Geotechnical Roadway Design for Karst Environments

Presented to:
GeoHazards 2011

Presented by:
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URS – Pittsburgh, PA

August 3, 2011

OVERVIEW

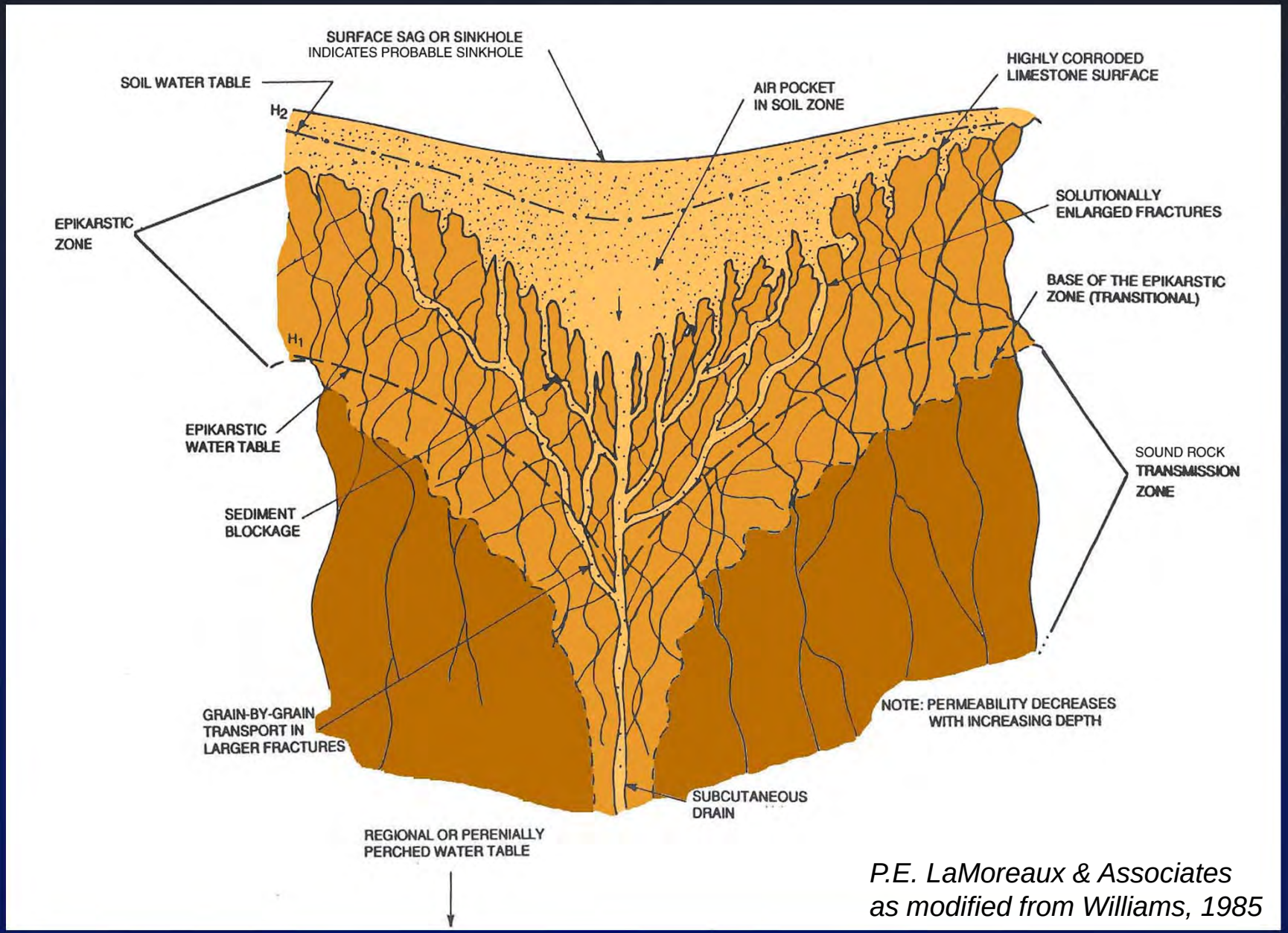
- Karst (from an engineer's point of view)
- Site Characterization
- Geotechnical Engineering
- Summary

KARST

WHAT IS KARST ?

- AGI defines karst as a “type of topography that is formed over limestone, dolomite or gypsum by dissolving or solution, and that is characterized by closed depressions or sinkholes, caves and underground drainage”.
- An irregular bedrock surface (cutters and pinnacles) is typical of most karst areas due to dissolution of joints and bedding planes.
- The highly weathered, highly permeable, interconnected, three-dimensional network is known as epikarst.

TYPICAL KARST DEVELOPMENT



P.E. LaMoreaux & Associates
as modified from Williams, 1985

KARST ORIGINS

- Karst terrane ultimately owe its origins to the dissolution of the bedrock by natural water.
- Acidity of water is greatest when it first encounters the rock (absorbs carbon dioxide through soil and becomes acidic).
- Acidified water flows laterally over limestone to fracture, dissolves and widens walls.
  - Widen fractures are “cutters”
  - Upward protruding remnants are “pinnacles”


CAT

TYPES OF SINKHOLES

Sinkholes result from two different processes, either the transport of surficial materials downward along solutionally enlarged channels or the collapse of roofs over large cavities.

Five types of sinkholes (Beck 1988):

- Solution sinkholes
- Cave collapse sinkholes
- Cover collapse sinkholes
- Cover subsidence sinkholes
- Buried sinkholes

Sinkholes do not occur randomly – they occur where pathways in the limestone through which cover sediment can be transported downward into deeper dissolved voids.

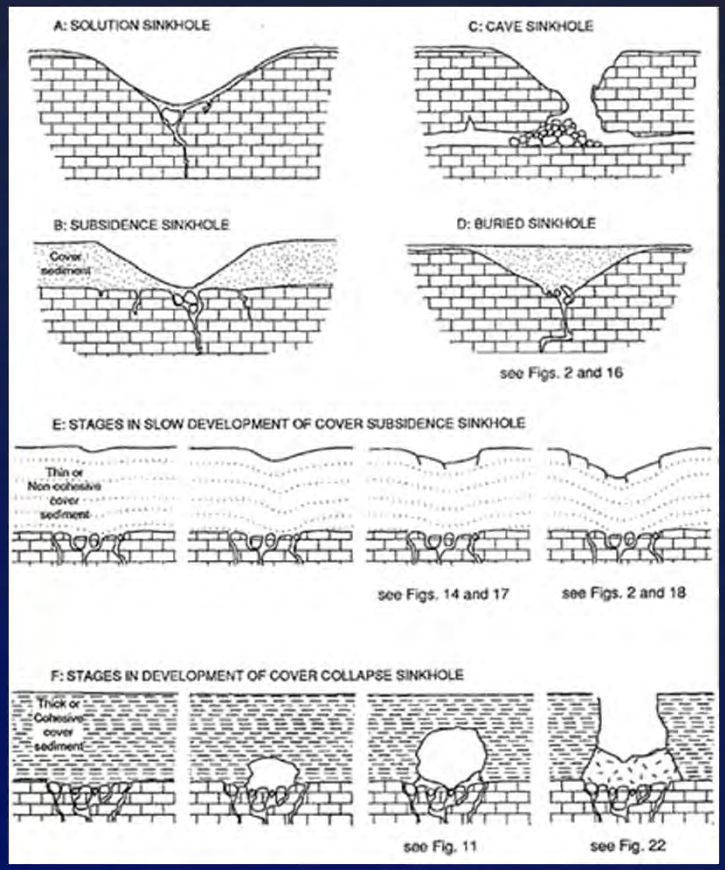


Figure: Beck and Sayed, 1991; Culshaw & Waltham, 1987

IMPORTANT CONCEPT

After a sinkhole has collapsed, it is important to understand that the position of the solution pipe and the processes operating in the subsurface have not changed, and that the erosion process can continue.


FOGLES

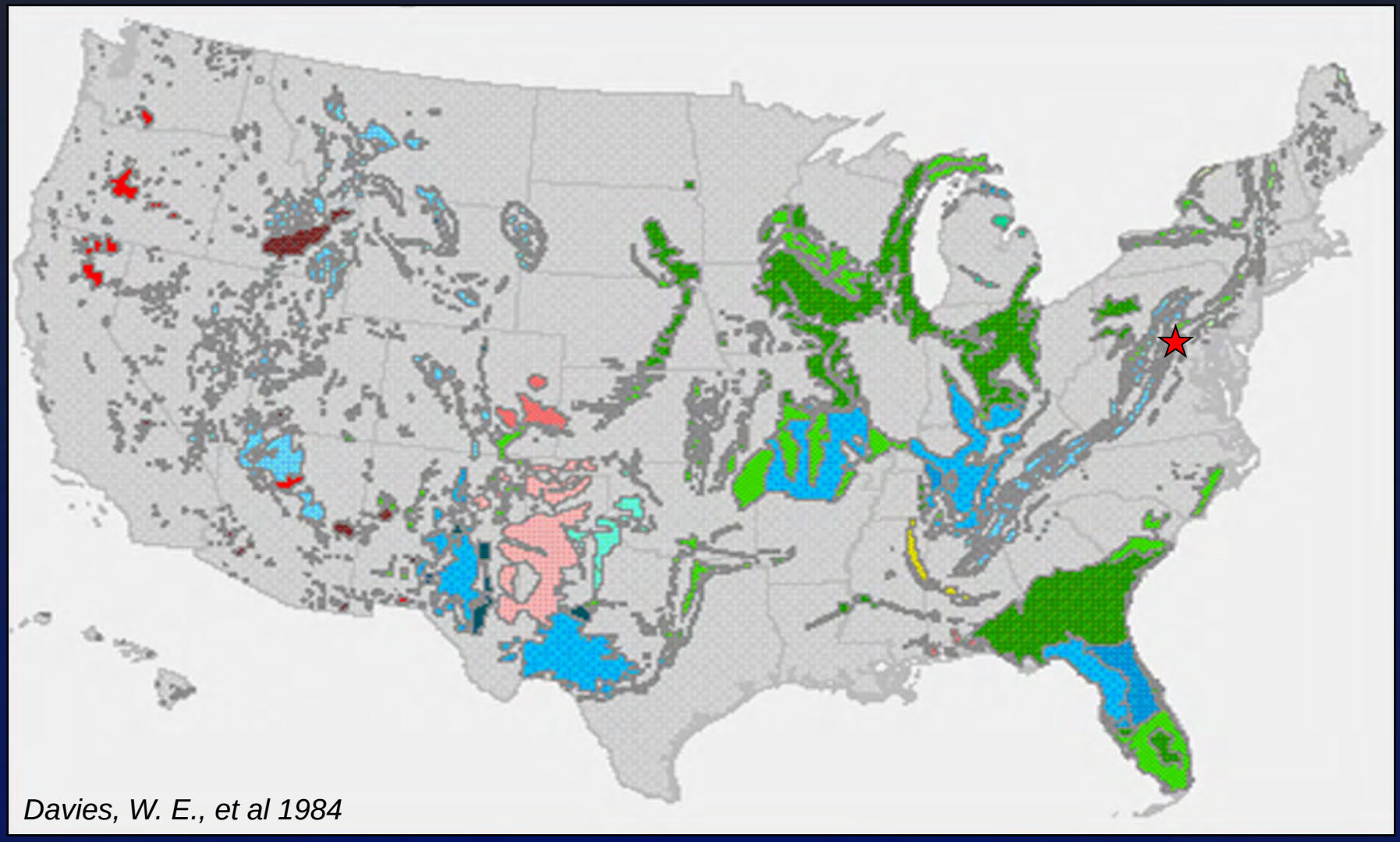
SITE CHARACTERIZATION

SITE CHARACTERIZATION

Common approaches use:

- Maps (geologic, USGS, aerial, etc)
- Test borings (air-trac, SPT, etc)
- Geophysical methods
- Geologic mapping
- Dye tracing
- Hydrographs (wells, stream, rain)

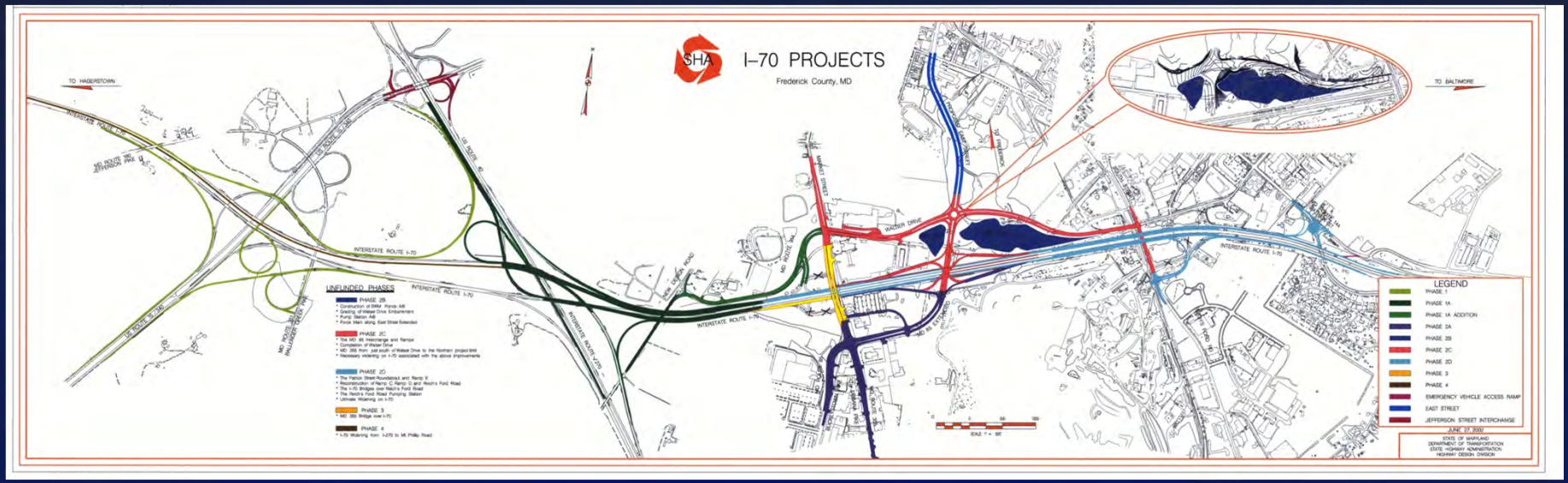
CASE HISTORY: I-70



Davies, W. E., et al 1984

CASE HISTORY: I-70

An aggressive sinkhole occurrence rate that averaged 8 sinkholes per year !

