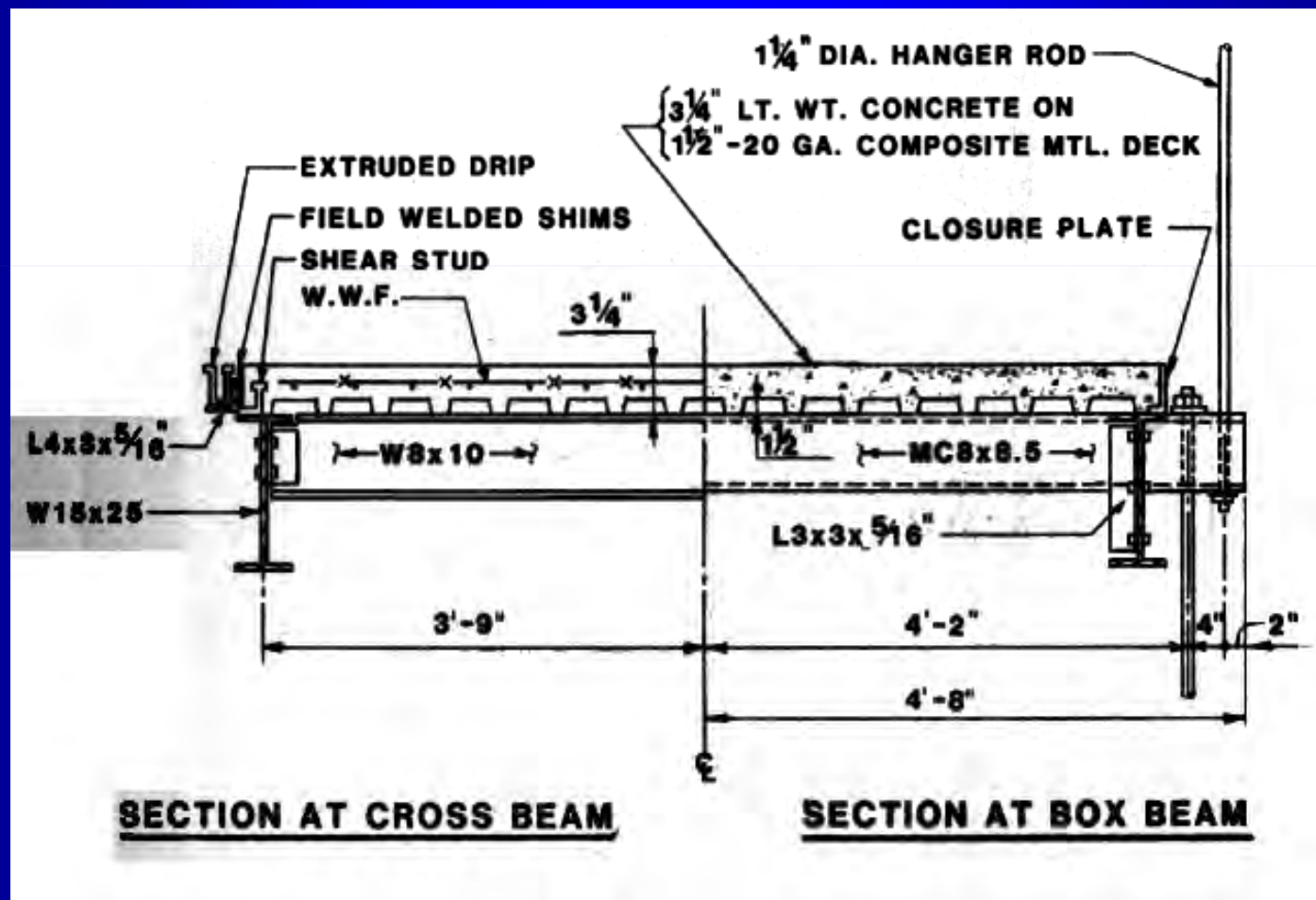
Famous Failures

Hyatt Regency Hotel in Kansas City (1981)

- Hanging walkway supported by steel rods
- Collapsed, killing 113 people
- Cause: poor connection detail
- Poor communication between engineer and steel fabricator involved

