Validation and Update of the Sinkhole Index
- Phase 2 -
(BED26 TWO 977-10)

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FDOT 37TH ANNUAL GRIP 2024

August 15th 2024

Outline

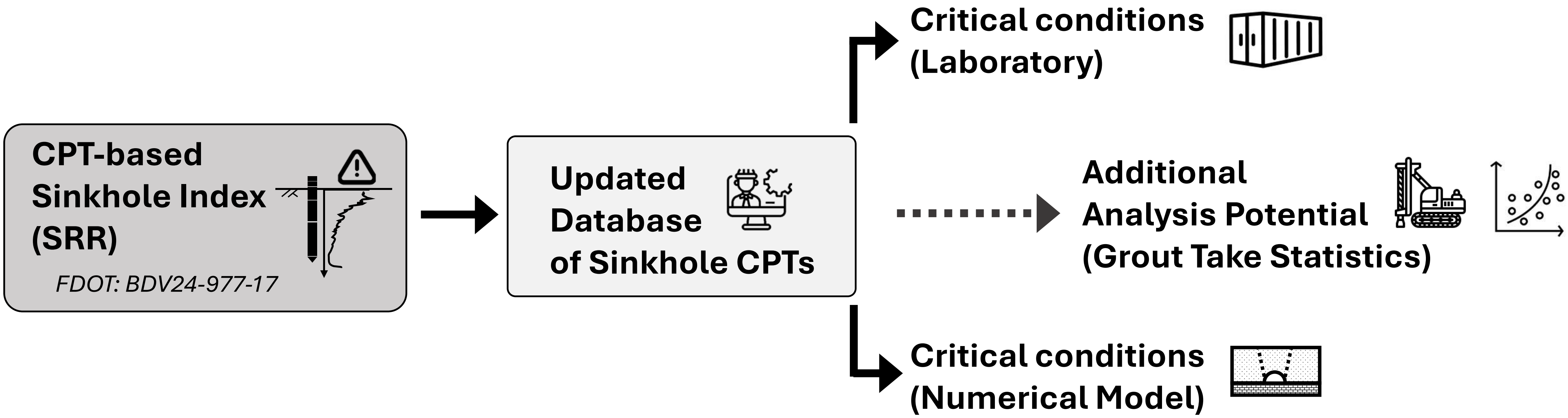
- Brief Project Overview
  - Objectives
  - Benefits

- Florida Sinkhole Refresher
- Sinkhole Index Refresher

- Progress
  - Physical Modeling
  - Numerical Modeling
  - Grout Take Correlation

Project Objectives [Phase 2]

1. Validate the **sinkhole index** via large-scale sinkhole simulation testing
2. Validate **sinkhole index thresholds** calculated in Phase 1, using
   a) Finite Element (FE) modeling, and
   b) Large-Scale Sinkhole testing using LSSB
3. Investigation into Sinkhole Indices' ability to estimate grout volume (repair)



Project Benefits

- *Qualitative*

  The updated index and chart that quantitatively characterize the raveling condition and depth characteristics will enable more accurate and effective sinkhole assessment, thus geotechnical engineers can make better decision in emergency response (e.g., lane closure), repair/mitigation plan, etc.

- *Quantitative*

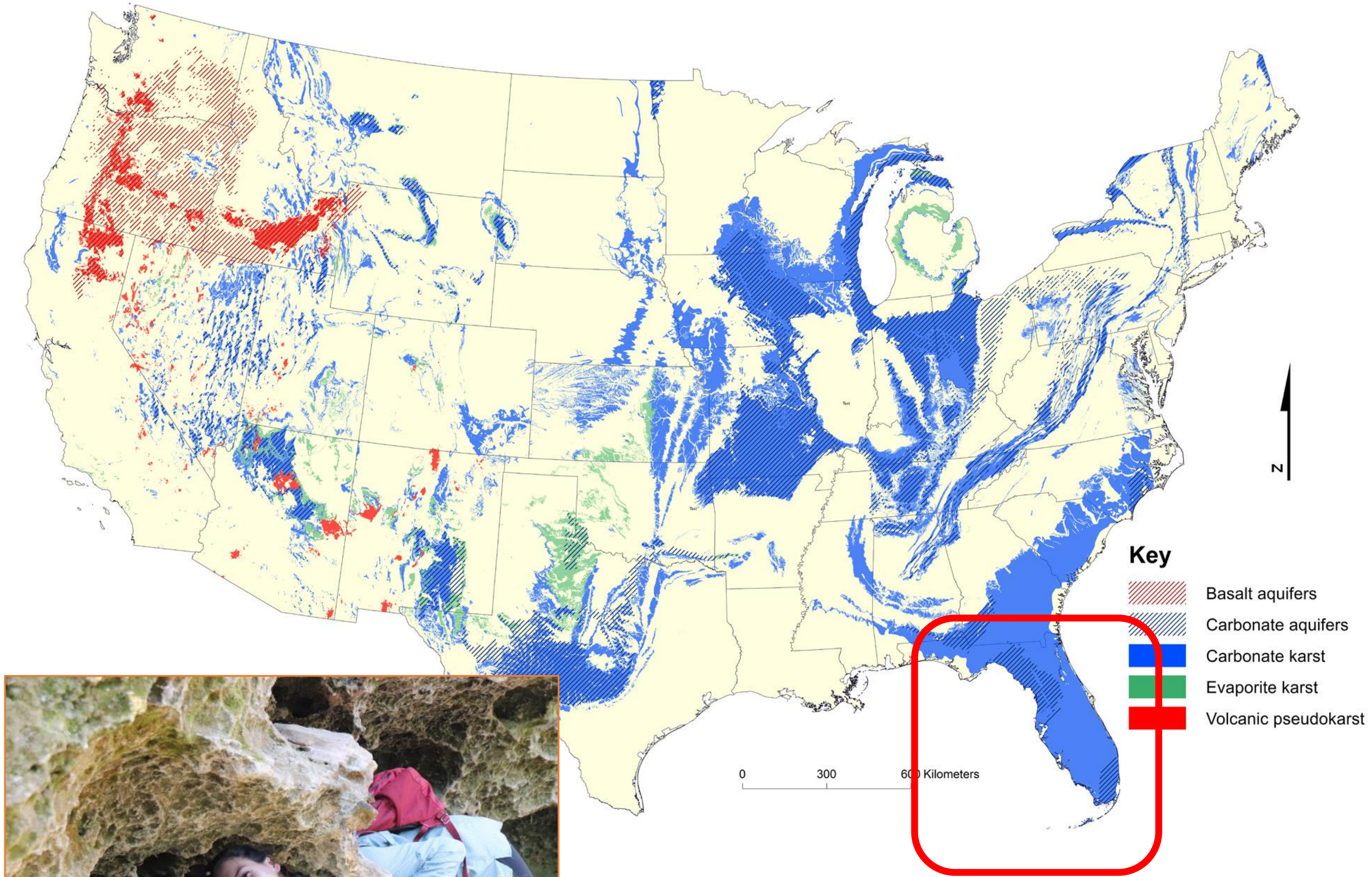
  The updated index and chart will help engineers perform more effective sinkhole assessment; thus, save time and reduce repair cost (e.g., optimum repair/mitigation scheme). The correlation between the index and grout-take volume can provide quantitative information of grout cost, amount, etc.

Karst:

Landscape developed by the dissolution of sediment and rocks.

“Eogenetic” karst:

- *youngest* karst (55mya)
- Extensive primary porosity
- “undisturbed” overburden



✓ Provides clean drinking water to the state.

✗ Creates a landscape vulnerable to sinkholes.

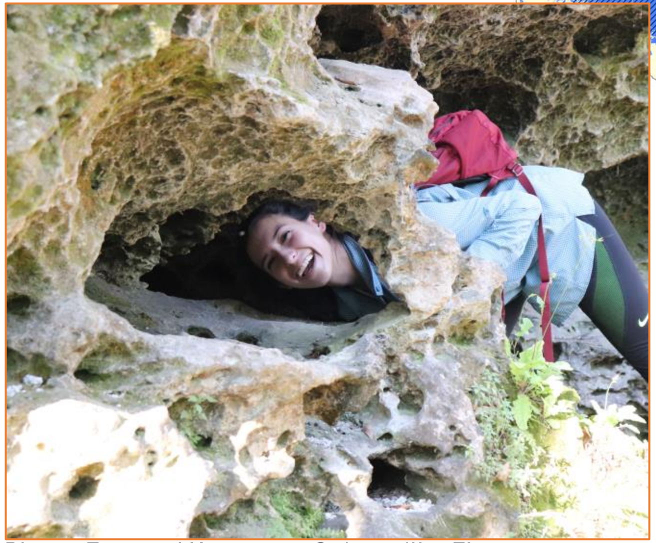


Photo: Exposed Karst near Gainesville, FL.
Wife to scale. Personal archival

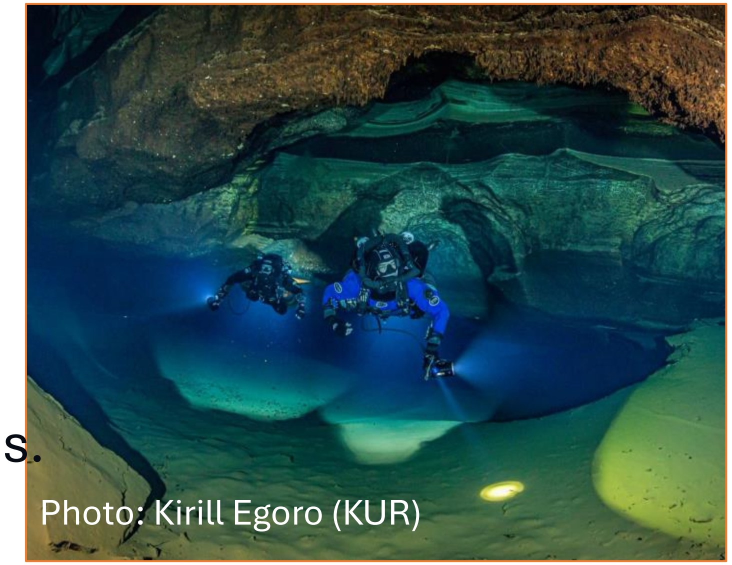


Photo: Kirill Egoro (KUR)