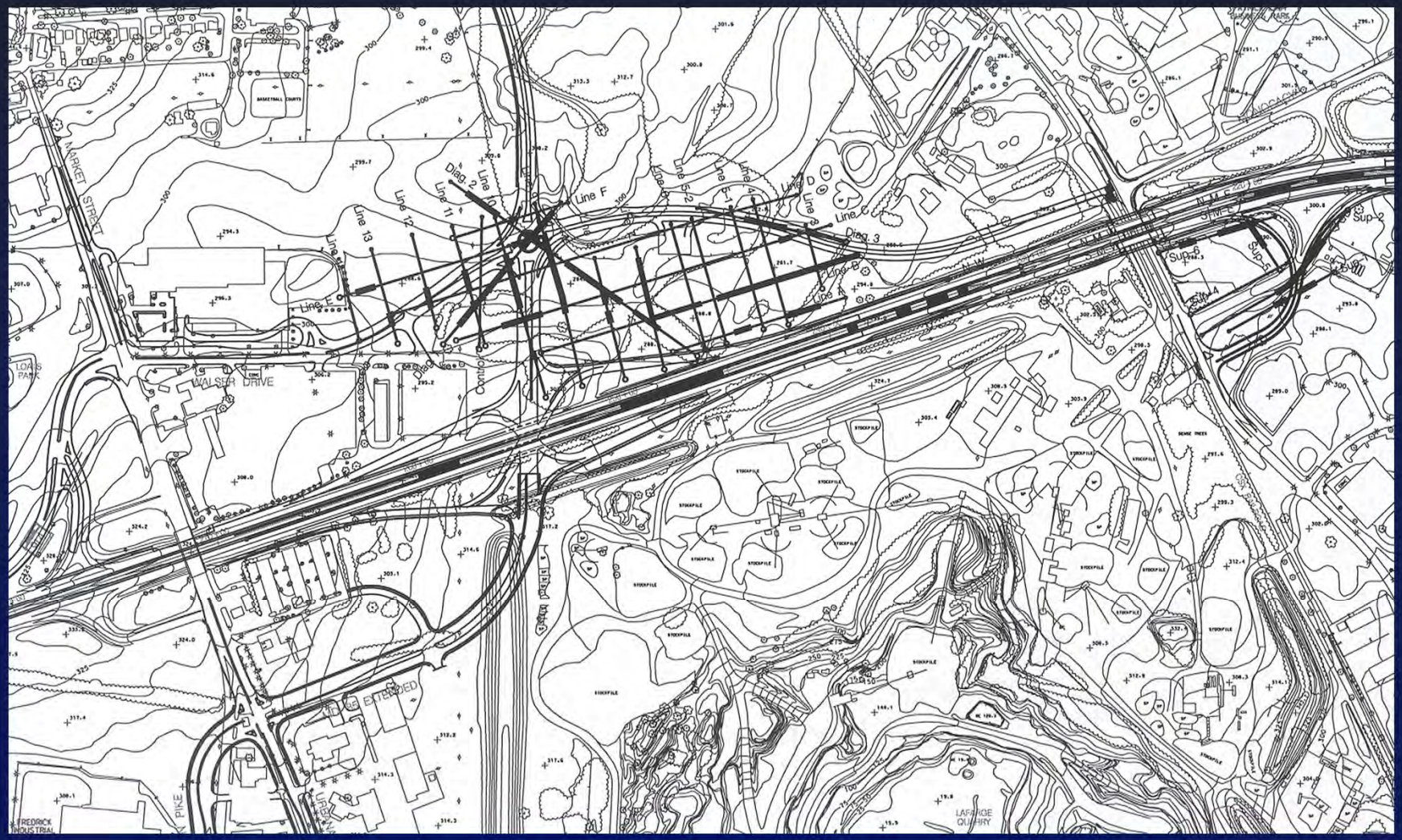


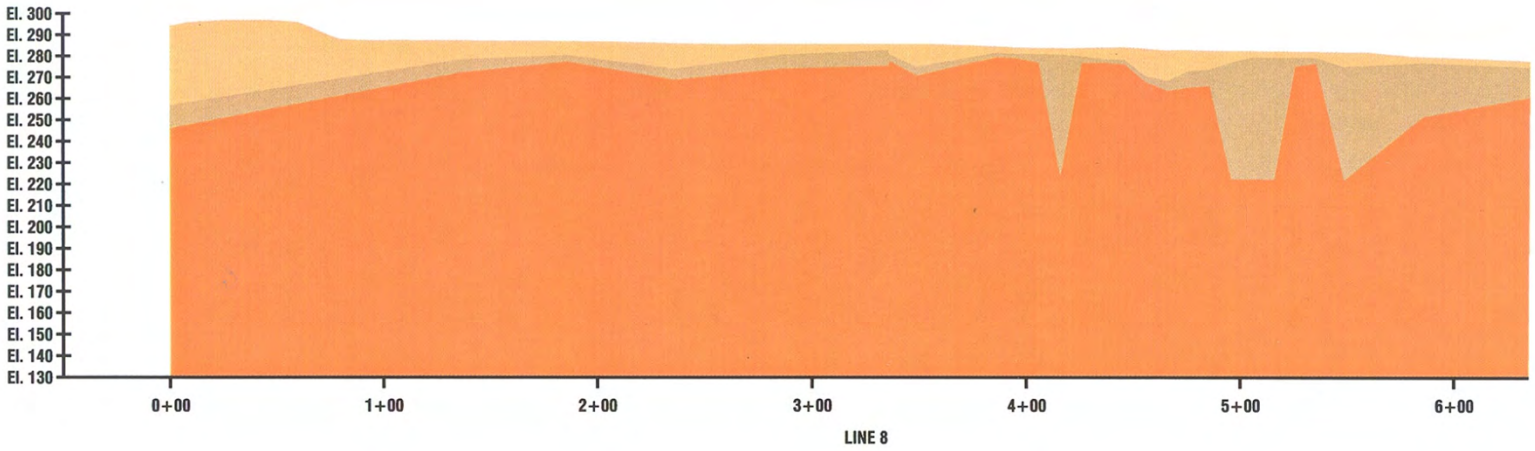
Dewey Jordan low bidder at $59,250,000

Aerial View of the Project Area

Aerial View of the Project Area

RESISTIVITY SURVEY LAYOUT

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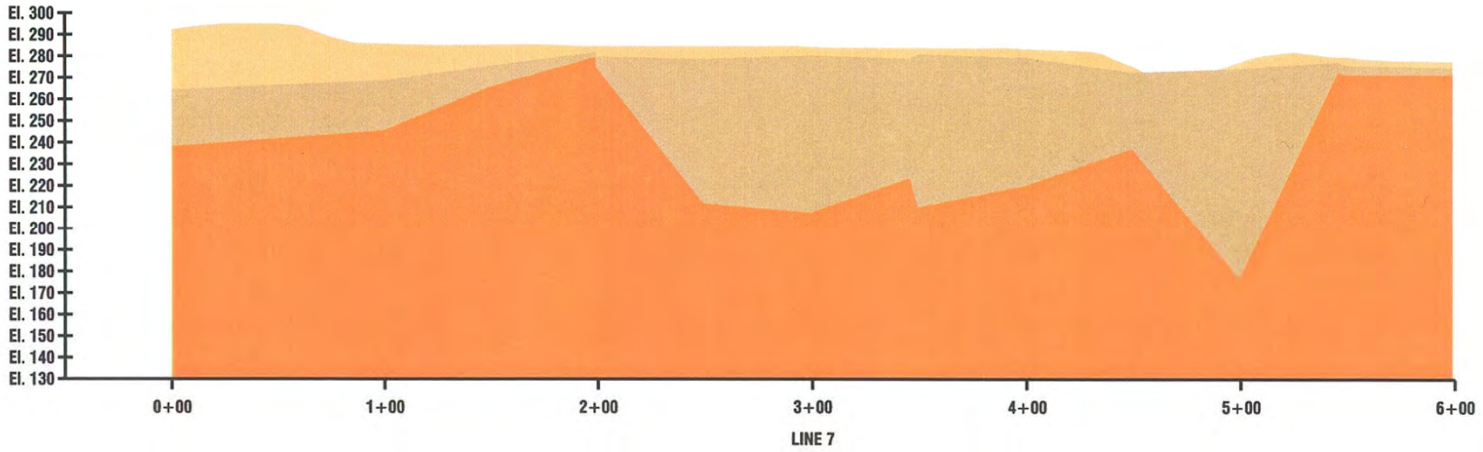
LINE 8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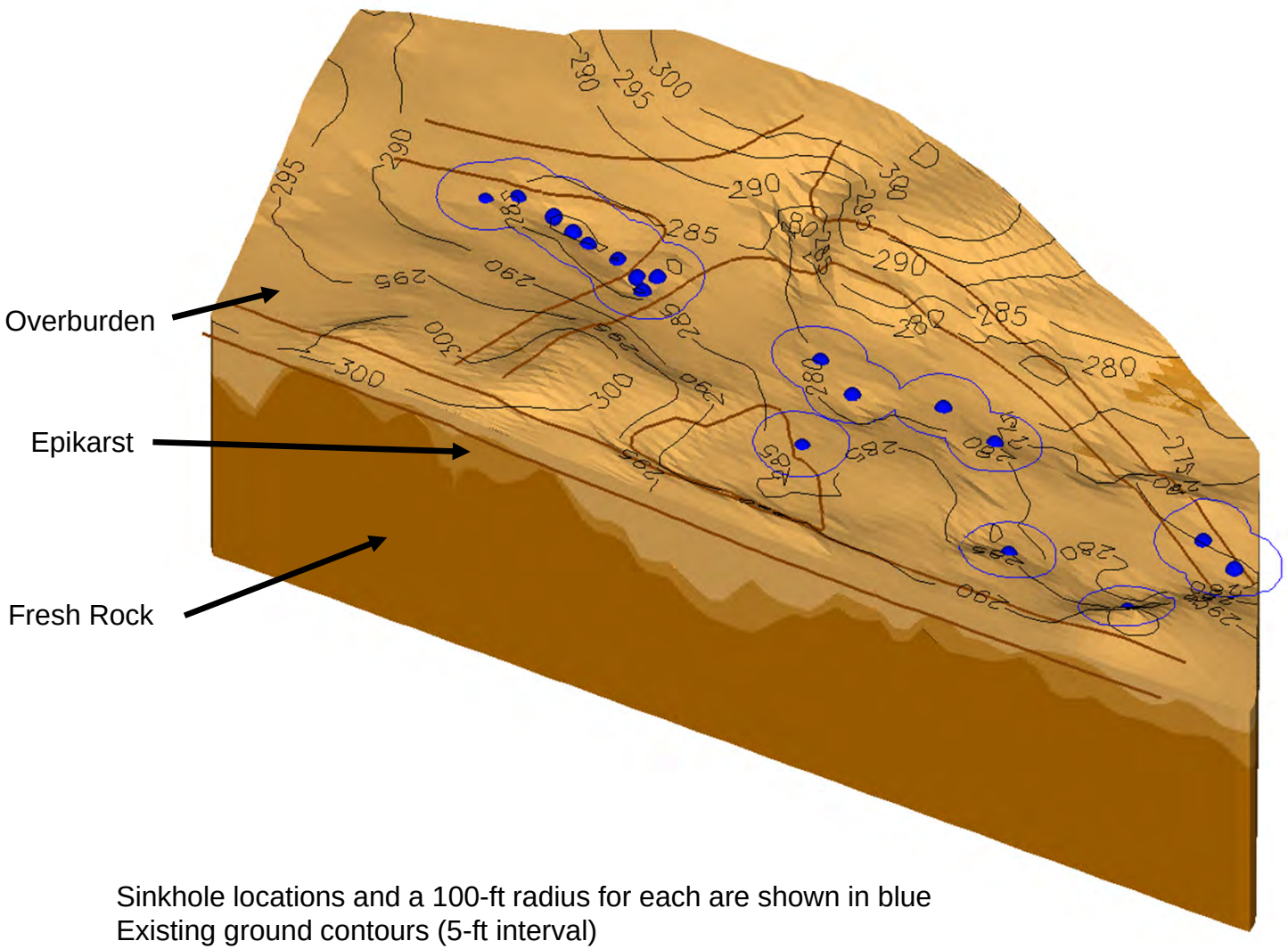
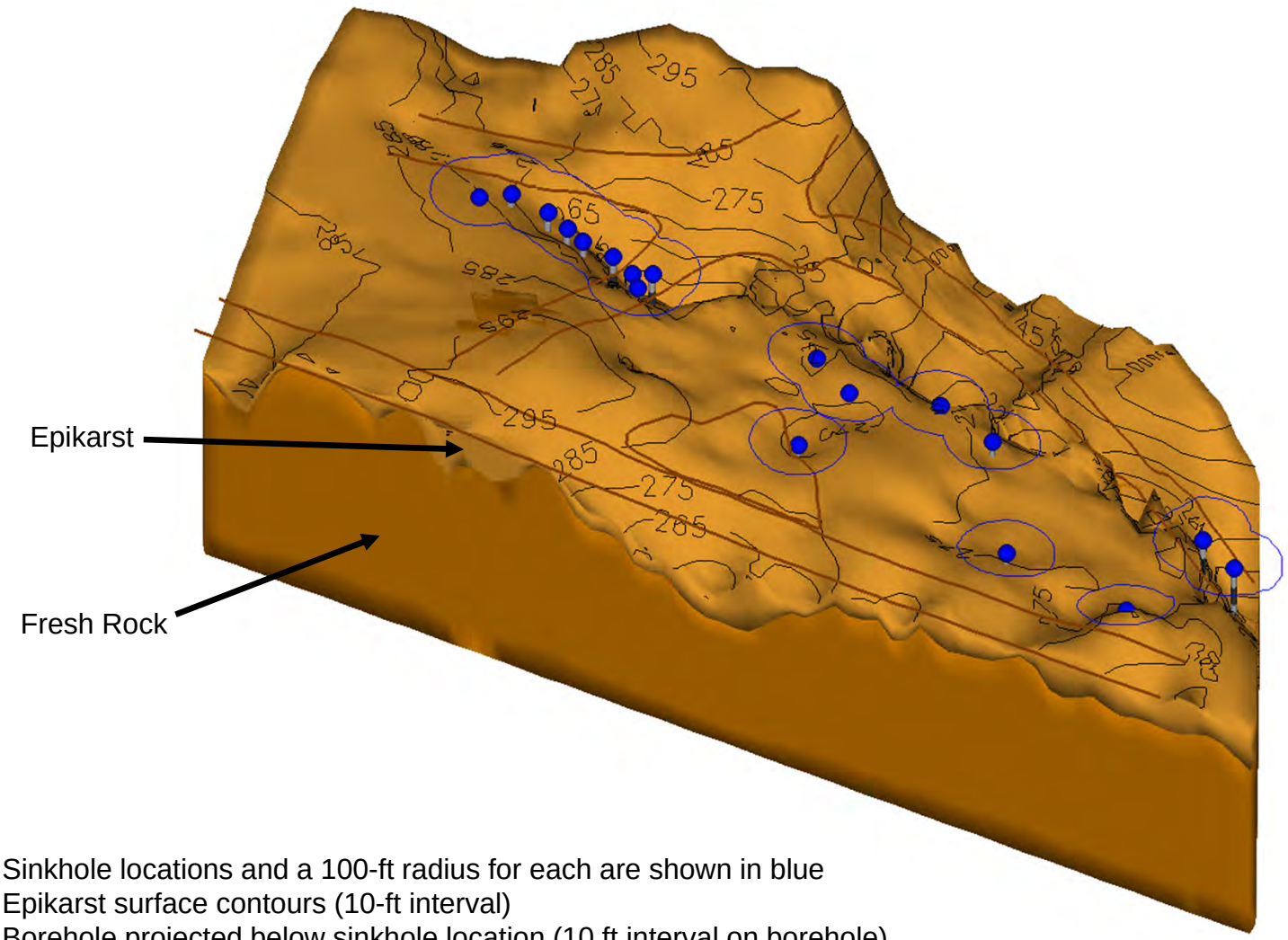
LINE 7