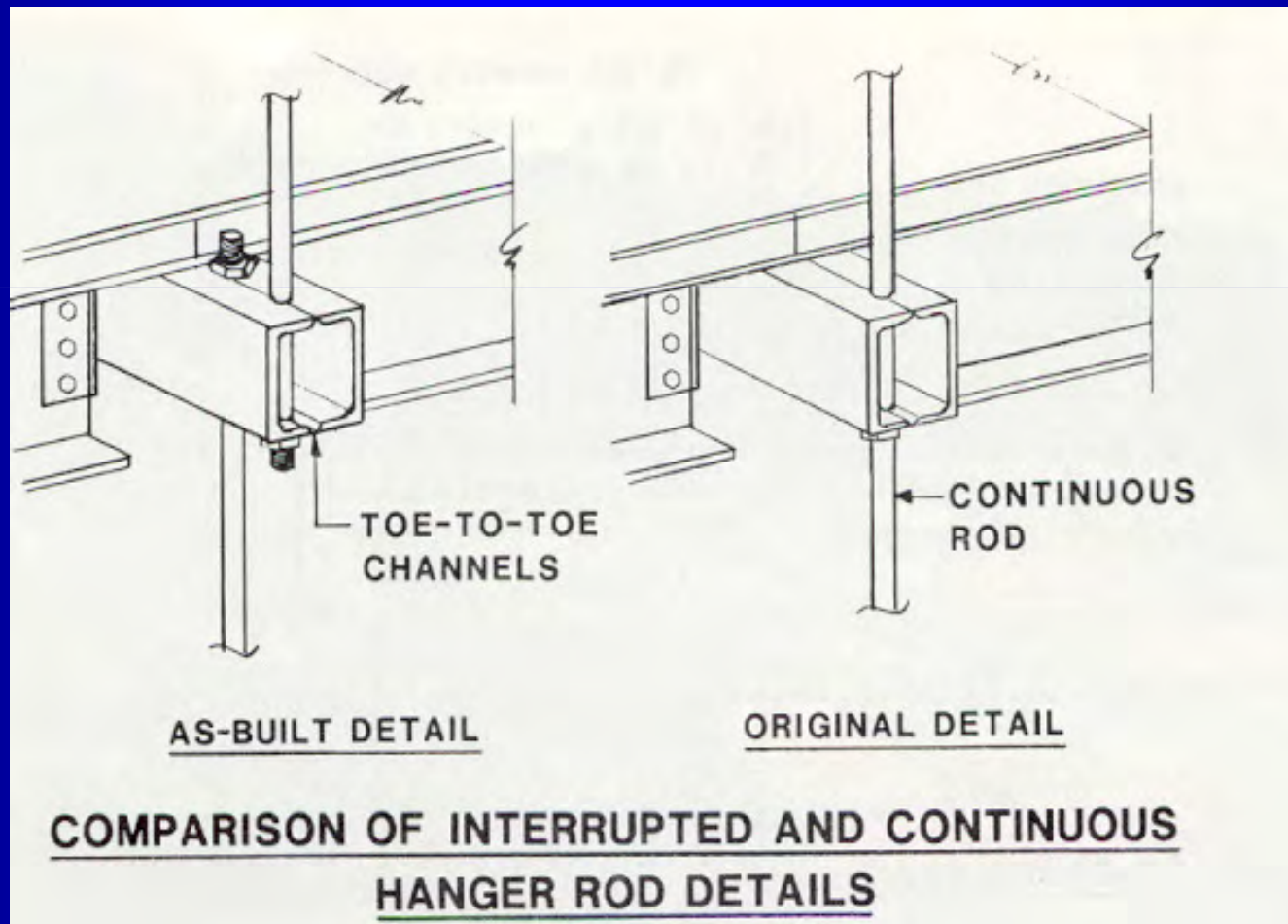
Famous Failures

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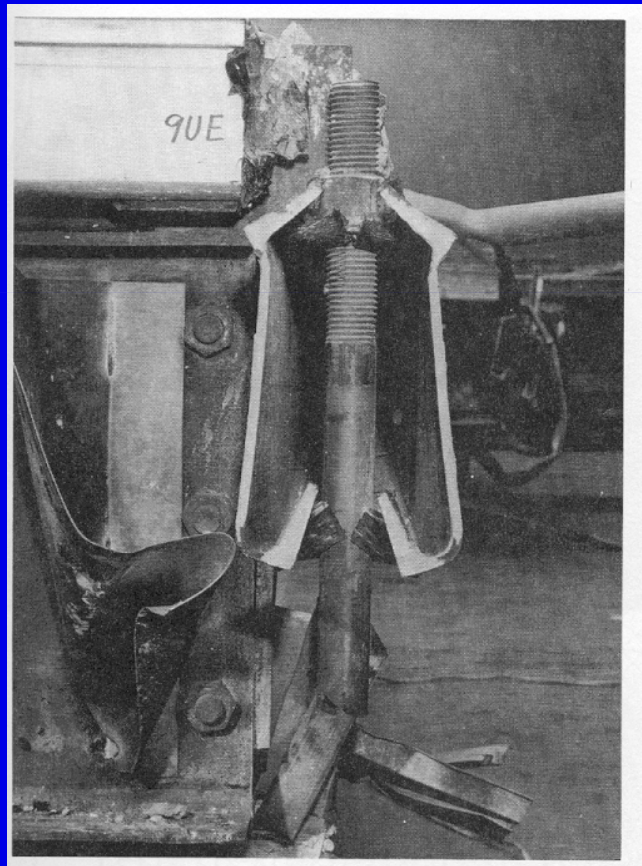
Famous Failures

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Famous Failures

Hyatt Regency Hotel in Kansas City (1981)



Hanger rod – box beam
connection

Ultimate Capacity of Connection

- Original Design: Ultimate capacity of connection only 60% of required capacity
- As Built: Ultimate capacity was just a little higher than the self weight of the structure
- Either way, connection was bound to fail!

Famous Failures

Big Dig Ceiling Panel Failure

- On 11 pm, July 10, 2006, four sections of precast concrete ceiling panels fell in a connector tunnel in Boston.
- 38-year-old Milena Del Valle, on the way to Logan Airport with her husband, was killed.
- The epoxy anchors holding the ceiling panels failed due to faulty construction and design.

The Accident Scene



Car Crushed by Ceiling Panel



The car that was crushed by falling ceiling panels, killing passenger Milena Del Valle in a Big Dig Tunnel in Boston.

However...

These are very dramatic but
most “failures” are far less
spectacular!

Why Did I Fail?



Scientific Method for Solving Forensics Problems

- State the problem
- Make observations
- State the likely causes of the failure
- Test the likely causes by making more observations, performing tests, doing calculations, doing a literature search, etc.
- Develop the most likely cause or causes

- Often the answer will be “yes, maybe” or “no, maybe”.
- There may be more than one contributing factor
- Developing a simple matrix is helpful in coming to the most likely causes.

Example Evaluation of Cracking

Tests	Possible Causes				
	Plastic Shrinkage	Drying Shrinkage	Alkali-Silica Reaction	Overload	Diff. Settlement
High Evap. Rate	X				
Restraint		X			
Petrographic exam			X		
Cracking pattern	X	O	X	O	O
Struct. Anal.				O	X

O Supports hypothesis

X Does not support



Symptom	Cause
Cracking shortly (minutes to hours) after placing (before setting)	Plastic shrinkage cracking (rate of evaporation > rate of bleeding)



Symptom	Cause
Cracking shortly (hours to days) after placing (after hardening)	Drying/thermal cracking (improper timing of spacing of joints)



Symptom	Cause
Cracking occurring after structure is in service	Structural cracking (improper placing or insufficient reinforcement)



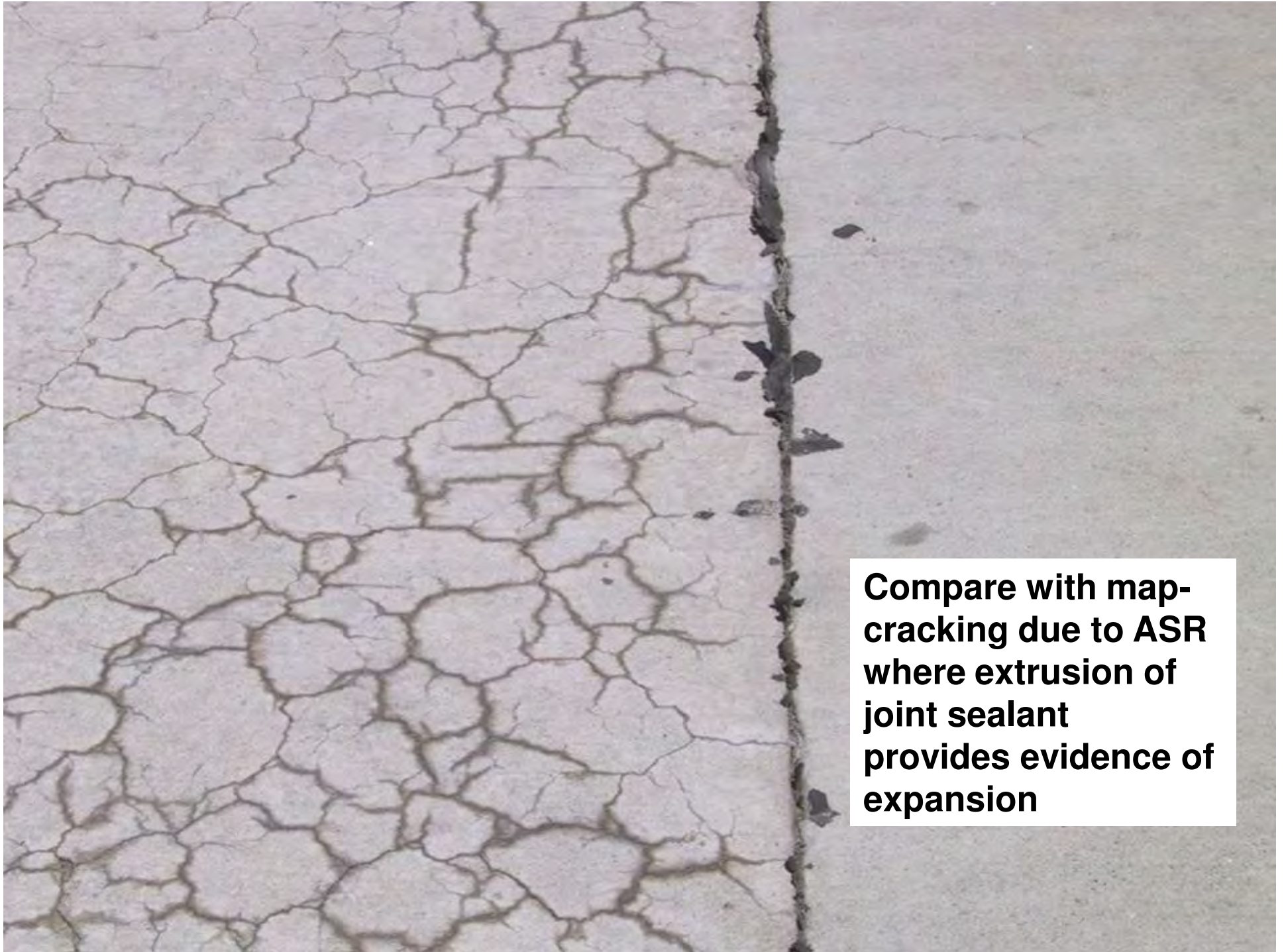
Symptom	Cause
Map cracking – typically occurring after 5 to 10 years	Volumetric expansion of concrete (in this case ASR)