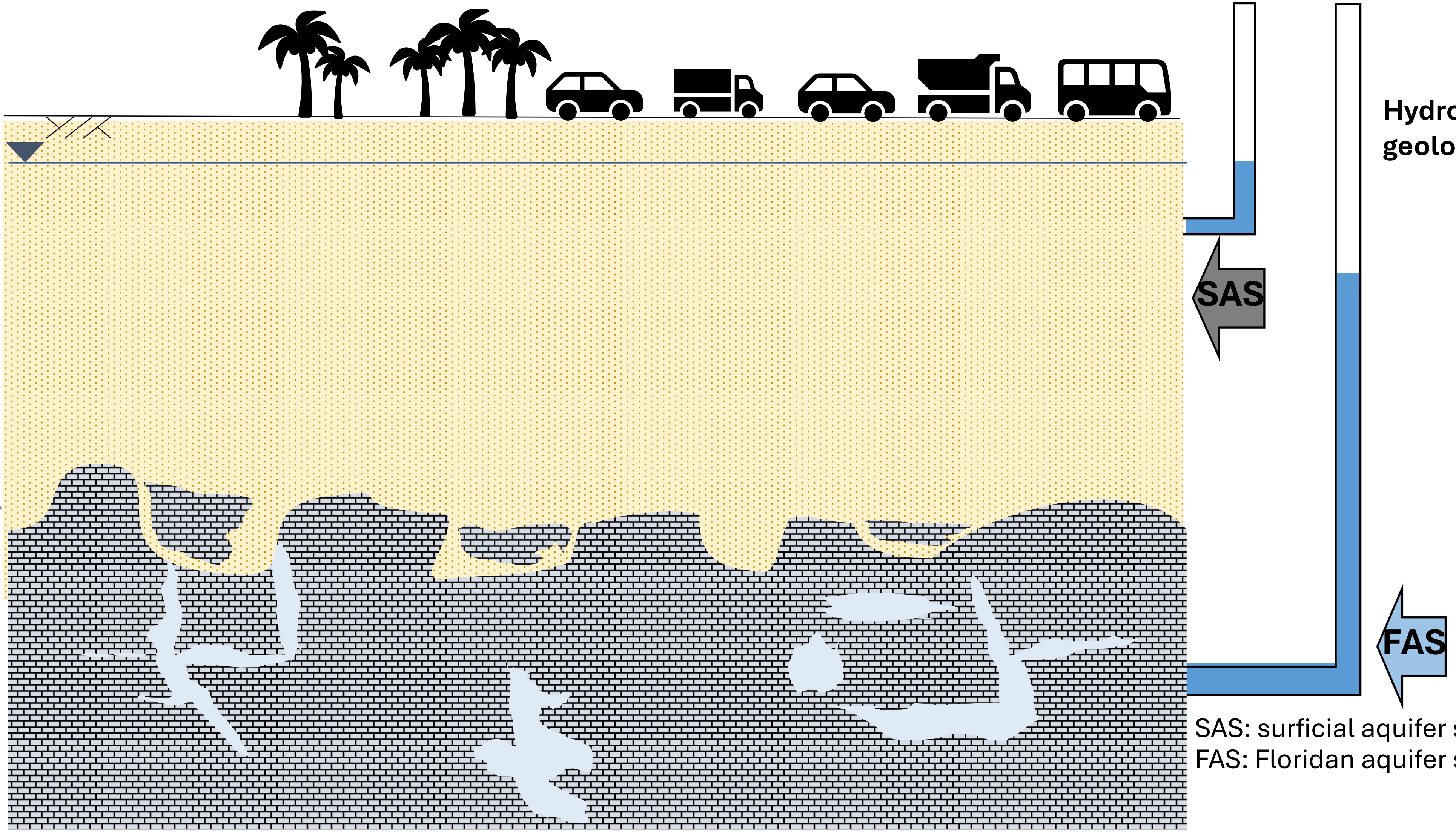
Karst Water's Institute: After Weary and Doctor (2014)
Upchurch et al. 2019: *Karst Systems of Florida*

Generalized* Florida Sinkhole Mechanism
(*VERY!)

Head different between aquifers Orlando ~ 30ft
(Wilson and Beck 1992)

Mixed Sands
SILTS
CLAYS
(overburden)

Cemented Silts and Sands, Limestone & Dolostone
(Floridan aquifer)



No Scale

SAS: surficial aquifer system
FAS: Floridan aquifer system

Modified from Braunstein et al. 1988 & Florida Geological Survey, 1962

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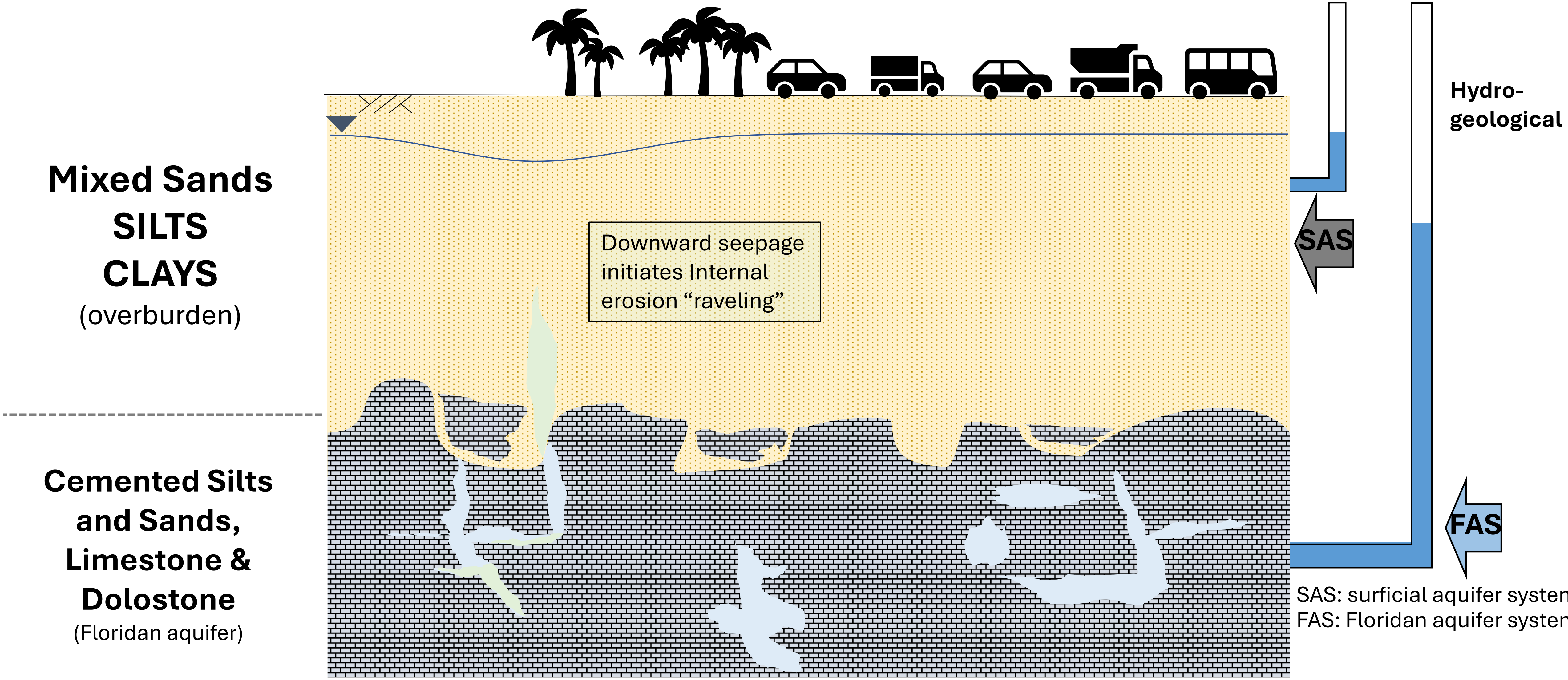

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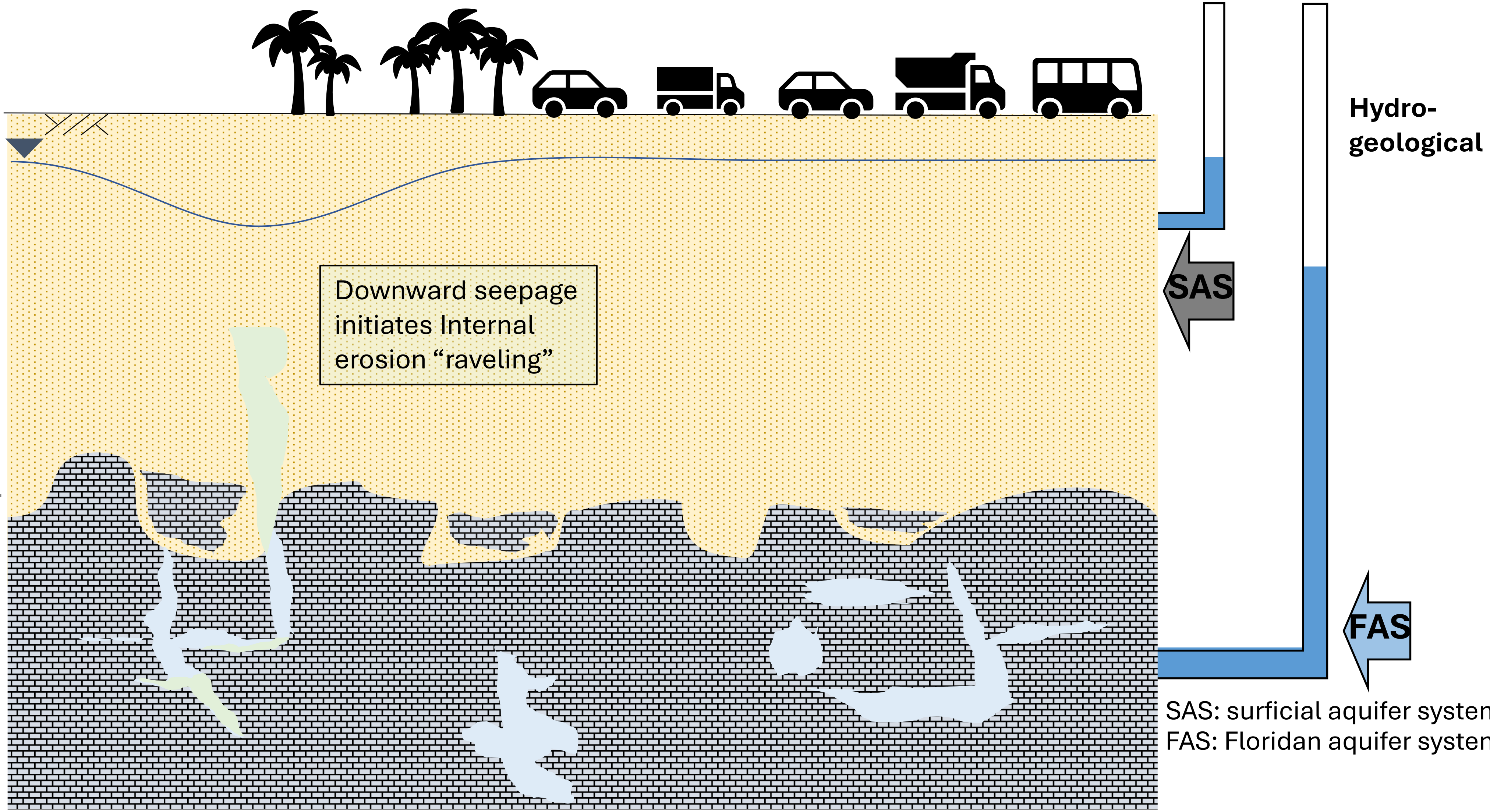

