INTERNATIONAL CONCRETE REPAIR INSTITUTE

WATER & WASTEWATER TREATMENT PLANT REPAIRS

"From Textbook to Practice: Case History of Failure and Repair of an Underground Wastewater Vault"

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Structural Diagnostics Services
Walter P Moore

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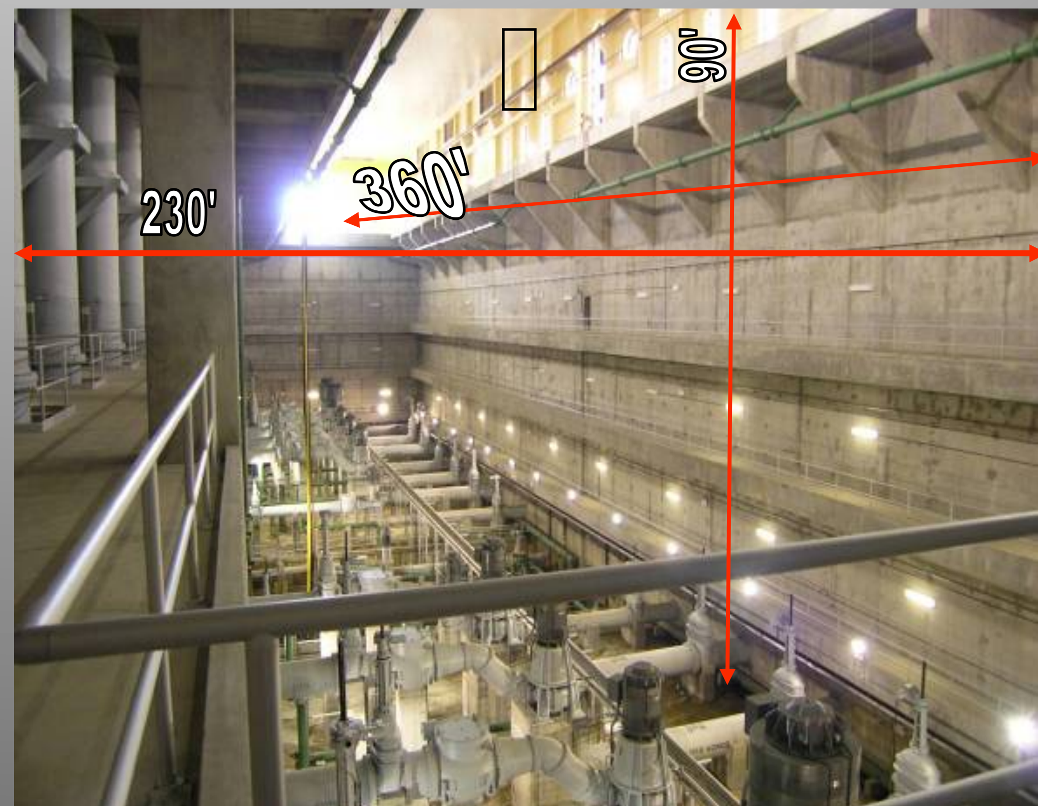
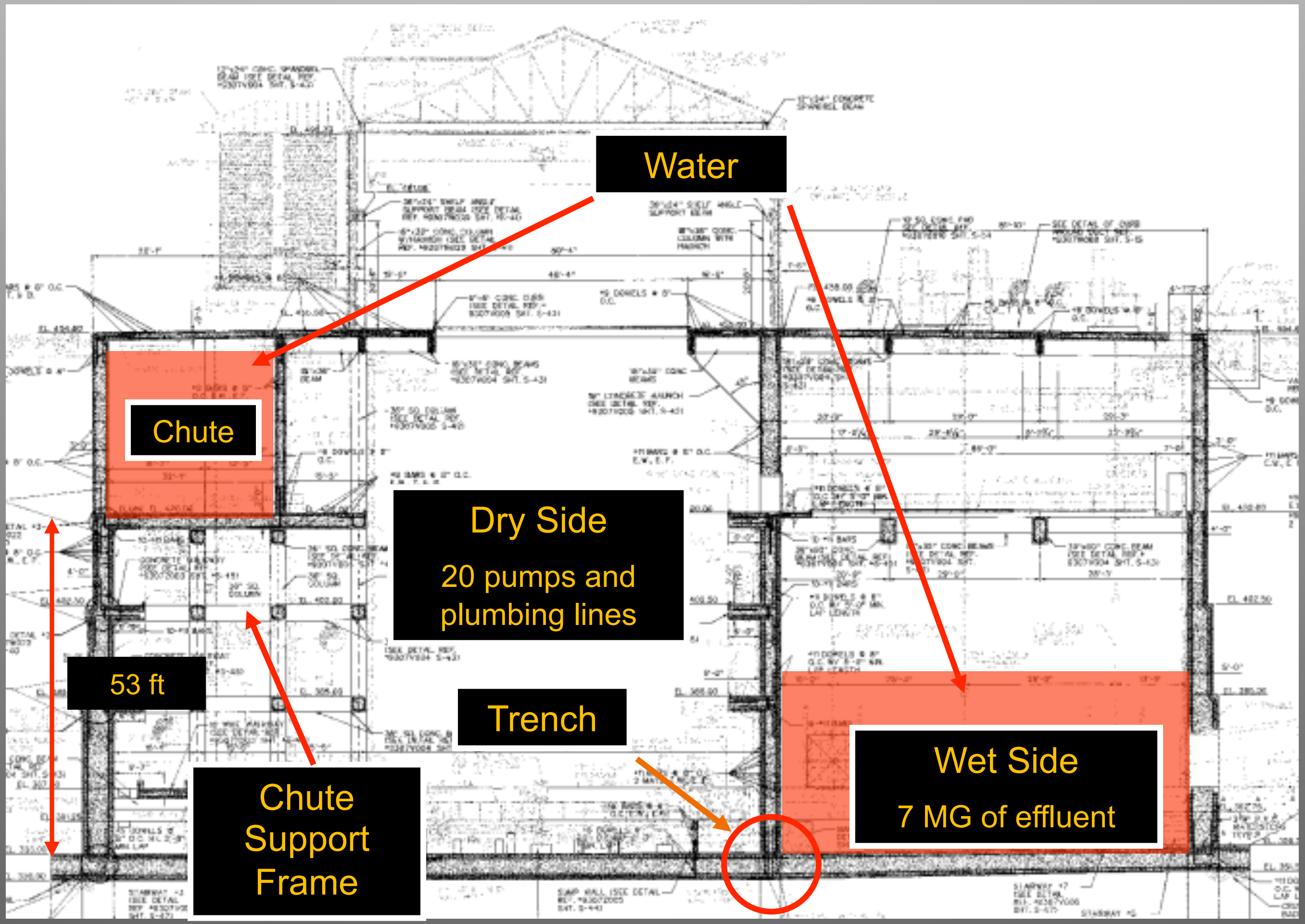
Size of wastewater vault

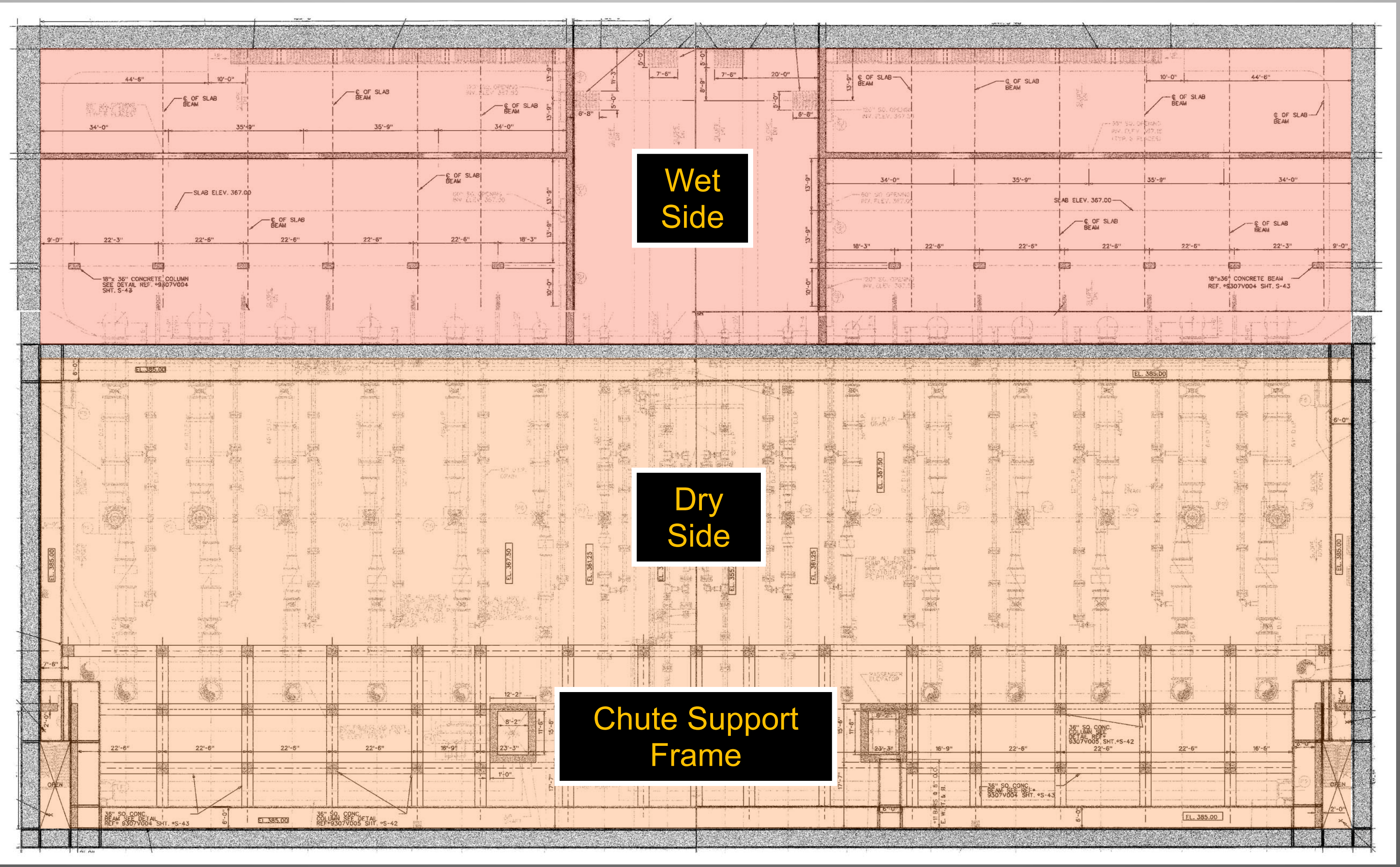
- 85 million gallons per day sewage treatment facility without pump station
- 600 million gallons per day with pump station
- Vault gross dimensions:
  - 230 ft. wide
  - 360 ft. long
  - 90 ft. deep
- Constructed using open excavation in limestone
  - Approximate side slope of 45 degrees



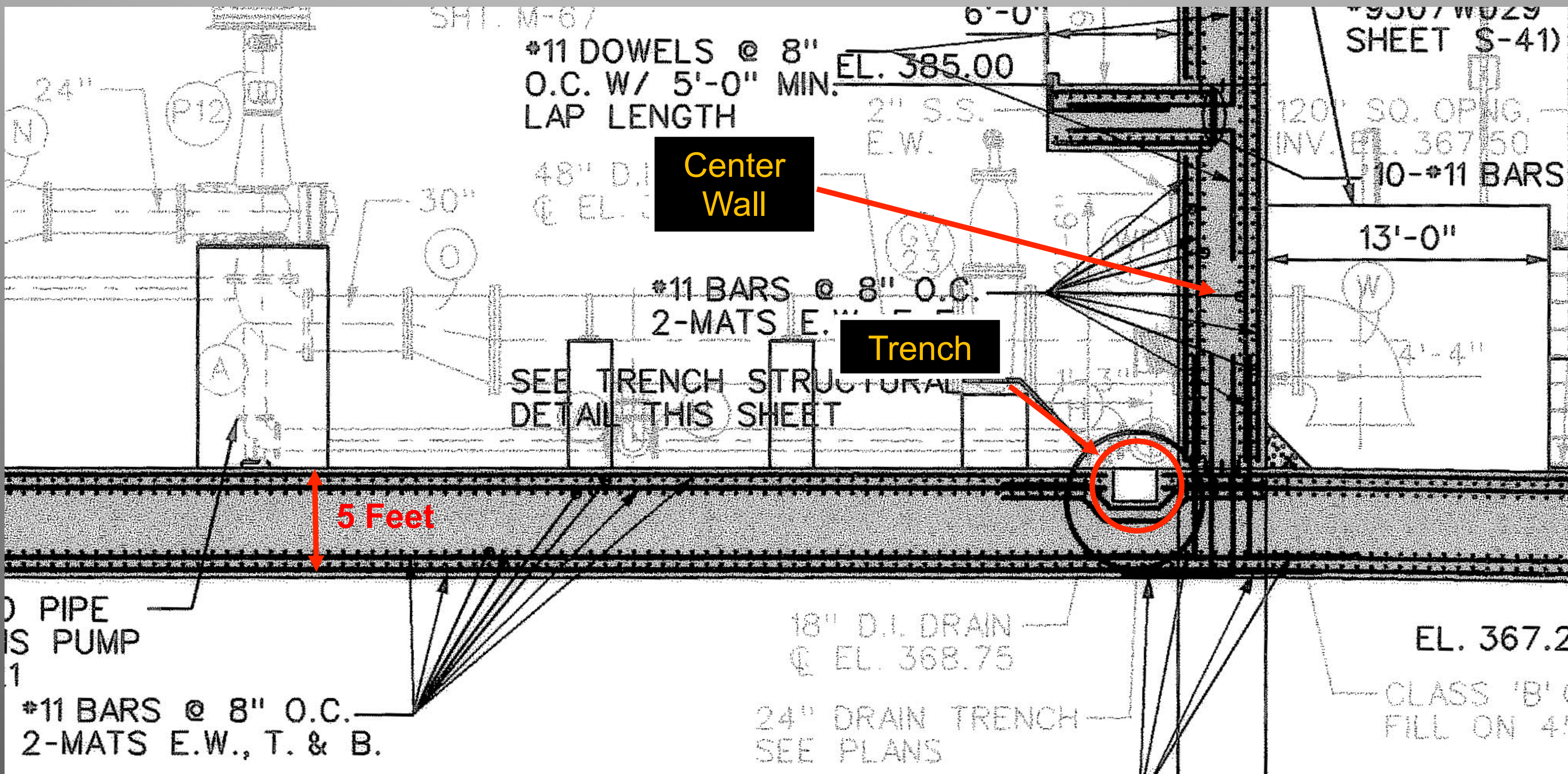
As-Designed
Vault Section: major functional areas