Symptom	Cause
Map cracking – typically occurring after 5 to 10 years	Volumetric expansion of concrete (in this case ASR & DEF)



Symptom	Cause
Map cracking – occurring anytime from weeks to years	Excessive drying shrinkage



Compare with map-cracking due to ASR where extrusion of joint sealant provides evidence of expansion



Symptom	Cause
Map cracking – typically occurring anytime from months to years	Freeze-thaw attack (non-air-entrained concrete that was also hit by truck)



Symptom	Cause
Surface scaling – occurring after approximately 5 years	Abrasion by vehicular traffic (in wheel path)



Symptom	Cause
Surface scaling – occurring after decades	Water abrasion



Symptom	Cause
Severe spalling of concrete surface	Fire damage (petroleum tanker crashed into bridge pier and ignited)



Symptom	Cause
Severe erosion of concrete – occurring after years	Sewer-pipe corrosion (chemical-biogenic attack of paste by sulfuric acid)



Symptom	Cause
Spalling and disintegration – occurring after a few years	Freeze-thaw attack (non-air-entrained concrete)



Symptom	Cause
Shearing of concrete column and spalling of concrete cover	Shoving of foundation due to expansion of adjacent pavement (ASR)



Symptom	Cause
Spalling of concrete over rebar	Corrosion of rebar initiated by chlorides (from roadway above)



Symptom	Cause
Spalling of concrete over rebar	Corrosion of rebar initiated by chlorides (from unwashed sea-dredged sand)



















Case of the Ruptured Slab

Background

- Residence located in South Texas
- Construction date unknown: estimated to be before 1950
- Enlarged at least once
- Owners purchased in 1992
- Construction
 - Slab on grade
 - Wood framing
 - Stucco exterior

Observations: Owner Interview

- Owner discovered that no water pressure existed on April 15, 2000
- Water going through meter; meter turned off
- On April 17, plumber located leak beneath laundry room slab.
- Broke slab and found copper water supply pipe had completely separated
- Pipe was repaired.

Observations: Owner Interview

- Owner had found N-S crack through slab earlier, before loss of pressure occurred.
- During that time, driveway cracked and door to bedroom stuck.
- Shortly after leak was found, owner heard loud noise and found that front of house had a severe crack and stucco had fallen off house.

Observations: Owner Interview

- Another noise was heard and crack was found on east wall; window in bathroom was broken.

Visual Observations

- N-S slab crack extending from north wall through house to utility
- Crack was in line with location of leak location
- Numerous other cracks in floor and walls