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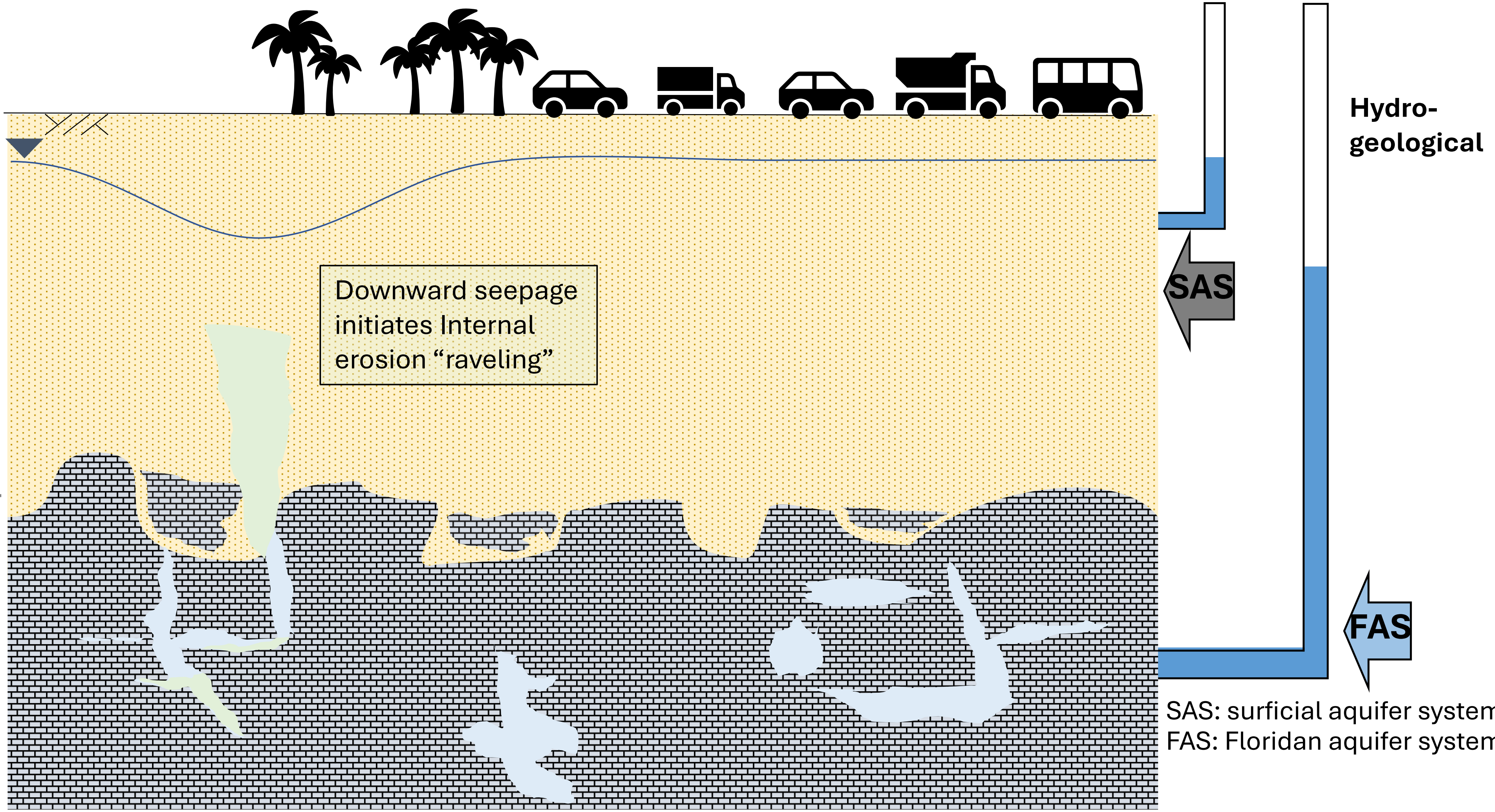

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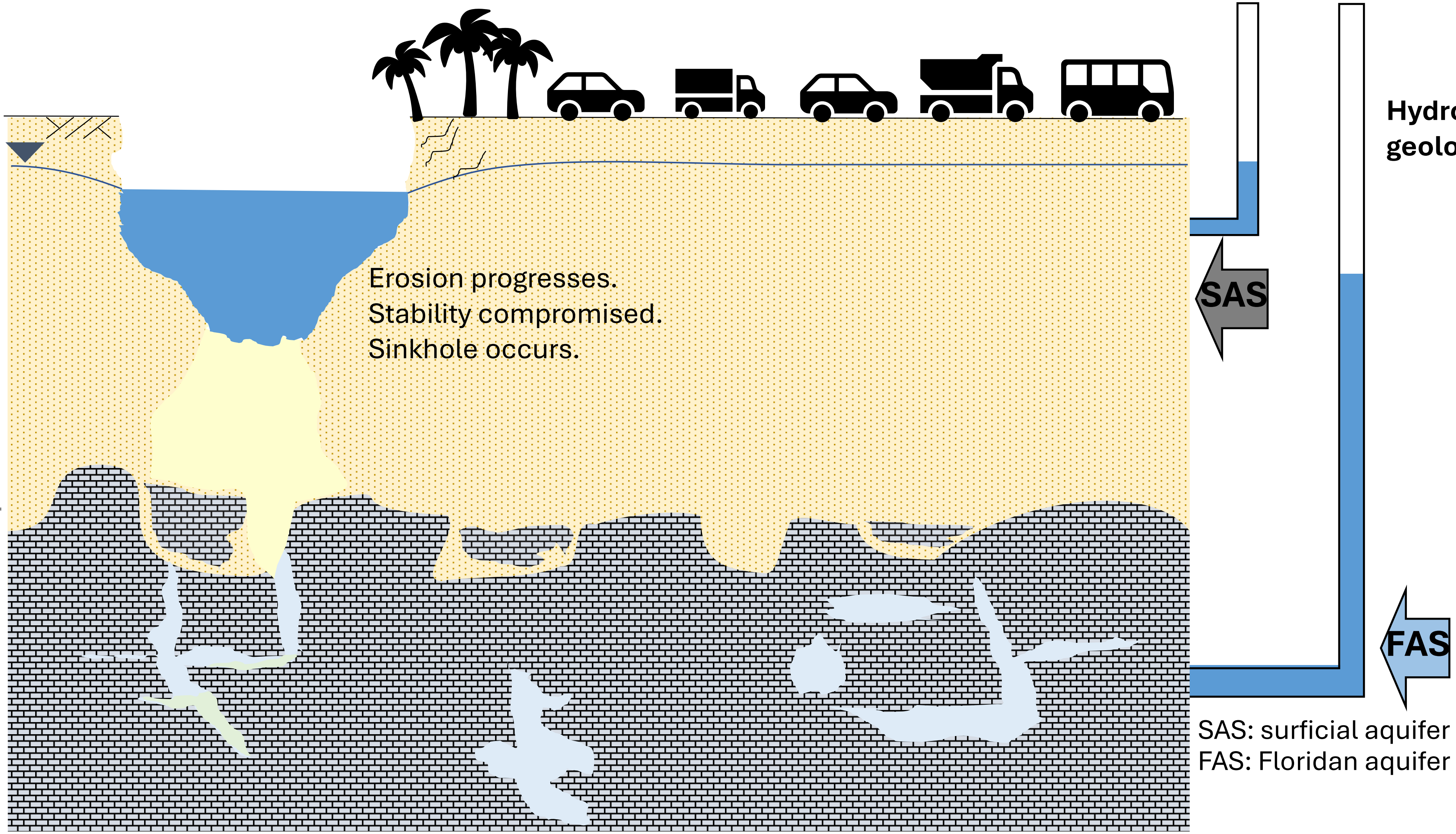


Hydro-geological

SAS: surficial aquifer system
FAS: Floridan aquifer system

No Scale

Modified from Braunstein et al. 1988 & Florida Geological Survey, 1962

"Assessment" Components

Sinkhole contributing factors: (Upchurch 2019)

- Cover Material
- Internal erosion (raveling) development
- Aquifer Potentials
- Rainfall
- Human Activities

During typical subsurface investigation in karst:

- Identify raveled (effected) soils
- Characterize the raveling severity
- Quantify the vulnerability to sinkhole