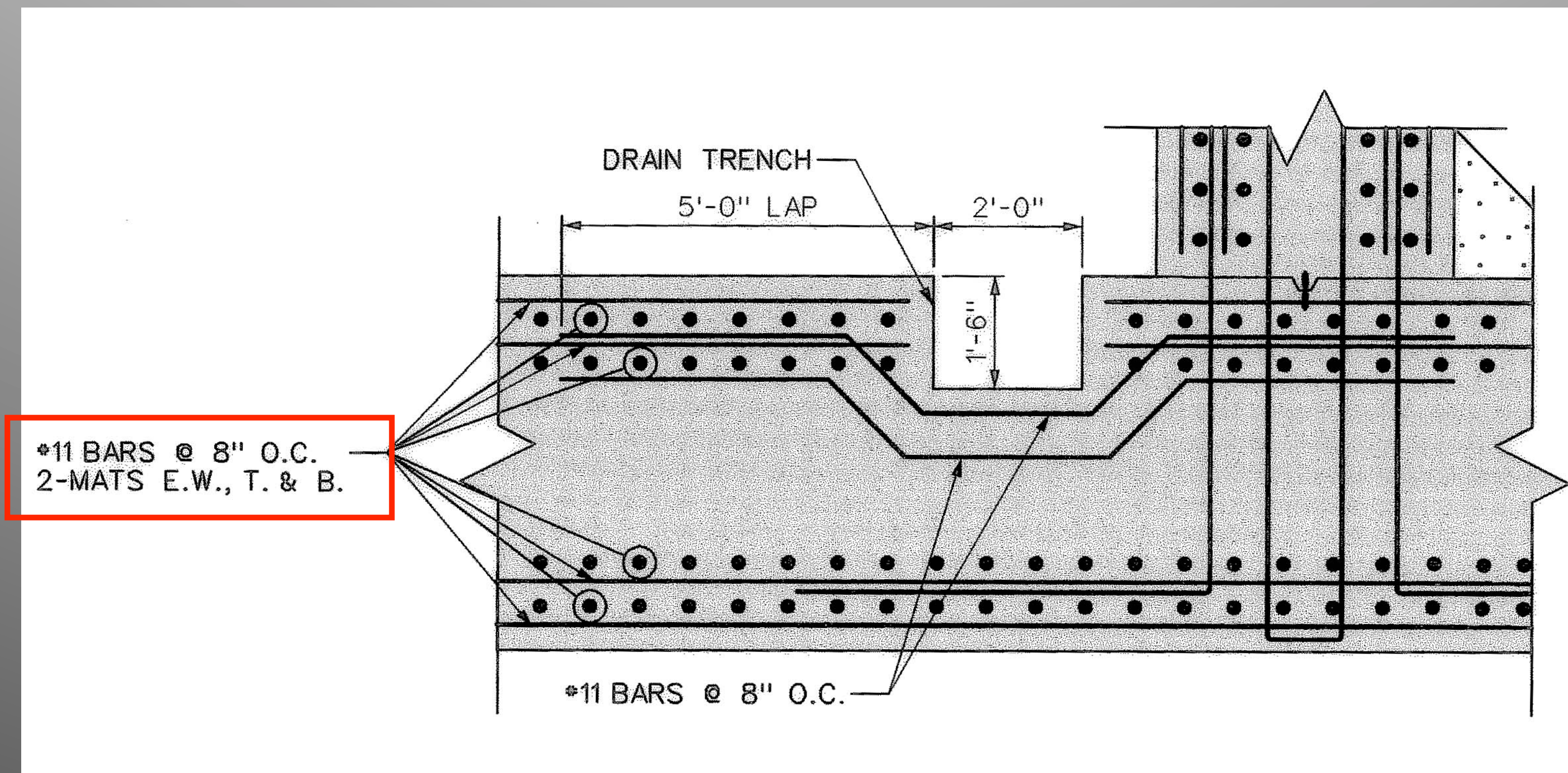
As-Designed Vault Plan



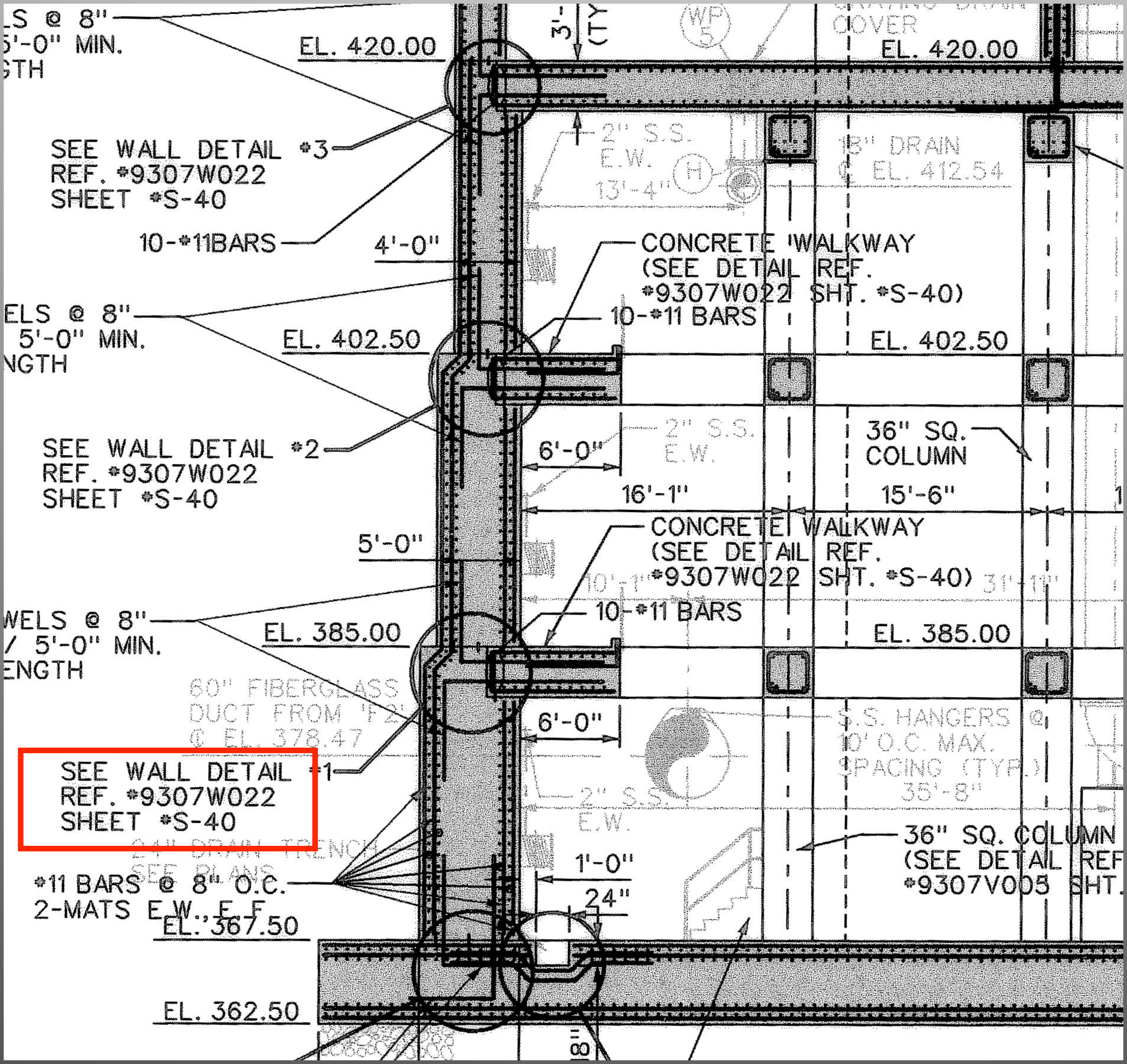
As-Designed
Mat Slab



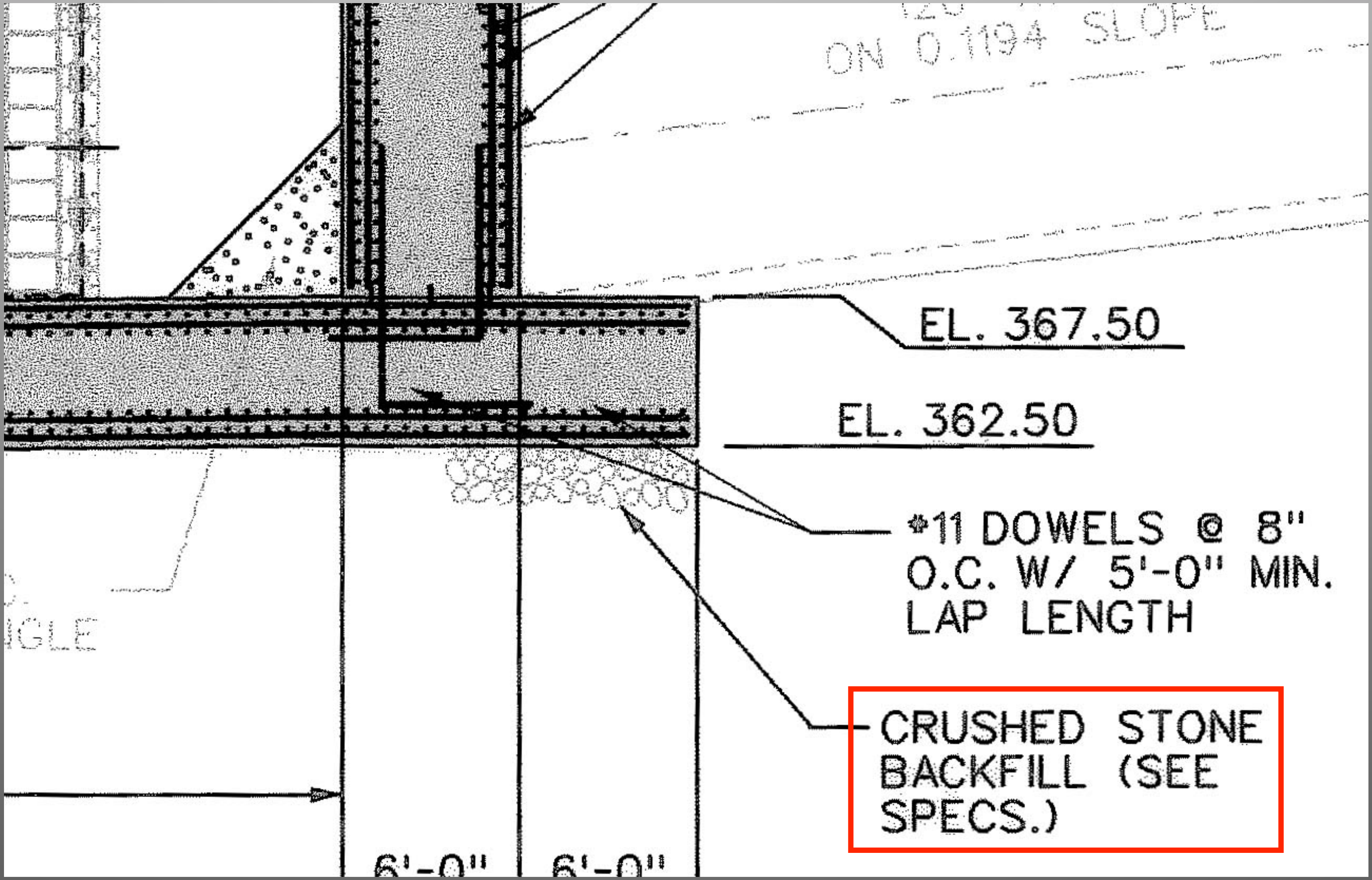
As-Designed
Trench at Interior Wall



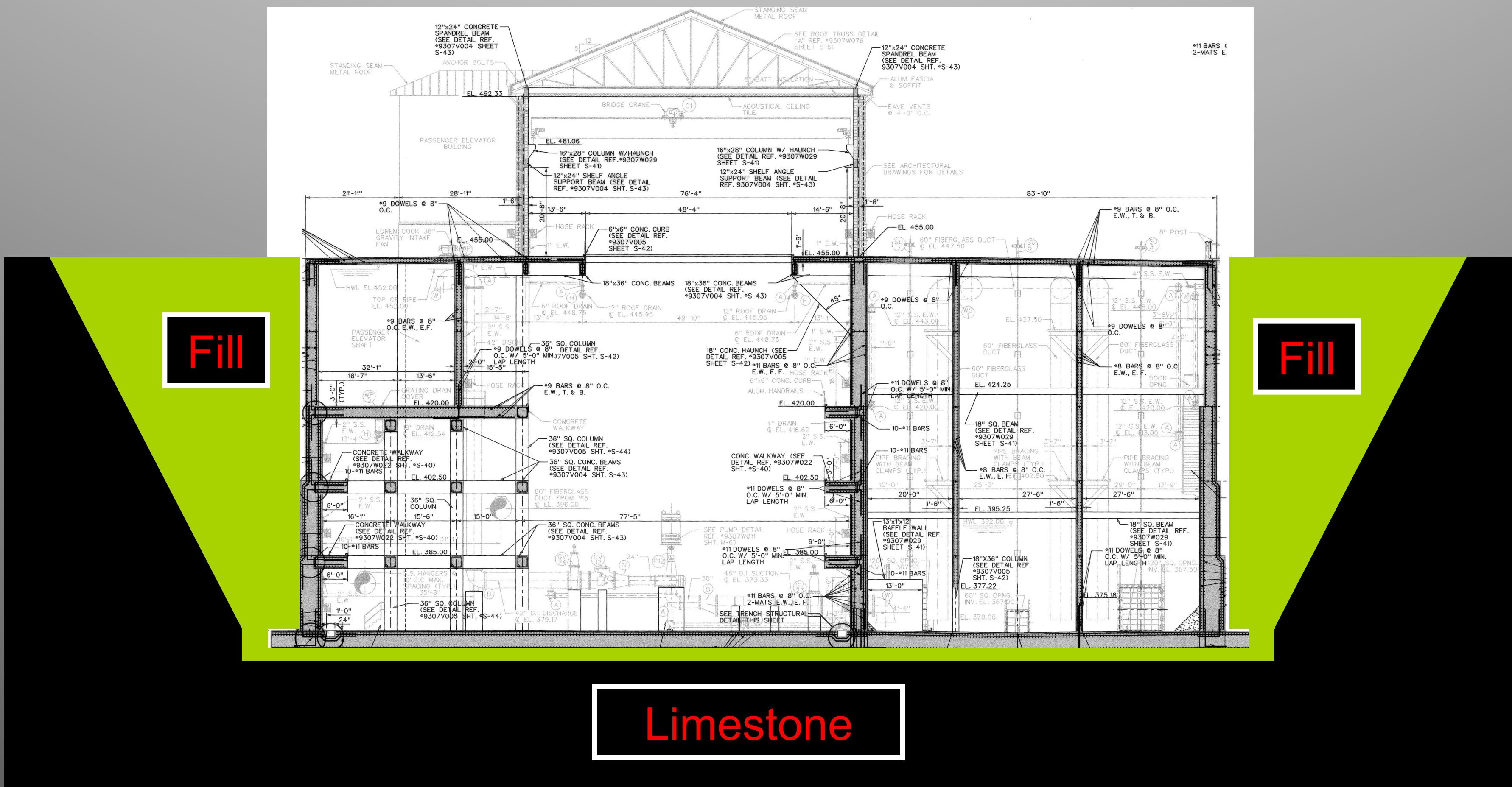
As-Designed Wall Section(Typical)



As-Designed Backfill Under Mat Slab



As-Built
Location of Backfill



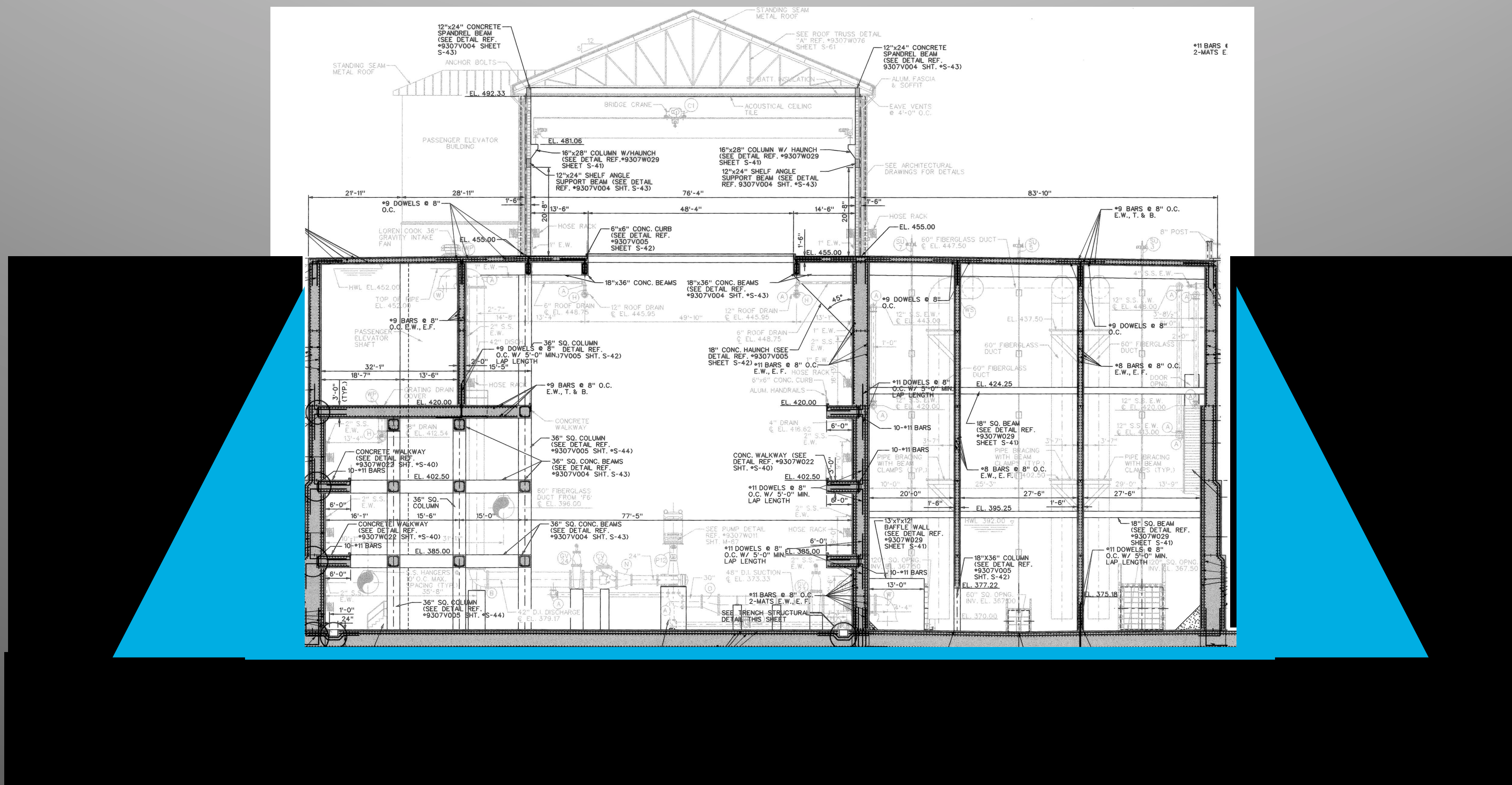
Geotechnical Design Considerations

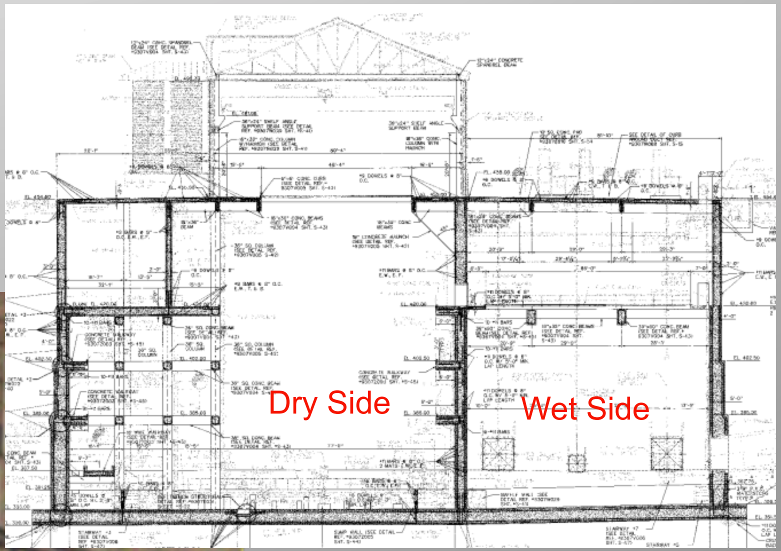
- Recommendations by Geotechnical Engineer
  - Wall backfill to be free-draining granular material.
  - Weep holes or foundation drains for walls required.
- Design parameters for walls by Geotechnical Engineer
  - Lateral earth pressure loads based only on fully drained conditions
  - Did not provide lateral design loads for saturated soil conditions.

Failure

- Heavy rains fell in the area days prior to the failure
- Failure occurred about three months after the vault was complete.
  - Loud “popping” noises
  - Water flowed into the dry side of the vault reaching 15 ft above the base of the mat
- Vault was evacuated
- Groundwater level outside the pump station 2 days after the failure was 70 feet above the base of the mat.

Failure





Groundwater flooded the dry side of the vault.

Post Failure Dewatering

- Dewatering wells were installed at the perimeter of the vault immediately after the failure.
- Groundwater level four days after the failure was found to be 70 feet above the base of the mat slab in this 90 feet deep vault.
- Continued dewatering removed millions of gallons of groundwater.
- Ground water was suspected to be coming from the nearby creek. However, no ground water infiltrations were observed during construction.

Possible modes of failures associated with loud “popping” sound

- Shear failure?
- Tension failure?
- Bending or flexural failure?
- Compression failure?
- Excessive cracking for sure!

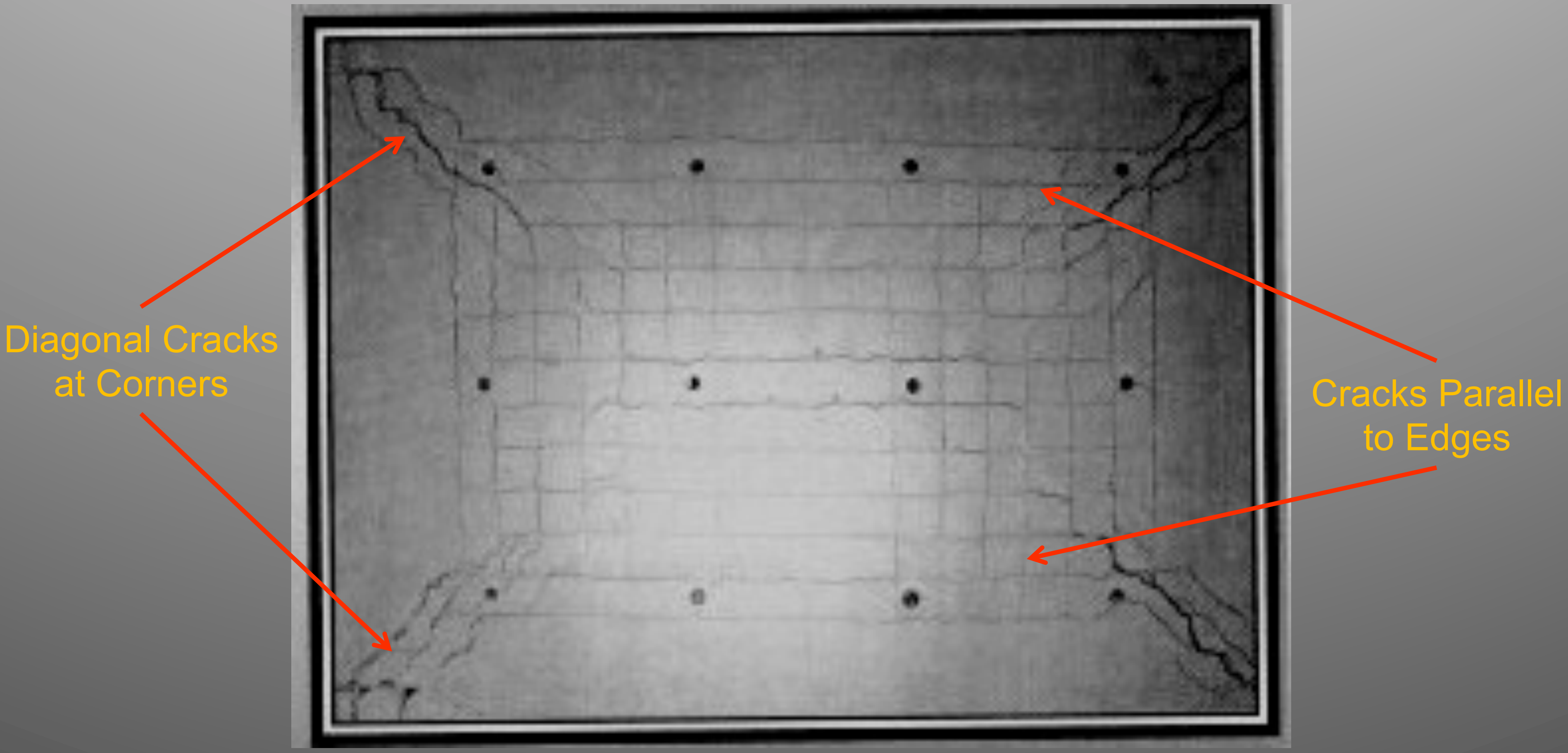
Field Investigation

- Damage Survey
  - Mat slab
  - Chute
  - Chute support structure
  - Perimeter walls
  - Interior walls (Not covered in this presentation)
  - Superstructure (Not covered in this presentation)
- Floor Level Survey