N-S Slab Crack: Looking down on crack after carpet removed



Location of Pipe Separation



Cut Out Section of Pipe



Repaired Water Pipe



Separation of Cabinet at Ceiling



Door Frame Planed due to Sticking Door



Wall-Ceiling Crack



Severe Wall Cracking on North Side



Cracking at NE Corner

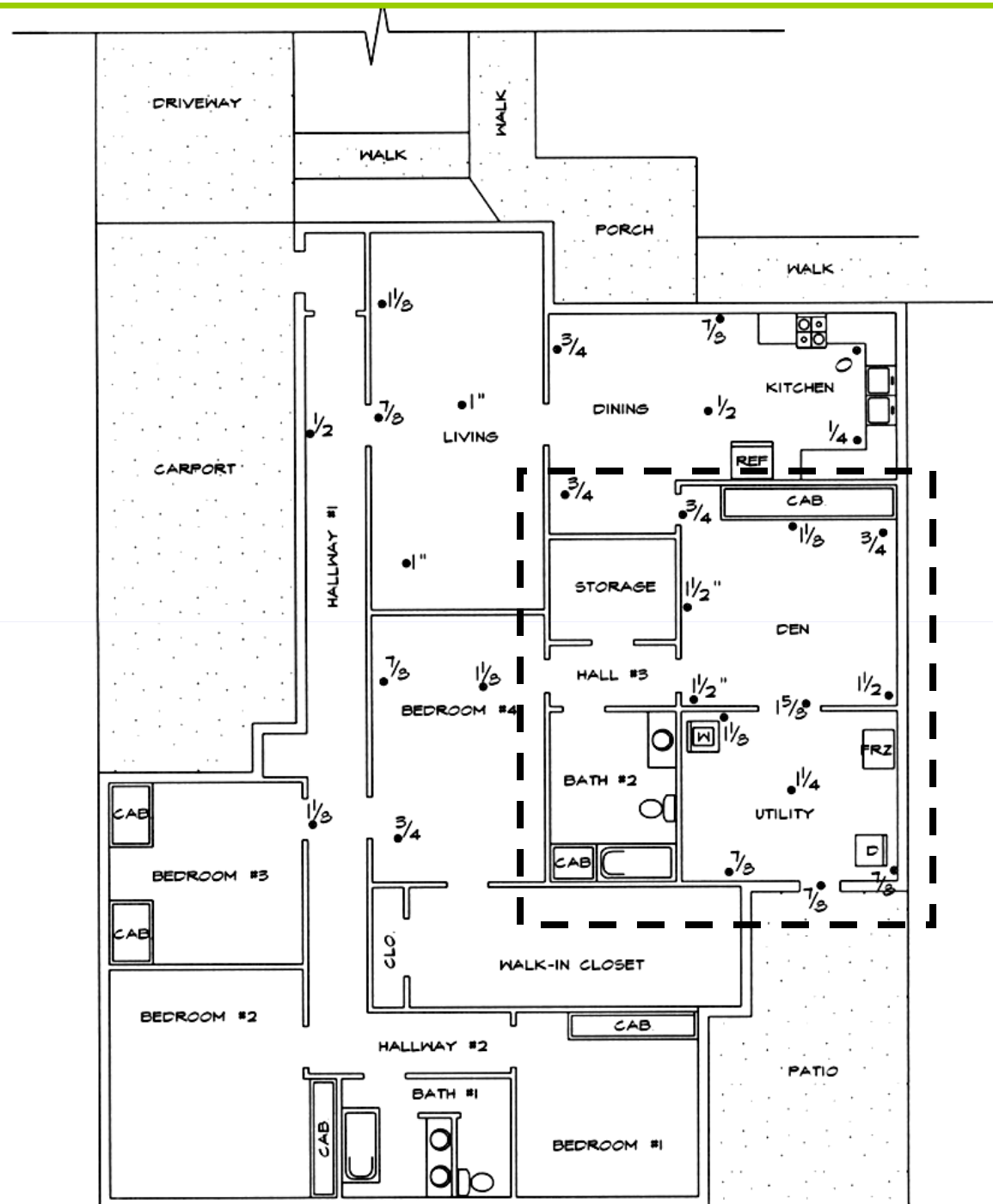


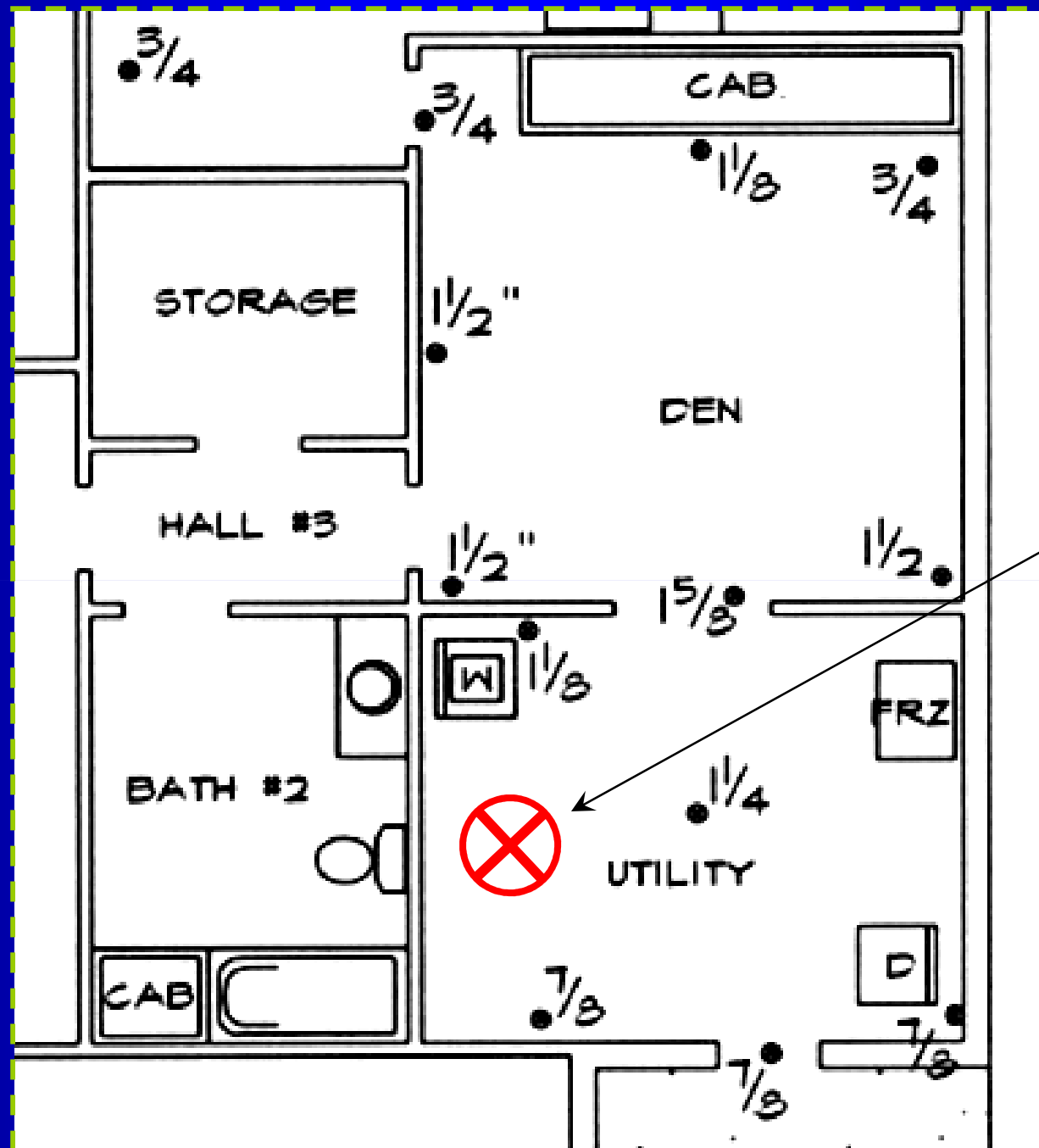
Stucco Cracking at Window



Findings: Floor Level Survey

- Floor levels were taken in June 2000 by defendant's expert; showed a "mound" in vicinity of leak.
- Floor levels taken by me in December 2000 were similar to those taken by defendant's expert.





Leak

Findings: Water Usage

Month Billed	1999	2000
January	18,000	23,000
February	21,000	17,000
March	18,000	17,000
April	21, 000	18,000
May	20,000	26,000

Findings: Water Usage

- Water usage indicates leak in April 2000 based on monthly usage (May bill)
 - 8000 gal. Between March and April 2000 usage
 - 6000 gal. Between April 1999 and April 2000
 - Equivalent to 100 to 150 drums of water

Defendant Expert Findings

- Plumbing leaks did not contribute to cracking.
- Causes of cracking attributed to:
 - Differential soil movement due to seasonal climatic effects
 - Inadequate compaction of soil
 - Infrequent water pattern around house
 - Trees near foundation

Defendant's Report

- However, defendant's report provided strong supporting evidence for leak as being the cause.
 - Levels (Found “mound” near leak)
 - Water usage; admitted that leak probably resulted in loss of 6000 gal.
 - Documented cracking (except N-S crack)

- Their report stated that moisture content in soil outside the house was not that much different than those near the leak; however, samples were taken 3 months after leak repaired and soil most likely was uniformly wet in all areas sampled.
- Their soil tests showed that soil had “low to moderate shrink/swell capacity.”
- I could have taken their report and made my case.

Most Probable Cause: Leak

- Severe cracking at time of leak
- Verified by neighbors
- 6000 to 8000 gal. of water leaked
- Slab “mounded” in area of leak
- Age of house precluded consolidation or climatic moisture changes.
- Hydraulic pressure accompanied by some soil swelling most likely mechanism.
- To put it crudely, the house received an enema.