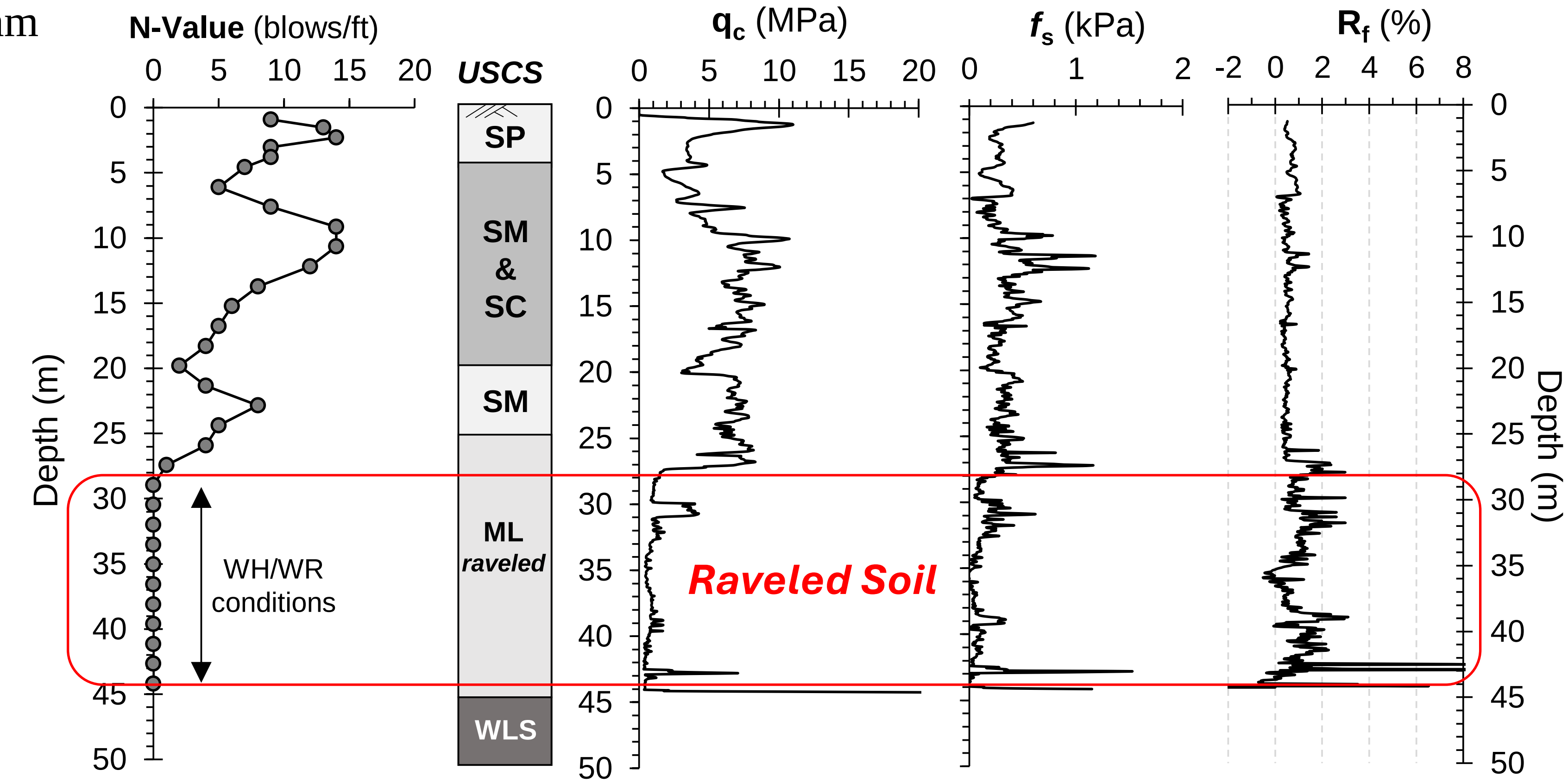
Objective:

Develop Subsurface characterization tools for better decision making in Florida's karst

Geotechnical Testing in Karst

Cone Penetration Test (CPT) SMO team

Standard Penetration Test (SPT) SMO team



SPT performed ~3m NE *of sinkhole*

CPT performed ~0.5m *from Boring B-1*

Cone penetration test (**CPT**): **0.16 ft** [60ft ~ **> 1 hr**]

Standard penetration test (**SPT**): **2.5 ft** [60ft ~ **half day**]

<u>Important for ground verification</u>

Sinkhole Index

Sinkhole Resistance Ratio (SRR)

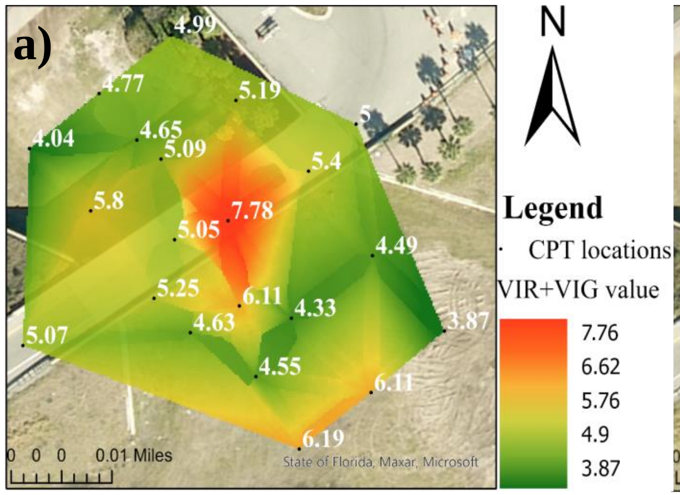
Nam et. al - FDOT: BDV24-977-17

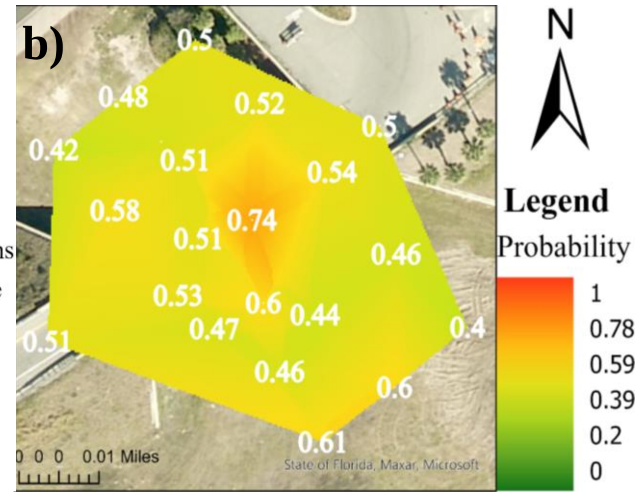
$$SRR = \left(\frac{q_{over} + q_{ravel}}{100 * \sigma'_{vo}}\right)\left(\frac{t_{over}}{t_{ravel}}\right)$$

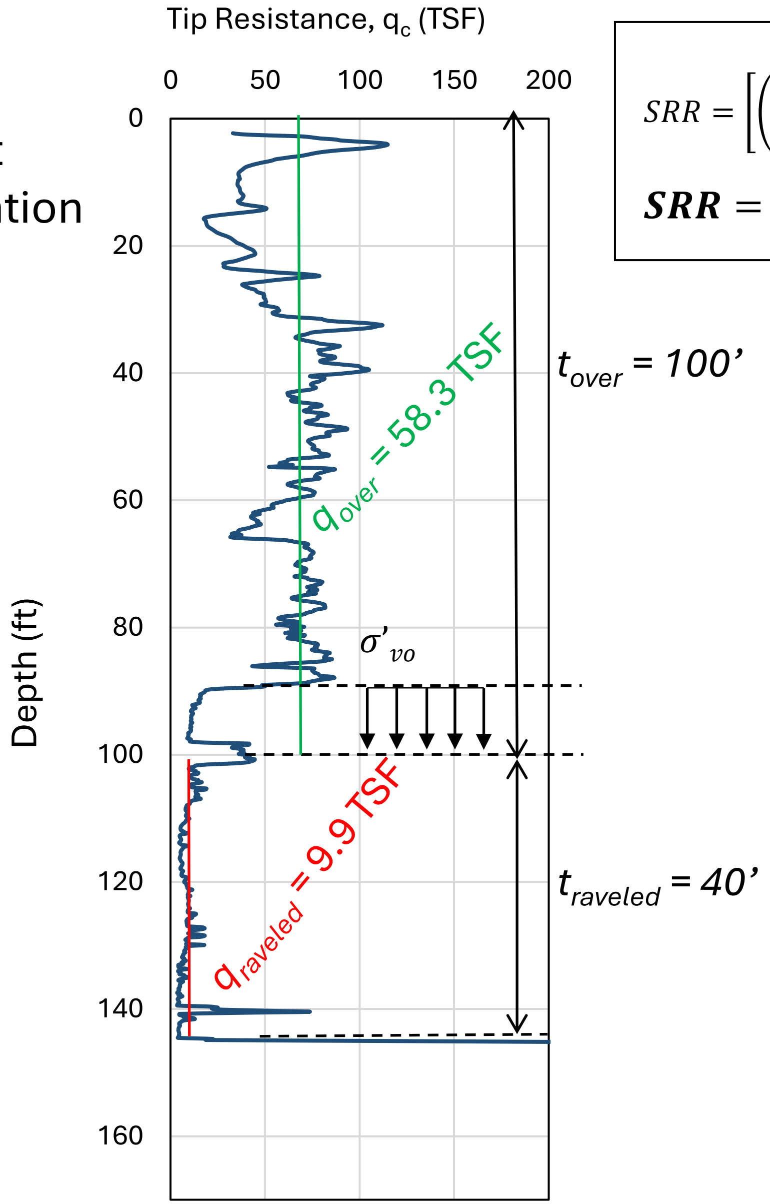
SRR ⇧ = "**safer**" against sinkhole formation

Where:

q_{over} = average q_t measured in overburden soils (TSF)
q_{ravel} = average q_t measured in Raveled soils (TSF)
σ'_{vo} = effective vertical stress at depth raveled soils start (TSF)
t_{over} = thickness of overburden (ft)
t_{ravel} = thickness of raveled zone (ft)
q_t = Corrected cone tip resistance (corrected for p.w.p)







$$SRR = \left[\left(\frac{100'}{40'}\right) * \left(\frac{58.3 + 9.9}{2.74 * 100}\right)\right]$$

$$\boldsymbol{SRR = 0.622}$$

Task 1: Sinkhole Physical Testing using the LSSB

- Simulation of large-scale sinkhole raveling and collapse to identify critical ratio of encountered stratigraphy geometry and reduction of soil resistance due to sinkhole formation (SRR parameters).