Damage Survey
Slab Cracks

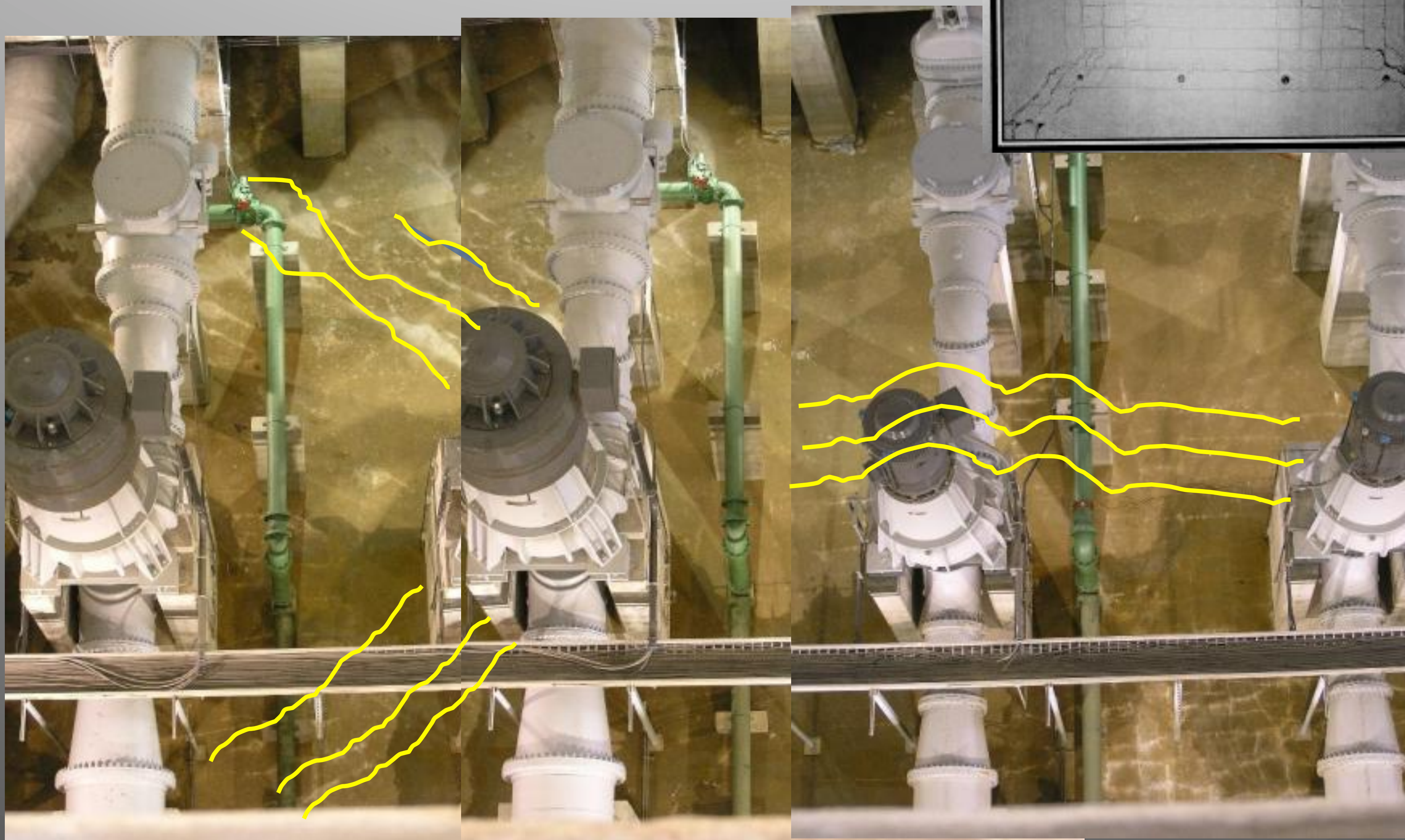
- Slab cracks noted in top face of slab.
- Crack patterns consistent with yield line pattern seen in uniformly loaded slabs.
  - Diagonal cracks at corners.
  - Cracks parallel to edges in middle.

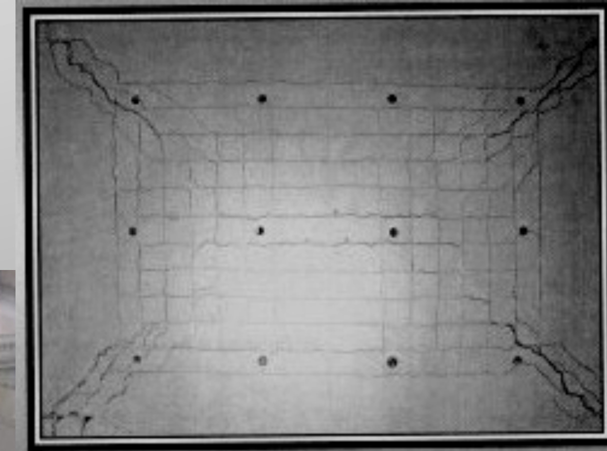
Classical Text Book Example
Rectangular Slab Failure Pattern



Damage Survey

Slab Cracking (Flexural Failure)

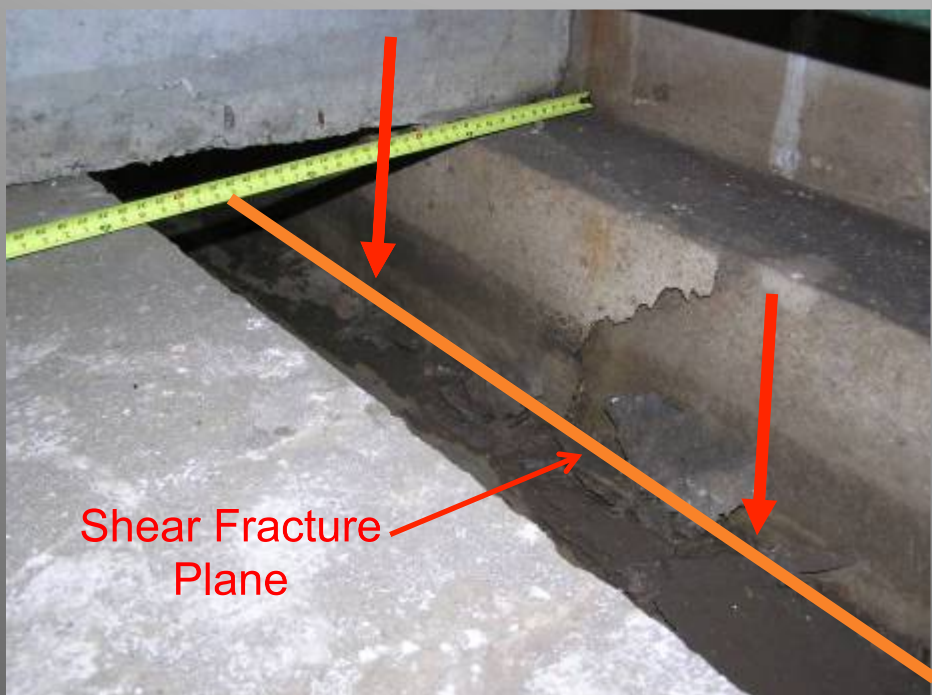




Yield Line Flexural Failure in Slab in Dry Side

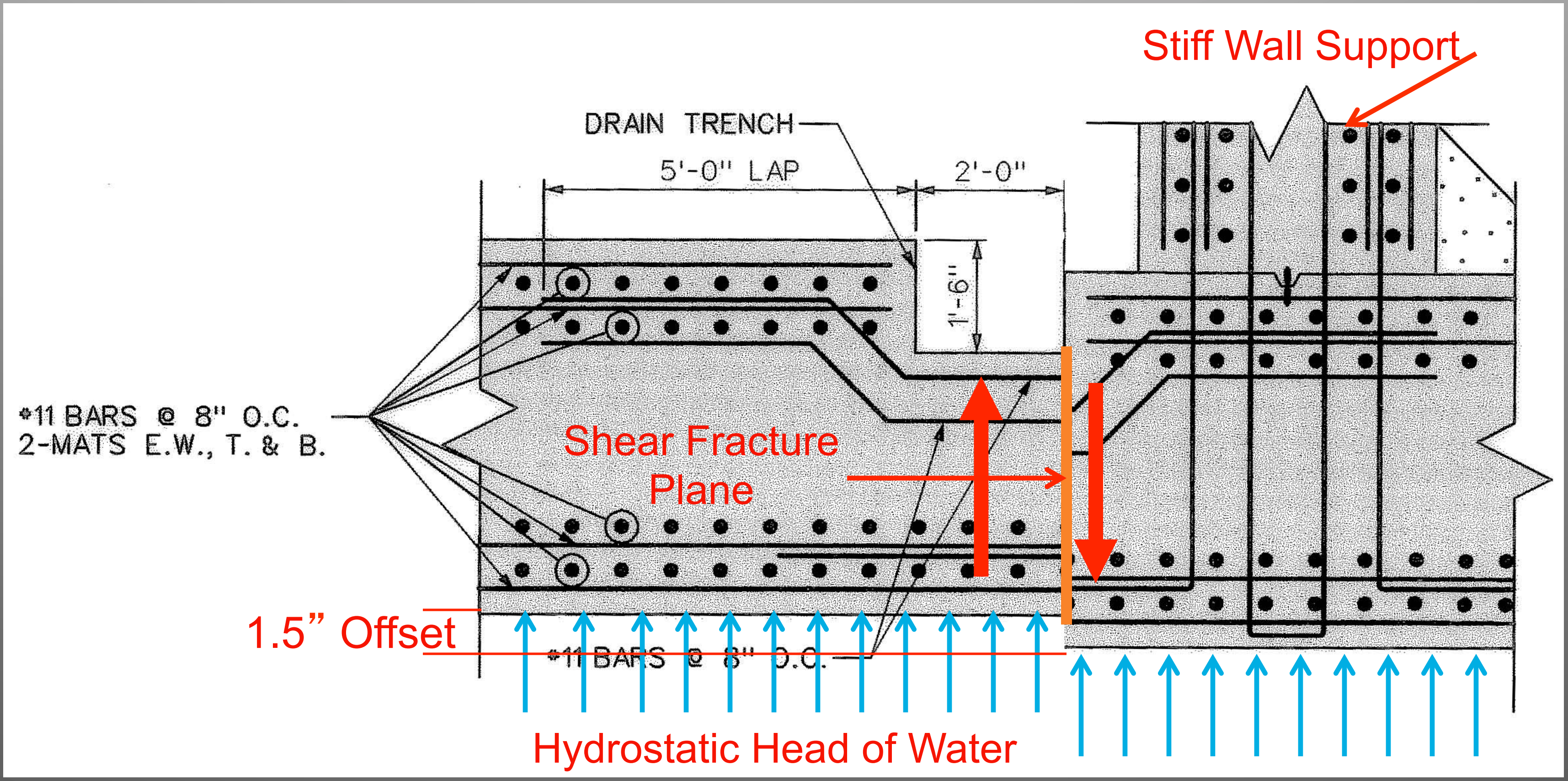
(Compare with text book example)

Damage Survey
Fracture at Interior Trench



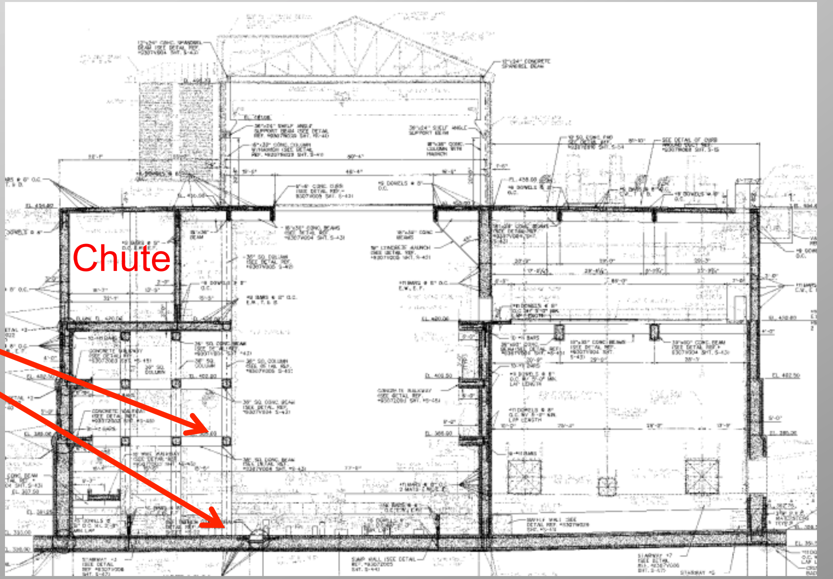
- Mat slab fractured at trench.
- Shear failure
- 1.5” floor level difference across fracture plane.
- Probable yielding of reinforcing at fracture plane.

Damage Survey
Fracture at Interior Trench



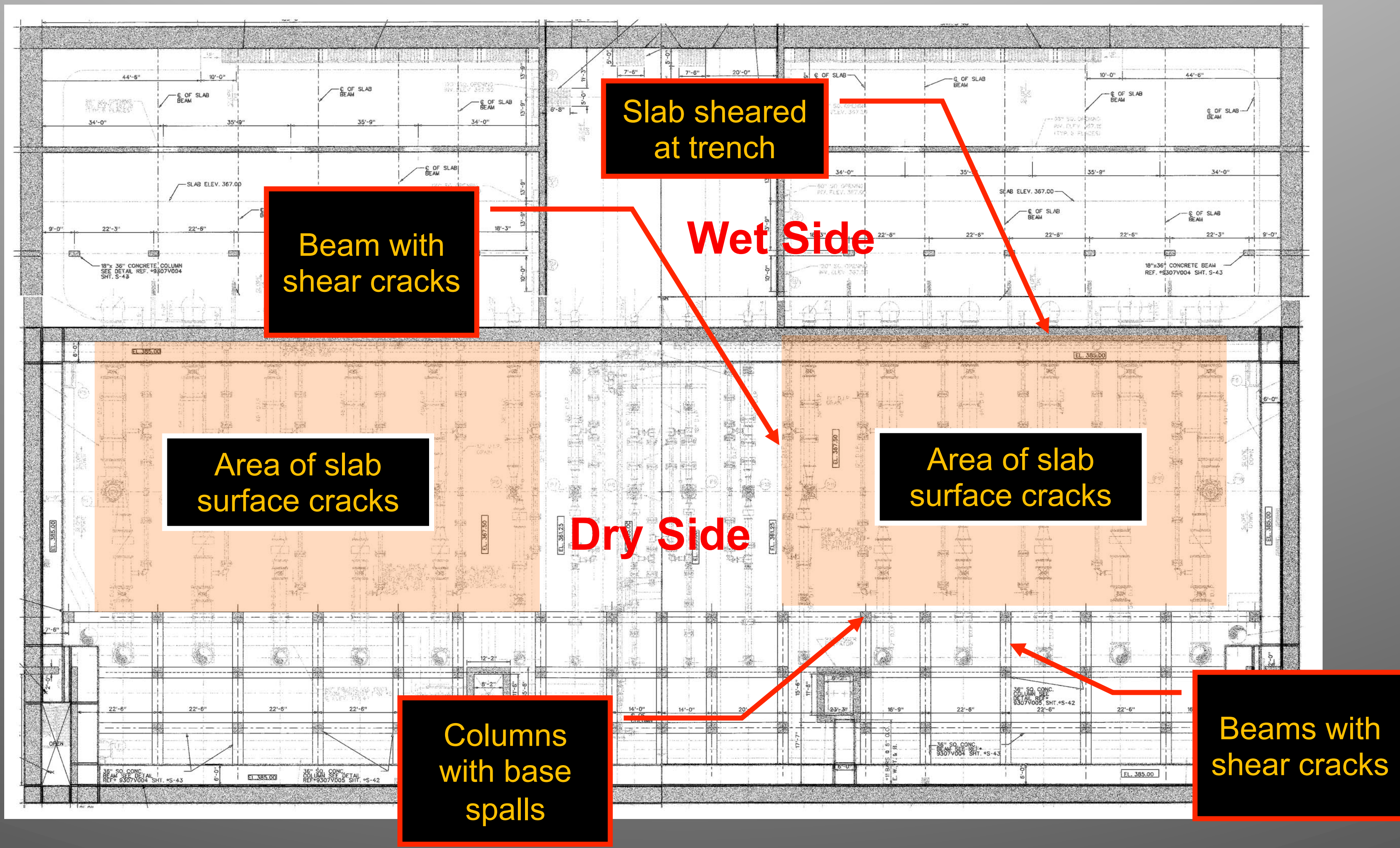
Shear Failure at Reduced (Weak) Section

Damage Survey
Chute Support Frame



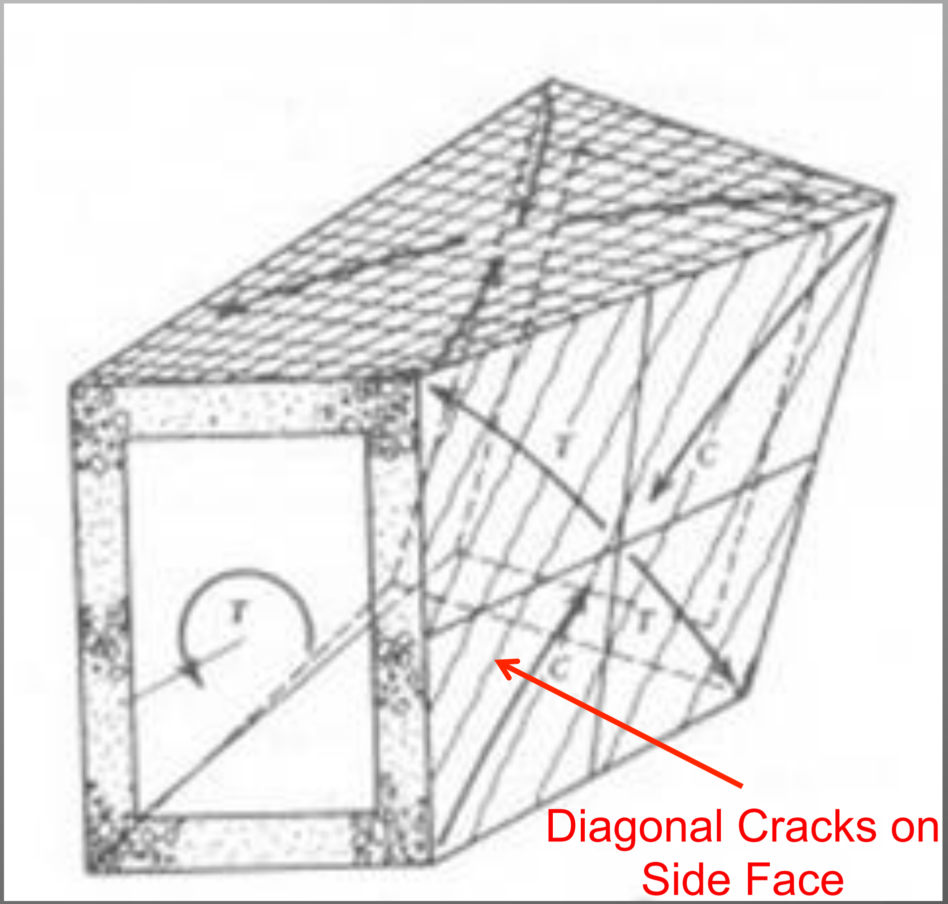
- Observations on 3’x3’ Beams and Columns supporting Chute.
  - Spalls at base of columns.
  - Shear cracks in beams perpendicular to chute axis.
    - Crack widths ranged from hairline to more than 2”.