Outcome

- Initially, no money offered
- After my report was presented, \$39,000
- After some serious negotiation, \$140,000

**Oops!! Talk a bout a
failure!**

A 12-STORY BUILDING LYING ON THE GROUND in CHINA





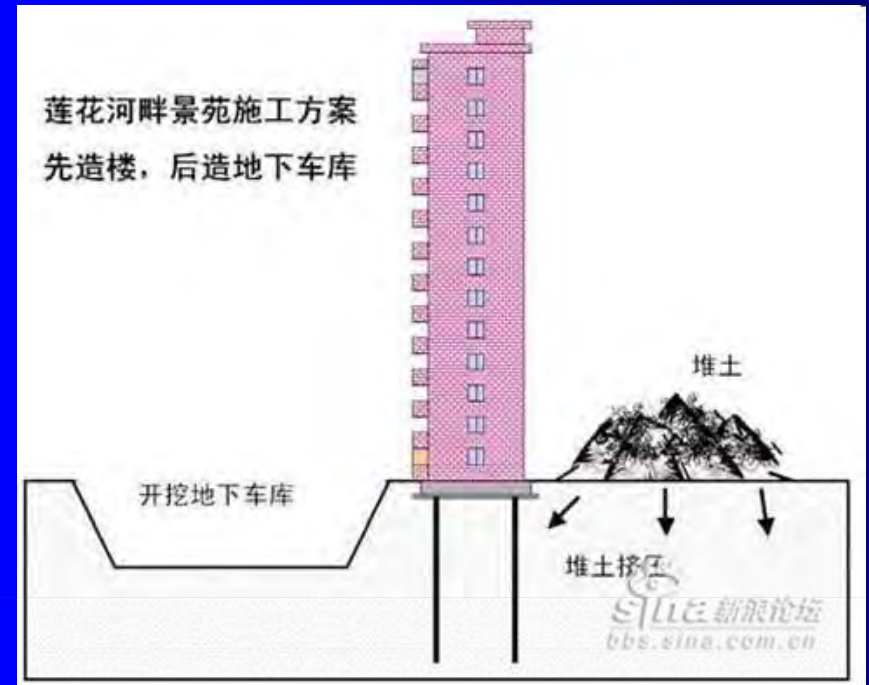
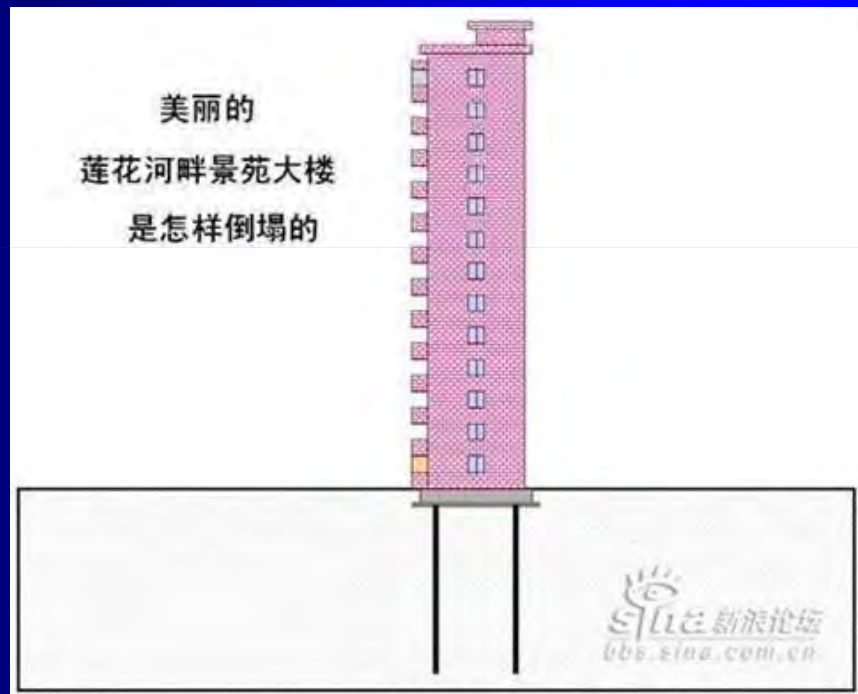
If the buildings were closer together there could also have been a domino effect.

What happened??

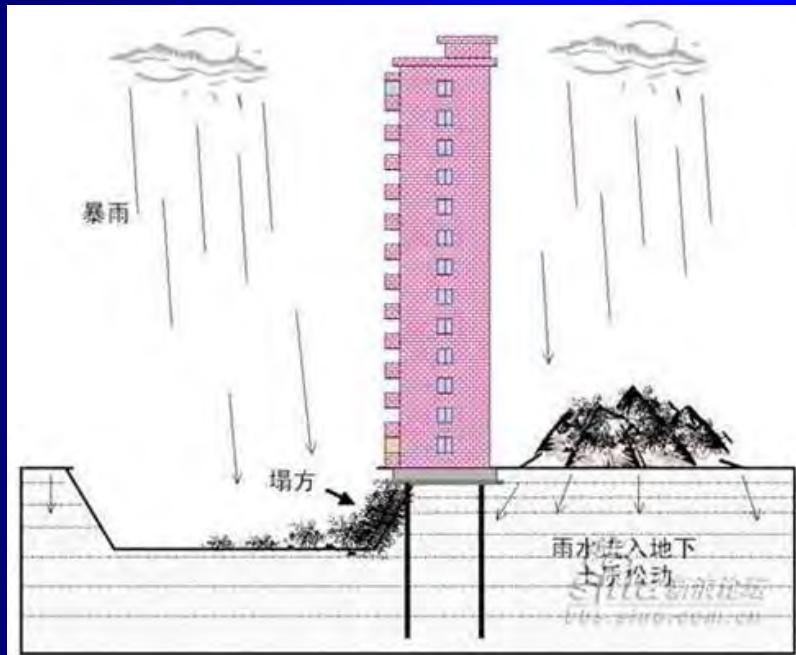
A 12-STORY BUILDING LYING ON THE GROUND

- An underground garage was being dug on the south side, to a depth of 4.6 meters
- The excavated dirt was being piled up on the north side, to a height of 10 meters
- The building experienced uneven lateral pressure from south and north
- This resulted in a lateral pressure of say 3,000 tonnes, which was greater than what the pilings could tolerate. Thus the building toppled over in the southerly direction

First, the apartment building was constructed



Then the plan called for an underground garage to be dug out. The excavated soil was piled up on the other side of the building.