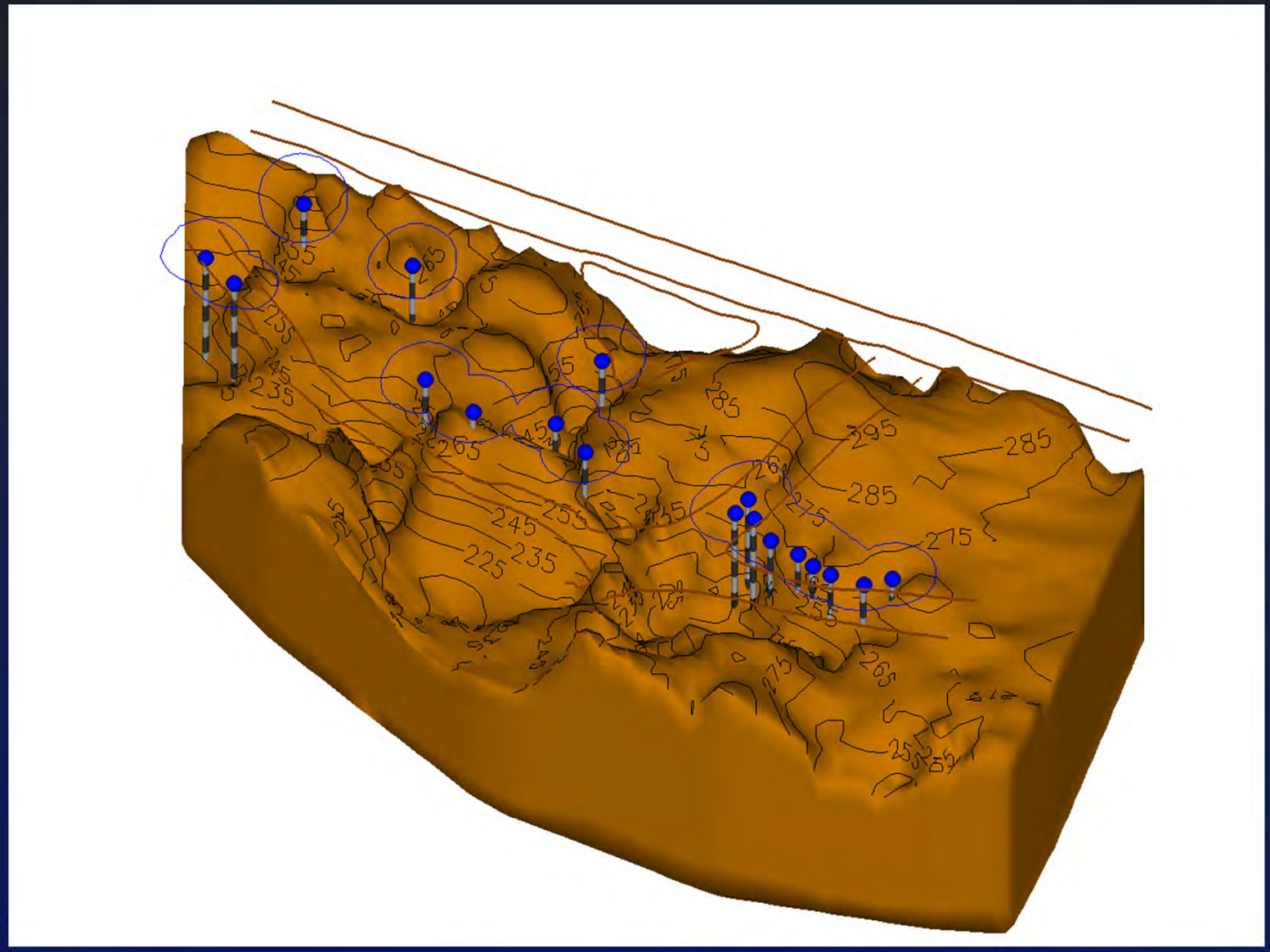
Sinkhole locations and a 100-ft radius for each are shown in blue
Existing ground contours (5-ft interval)
Vertical Exaggeration = 5X

Oblique View of Surface
Surface Looking Northwest



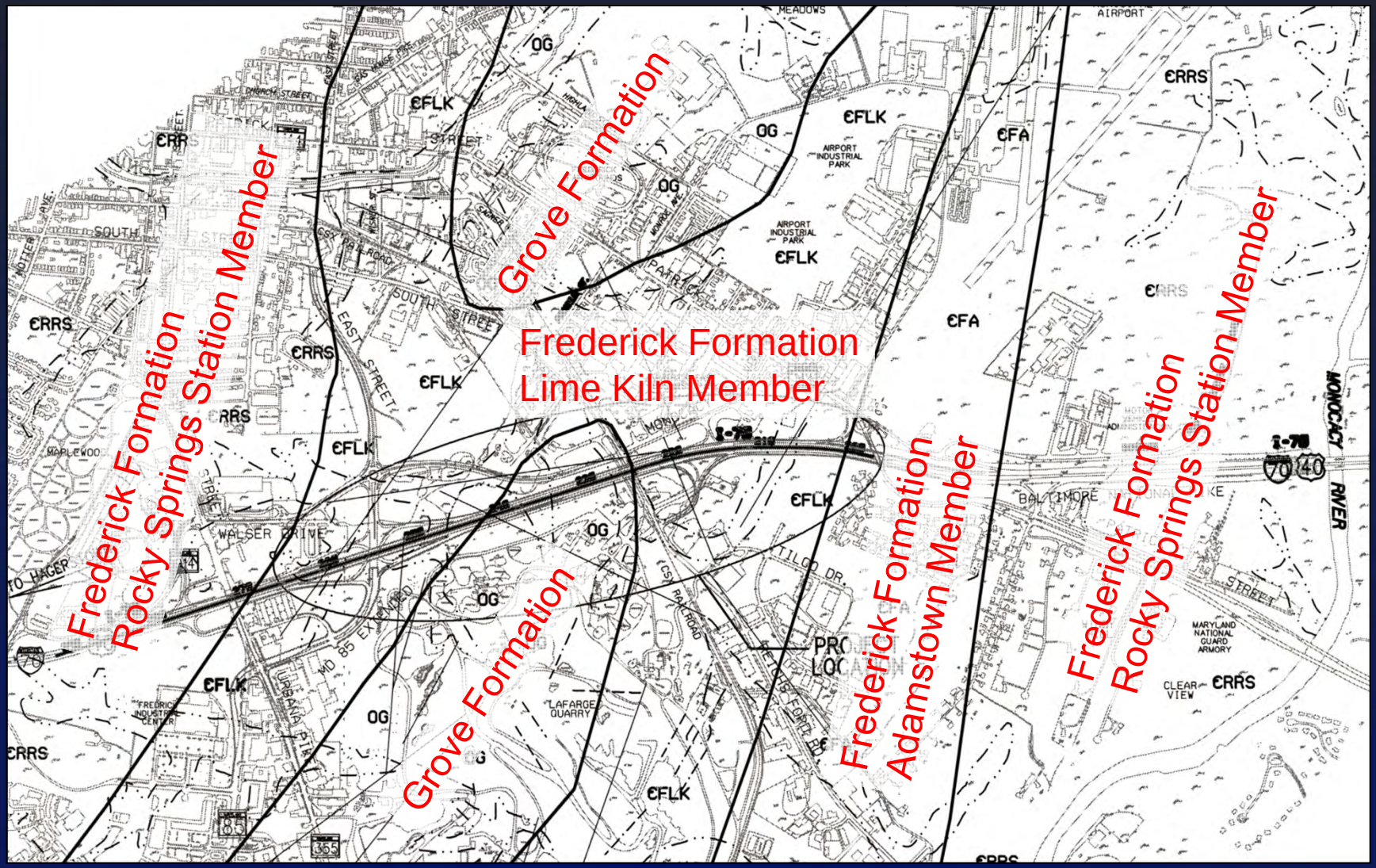
Sinkhole locations and a 100-ft radius for each are shown in blue
Epikarst surface contours (10-ft interval)
Borehole projected below sinkhole location (10 ft interval on borehole)
Vertical Exaggeration = 5X