Damage Survey
Locations of Noted Damage



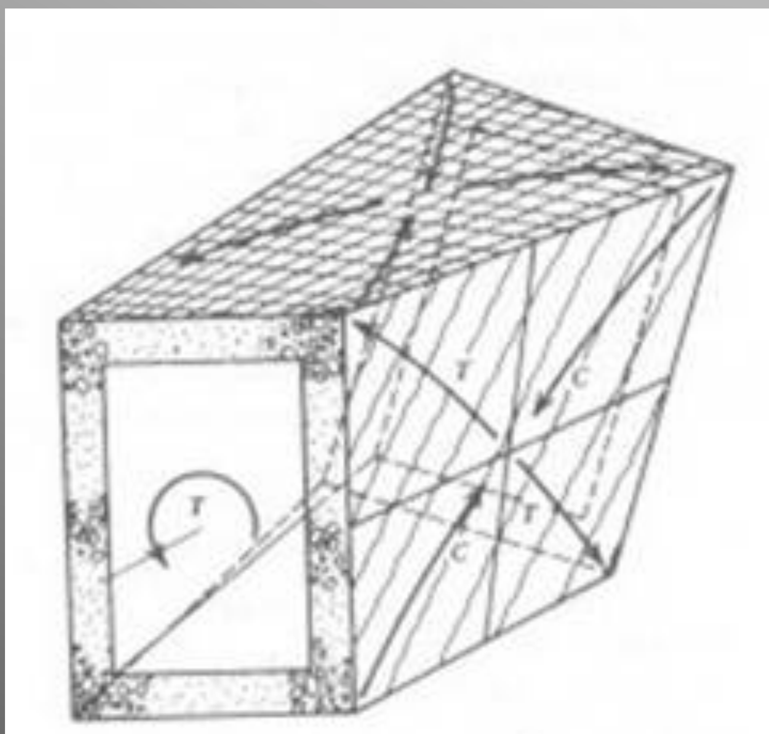
Damage Survey
Torsional Cracking of Chute

- Chute is a hollow square section measuring 35’ X 35’.
- Diagonal cracks found on sides and bottom at both ends (points of restraint).
- Crack patterns similar to torsion cracking of a hollow tube.

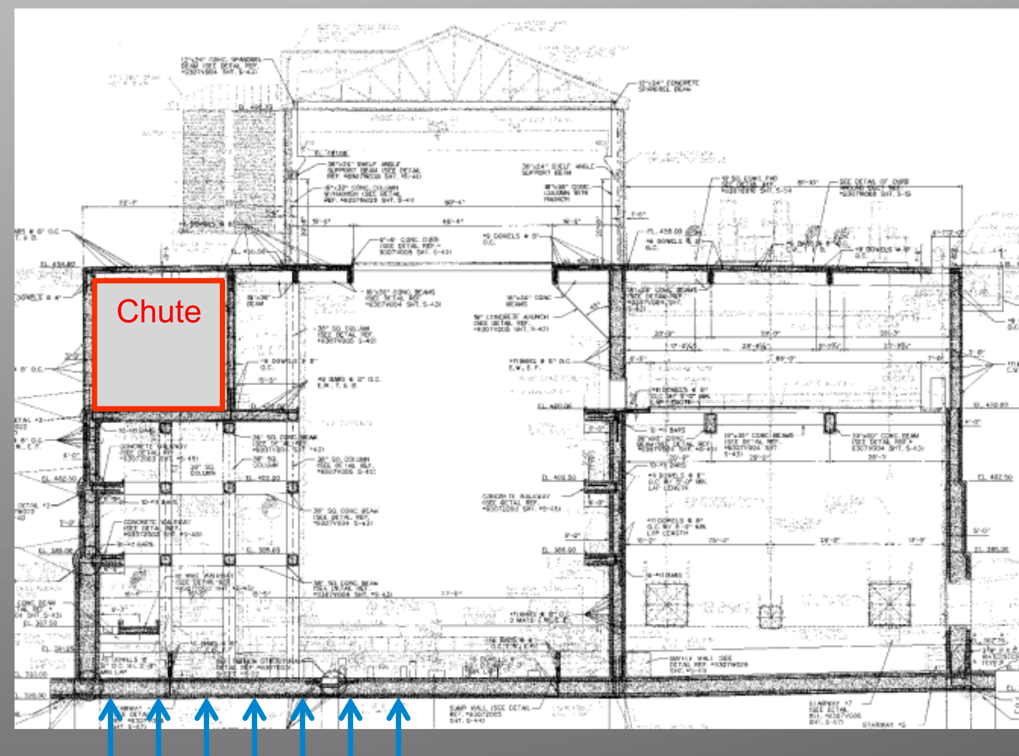


Text Book Example of Torsional Cracking of Hollow Tube

Damage Survey
Torsional Cracking of Hollow Tube and Chute



Text Book Example of Hollow Tube Subjected to Torsional Force

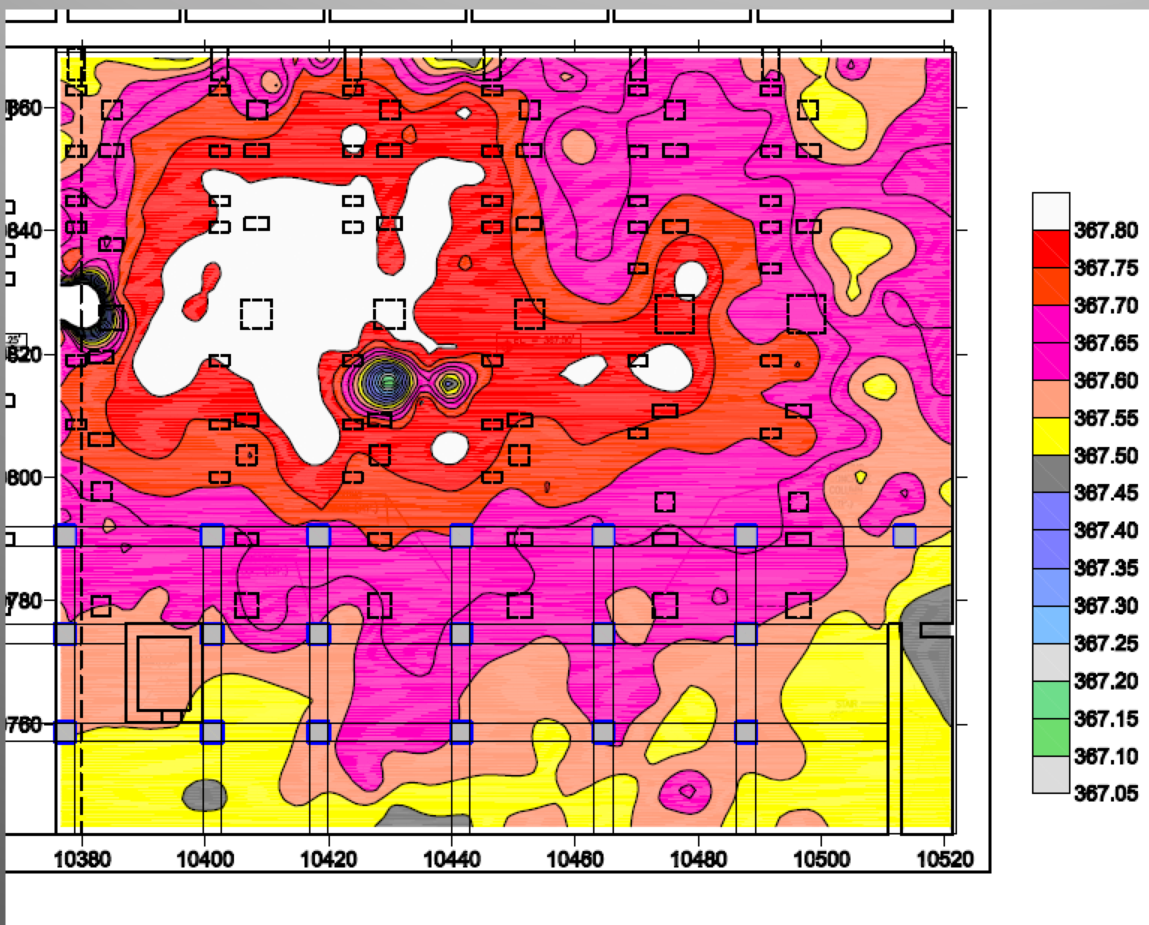


Chute in Vault Subjected to Torsion Due to Upward Force in Mat Slab on Chute Support Frame

Damage Survey
Torsion Cracking of Chute Side Wall

Damage Survey
Torsion Cracking of Chute Bottom Face

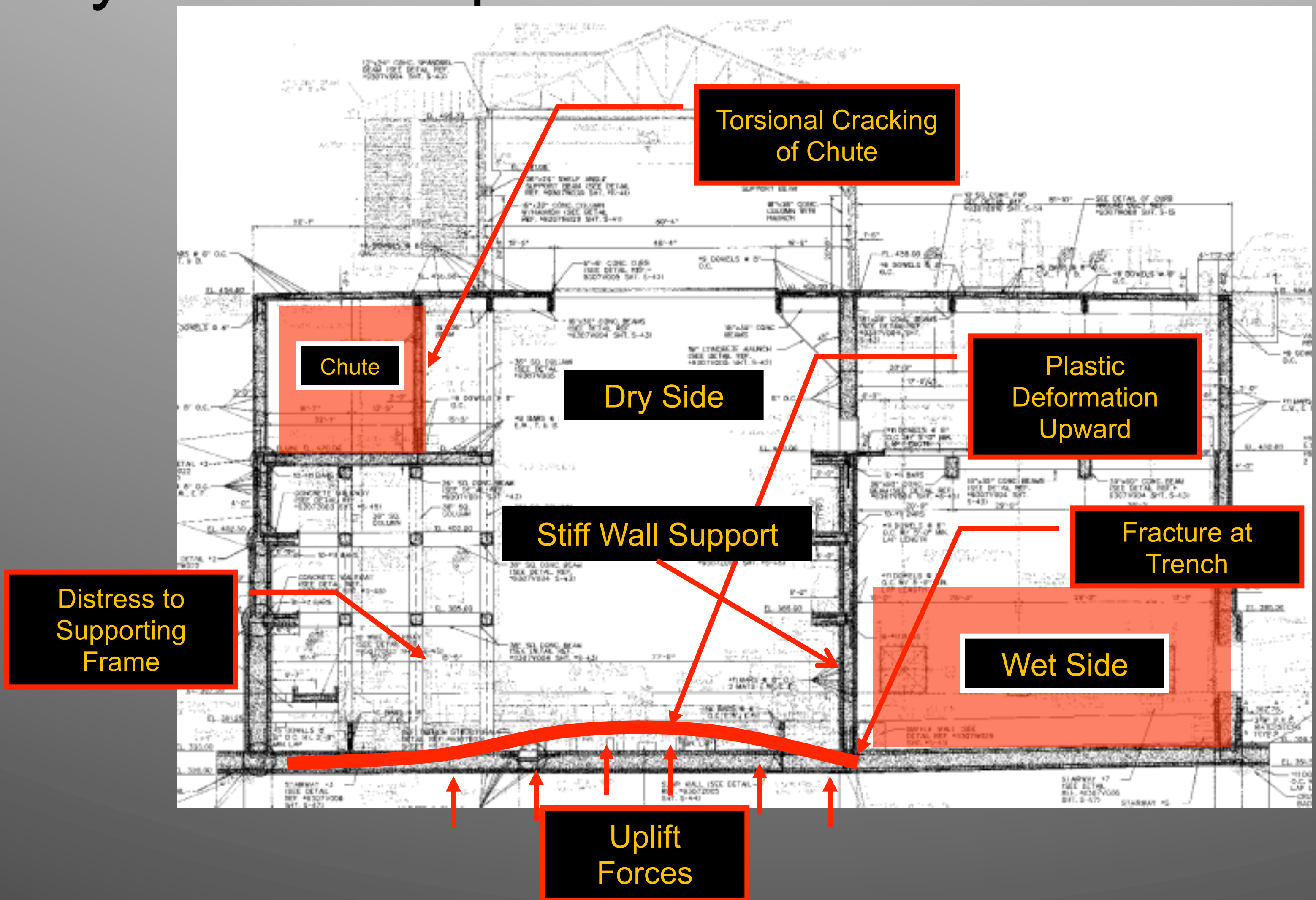

Field Investigation
Floor Level Survey



- 4”-6” of floor level variations from reference floor level.
- 1”-2” permanent heave on dry side.

Failure Mechanism Based on Field Observations

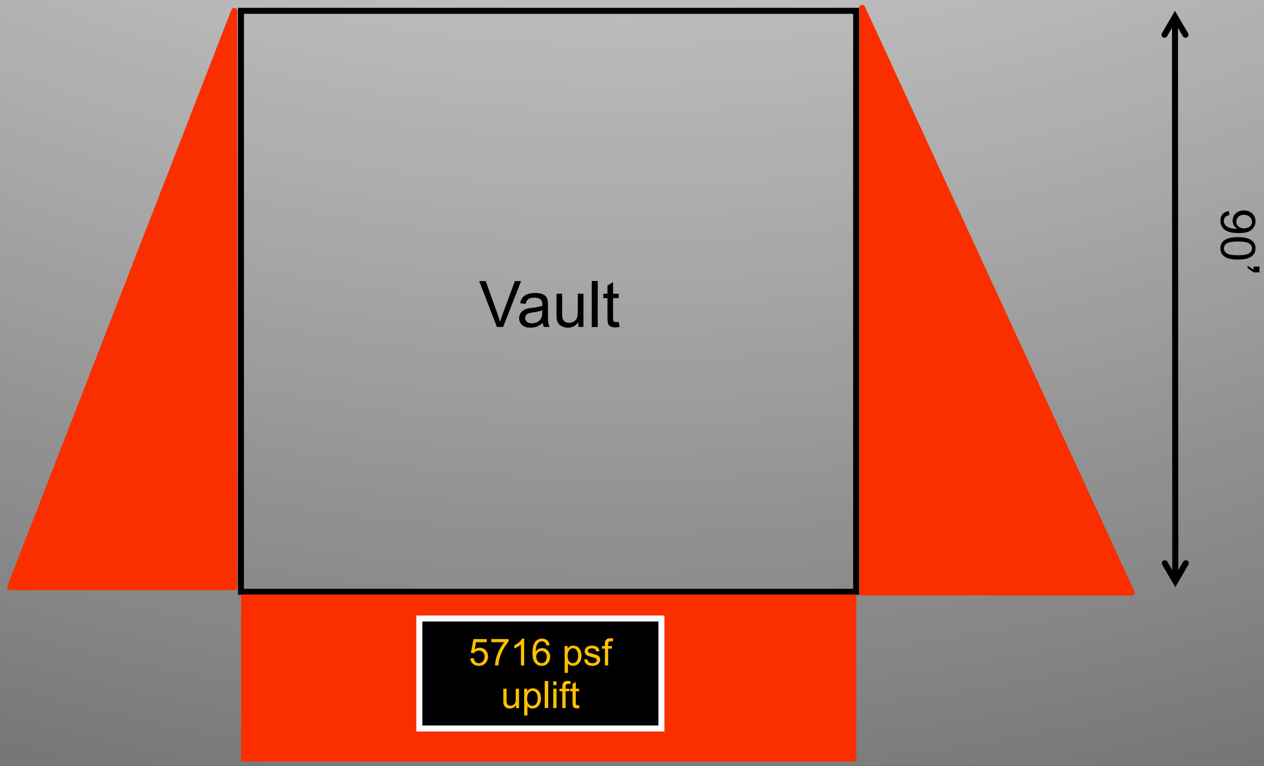
Hydrostatic Uplift



Geotechnical Investigation

- Sinkhole investigation (Not covered in this presentation)
- Groundwater study
- Evaluation of lateral earth loads
- Evaluation of uplift resistance

Geotechnical Investigation
Groundwater Study

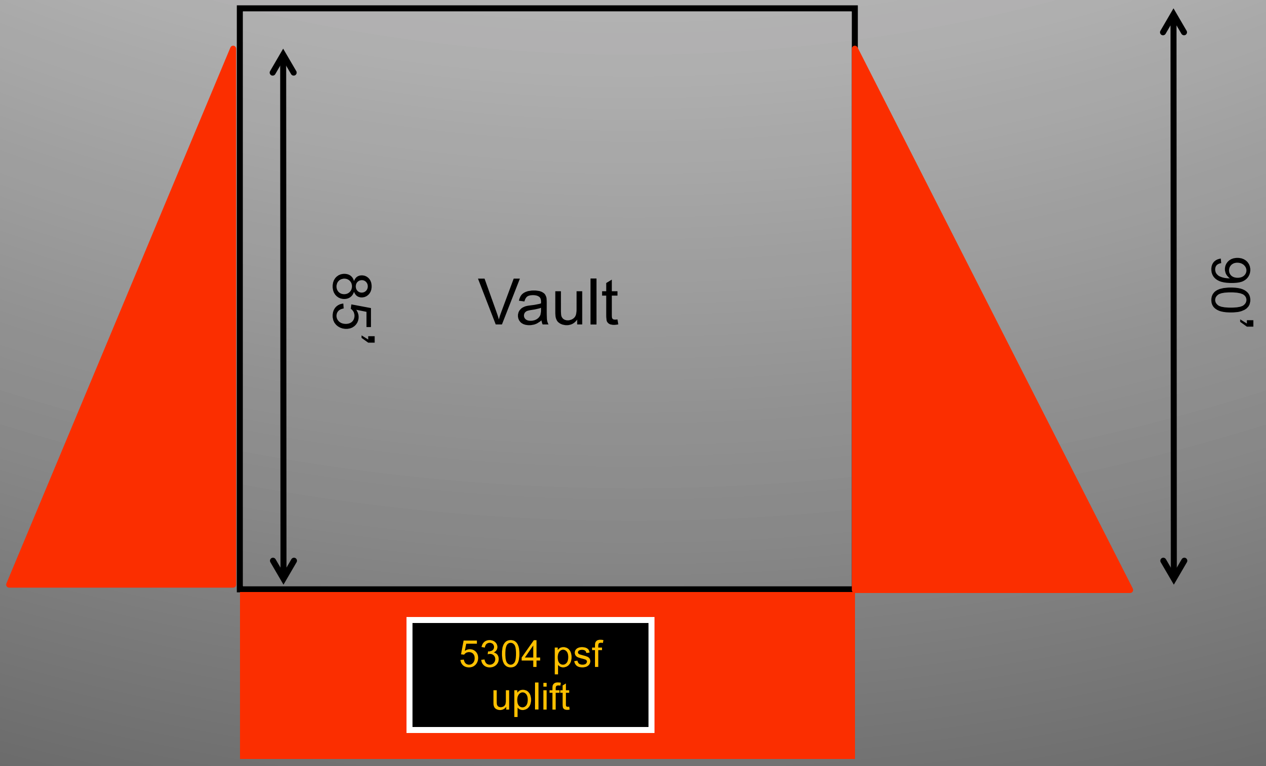


Forensic study – Recommend design condition for base mat slab under hydrostatic loads from groundwater

Groundwater Elevation at Time of Failure

- Groundwater level four days after the failure: 70 feet above the base of the mat slab.
- Groundwater elevation at time of failure: 85 feet above base of mat slab
  - Estimate based on the following
    - Flow of volume of water into vault
    - Porosity of backfill

Groundwater Elevation at Time of Failure



Geotechnical Investigation - Lateral Loads: Earth plus Water

- Original GEOR provided design lateral loads for earth pressure only (not saturated conditions), assuming fully drained backfill: 45 pcf.
- Forensic analysis determined design lateral loads for fully saturated conditions: 82 pcf