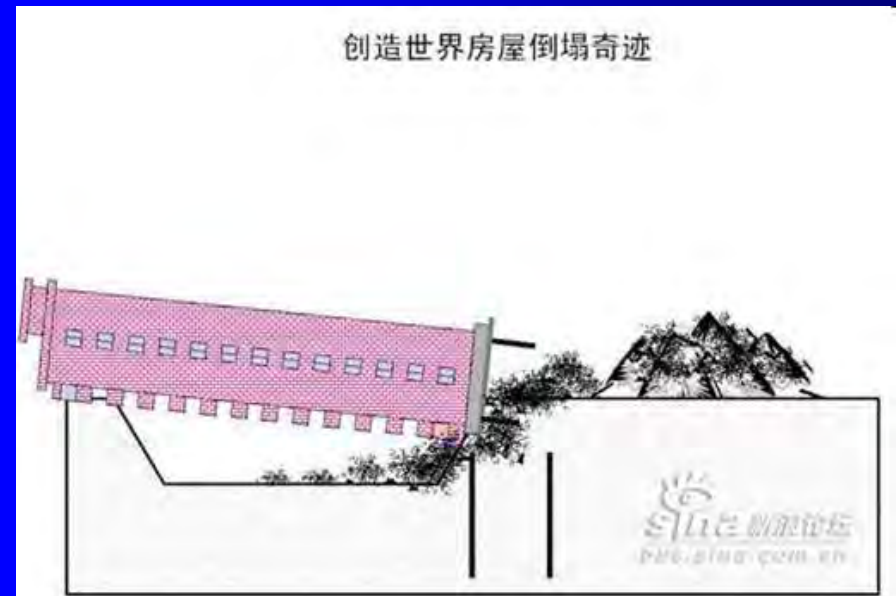


Heavy rains resulted in water seeping into the ground.



The building began to shift and the concrete pilings were snapped due to the uneven lateral pressures.

The building began to tilt.



And thus came the eighth wonder of the world...













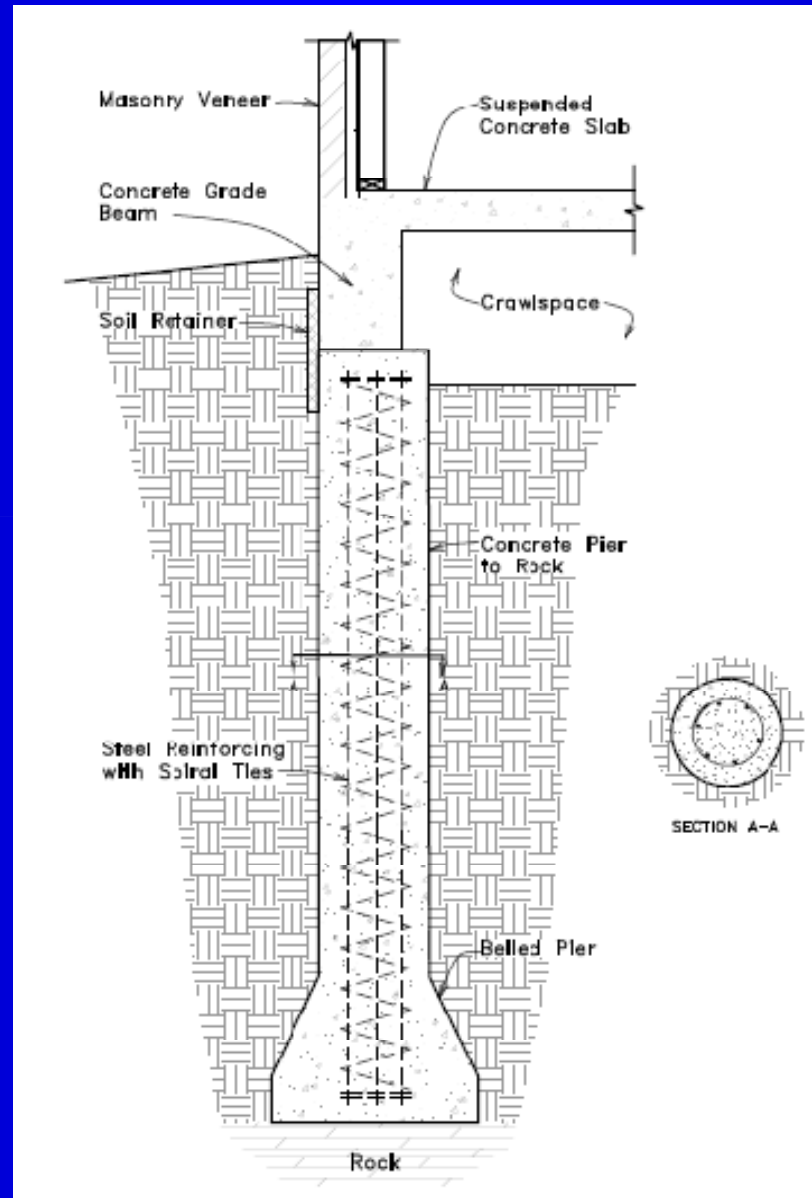




On Piers and Still Problems

- An educational building for a church was constructed on expansive clay.
- The structural engineer had a soil investigation performed and designed the piers to go about 20 ft. into the clay.

Pier as designed

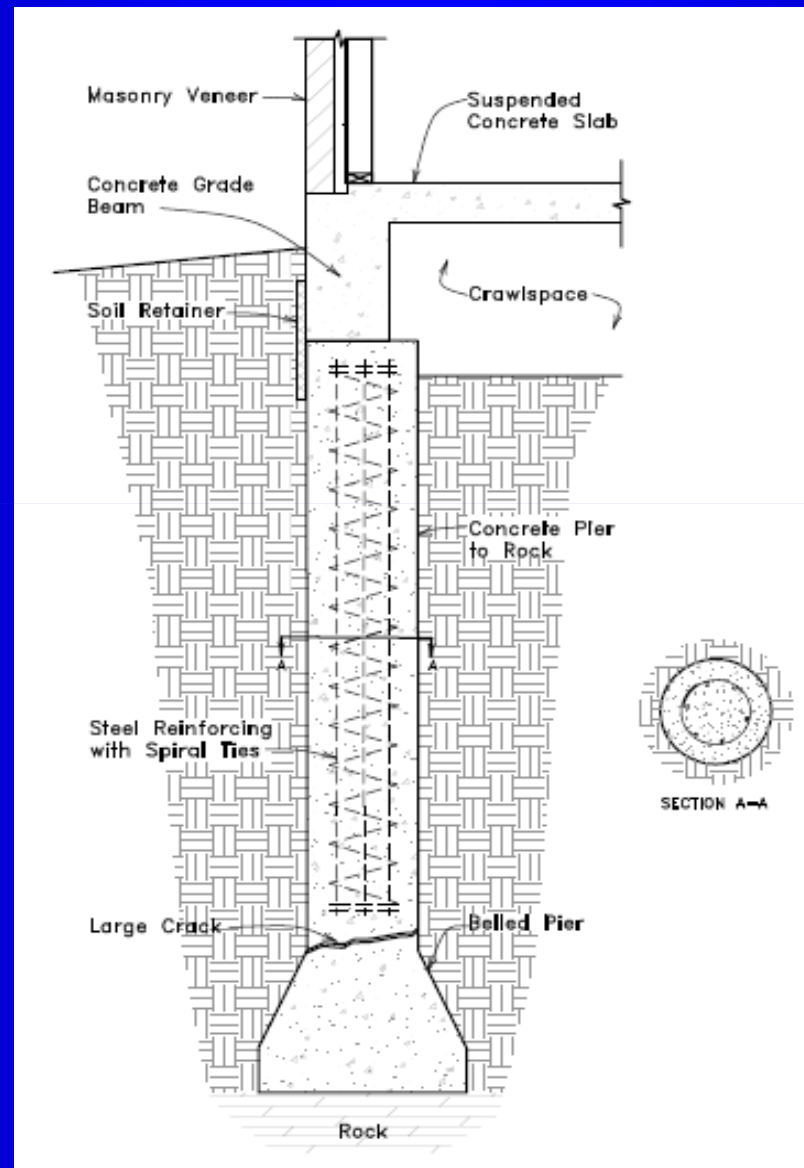


What happened?