Oblique View of Epikarst
Surface Looking Northwest

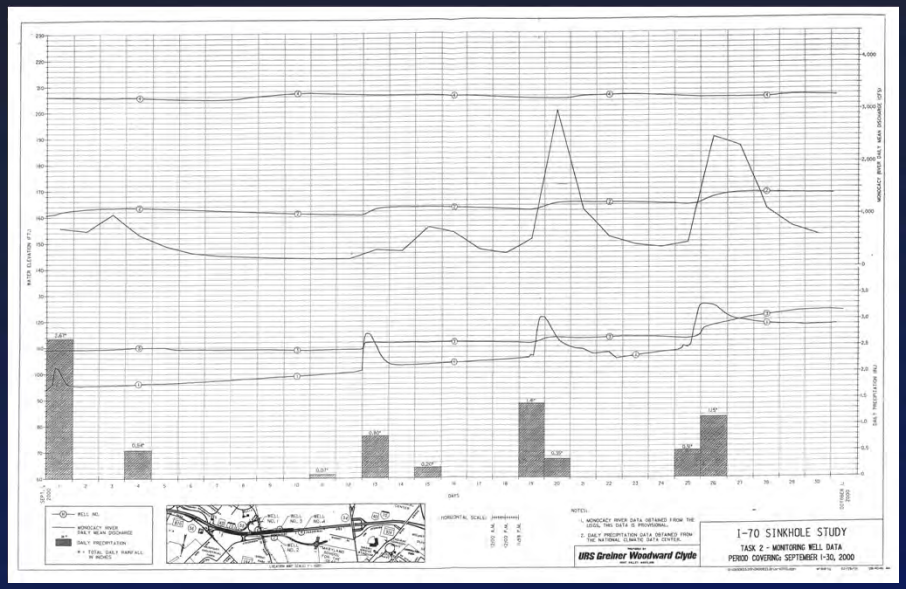


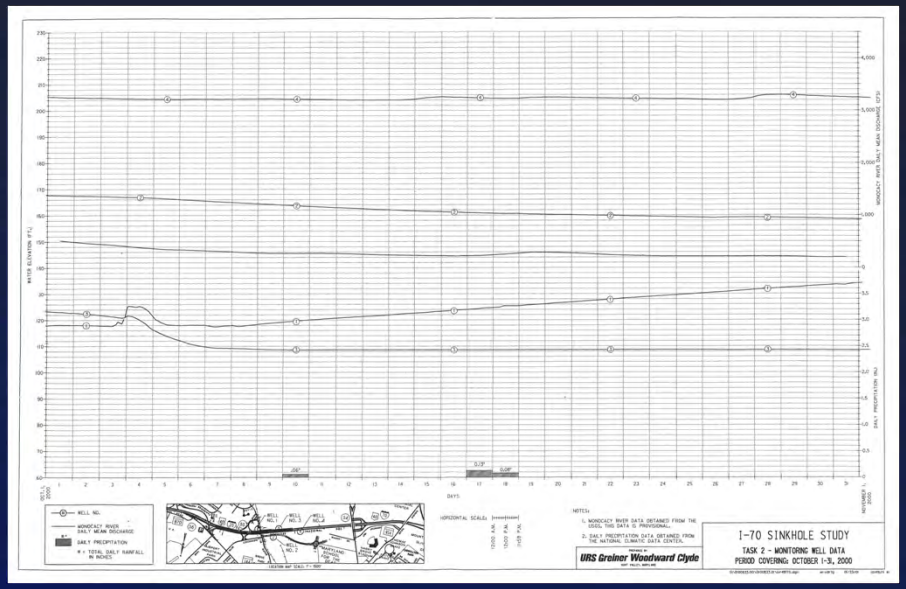
Oblique View of Sound Rock
Surface Looking Southeast

GEOLOGIC SETTING



HYDROGRAPHS





- Rail improvement project involved a grout program that created a cut-off wall perpendicular to the synclinal axis.
- Well 1 recorded a 40-ft increase in a 3-month period – the largest ever noted during a 5-year study.
- A few months later ----

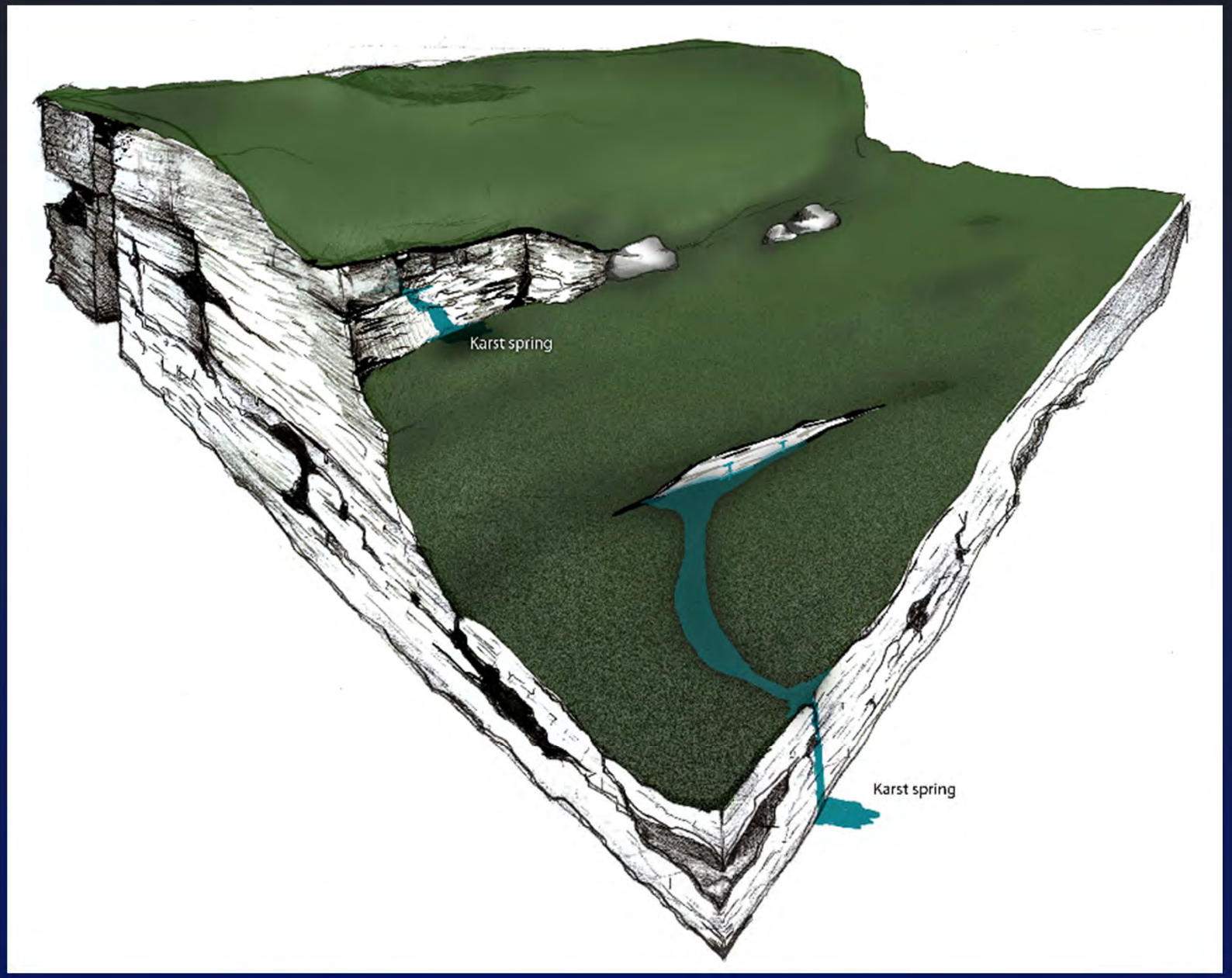
DYE TRACING

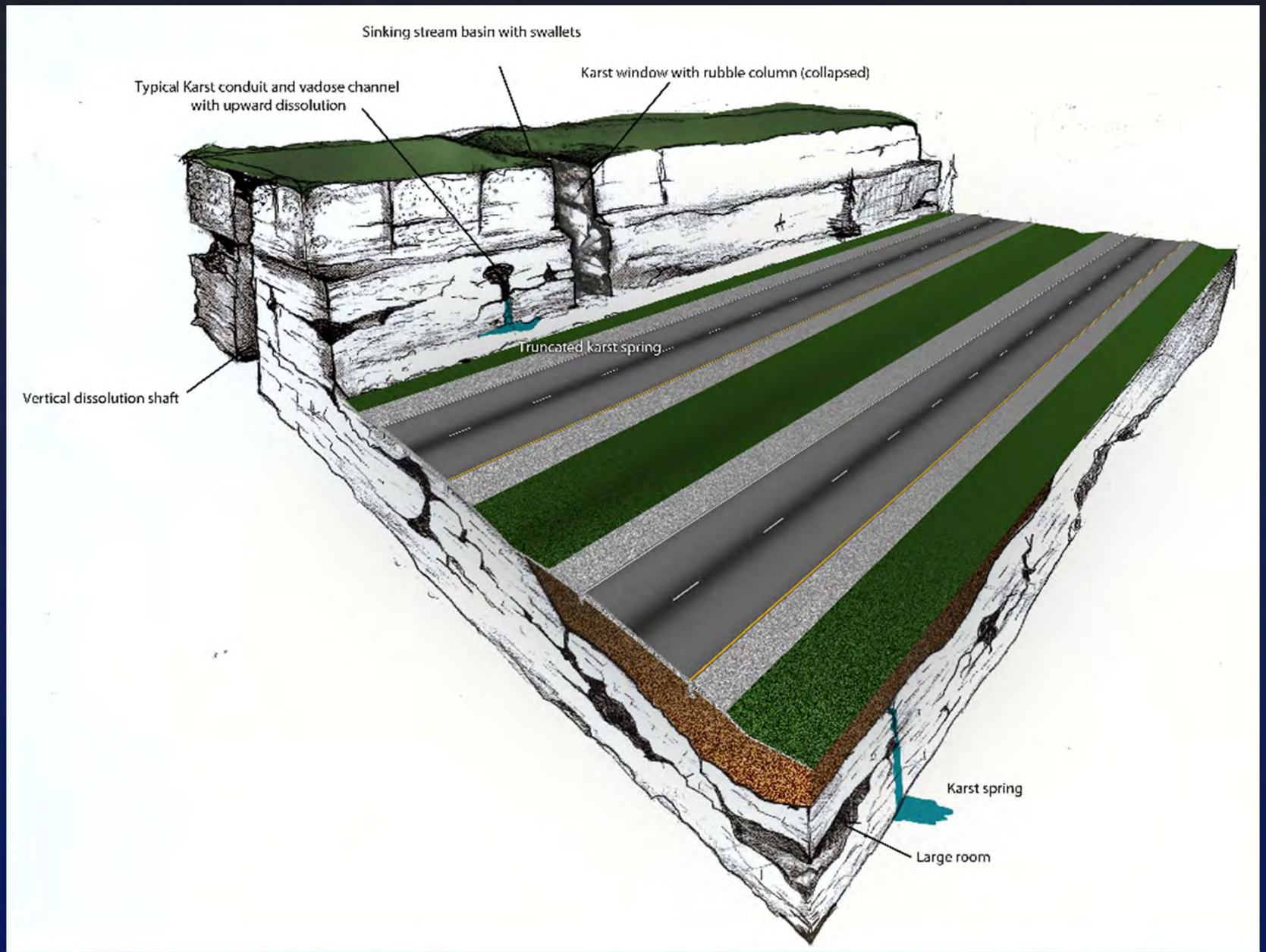
- Dye traces are used to study karst hydrology and delineate and characterize karst drainage basins.
- Small quantities of non-toxic dye prove a hydrologic connection between two points (sinking stream (inlet) and a karst spring (outlet)).
- Dye traces can prove 'obvious' hydrologic connections between two points or they can just as easily prove that you know nothing about the groundwater system.
- Potential for contamination is great in karst aquifers, these studies should be performed as early as possible.

Photo courtesy of:
Hydrogeology, Inc., Bloomington, IN

ENGINEERING

Sinkhole Treatments
Grouting
Structure Support
Instrumentation


Karst spring
Karst spring


Sinking stream basin with swallets
Typical Karst conduit and vadose channel with upward dissolution
Karst window with rubble column (collapsed)
Truncated karst spring
Vertical dissolution shaft
Karst spring
Large room

GEOTECHNICAL DESIGN

A significant aspect for deterring sinkhole development is understanding and controlling surface (stormwater) and subsurface water (Sowers,1996 and Hubbard, 2001).