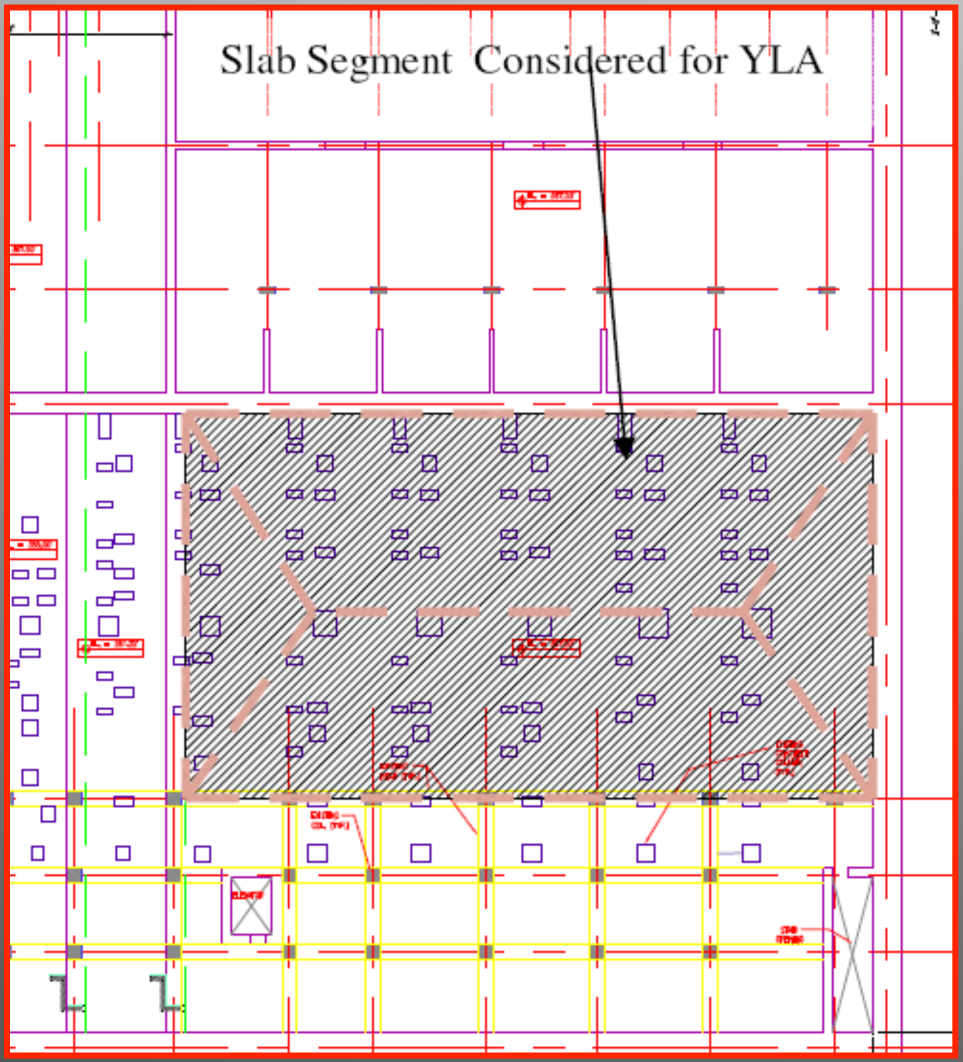
Structural Design Review

- Review of Engineer of Record design calculations
- Only 4 pages of engineering calculations found for perimeter walls
  - Other calculations "lost"
  - Serious errors in calculations in all 4 pages

Structural Design Review

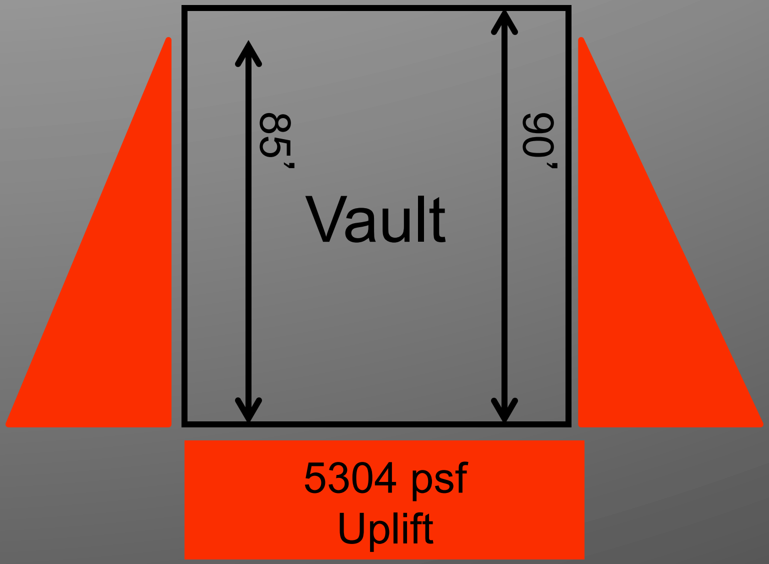
- Slab failure analysis
  - Yield line analysis
  - Finite Element Analysis
- Global structural design review
  - Finite Element Analysis
  - Hand calculations (sanity check)
- Uplift analysis.

Design Review
Yield Line Analysis

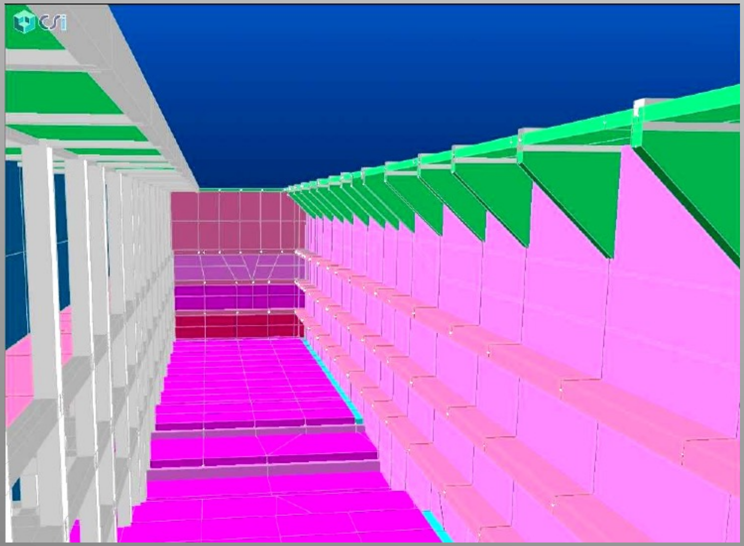


Failure Load

- Calculated failure load of slab: Hydrostatic uplift from ground water 2' below ground surface.
- Estimated groundwater elevation at time of failure: 5' below ground surface.



Design Review - Finite Element Analysis



3-D Finite Element Analysis of entire vault.

- Detailed model considering all structural elements.
- Linear elastic model.
- Considered load cases:
  - Design
  - Failure

Design Review

Finite Element Analysis
Perimeter Wall Forces

Wet Side

Dry (Chute) Side

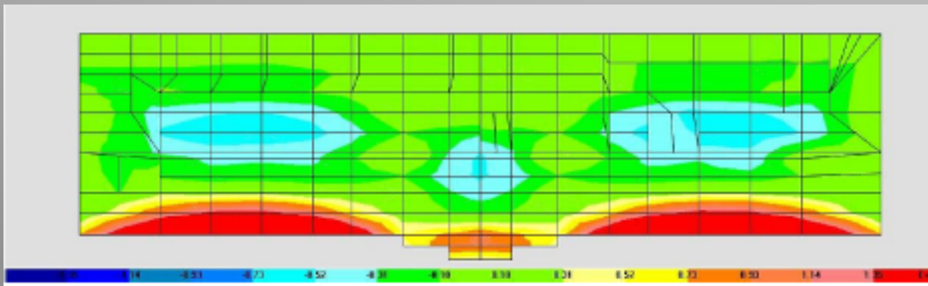


Figure 21. Wet Well Side Retaining Wall Bending Moments (M_{22})

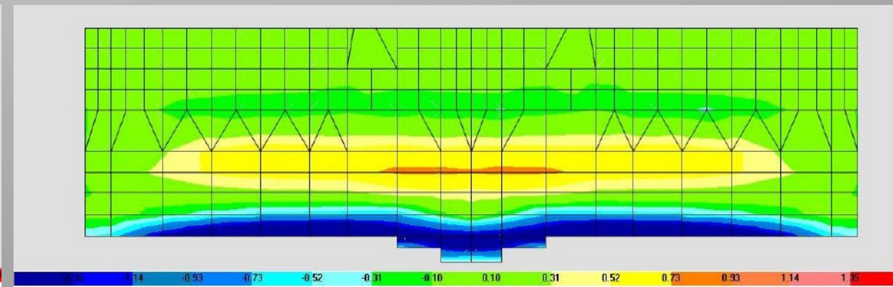


Figure 23. Flume Side Retaining Wall Bending Moments (M_{22})

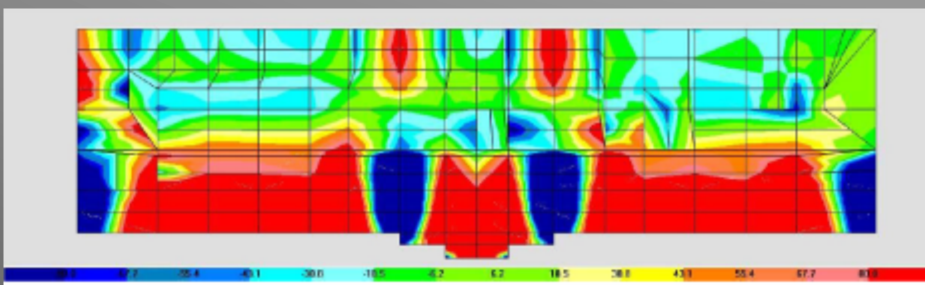


Figure 22. Wet Well Side Retaining Wall Shear Forces (V_{23})

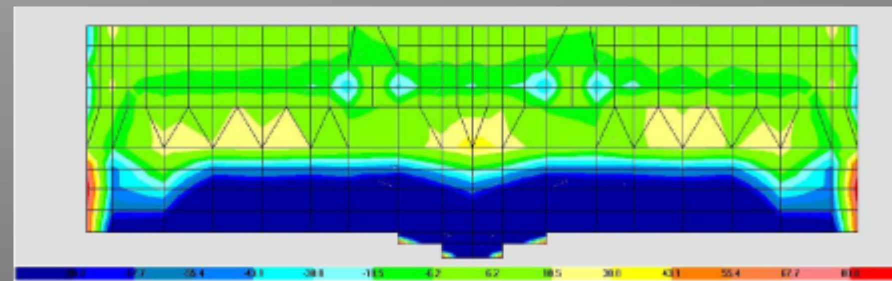


Figure 24. Flume Side Retaining Wall Shear Forces (V_{23})

Forces exceed capacities in zones shaded in dark red and dark blue

Design Review
Finite Element Analysis: Base Mat Slab

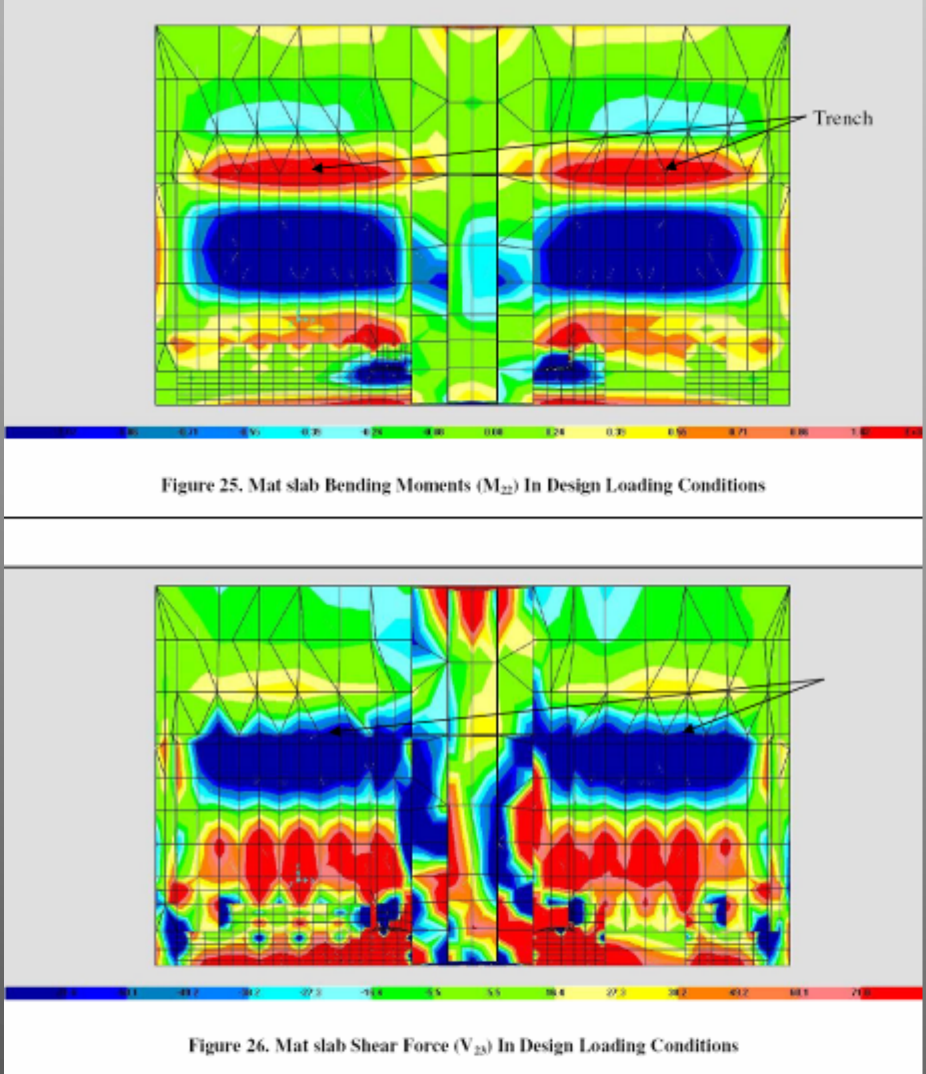


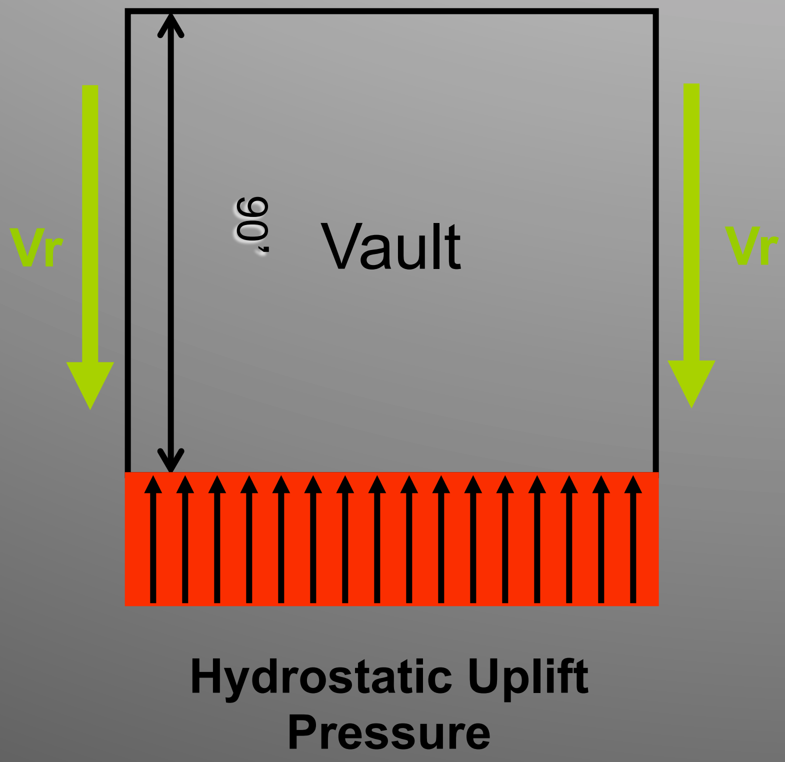
Figure 25. Mat slab Bending Moments (M_{22}) In Design Loading Conditions

Figure 26. Mat slab Shear Force (V_{23}) In Design Loading Conditions

Forces exceed capacities in zones shaded in dark red and dark blue

- Groundwater pressure was applied under the base mat
- Failure condition
  - Along the trench
  - Middle of the slab
  - Under columns

Design Review
Uplift Resistance

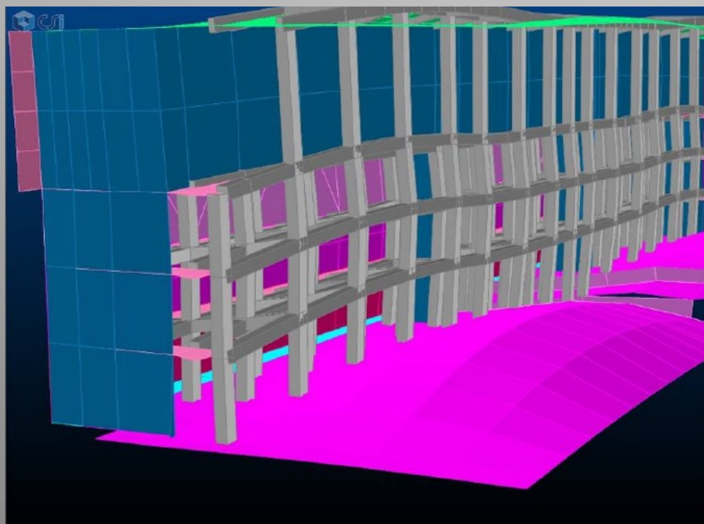


- As designed factor of safety against uplift = 0.5.
- Acceptable design requirements = 1.5.
- Analysis indicates vault would have floated out of the ground if the base mat had not failed.
  - Failure relieved external water pressure.

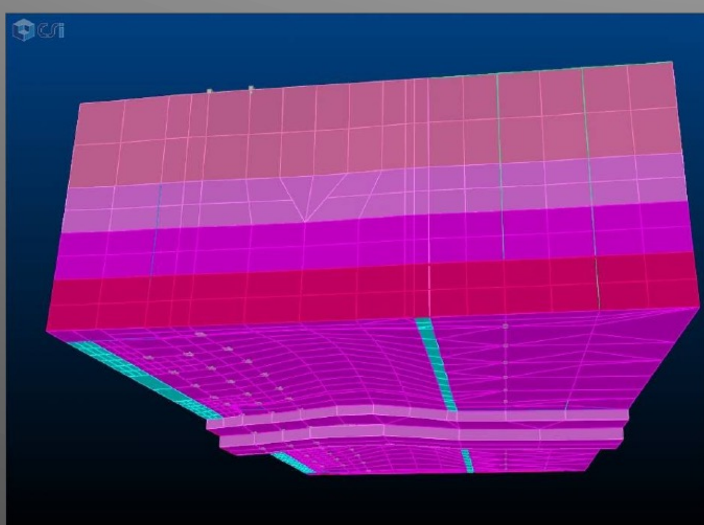
Design Review
Conclusions and Recommendations

- Wastewater treatment vault not properly designed to resist applied design forces.
  - Perimeter Walls: Not designed adequately to resist shear from lateral earth pressures.
  - Base Mat: Not properly designed to resist uplift forces from groundwater.
  - Chute Support Frame: Not properly designed to accommodate lateral displacement of perimeter wall.
  - Structure as a Whole: Not properly designed to resist uplift forces.

Failure Analysis
Uplift from Hydrostatic Forces



Note Frame Racking and Chute Torsion



Note Slab Heave

- Groundwater pressure applied under the base mat.
- Analysis results:
  - Slab heave
  - Racking of frame
  - Torsion of chute
- Results very consistent with observed distress conditions.