- The addition was built during a severe drought
- When the drought broke, the building experienced wall cracking and other distress.
- The engineer suspected that the contractor had not installed earth retainers beneath the beam.

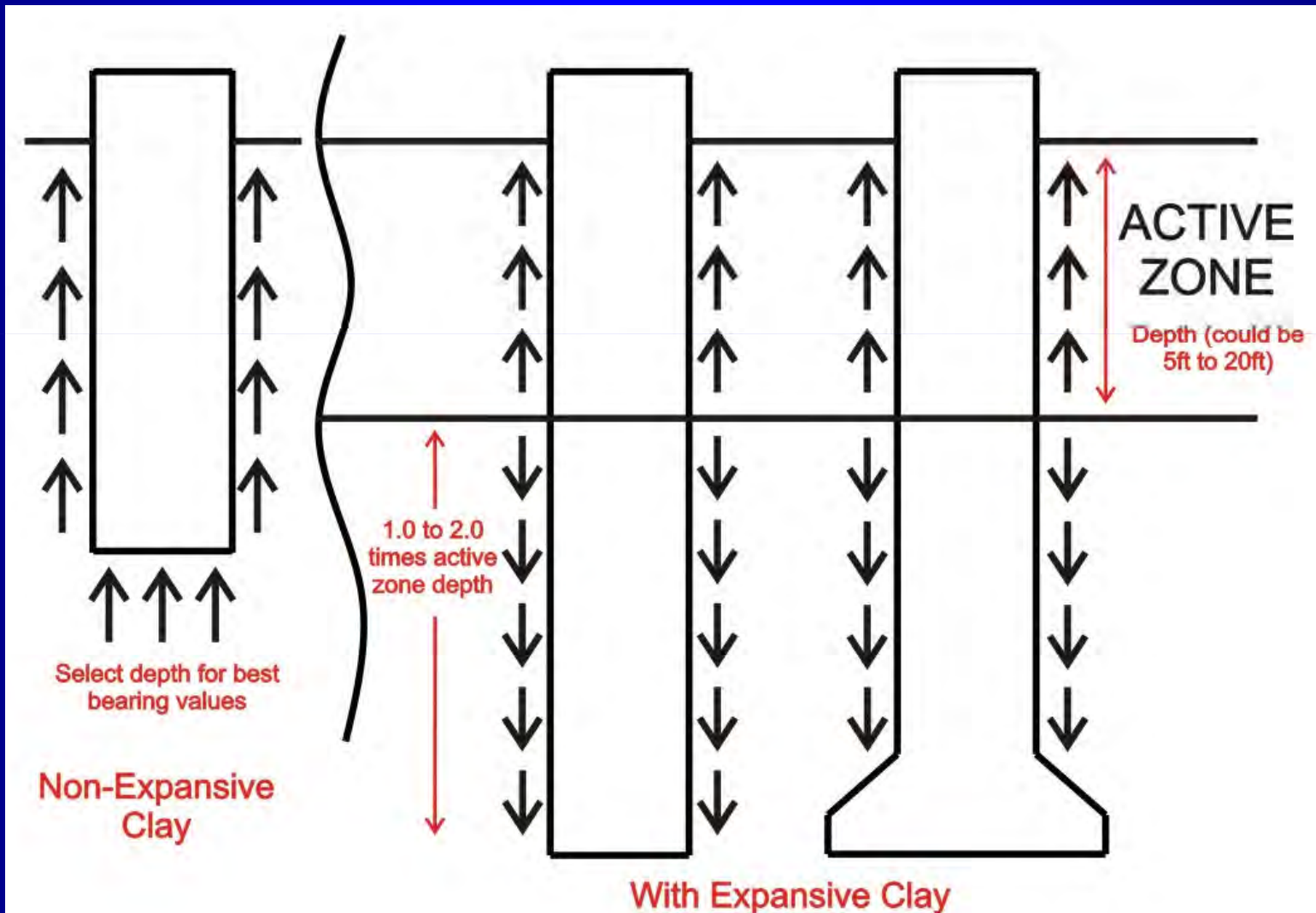
- The engineer recommended to the church that they excavate beneath the beams to find out if the earth retainers had been left out.
- When they did, guess what?
- The retainers were in place! Soil was not touching the bottom of the beams.
- What next?
- They dug to bottom of piers to see if piers were founded on rock.
- What do you think they found?

Pier as built



- The crack was at the top of the bell.
- A close inspection indicated no steel across the crack.
- The steel stopped just above the bell.
- What happened?

Design of Pier Foundations



- When the drought broke, the moisture caused swelling of the soil, the clay in the active zone created skin friction on the surface of the pier and lifted it up.
- But how could the skin friction uplift break the concrete?
- How much force would it take to break the pier?
- How much stress would it take to break the concrete?