ENGINEERING

Sinkhole Treatments

Grouting

Structure Support

Instrumentation

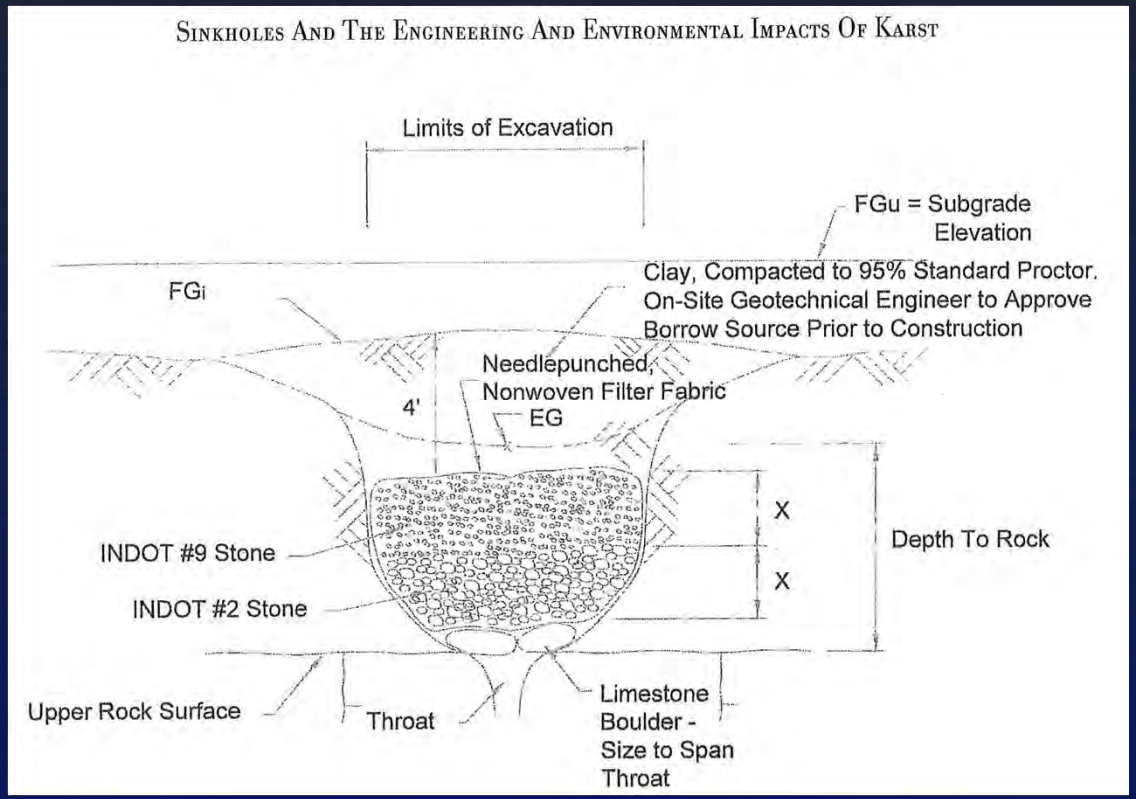
SINKHOLE TREATMENTS

- Although a grout plug is thought to be the most effective means to repair a sinkhole, it is not the most effective means to deter future sinkhole development (NJDOT, MDDOT, VADOT, etc.) as grouting creates a “subsurface bathtub”.
- Geotechnical engineers must understand both surface and subsurface water to control sinkhole development - inverse aggregate graded filters, grout programs or both?

INVERSE AGGREGATE GRADED FILTER

- Inverse aggregate graded filter consists of placing rocks / boulders wider than about half the throat opening width into the solution enlarged fracture / joint to arch across the bottom opening. Successive layers are sized finer than the underlying layer but coarse enough not to pass through the interstitial spaces of the bed beneath.
- The filter is topped with an appropriate geotextile fabric and the final surface constructed to preclude surface water runoff from entering the area.
- This design allows subsurface water moving at the soil / bedrock interface to access the epikarst drain and groundwater recharge to occur.
- It should be noted that when there is considerable downward infiltration, blocking downward seepage at one point could aggravate raveling, erosion, and new sinkhole activity (Sowers, 1996).
- TN DOT Site – Filtered water draining into sinkhole.

INVERSE AGGREGATE GRADED FILTER



REF: Hagerty, P. H. (2008) from ASCE Karst Conference 2008.

GROUT PLUG

- A grout plug is the most effective approach to remediate a sinkhole (Sowers, 1996).
  - The objective is to plug the sinkhole throat with concrete to an approximate depth of 1.5 times the width of the throat.
  - To the extent possible, any clay coating along the throat should be removed before concrete placement to secure a good bond between the concrete and rock.
  - If it is not practical to excavate into the throat of a sinkhole, compaction grouting can often form a relatively impervious plug, depending on the thickness and stiffness of the clay coating along the rock throat.
- However, a hazard of using grout to seal the solution throat of a sinkhole is the potential to restrict the under-draining conduit that could lead to back flooding of other sinkholes draining up-gradient into the same conduit.
- Occluded conduit systems might also trigger quick soil conditions or new sinkhole formation at unmarked epikarst drains (Hubbard, 2001).

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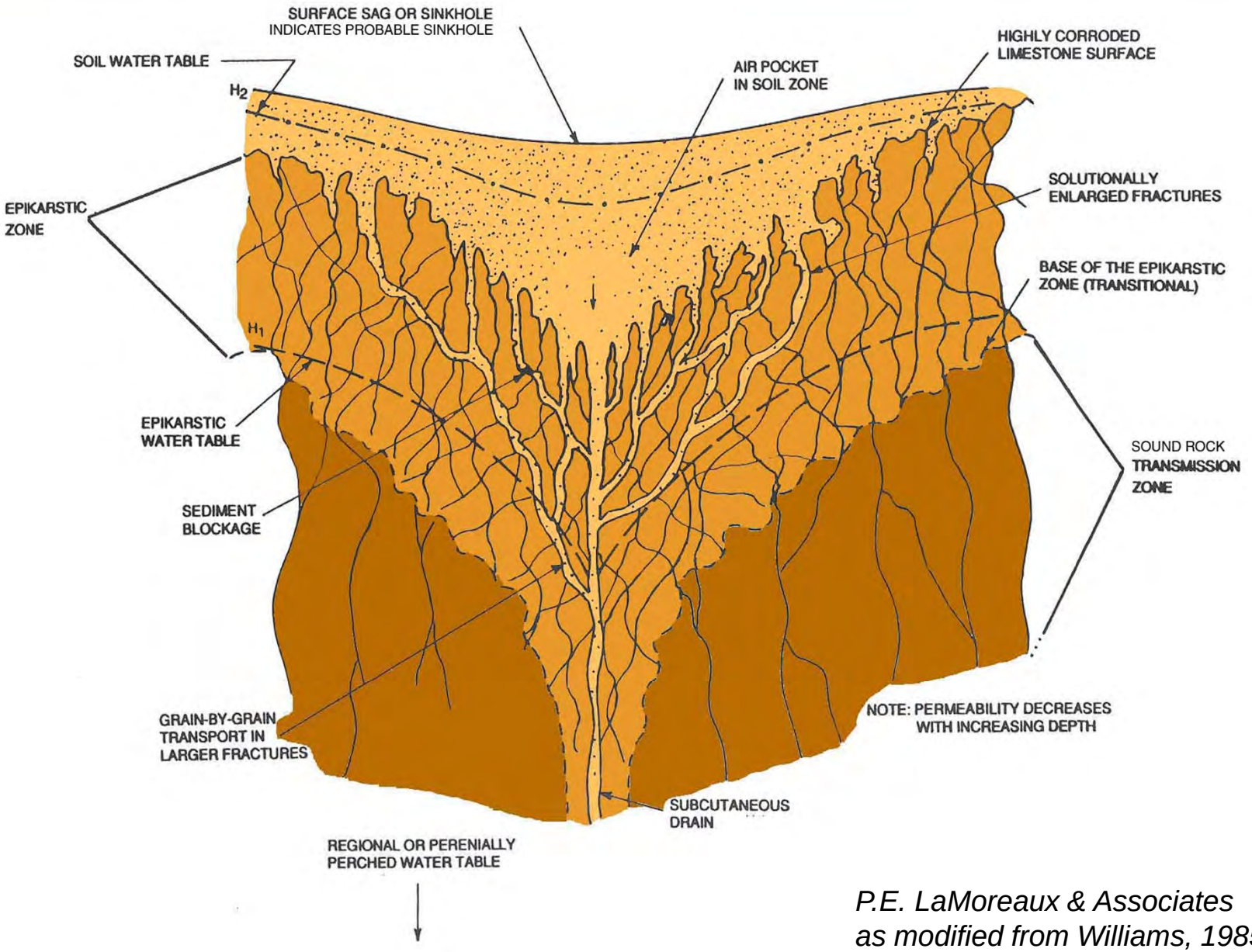
GROUT PROGRAMS

- Engineers often tackle karst with various forms of grout programs and neglect to consider its effect on subsurface water.
- Sealing a drain may result in pooling and saturation of the peripheral area with a consequence of increased subsurface drainage to adjacent epikarst drains – back flooding, quick soil conditions and new sinkhole formation.
- Sowers (1996) and Hubbard (2001) agreed that grouting a sinkhole closed when that sinkhole is exposed to significant infiltration is not advisable.

TYPICAL KARST DEVELOPMENT



P.E. LaMoreaux & Associates
as modified from Williams, 1985

GROUT PROGRAMS

- Compaction Grouting
- Low Mobility Displacement Grouting
- Slurry Grouting
- Cap Grouting
- High Mobility Grouting
- Jet Grouting

Much confusion!

What is the goal?

Resource:
Mr. James Warner

SLURRY / CAP GROUTING

- Improvement of overburden soil is not an objective.
- Low grout pressure (20 psi or less).
- Close grout hole spacing (about 3-feet).
- Grout is placed at low pressure at the rock surface to fill voids, plug slots and displace soft soil to provide support to the upper crust.
- Closer grout hole spacing requires greater drilling footage. Cap grouting philosophy generally results in lower grout takes.
- Closer grout hole spacing provides better coverage to intersect sinkhole features. Very little potential for lifting structures / roadways.

COMPACTION GROUTING

- Improvement of the overburden soil is possible.
- Relatively high grout pressures (200 psi or greater).
- Primary grout hoses typically spaced at 10 to 15 feet.
- Grout is placed at high pressures to fill voids, plug slots over a larger less focused area per hole and displace / improve overburden soil.
- Higher grout pressures, greater grout hole spacing, higher grout quantity refusal criteria, and overburden treatment generally results in larger grout take.
- Greater primary grout hole spacing may not intersect sinkhole features.
- Allows for controlled lifting of structures / roadways.

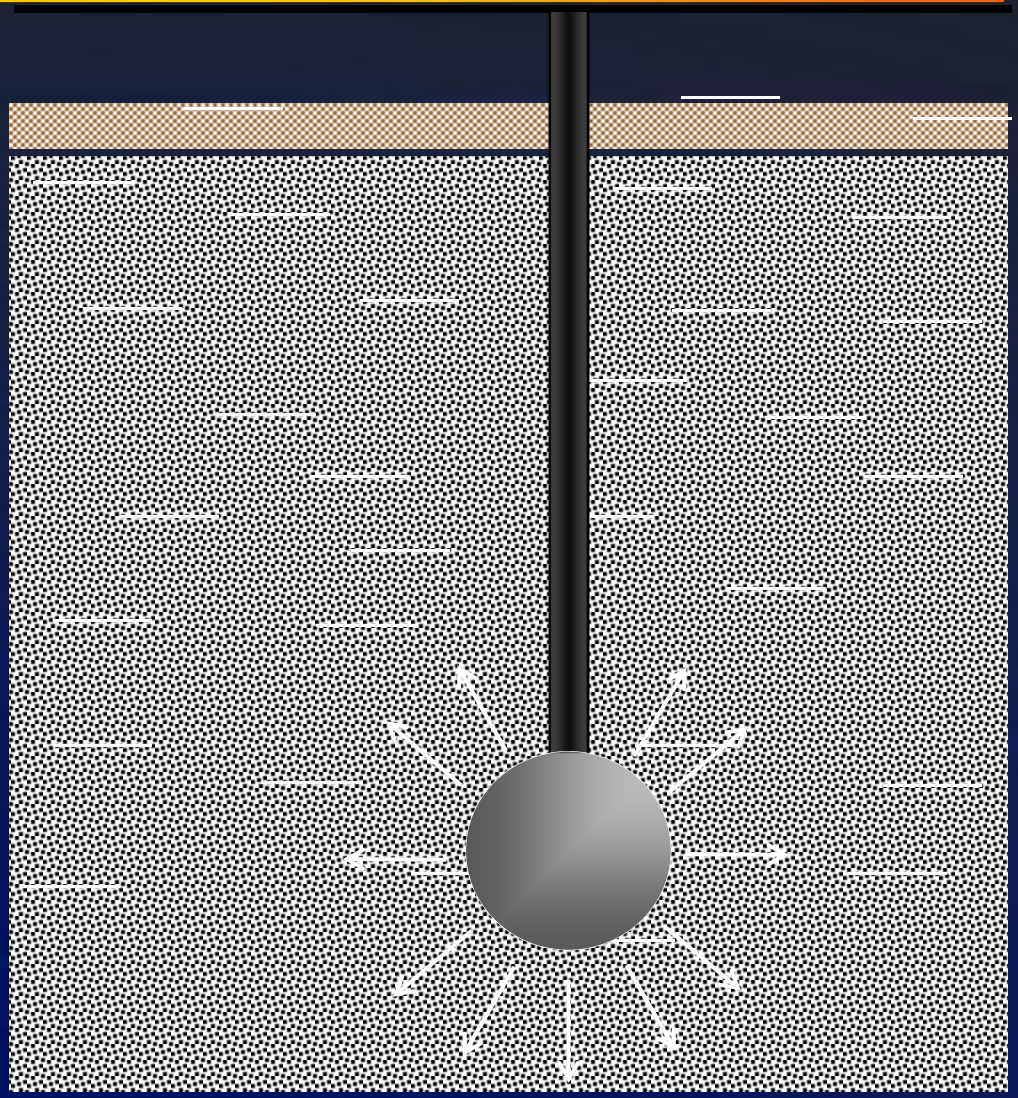
COMPACTION GROUTING

The Basic Principle

Can fracture soil !