Failure Analysis
FE Analysis/Base Mat Heave (Text Book Case)

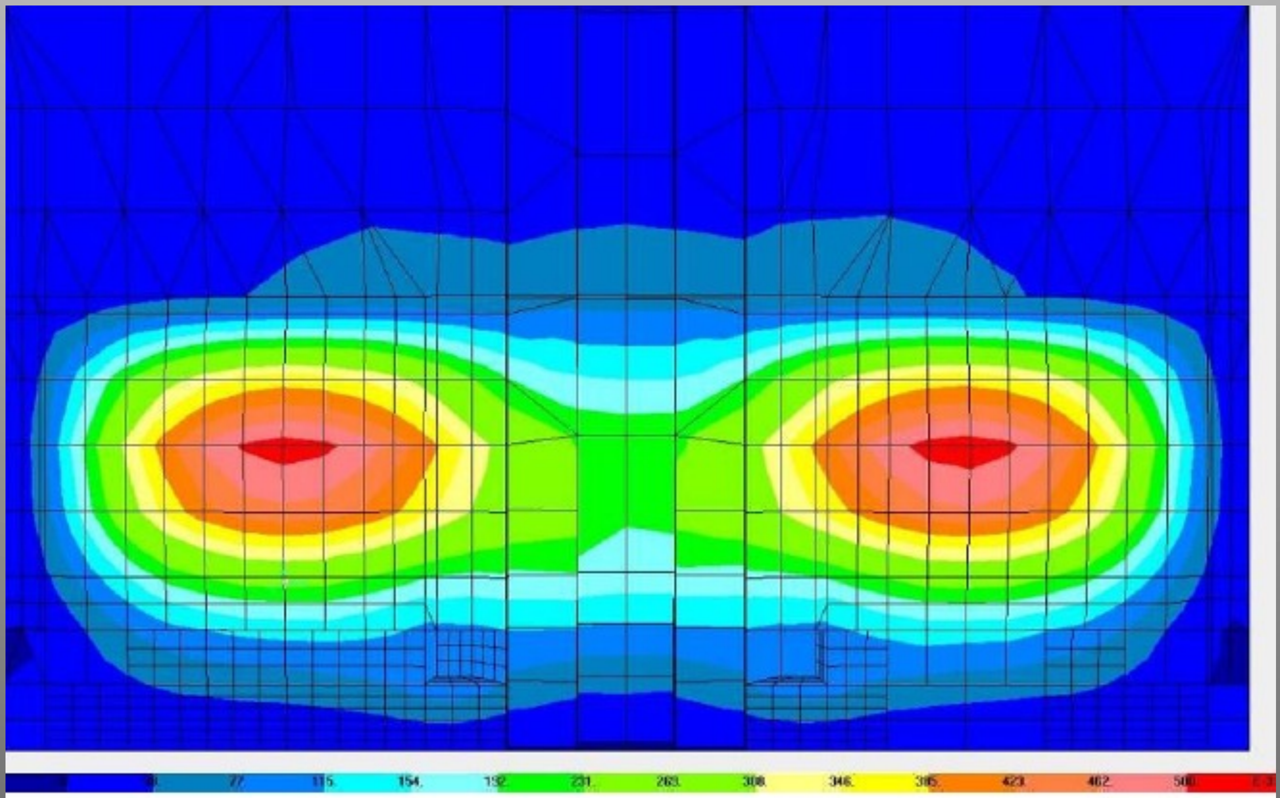


Figure 29. Vertical Displacement Contours of the Mat slab During Failure

Analytical Study Model

Failure Analysis

Base Mat Slab

Compare "Text Book" Example with Field Observation

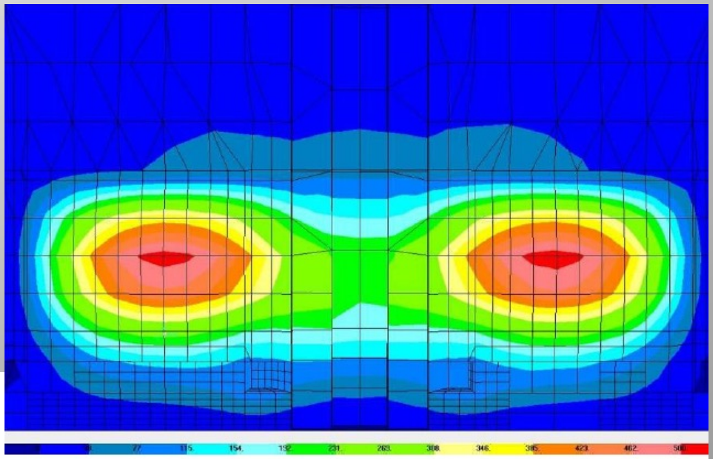


Figure 29. Vertical Displacement Contours of the Mat slab During Failure

Analytical Study Model

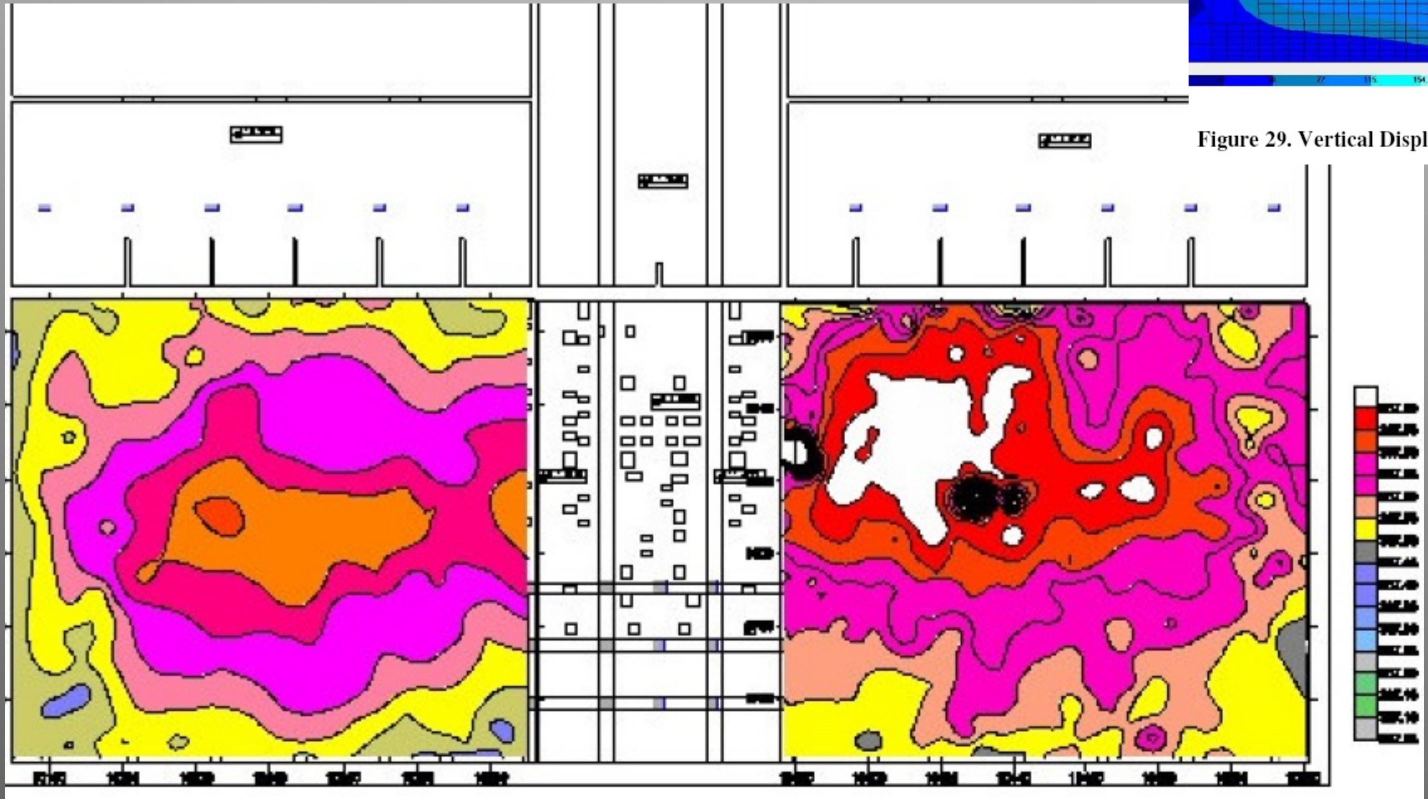


Figure 30. Measured Heave Contours of the Mat slab (See Appendix A)

Base Mat Contour Survey

Failure Analysis
Finite Element Analysis: Base Mat

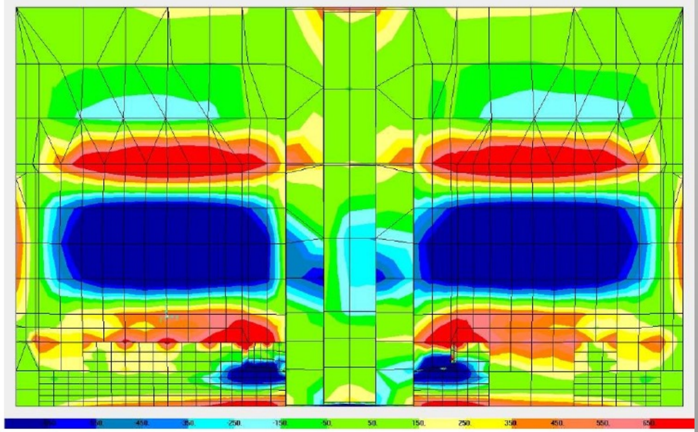


Figure 31. Mat slab Bending Moments (M_{22}) In Failure Loading Conditions

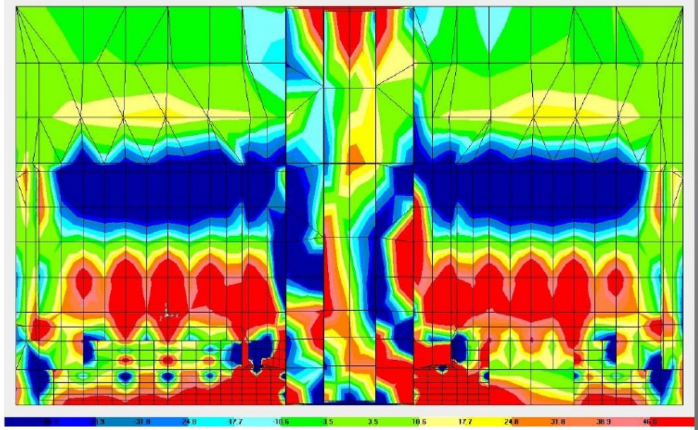


Figure 32. Mat slab Shear Force (V_{23}) In Failure Loading Conditions

Forces exceed capacities in zones shaded in dark red and dark blue

- Groundwater pressure was applied under the base mat
- Locations of failure conditions are in general agreement with field observations.

Failure Analysis
Conclusions

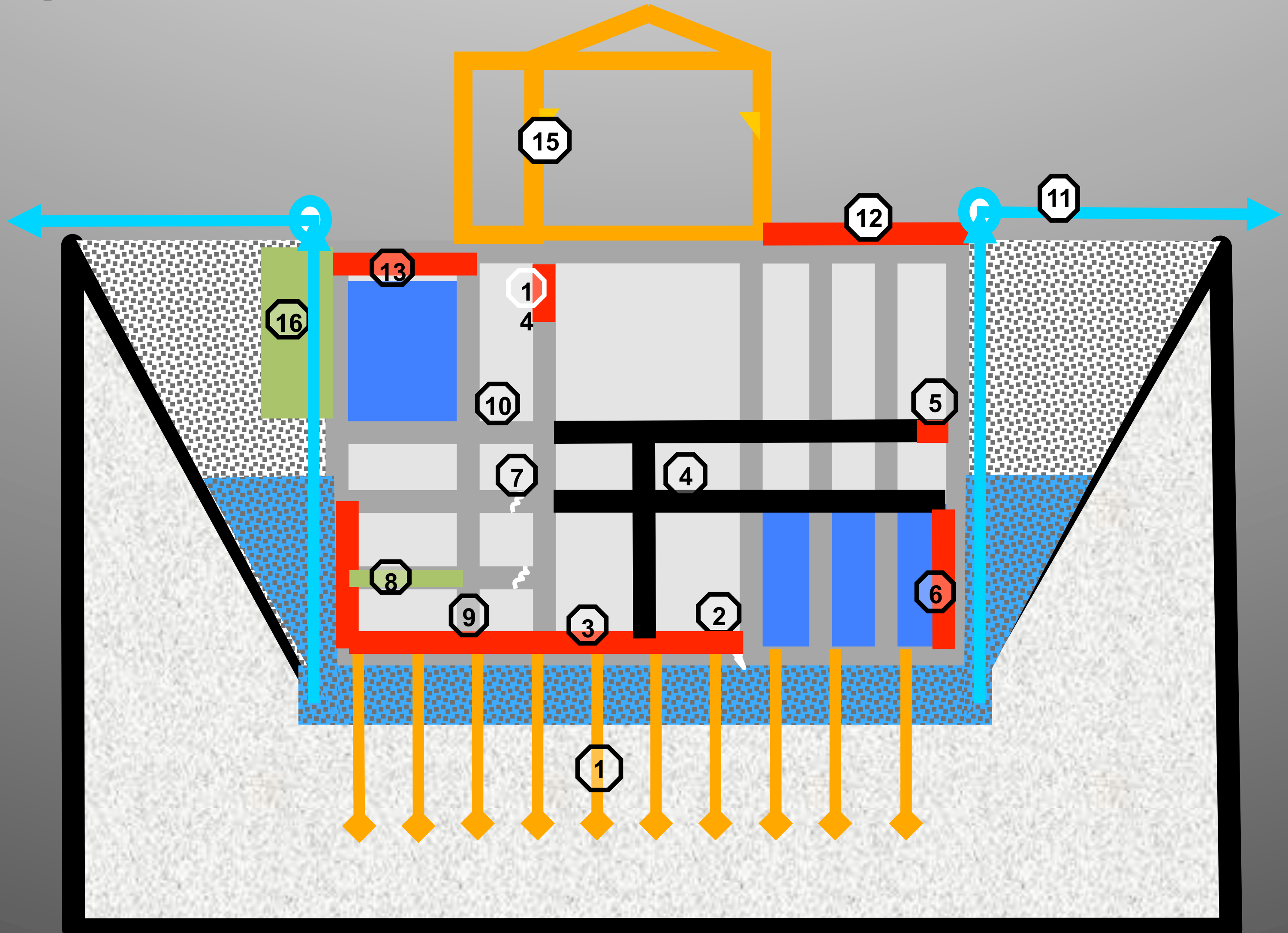
- Failure of the base mat: Due to uplift forces from groundwater.
- Groundwater elevation at time of failure: Near the ground surface.

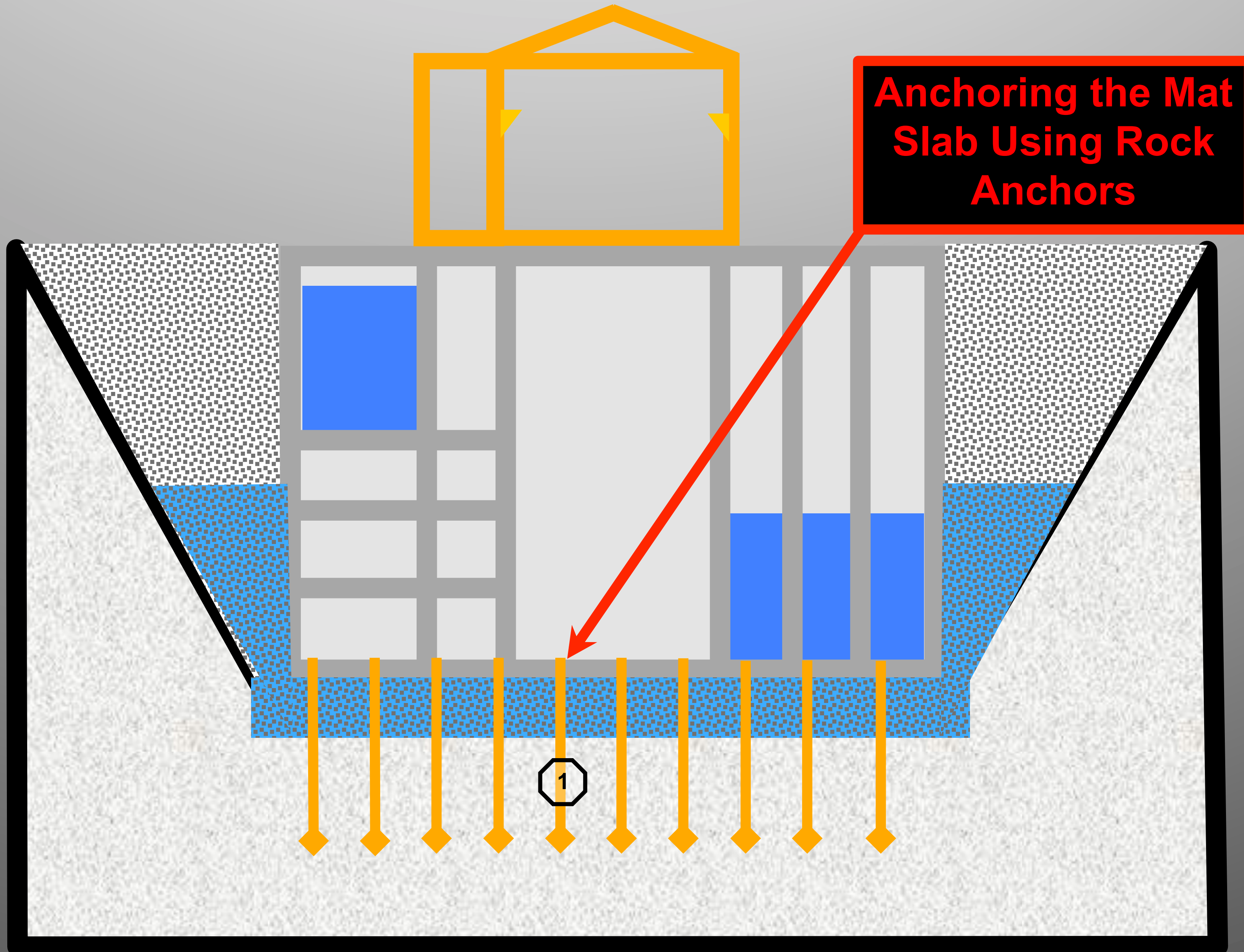
Conclusions

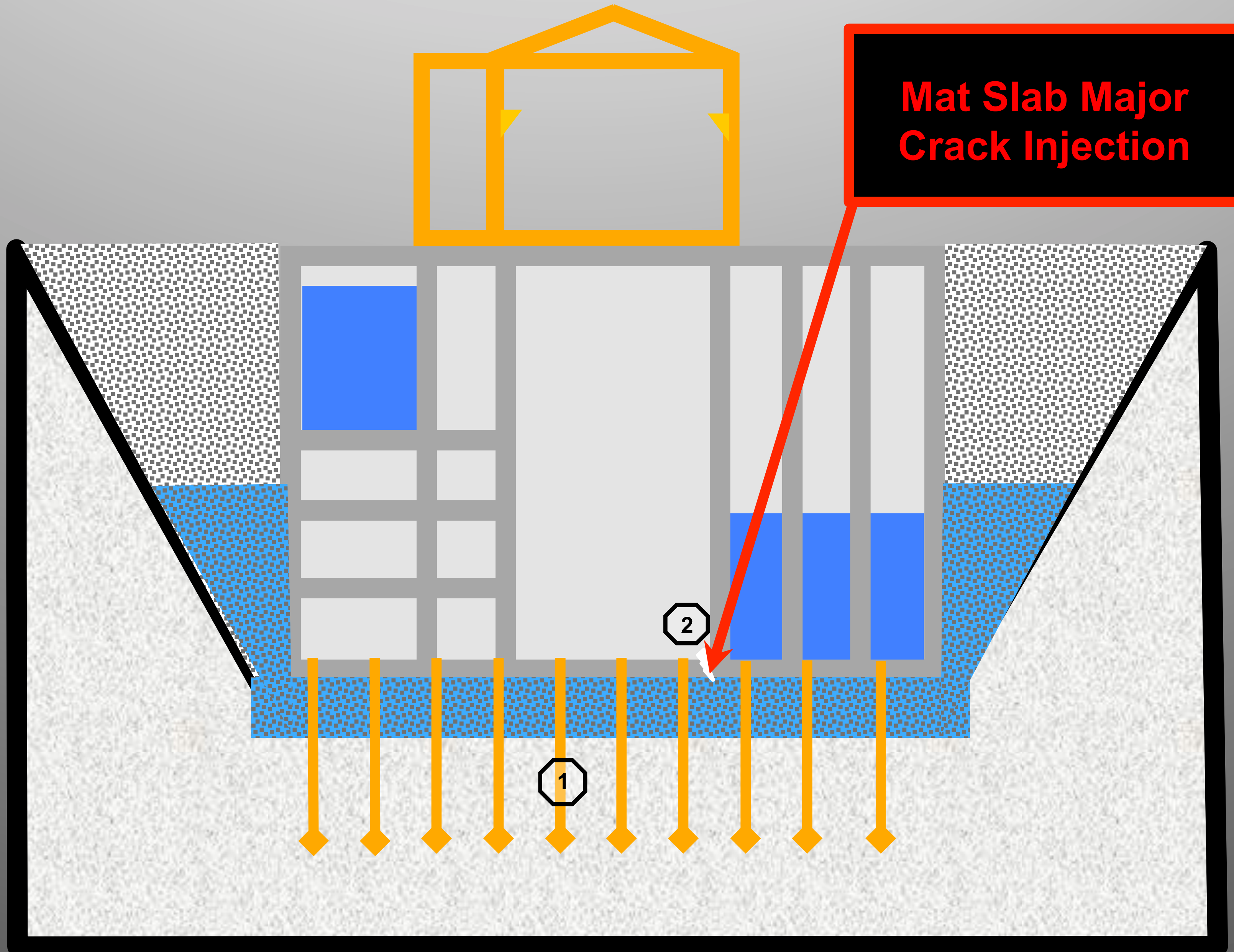
- Structure inadequately designed to resist:
  - Lateral earth pressure
  - Groundwater pressure on sides or bottom.
  - Uplift forces.
- Structure failed
- Repair completed by April 2008