Large-Scale Soil Box (LSSB) Testing Layout

Modifications for Sinkhole Simulation

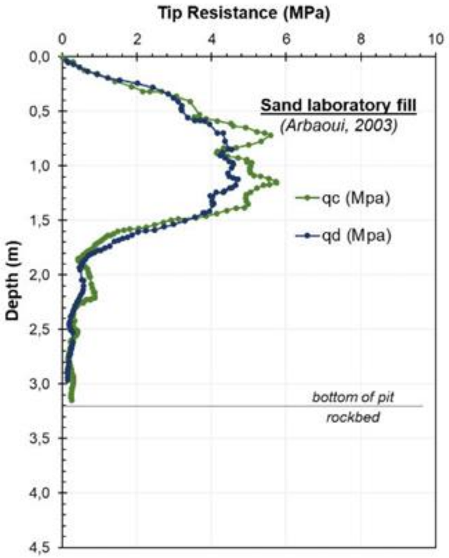
- Pressure cell array
  - Density, arching and horizontal stress during collapse.
- Inflatable void options (yacht fender)
- Boundary conditions (plastic liner and waterproof)
- Catchment basin for effluent eroded slurry

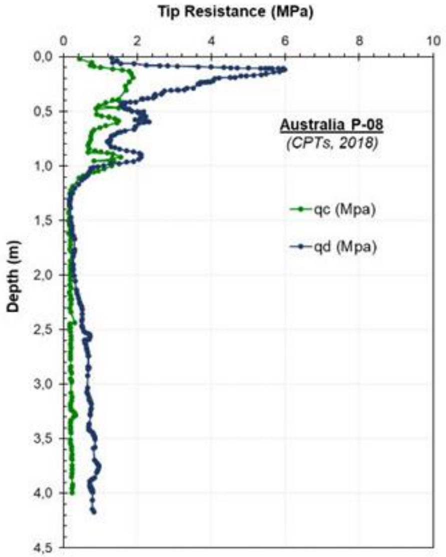
24” x 52” - 29” x 18” - 42” x 18’

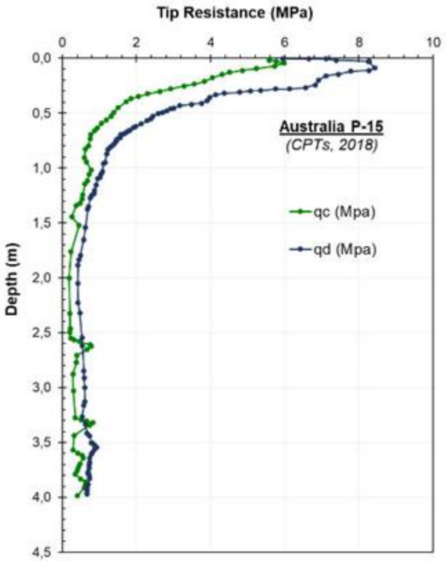
Task 1: Sinkhole Physical Tests using the LSSB

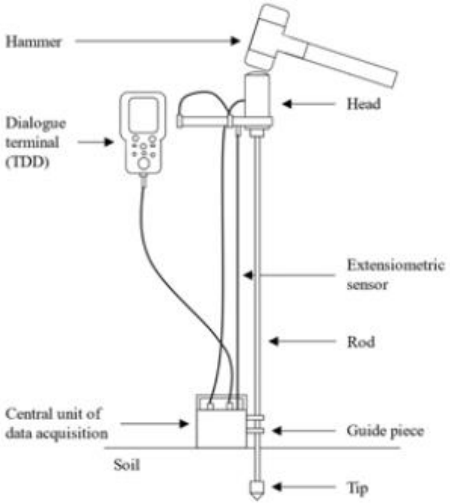
Soil testing will be performed using the PANDA variable energy Dynamic CPT.

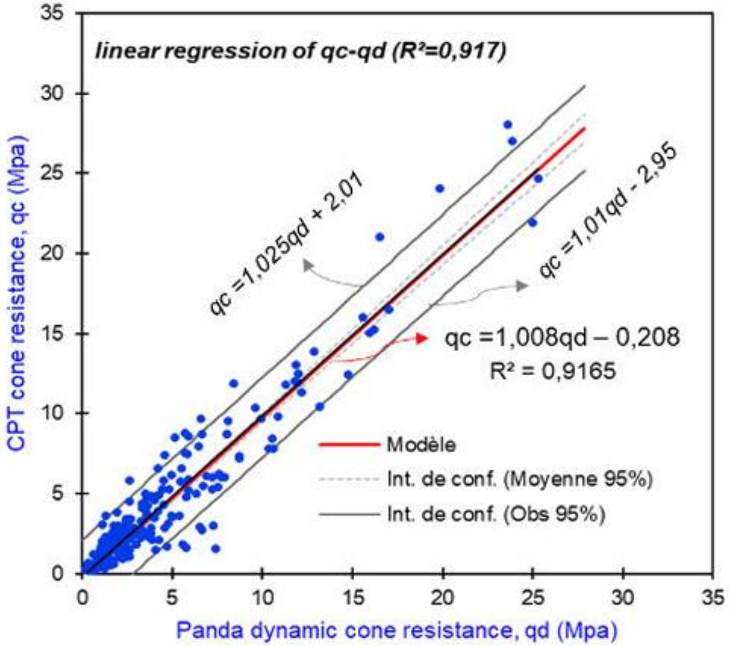
- Variable Energy allows user to control penetration depth
- French standard for compaction control of subgrade
- Used in liquefaction assessment and mitigation testing Hubler and Hanley (2021) and Retamels et al. (2021)











SRR = *f*(cone tip resistance) → q_c

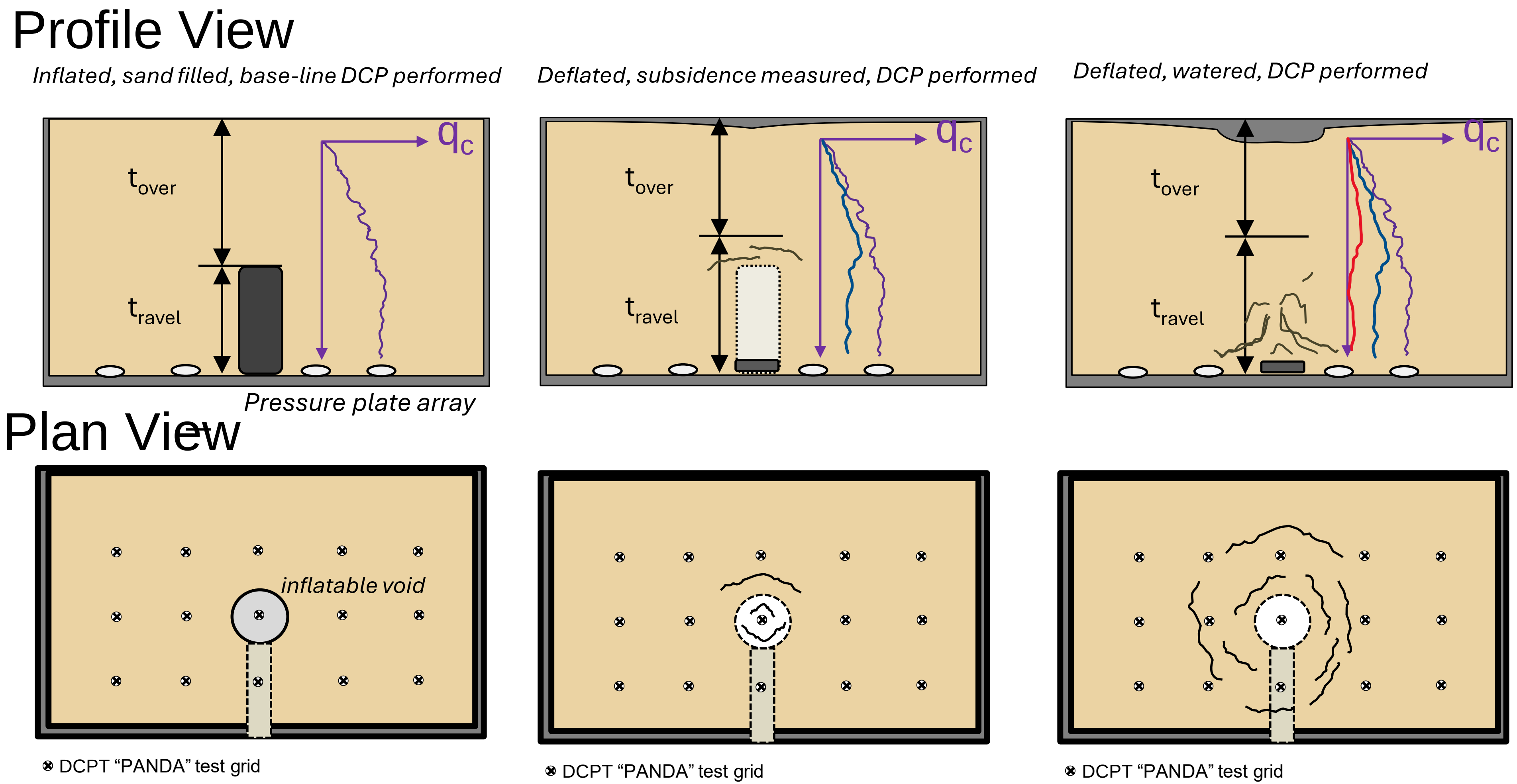
Dynamic CPT → q_d

$$q_c = 0.87 q_d \ to \ 1.11 \ q_d$$

Benz-Navarrete et. al (2020)

Retamels et. al (2021)

Task 1: Sinkhole Physical Tests using the LSSB



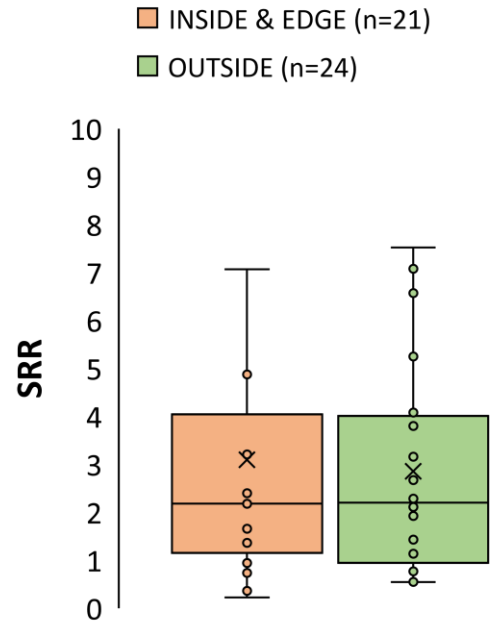
Planned Steps:

1. Subsurface void: installation of in situ (controllable) volume and drainage port
2. Soil fill and density check (baseline)
3. reference q_c profiling (DCPT PANDA®)
4. Erosion monitoring, Post-collapse forensics → **Sinkhole Indexing**

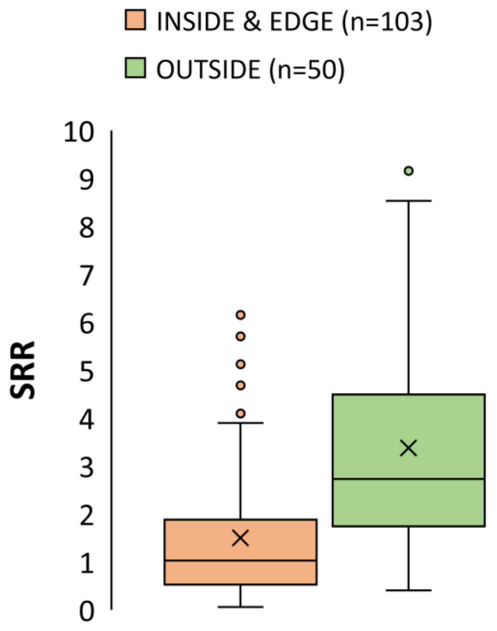
Task 2: Establish the severity criteria of the sinkhole index and correlate the index to the grout-take volume

1. Qualitative meaning of the SRR values will be assigned and the corresponding severity criteria will be established.
   - SRR based on database and numerical modeling (e.g., probability of collapse, Factor of Safety)
   - Use of LSSB testing results to validate the SRR. → $SRR_{critical?}$
2. Correlation between SRR and the grout-take volume in mitigated sites.