(I-70 closure)

Uniform densification? (minor principle stress)



GROUT PROGRAM

ENGINEERING

Sinkhole Treatments

Grouting

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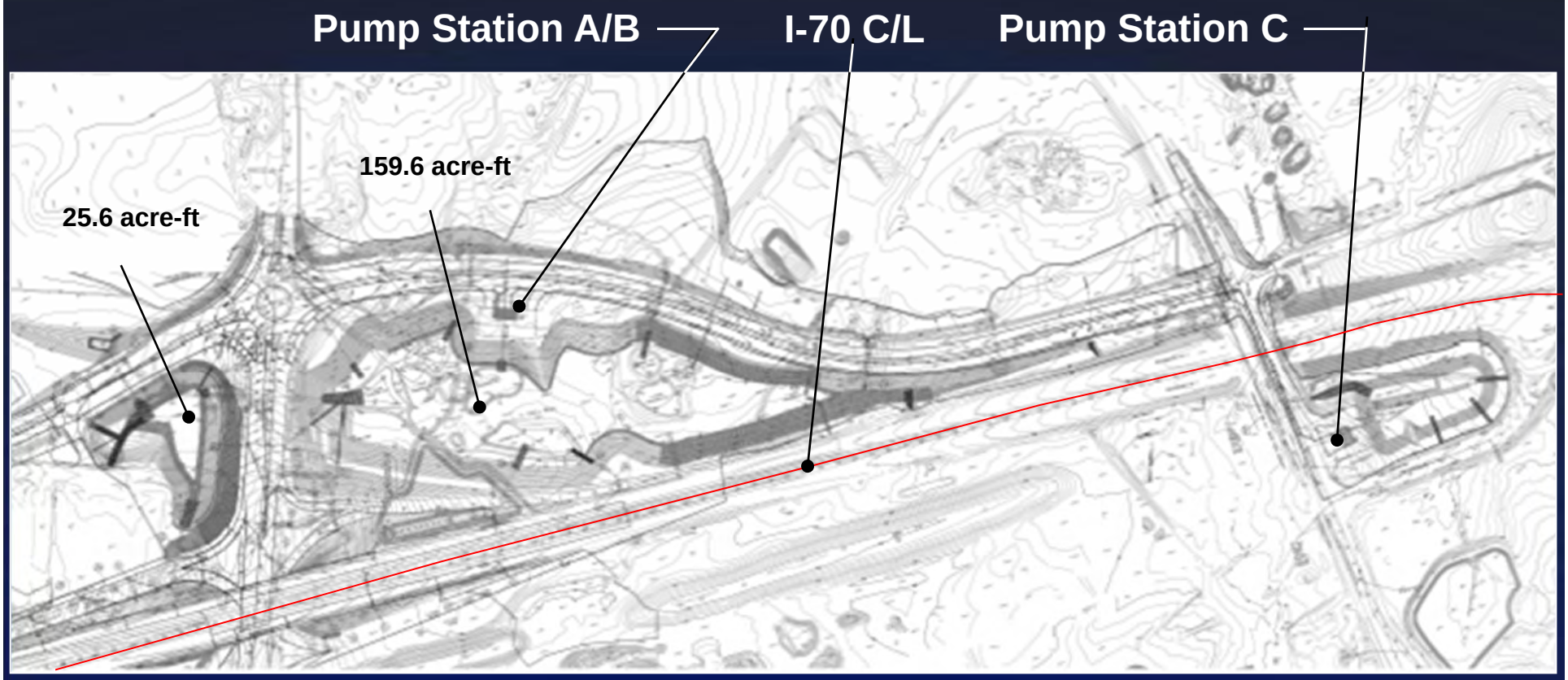
CASE HISTORY: PUMP STATIONS



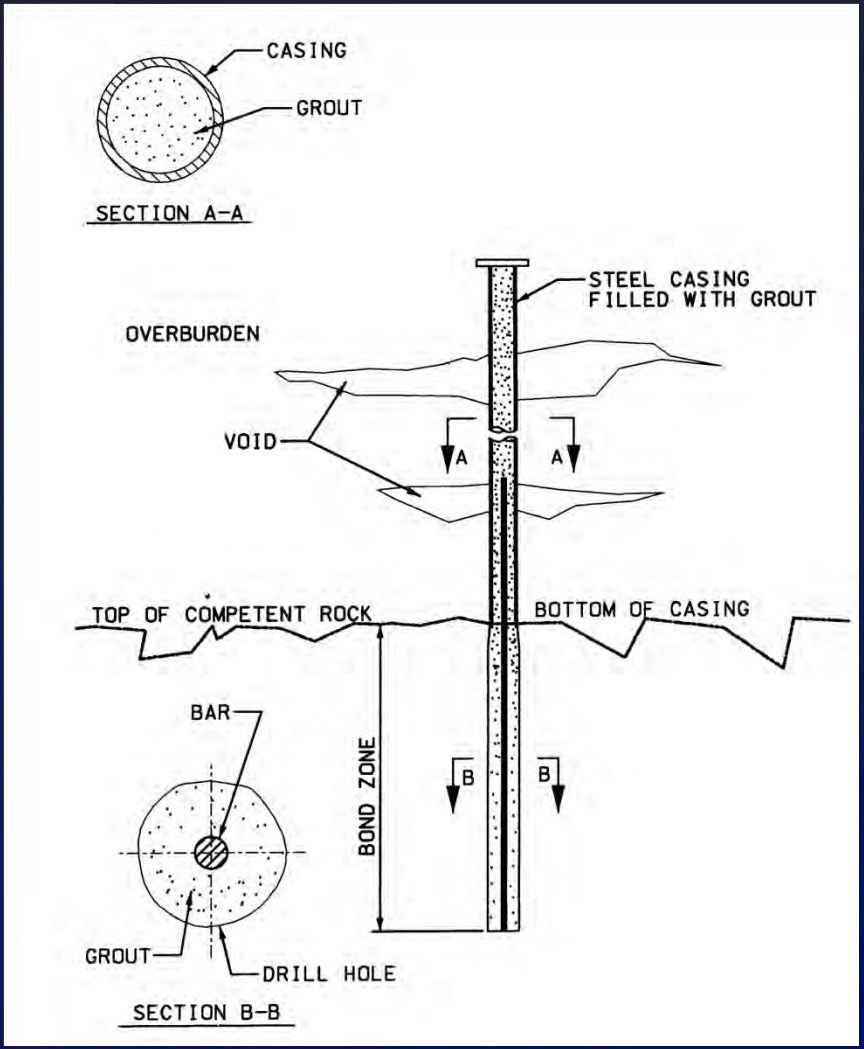
- Two pump stations (Pond A/B and Pond C).
- 1.1 ± mile force main system connects the ponds to Carroll Creek, located north of the project area.
- Facilities are of paramount importance to the project and the foundation system must not be susceptible to loss of ground support.

SWM POND LINER

- Minimize surface water infiltration with the use of a geomembrane polymeric barrier. Short listed materials included:
  - LLDPE - Linear Low Density Polyethylene
  - EPDM – Ethylene Propylene Diene Monomer
  - PVC – Polyvinyl Chloride - Soft

  These liners have high resistance to deformation and puncture - strains greater than 250%.
- Slope stability concerns with EPDM and PVC materials since these materials have lower interface shear characteristics against the protective geotextiles.
- LLDPE material manufactured in both smooth and textured surfaces. Textured surface results in high interface friction and interface shear resistance for the predominantly 3H:1V slopes.
- Variable cover soil thickness to maintain as near as practical a rectangular grading pattern to minimize complex panel layout as well as extensive field seaming

MICROPILE DESIGN



Typical Type A Micropile

GEOTECHNICAL

$$P_{all} = \left(\frac{\alpha}{FS}\right)(\pi)(DIA)(L_{BOND})$$

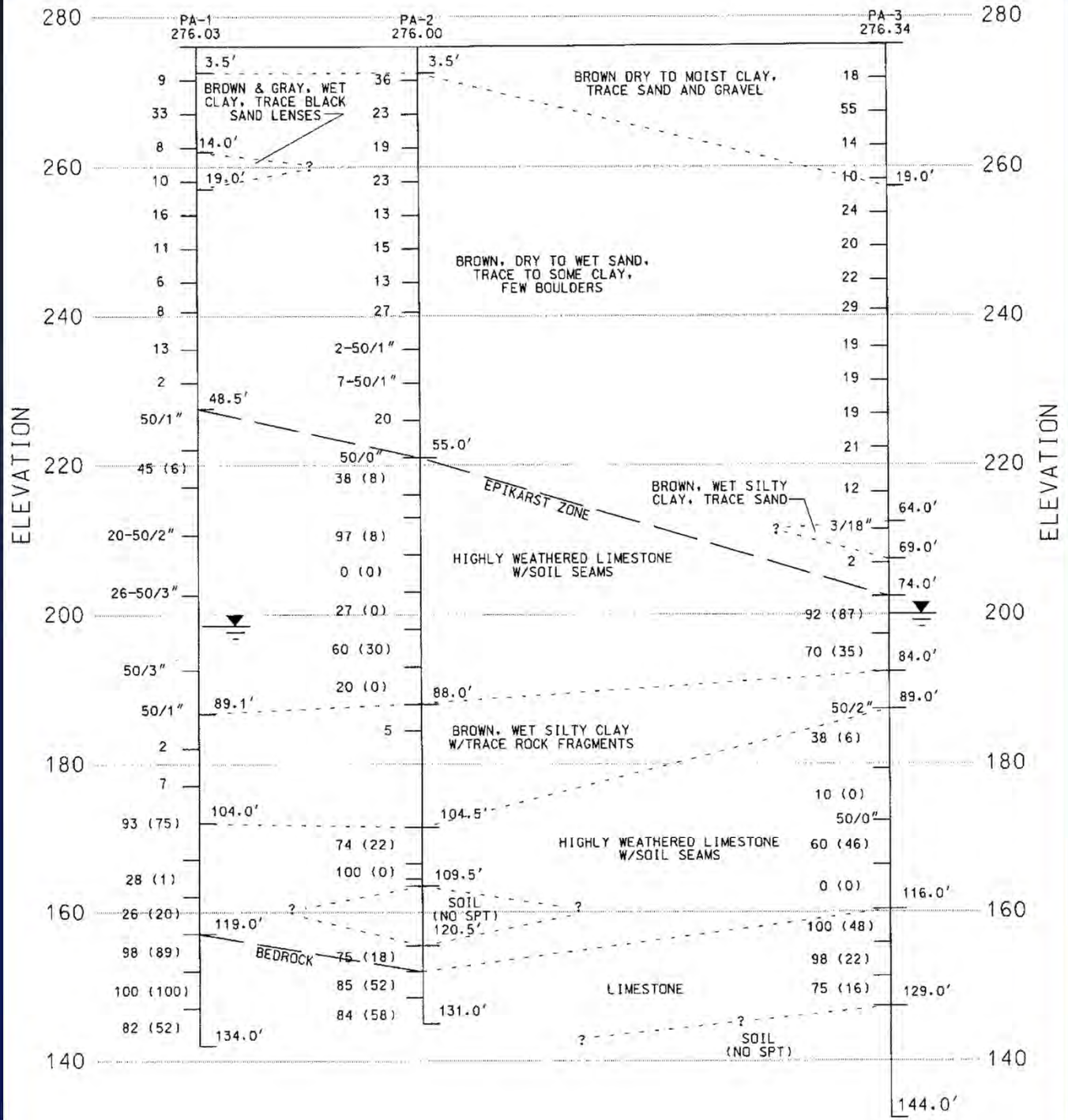
STRUCTURAL

$$P_{all} = 0.25(F_y)(A_{CASING}) + 0.4(f_c')(A_{GROUT})$$

$$P_{all} = 0.35\left[(F_y)(A_{REBAR}) + 0.85(f_c')(A_{GROUT})\right]$$

α dependent on subsurface material and installation method

No smaller than 7-inch diameter casing in karst


PA-1
276.03
PA-2
276.00
PA-3
276.34
ELEVATION
ELEVATION
280
260
240
220
200
180
160
140
3.5'
BROWN & GRAY, WET CLAY, TRACE BLACK SAND LENSES
14.0'
19.0'
BROWN DRY TO MOIST CLAY, TRACE SAND AND GRAVEL
BROWN, DRY TO WET SAND, TRACE TO SOME CLAY, FEW BOULDERS
48.5'
55.0'
EPIKARST ZONE
BROWN, WET SILTY CLAY, TRACE SAND
64.0'
69.0'
74.0'
HIGHLY WEATHERED LIMESTONE W/SOIL SEAMS
BROWN, WET SILTY CLAY W/TRACE ROCK FRAGMENTS
89.1'
88.0'
84.0'
89.0'
104.0'
104.5'
HIGHLY WEATHERED LIMESTONE W/SOIL SEAMS
109.5'
116.0'
SOIL (NO SPT)
119.0'
120.5'
BEDROCK
LIMESTONE
129.0'
131.0'
134.0'
SOIL (NO SPT)
144.0'