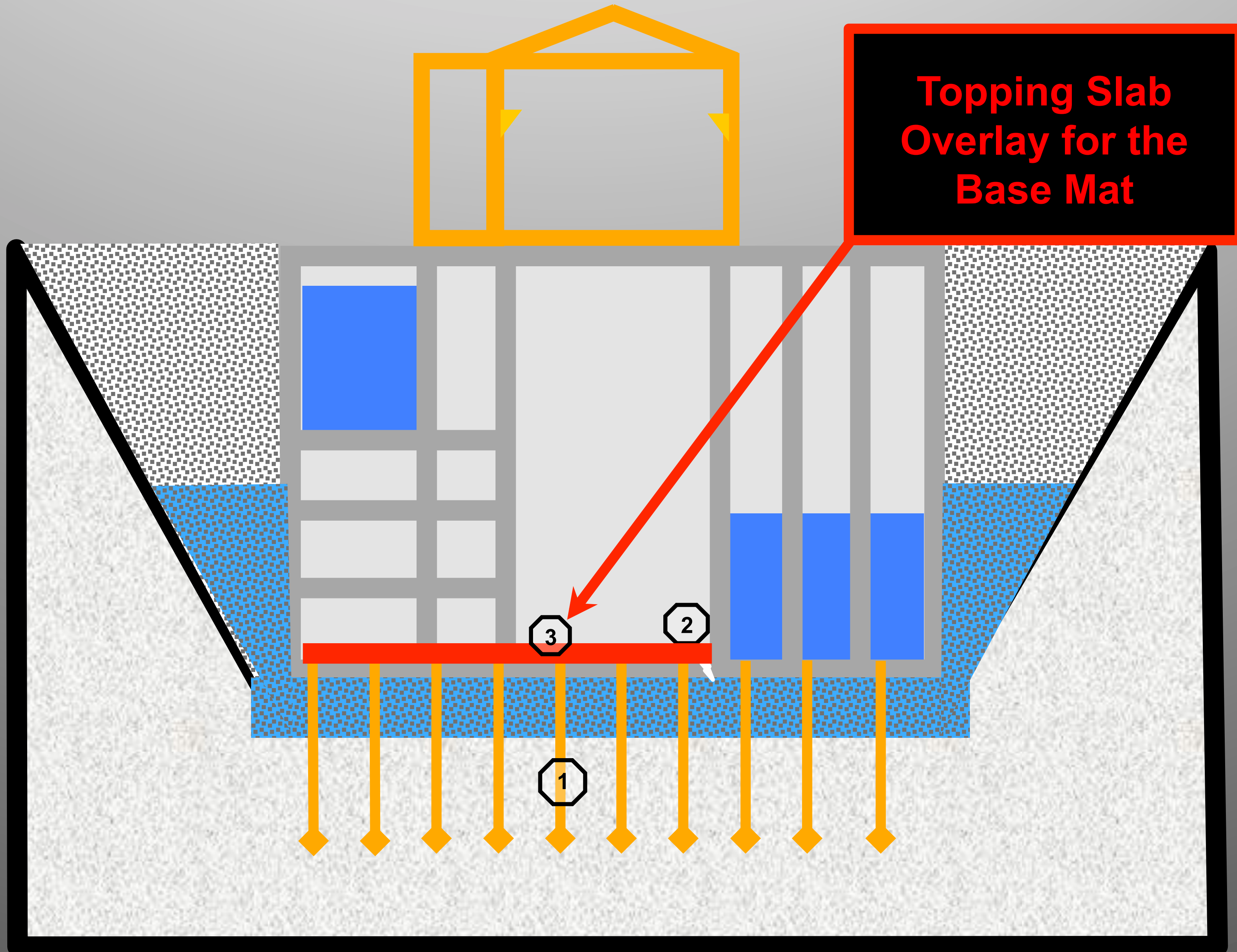
Some Repair Highlights

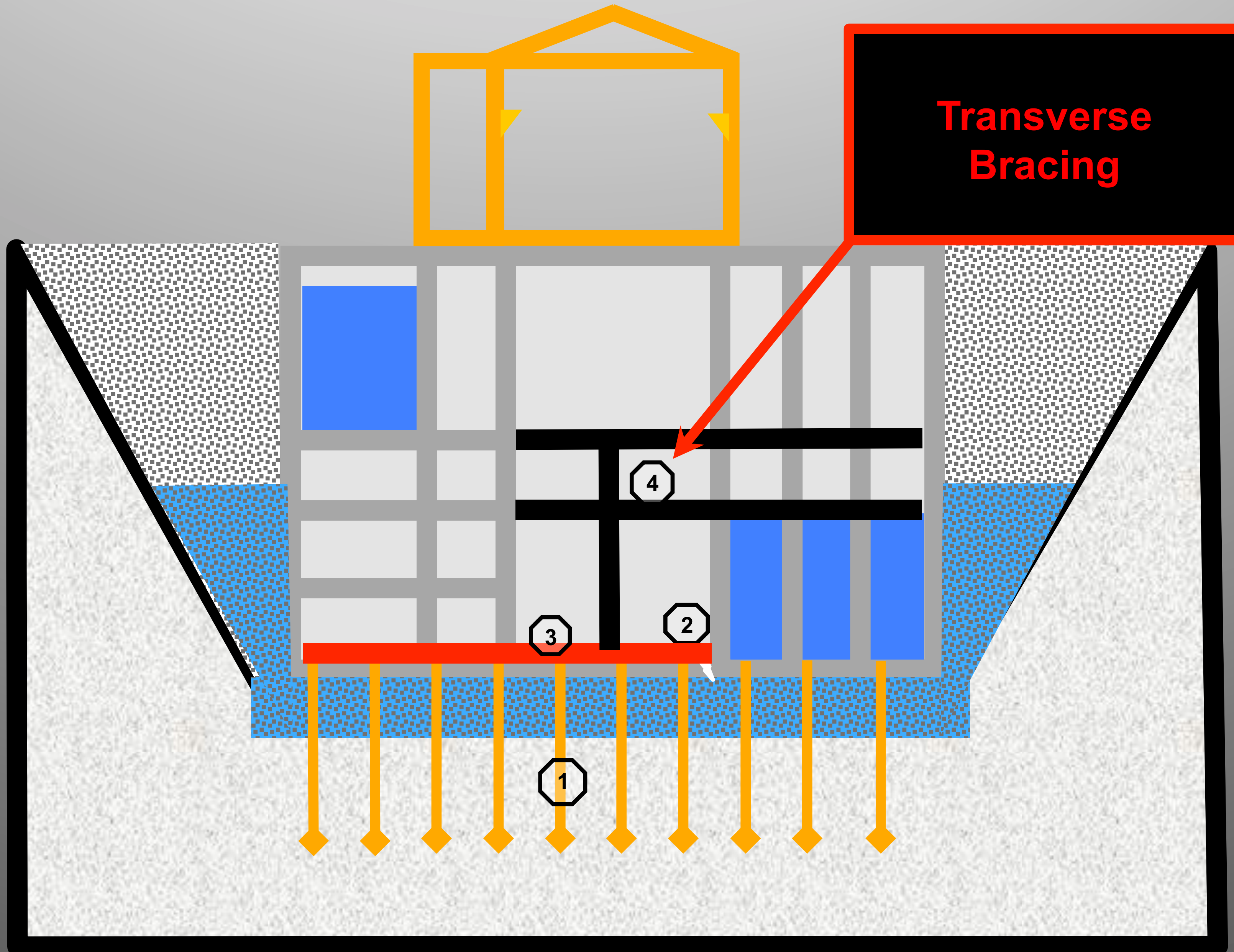
Repairs



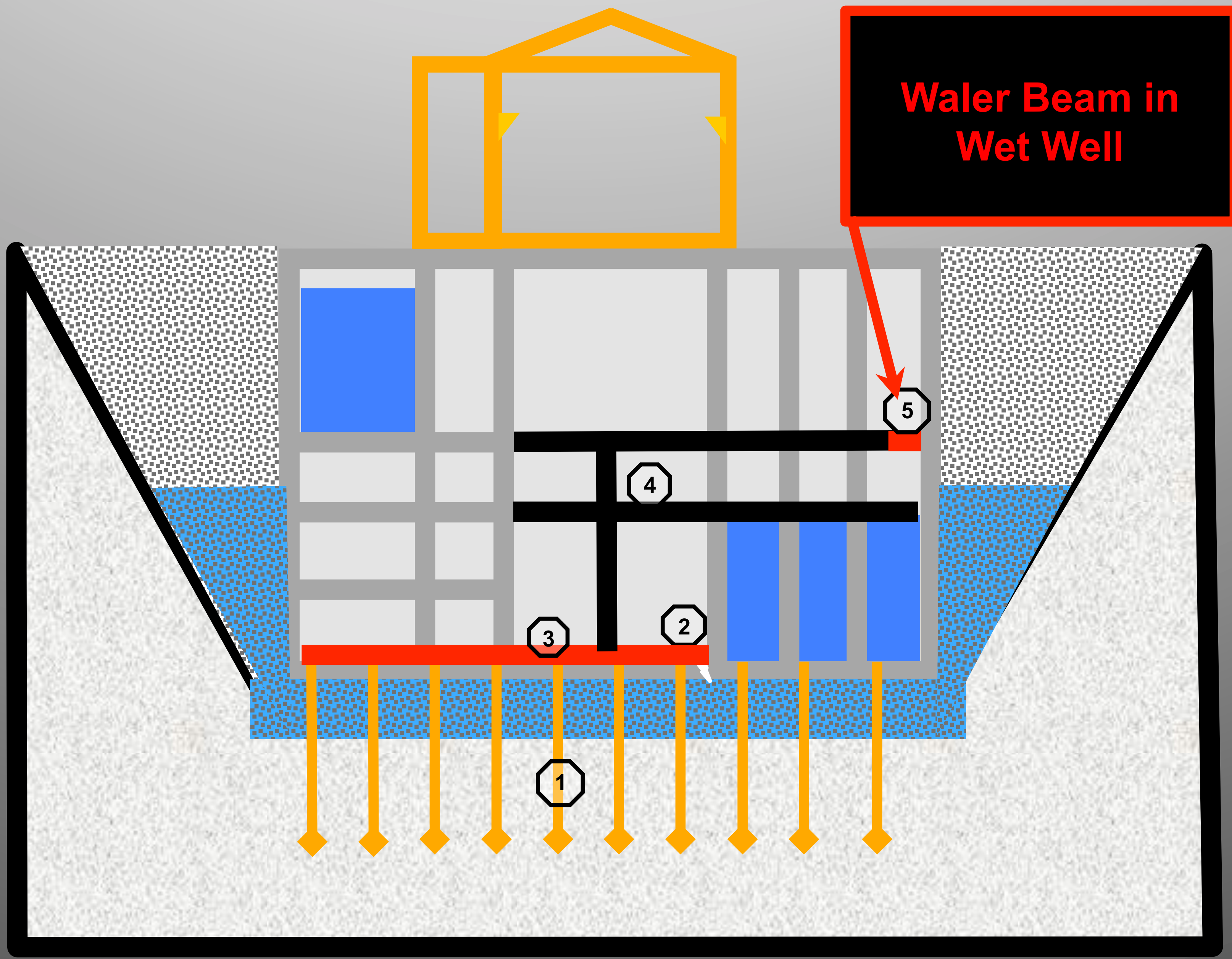

Anchoring the Mat Slab Using Rock Anchors
1

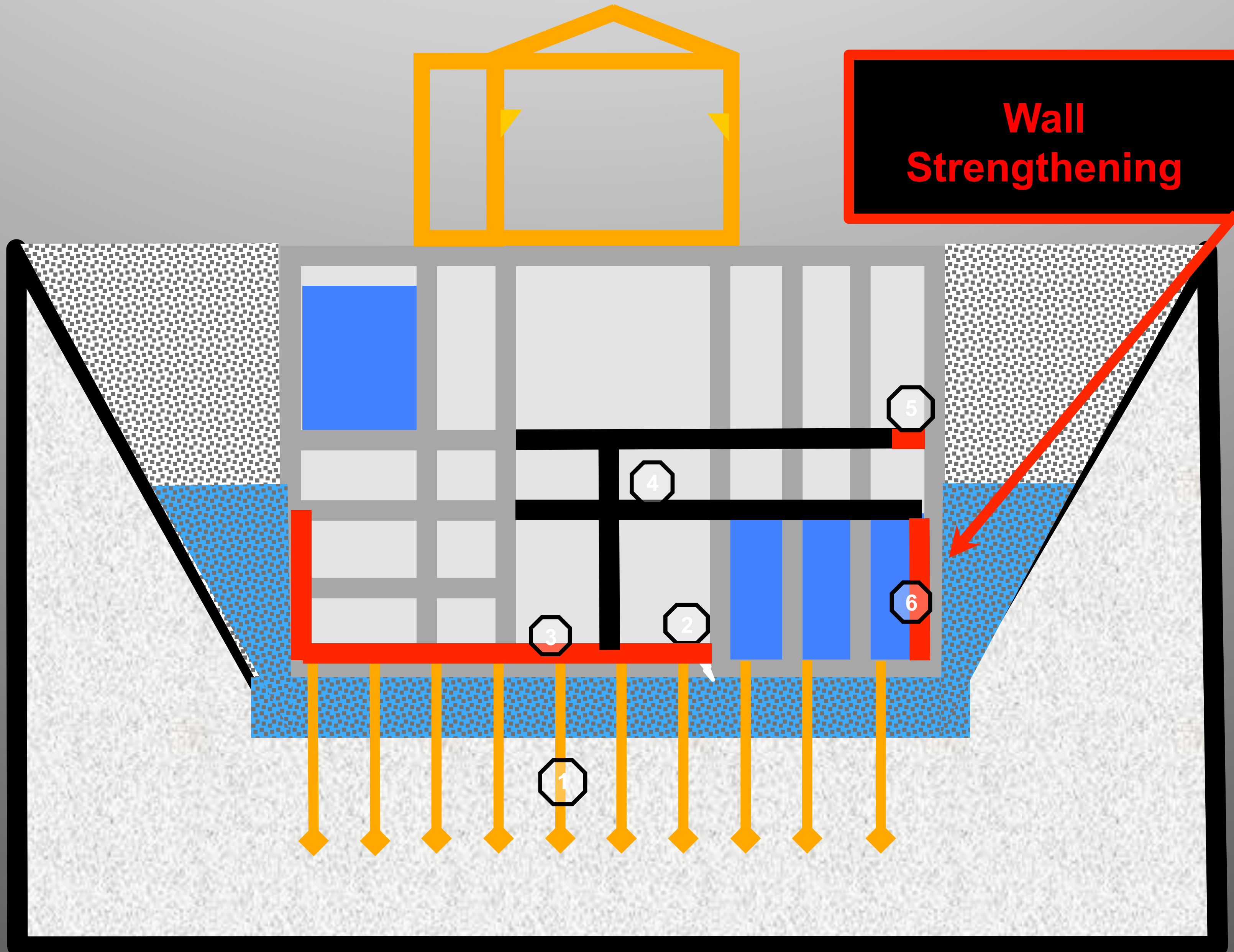

Mat Slab Major Crack Injection
2
1


Topping Slab
Overlay for the
Base Mat
3
2
1

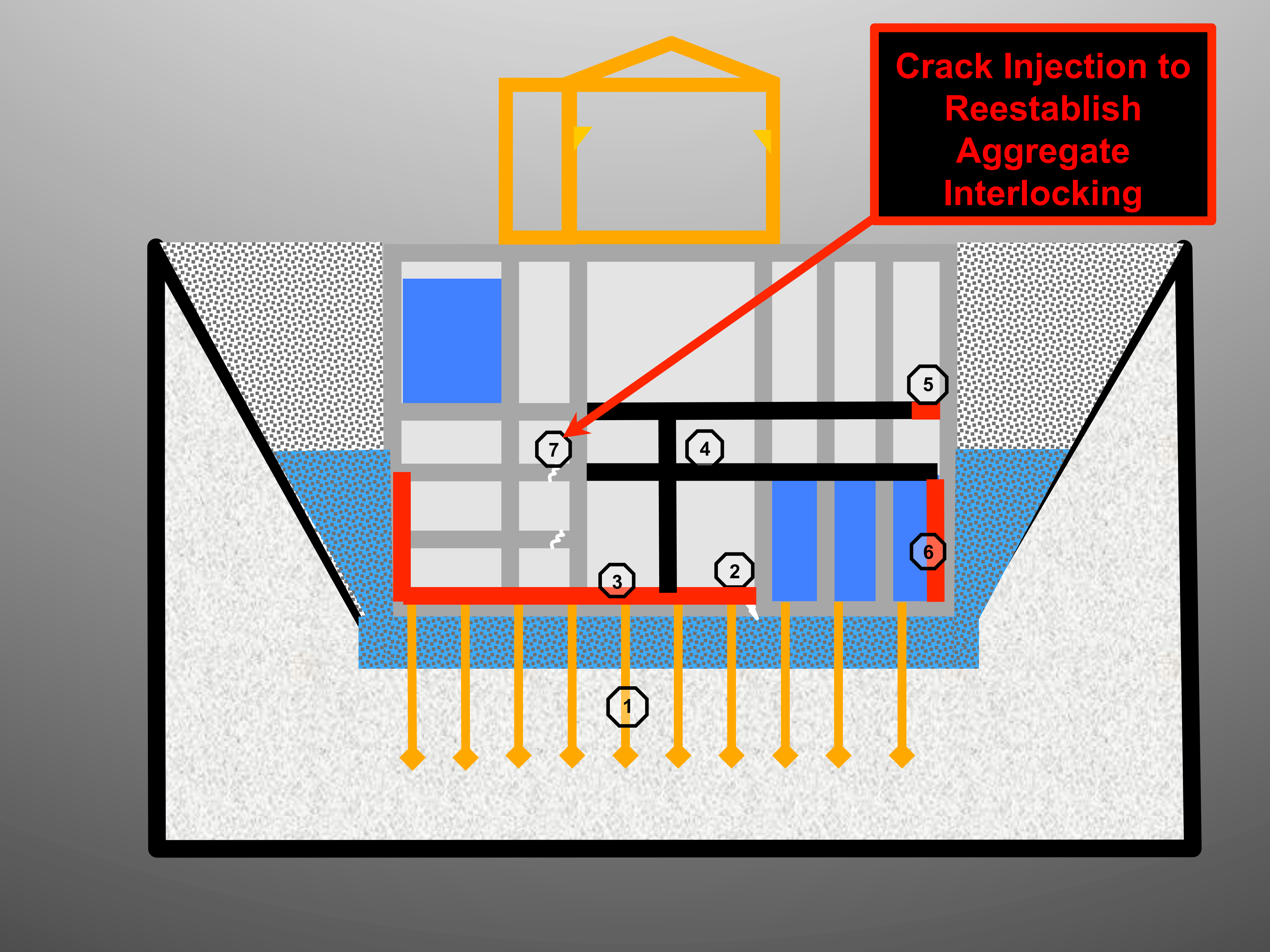


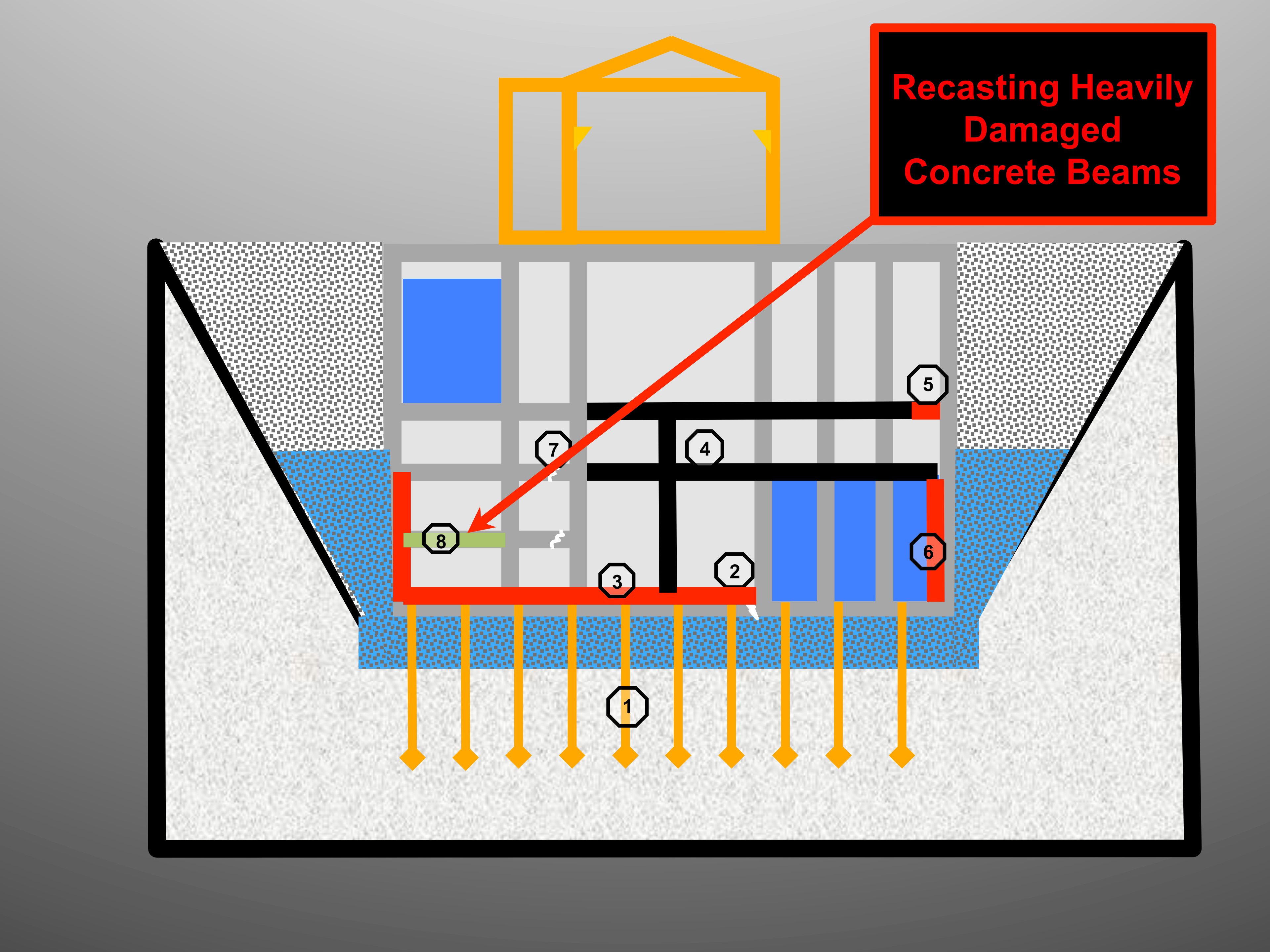
Transverse Bracing
4
3
2
1


Waler Beam in Wet Well
5
4
3
2
1



Wall Strengthening
5
4
3
2
6
1


Crack Injection to Reestablish Aggregate Interlocking
5
7
4
6
3
2
1



Recasting Heavily Damaged Concrete Beams