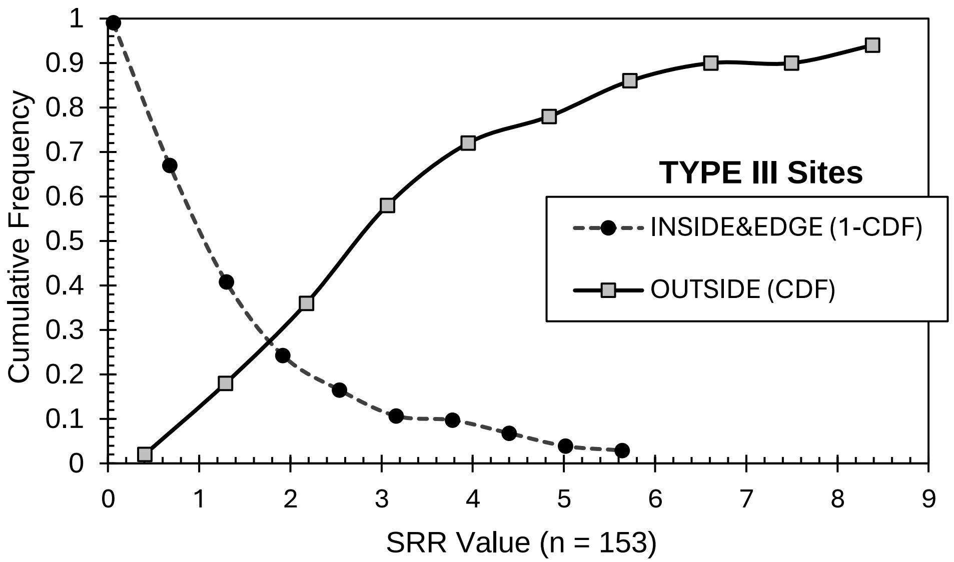
Task 2: Establish the severity criteria of the sinkhole index
and correlate the index to the grout-take volume



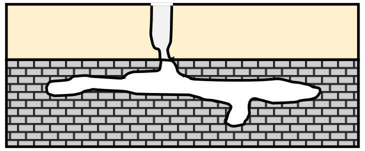
TYPE 1 Sinkholes
(Gainesville/Ocala)

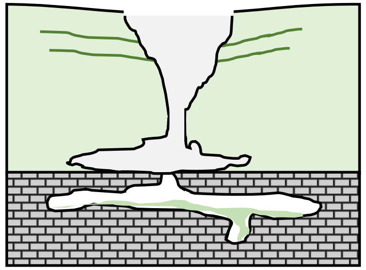


TYPE 3 Sinkholes
(Orlando/Tampa)



SRR value of ~2.0 suggested "breakpoint"





In area w/ shallow cover material:
SRR not conclusive based on field data

Where Cover Collapse Sinkhole form
SRR < 2.0 suggests critical conditions

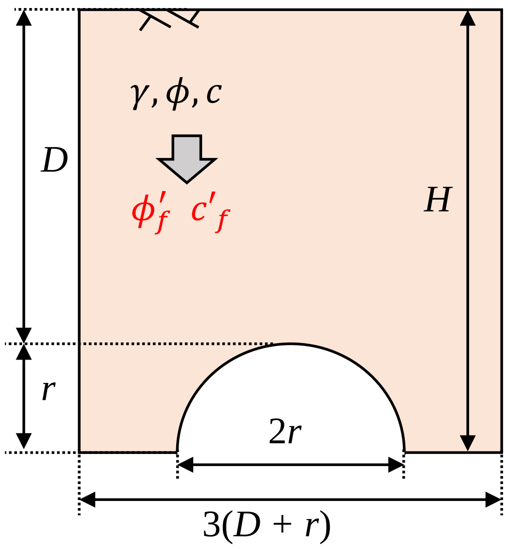
Task 2: Establish the severity criteria of the sinkhole index

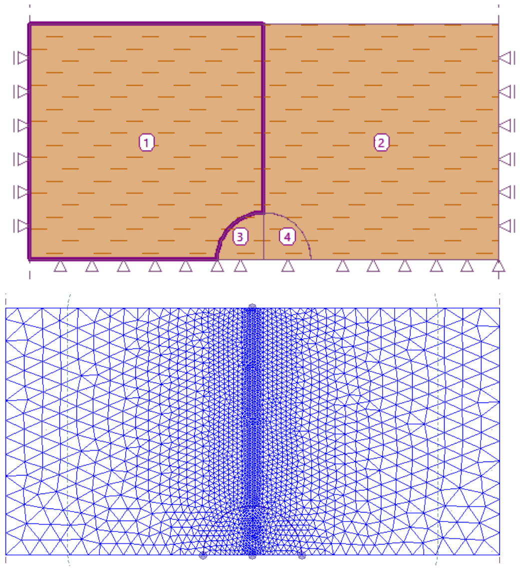
and correlate the index to the grout-take volume

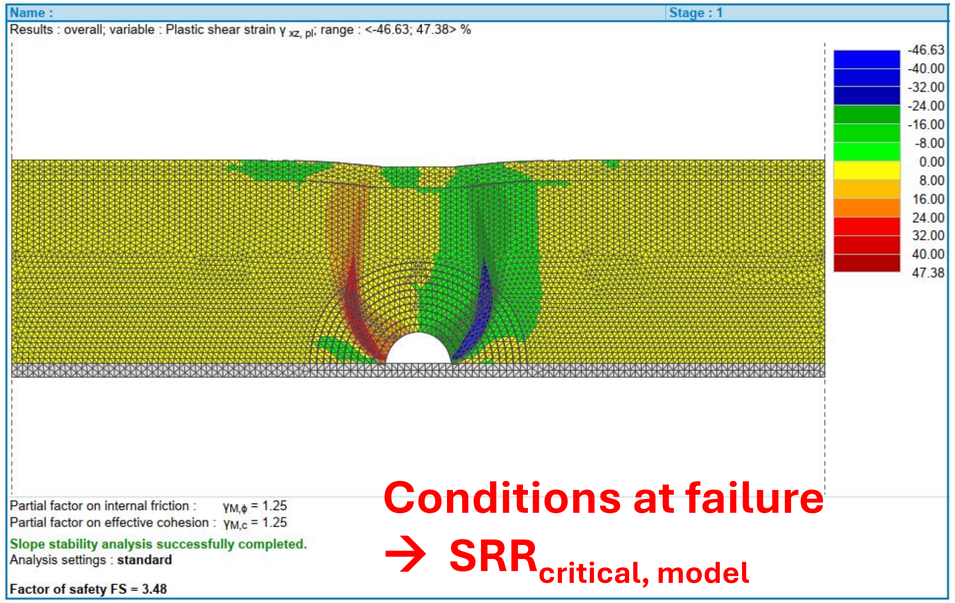
numerical modeling ➡ Factor of Safety

115 Stability Simulations
as of 8/11/2024

2D plane strain

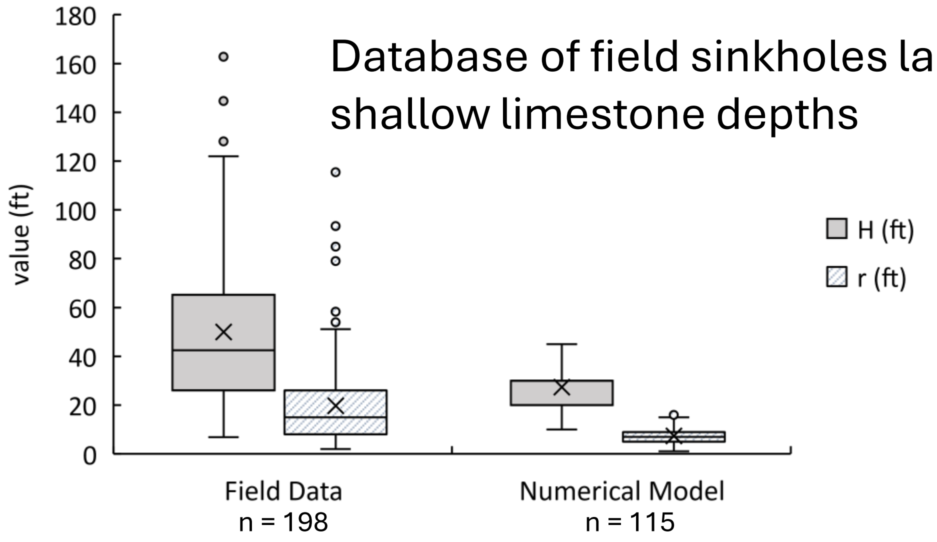




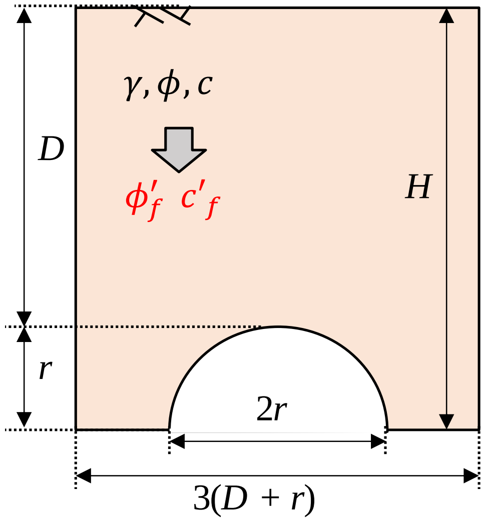


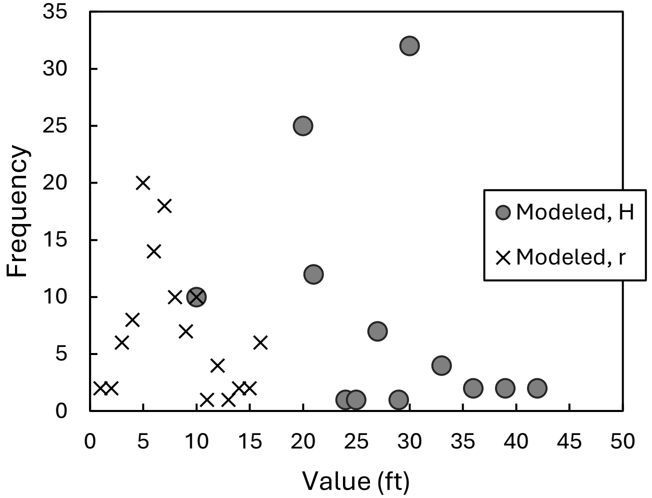
Stability "Strength Reduction Factor" FEM simulations to determine conditions which cause sinkhole to collapse (i.e., F.S. = 1.0)