TYPICAL CASING

City of Lakeland, FL

Hagerstown, MD

Frederick, MD

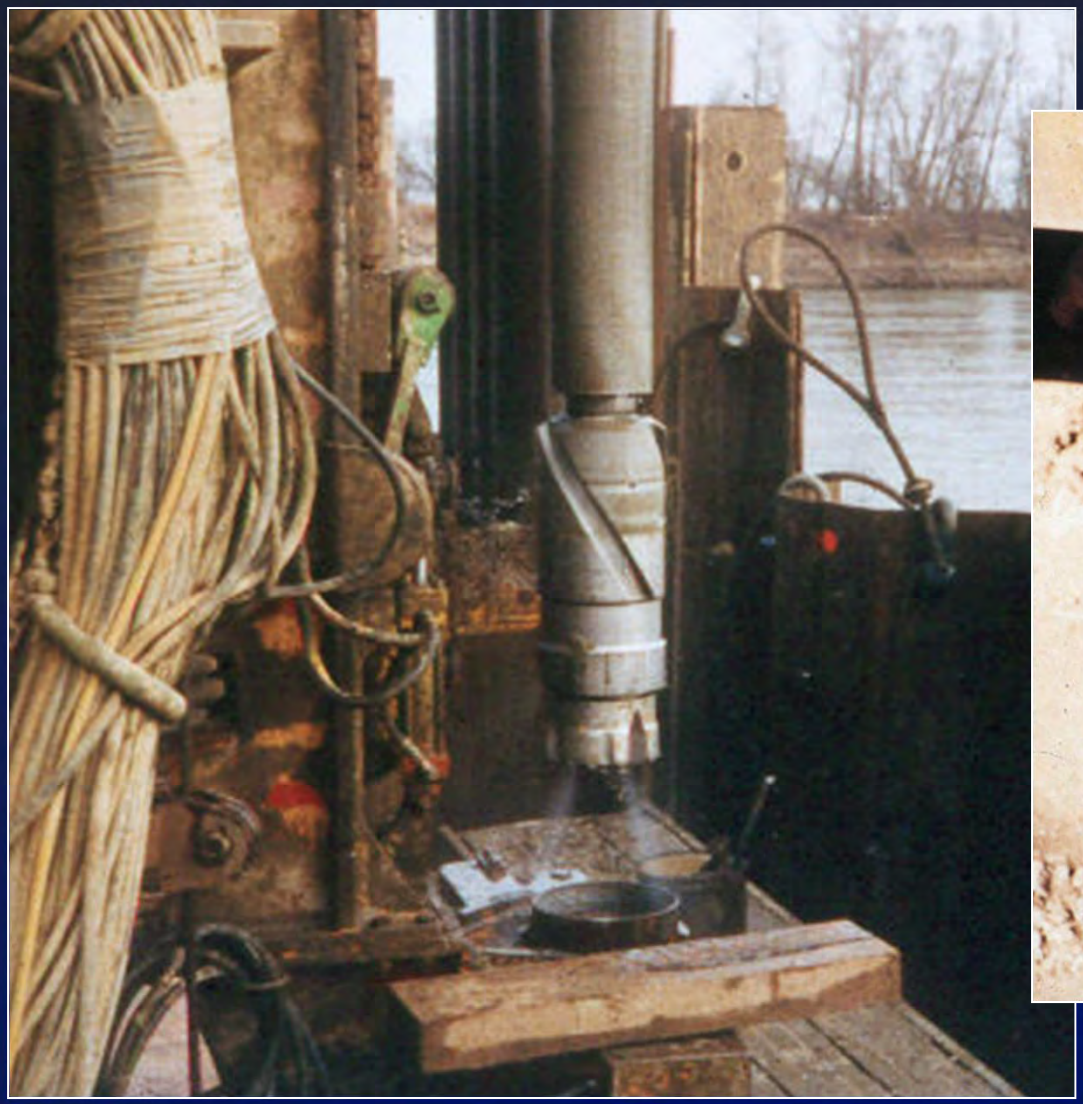
Mifflin County, PA

TYPICAL MICROPILE DRILLS

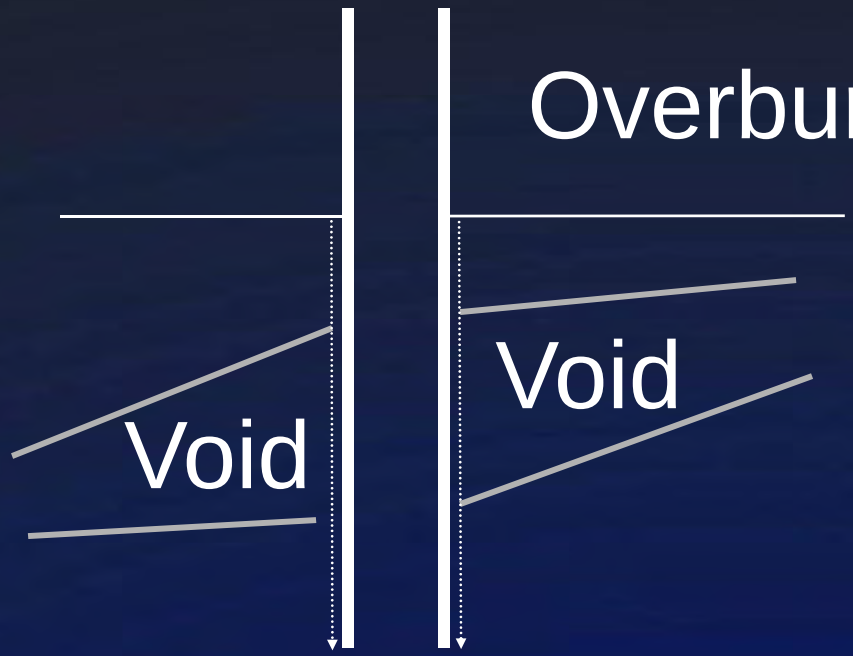
KARST - MICROPILE INSTALLATION

- Rotary Percussive Duplex Drilling.
- Advance the casing while drilling hole, never open hole drilling.
- Drills bond zone with percussive hammer.
- As pile is advanced, competent material is verified - no exploratory probing – micropile is “exploratory”.
- Anti-washout admixture.
- 7-in diameter (min).