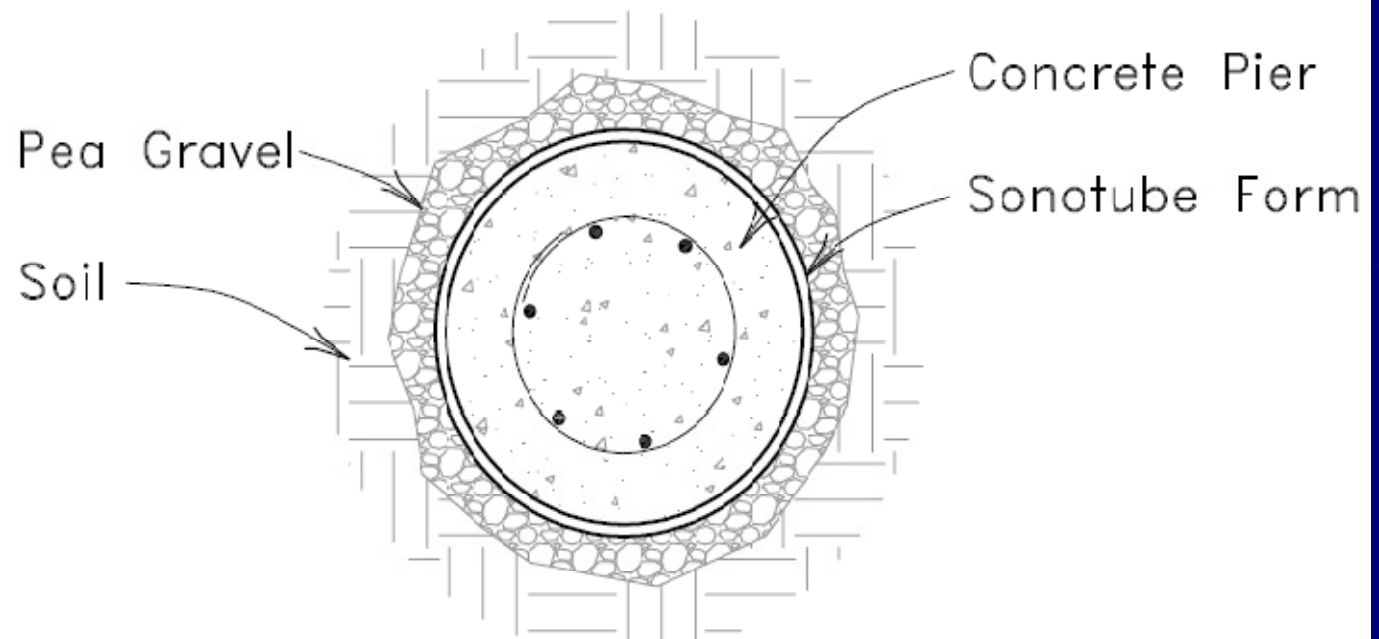
- Stress required to break concrete in tension is about

- Stress required to break concrete in tension is about 10% of compressive strength, $0.1 \times 3000 \text{ psi} = 300 \text{ psi}$
- An 18-inch diameter pier has an area of $18 \times 18 \times \pi/4 = 254 \text{ sq. in.}$
- The uplift required to break concrete is $254 \text{ sq. in.} \times 300 = 76,300 \text{ lbs.}$
- But in addition to the upward force to break the concrete, it also has to hold up the weight of the building which is about 30,000 lbs.

- The total uplift provided by the soil on the pier is over 100,000 lbs.
- Had the steel been placed to the bottom of the bell, it would not have stopped the crack from forming but it would have kept the crack from opening wide.
- The bell would have served as an anchor preventing the pier from moving upward.
- But this illustrates the force clay can exert in lifting up a structure.

Foundation Solution

Alternate
Design



SECTION A-A

**A few final failures for your
viewing pleasure....**

2.

Where does the stair go?



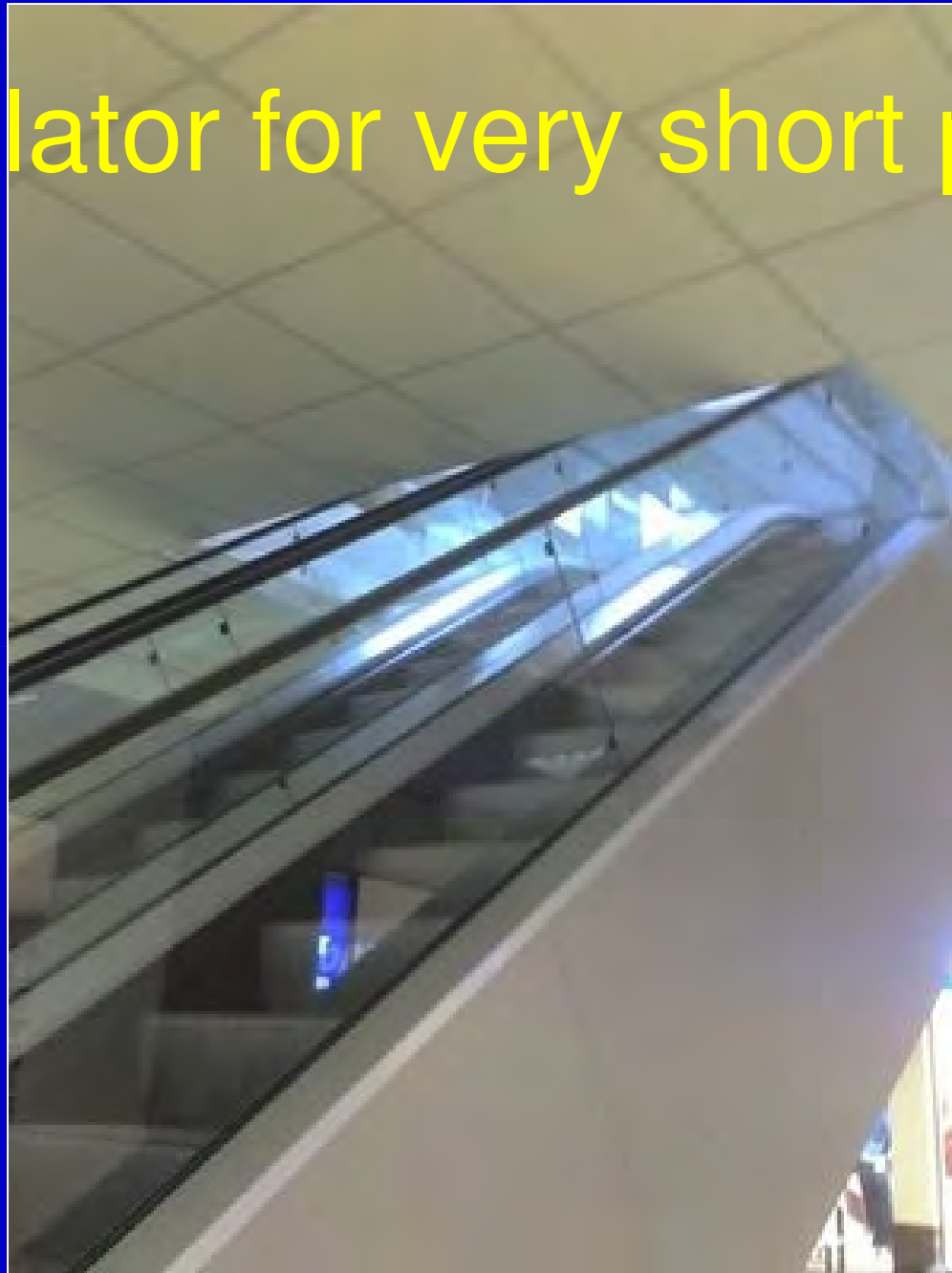
5.

How do I get up these stairs?



6.

Escalator for very short people



9.

Someone forgot about the light pole



11.

We need to grow taller people



And the winner is . . .

No comment needed!



You may be the next engineering
Sherlock Holmes!



Does it pay well?

2001 Salaries

• General Civil	\$73,000
• Civil (Structural)	75,000
• Geotechnical	68,000
• Forensic	143,500

View these as relative, but they are higher than in 2001.

Final Thoughts

- Forensic engineering is practiced by nearly every consulting firm.
- Some firms now specialize in forensic engineering and are growing very fast.
- Forensic engineering is an option that you may wish to consider as a career.

Questions?



Winner: “Not My Job” Award