Task 2a: Severity Criteria of SRR



Database of field sinkholes lack data from shallow limestone depths





Range of geometry values in FEM

GOAL: relate FEM to SRR

$$SRR = \left(\frac{t_{over}}{t_{ravel}}\right)\left(\frac{q_{over} + q_{ravel}}{C \times \sigma'_{vo}}\right)$$

From stability FEM: c_f & ϕ_f of overburden soil.

q_{over} → undrained shear strength, S_u (Robertson 2009)

$$Su = \frac{q_t - \sigma_v}{N_{kt}} \qquad q_t = S_u N_{kt} + \sigma_v$$

$$S_{u,failure} = c_f + \sigma'_v \tan(\phi_f)$$

$$q_{t,failure} = S_{u,f} N_{kt} + \gamma D$$

Model assumes q_{ravel} = 0 (empty void)

→ $SRR_{failure,FEM}$

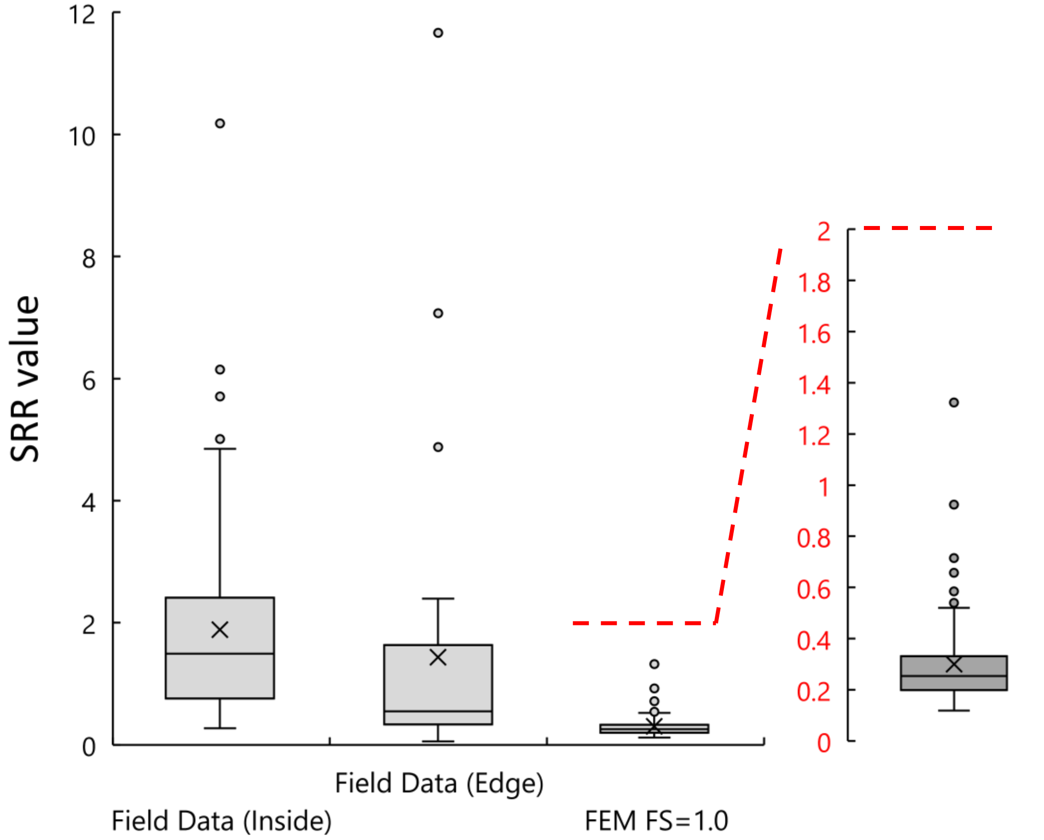
Task 2a: Severity Criteria of SRR

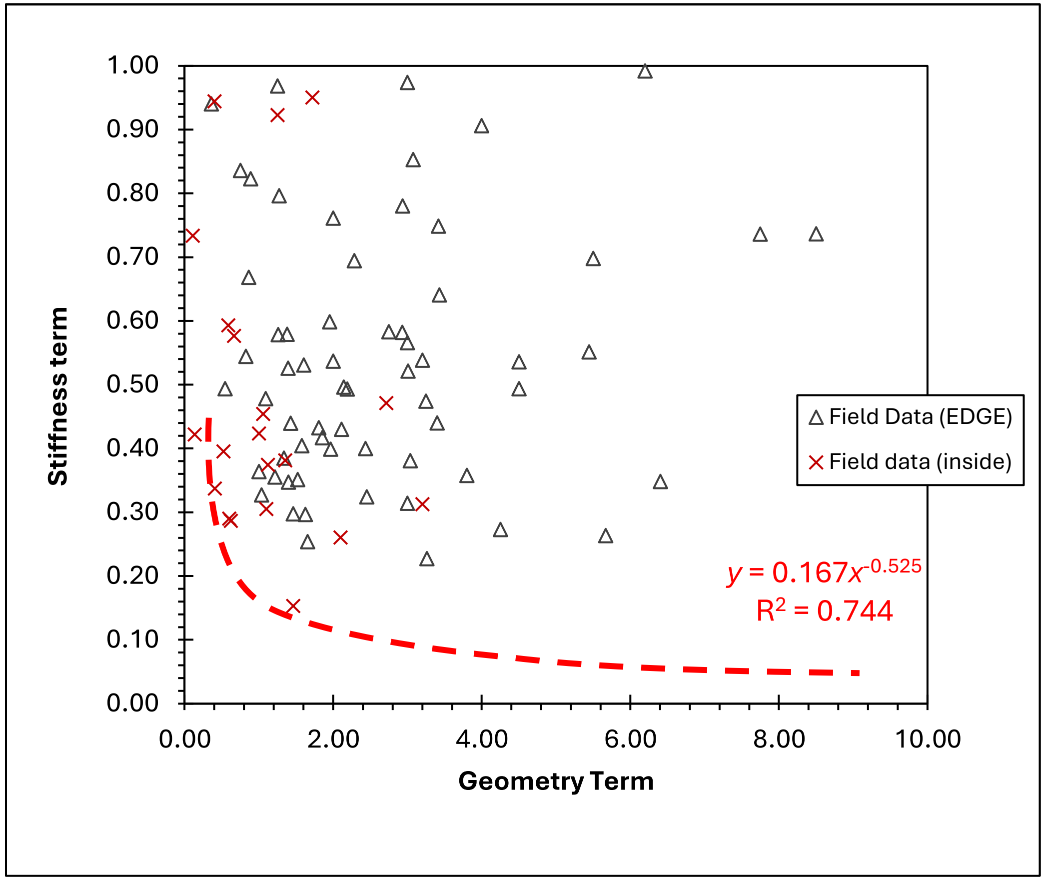
$$SRR = \left(\frac{t_{over}}{t_{travel}}\right)\left(\frac{q_{over} + q_{ravel}}{C \times \sigma'_{vo}}\right)$$

Geometry

Stiffness

Comparison of Field vs Numerical SRR values





$SRR_{Field\ data,\ Critical} \sim 2.0$

$SRR_{Simulated,\ FS=1.0} \sim 0.3$

- Based on stability failure, homogeneous soil
- MC failure w/ correlation to q_c

Task 2: Establish the severity criteria of the sinkhole index and correlate the index to the grout-take volume

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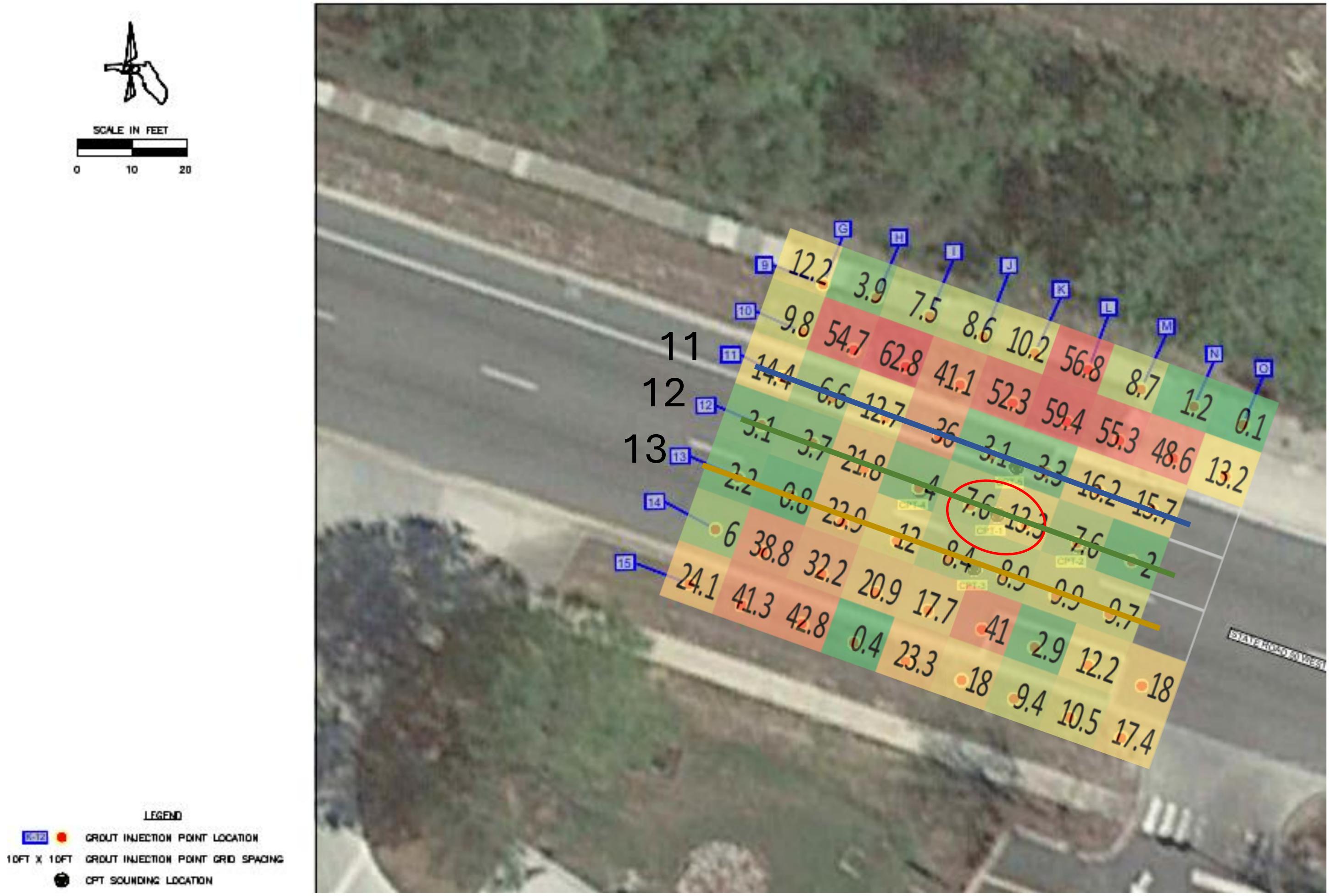
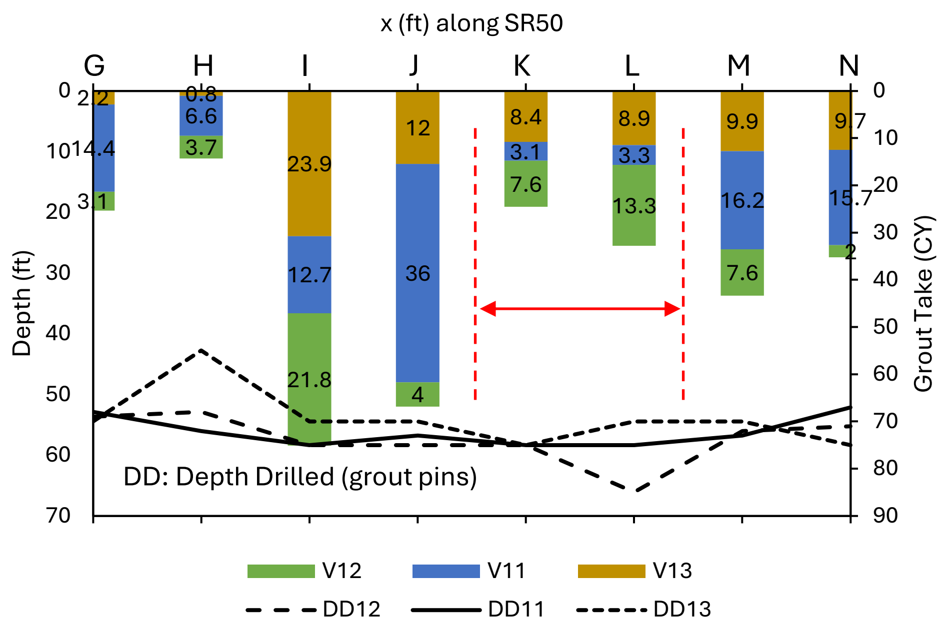
2. Correlation between SRR and the grout-take volume.