TUBEX

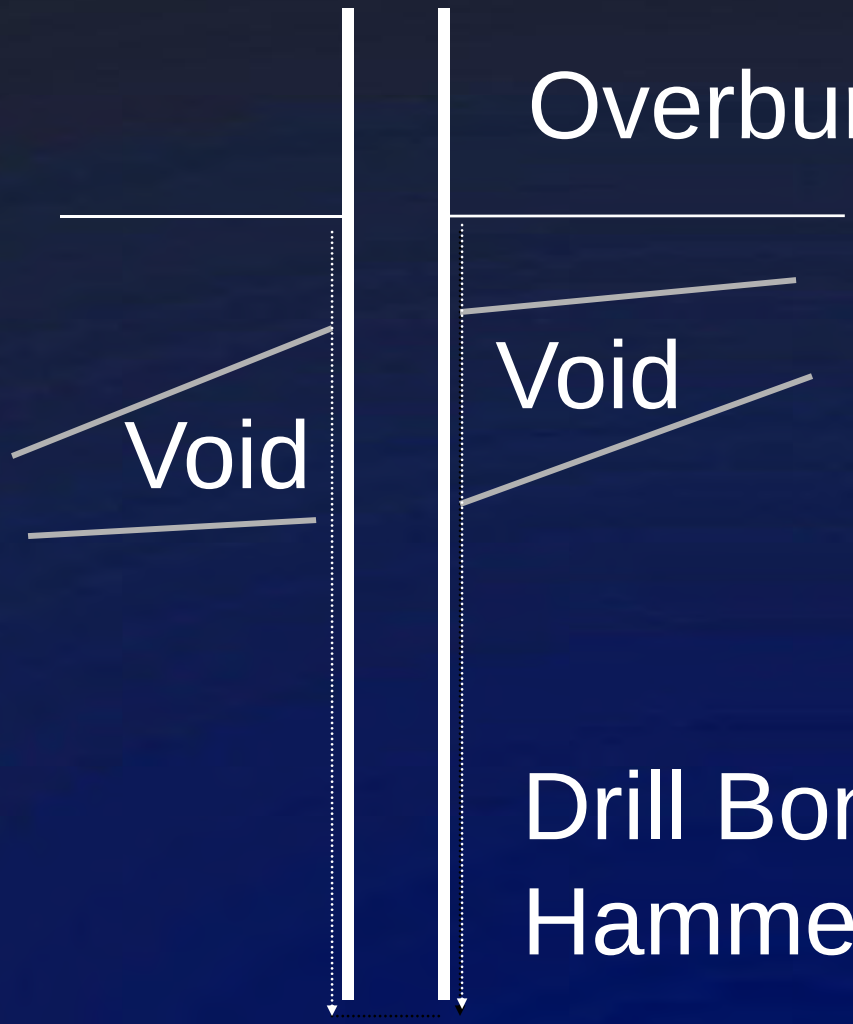


TUBEX

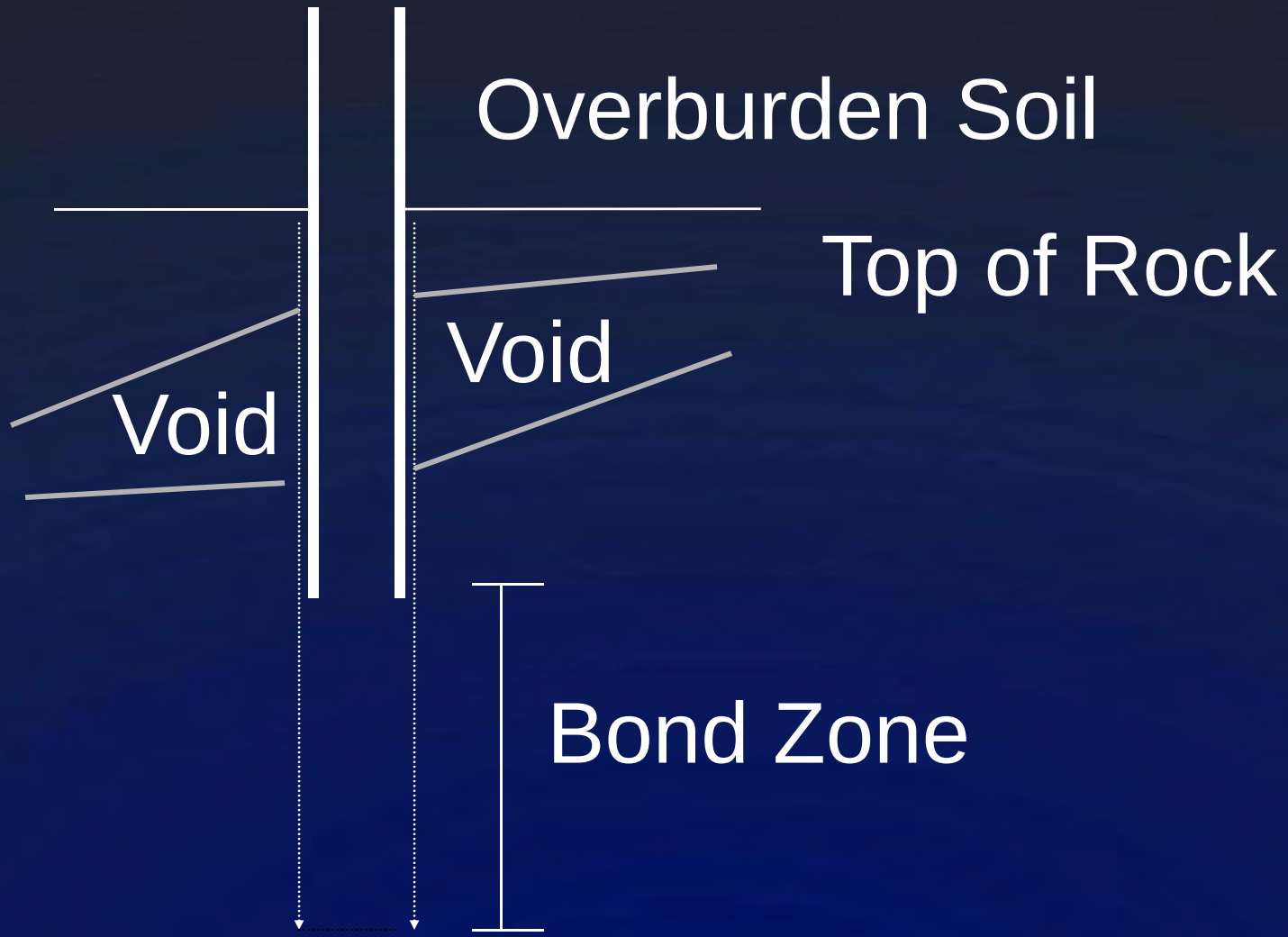


No Open Hole Drilling

TUBEX


Overburden Soil
Top of Rock
Void
Void
Drill Bond Zone -
Hammer Response

TUBEX



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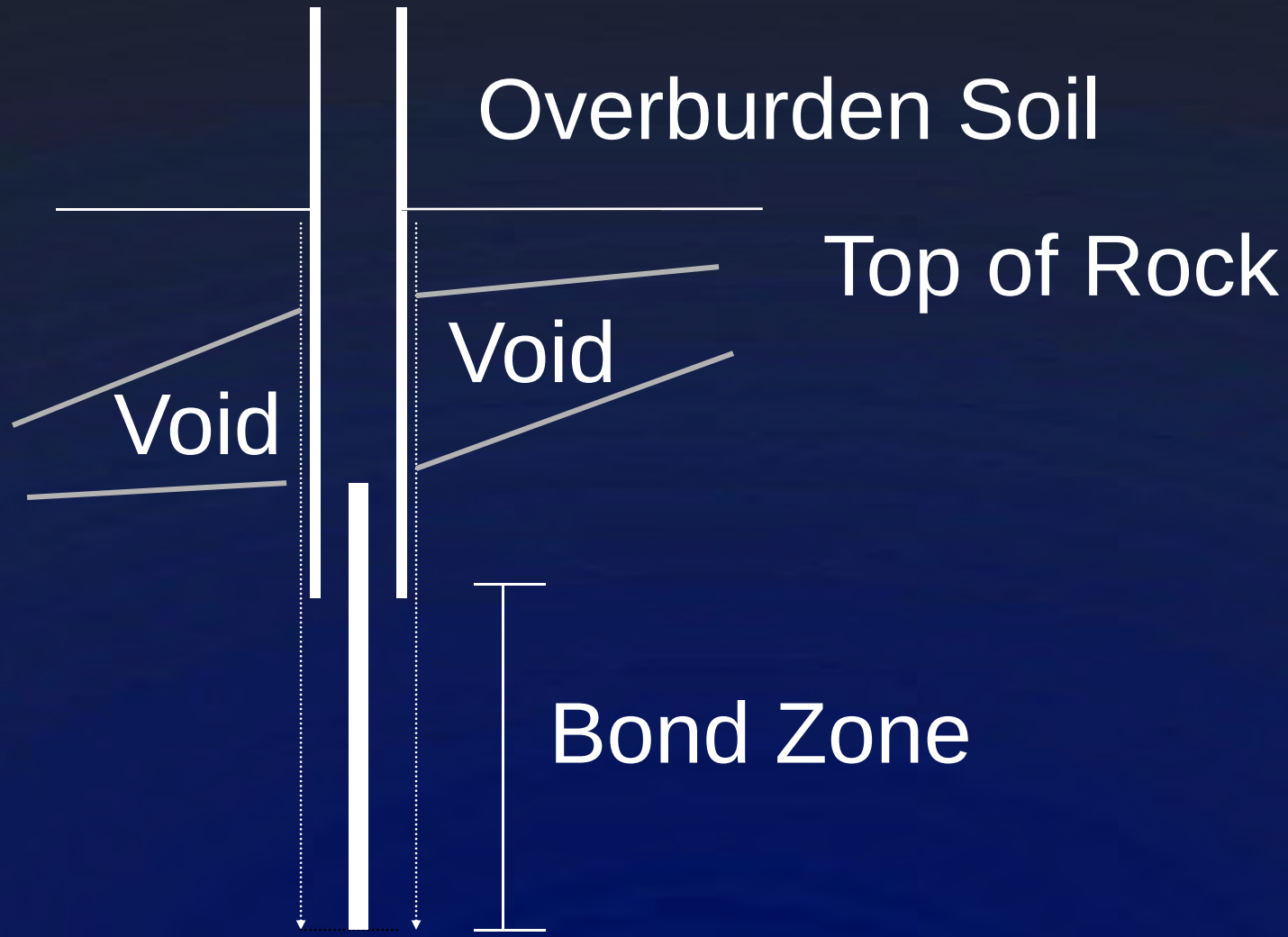


TERMINATION CRITERIA

If during drilling of the bond zone, voids are encountered that sum:

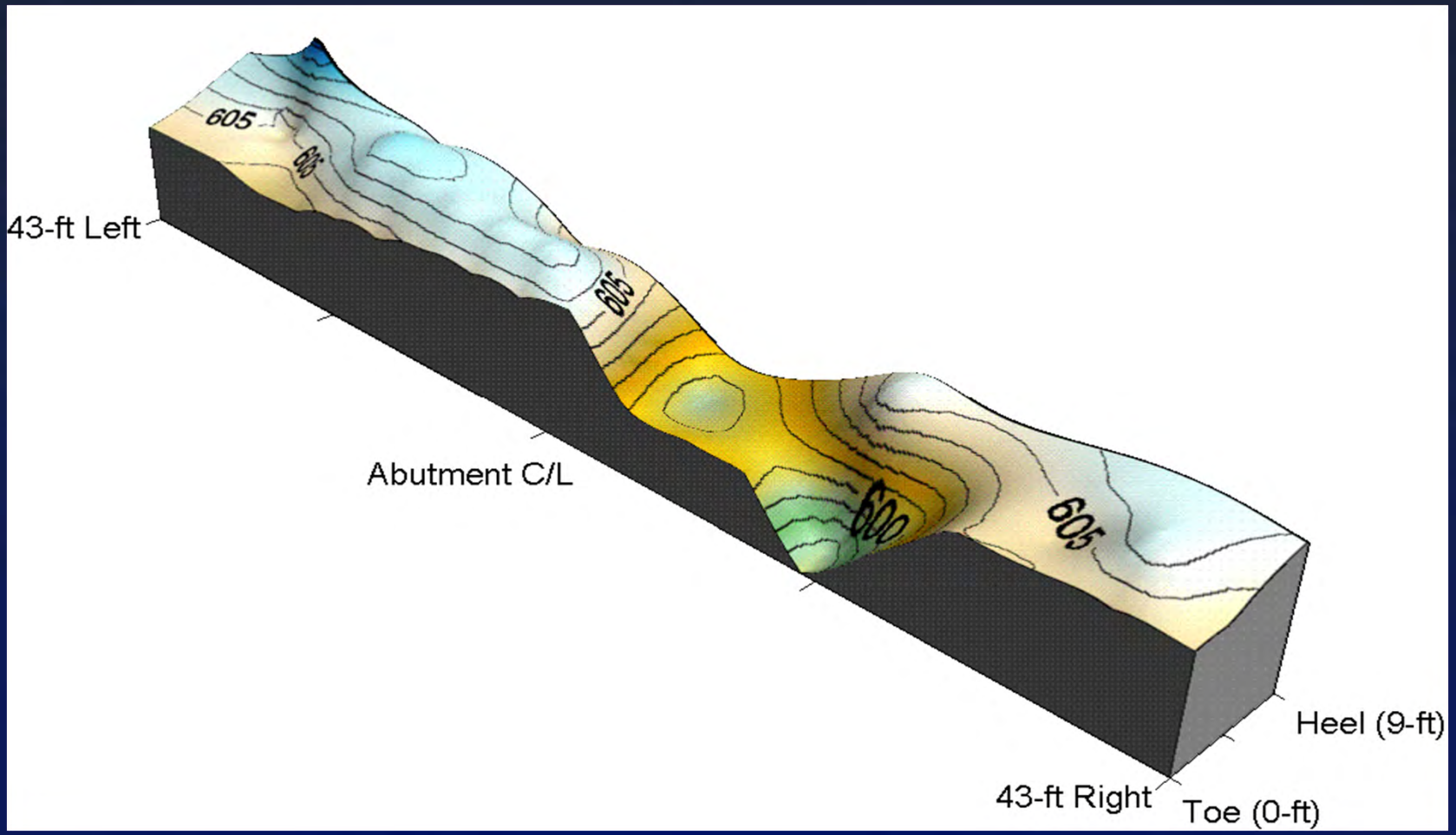
a) Less than 6-in, bond zone remains unchanged.

b) Greater than 6-in but less than 12-in, extend bond zone one foot.

c) Greater than 12-in, restart count from the bottom of the void to meet above criteria.

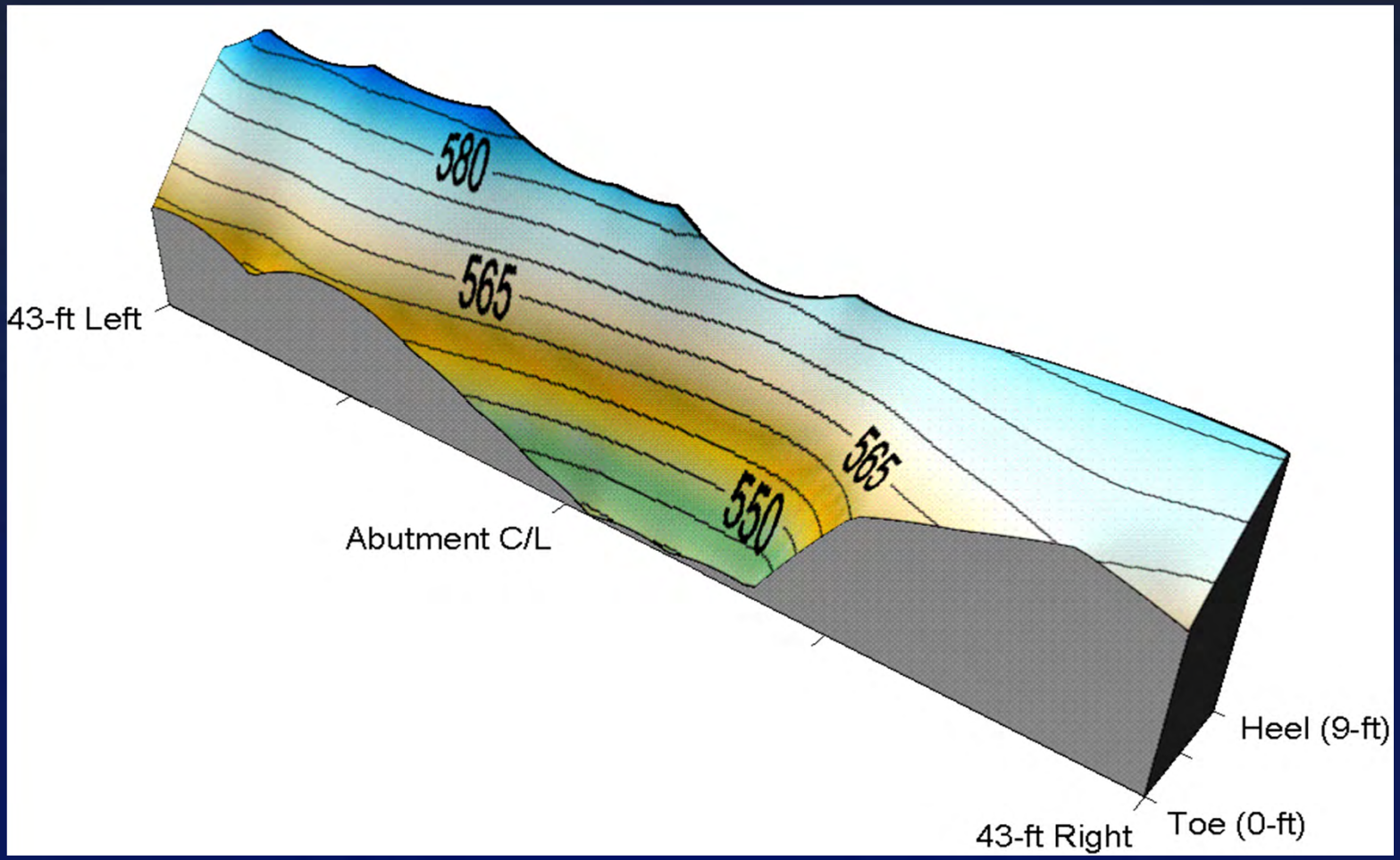
STRUCTURE 5A – ABUTMENT 2

Top of “rock” contours based on exploratory test hole data



STRUCTURE 5A – ABUTMENT 2

Top of rock contours based on micropile data



ENGINEERING

Sinkhole Treatments

Grouting

Structure Support

Instrumentation

INSTRUMENTATION PROGRAM

- Time Domain Reflectometry (TDR) can be used to monitor zones considered high risk for sinkhole development.
- Similar systems used to monitor roadway subsidence traversing active and abandoned mines.
- Should the system detect movement / moisture beyond the threshold, the system can automatically activate auto-dialers to notify appropriate personnel.

SUMMARY

SUMMARY

- After a sinkhole has collapsed, it is important to understand that the position of the solution pipe and the processes operating in the subsurface have not changed, and that the erosion process can continue.
- Site characterization (published literature, test borings, geophysical methods, geologic mapping, dye tracing, hydrographs).
- Geotechnical engineers must understand both surface and subsurface water to control sinkhole development - inverse aggregate graded filters, grout programs or both?

How will roadway design impact both surface and subsurface water? (maintain or change flow paths - consequences)

Known Unknowns and Unknown Unknowns

Need a good hydrogeologist on project team !

THANK YOU

URS