5
7
4
8
6
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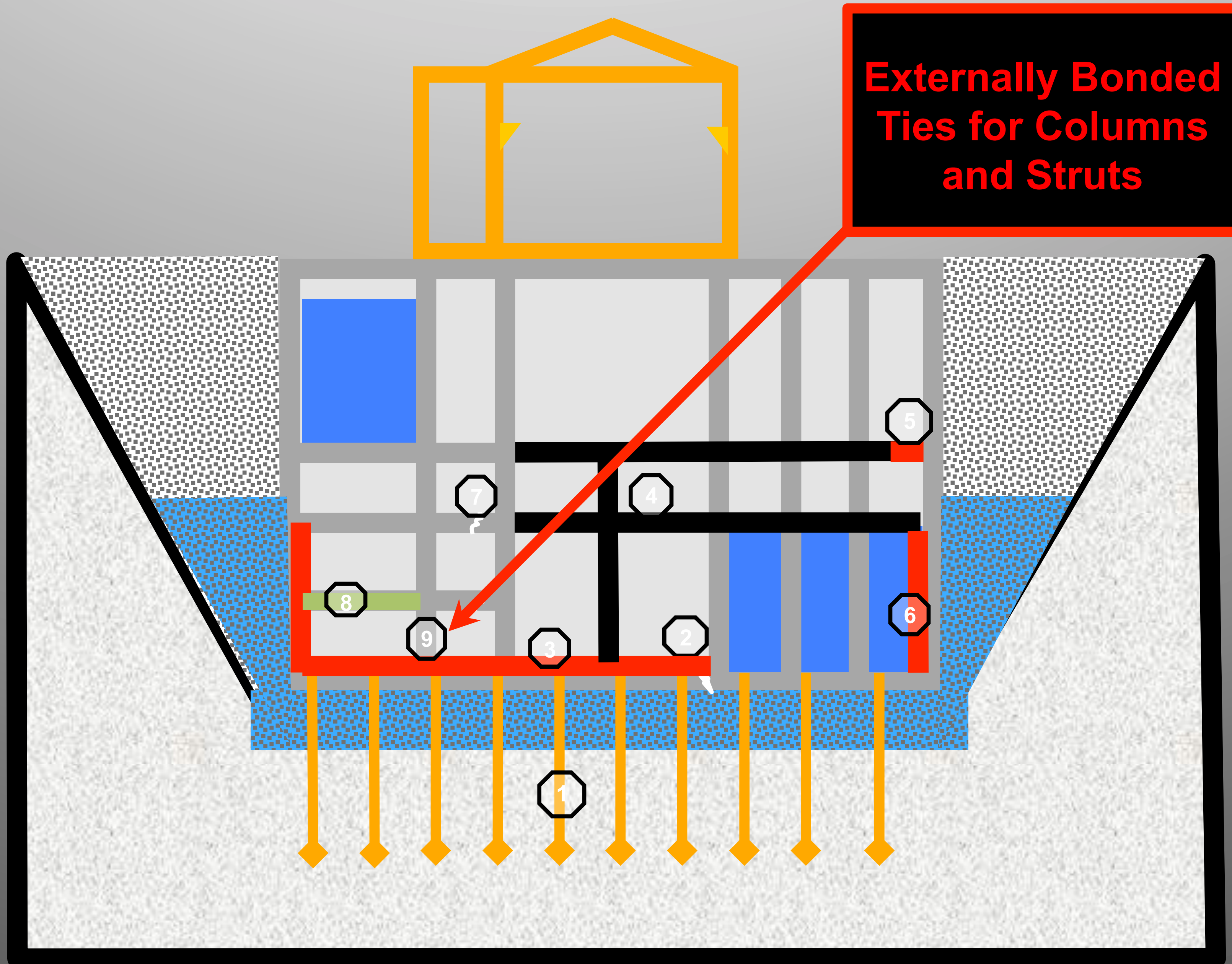
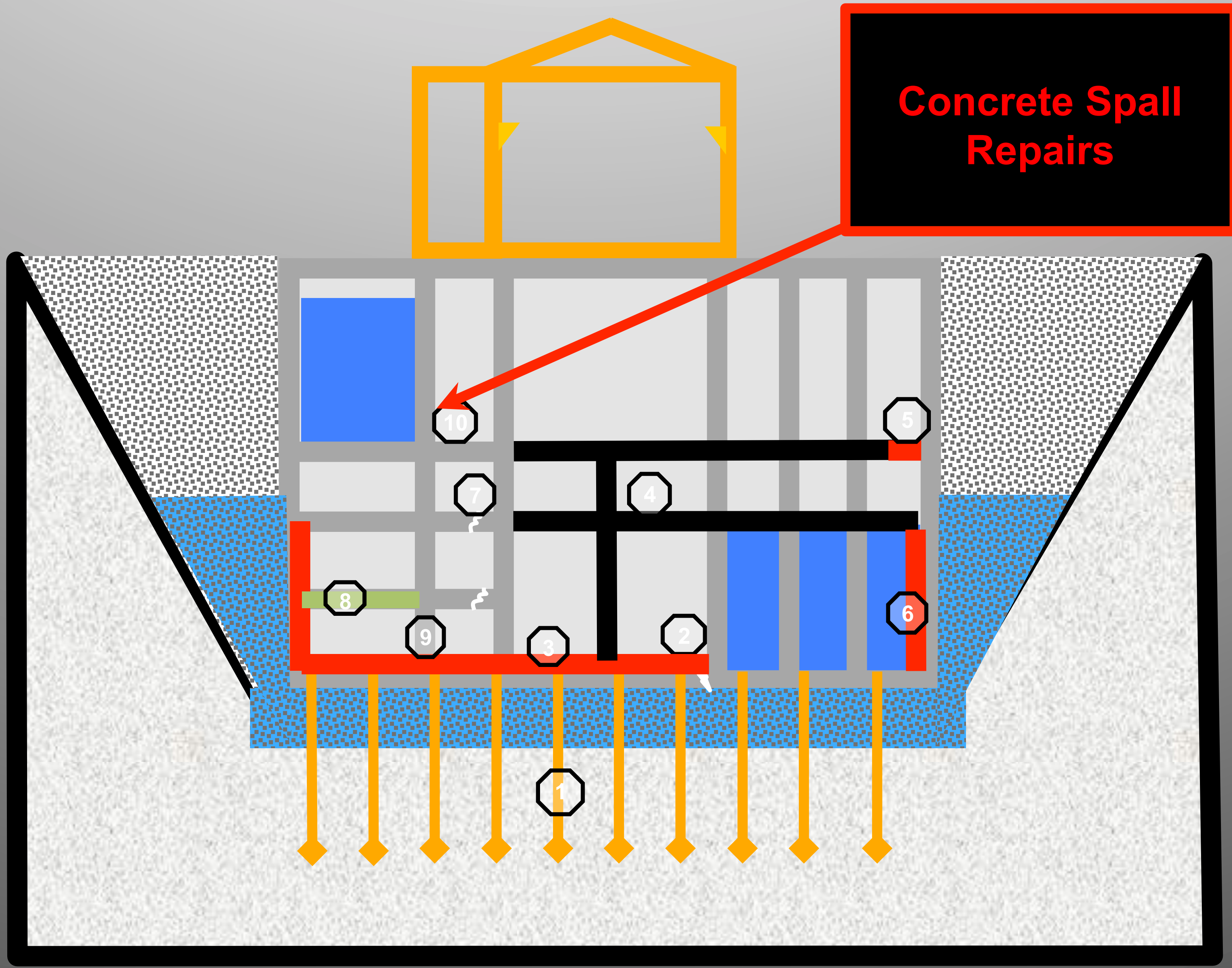

Externally Bonded Ties for Columns and Struts
5
7
4
8
9
3
2
6
1


United Rentals


Concrete Spall
Repairs
10
5
7
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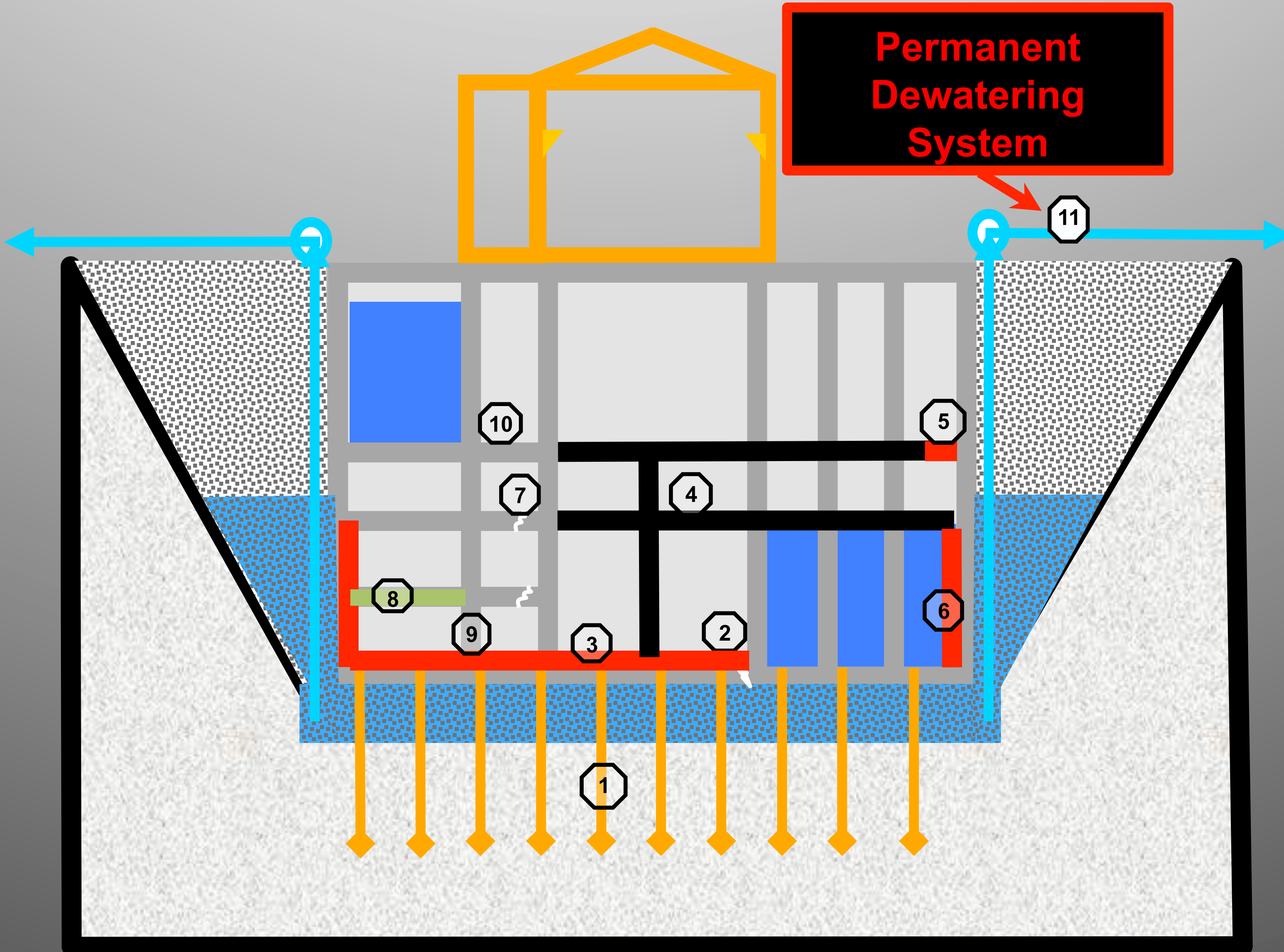

Permanent Dewatering System
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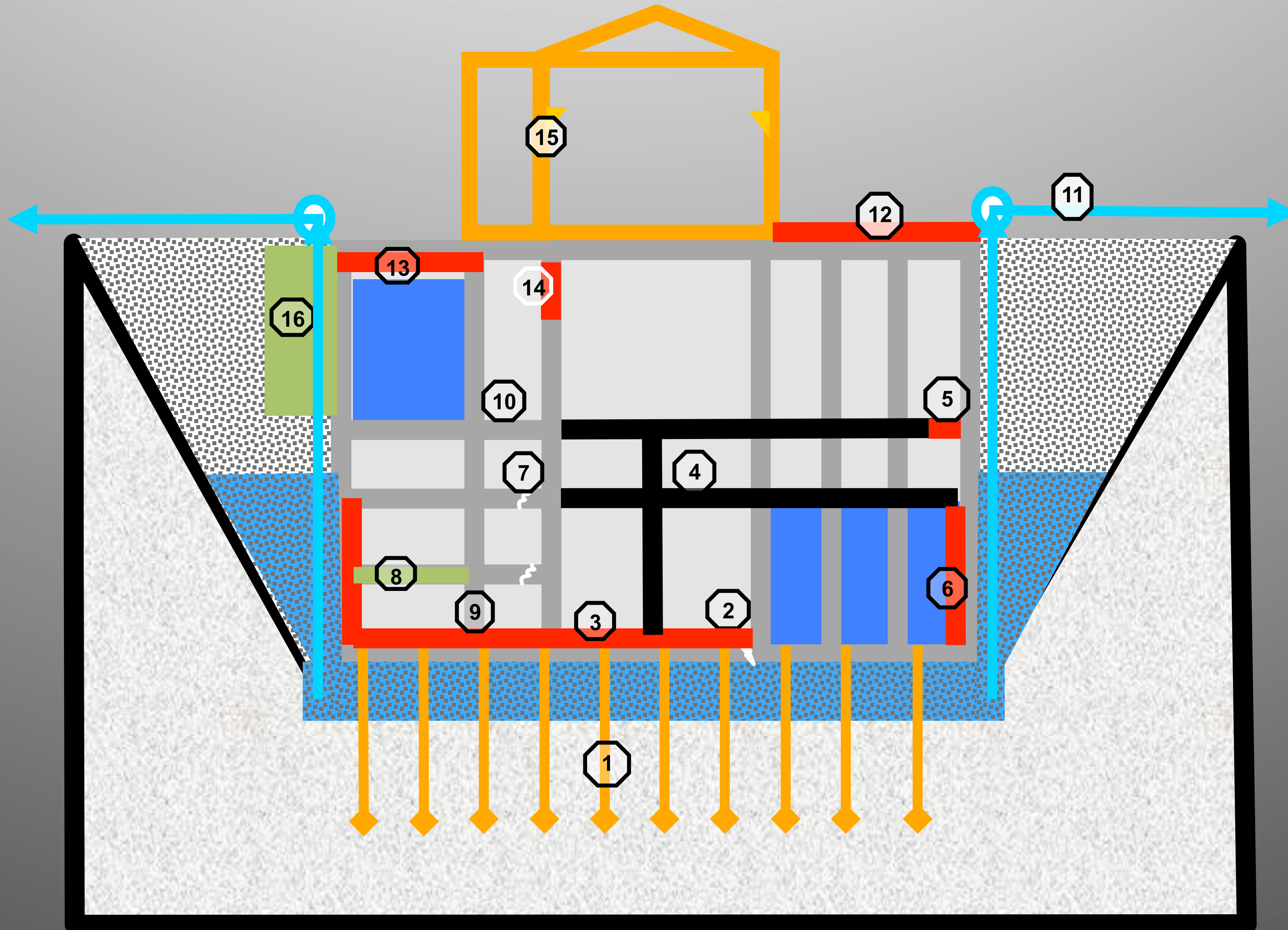

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Questions?

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