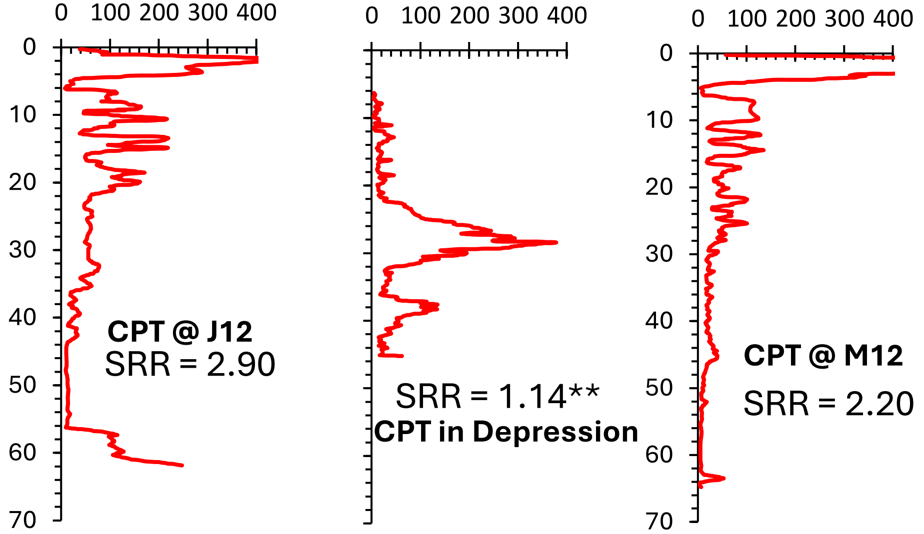
Site ID	Sinkhole Type	County (District)	lat	long	#CPTs	# Grout Points	Total Grout Volume (CY)
Wekiva Parkway Sec.6 STA 775 2019	Collapse	Lake (5)	28.812882°	-81.464594°	12	274	3109
SR50 Groveland 2020	Depression	Lake (5)	28.561992°	-81.858400°	5	60	1130
I4 Rest Area 2011	Collapse	Polk (1)	28.174157°	-81.767350°	3	27	1100
US27 Polk South 2010	Collapse	Polk (1)	27.847627°	-81.585336°	2	19	384
US27 Polk NORTH 2010	Collapse	Polk (1)	27.861023°	-81.588964°	2	14	260
Wekiva Parkway Sec.6 STA 1130	Collapse	Lake (5)	28.813058°	-81.463690°	5	203	5354
US19 Sealawn 2011	Depression	Hernando (7)	28.478269°	-82.611443°	5	65	569

2. Correlation between SRR and the grout-take volume.



Grout Takes along **Line 12**, **Line 11**, **Line 13**

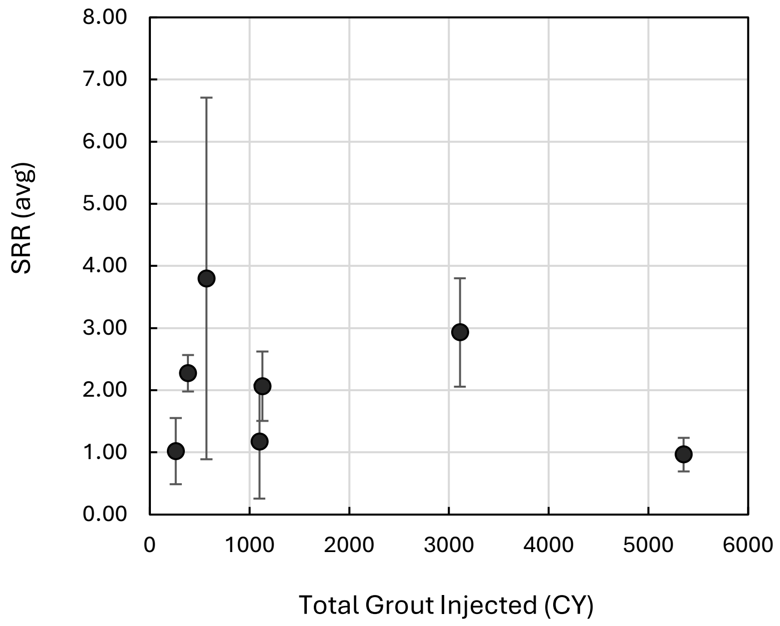


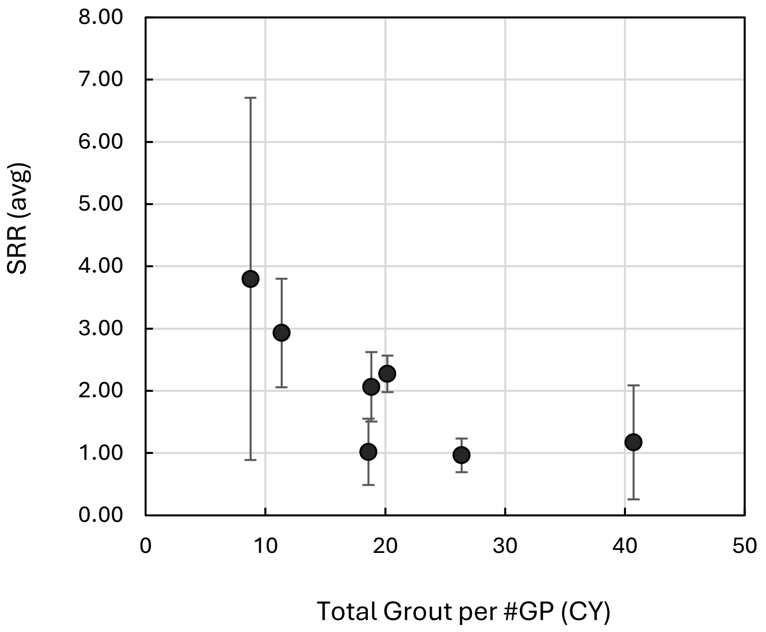


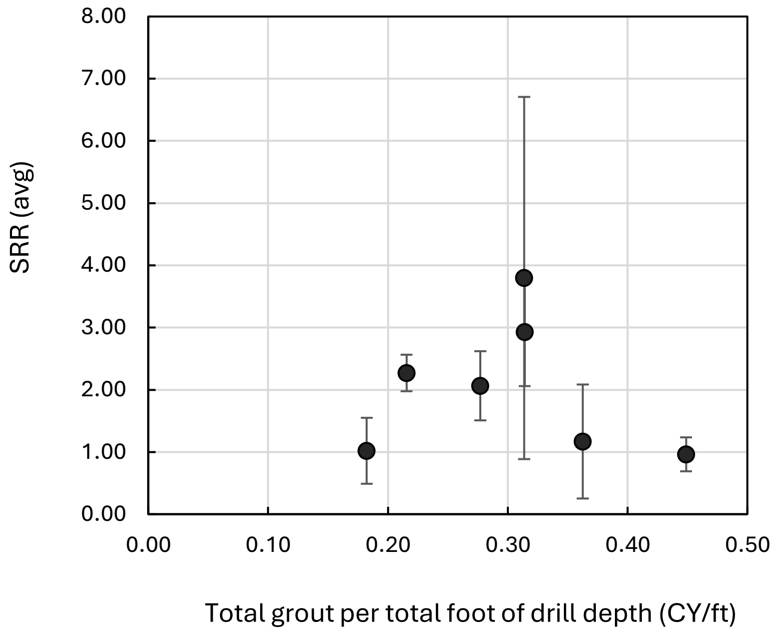
2. Correlation between SRR and the grout-take volume.

Approach 1: Site-based assessment **(n = 7)**

- *Averaged Subsurface indices near sinkhole will show some trend of overall anticipated grout volume at site.*
  - IF CPT performed near collapse showed residual soil; removed.
- Dependent on grout plan (number, spacing, depths, etc)



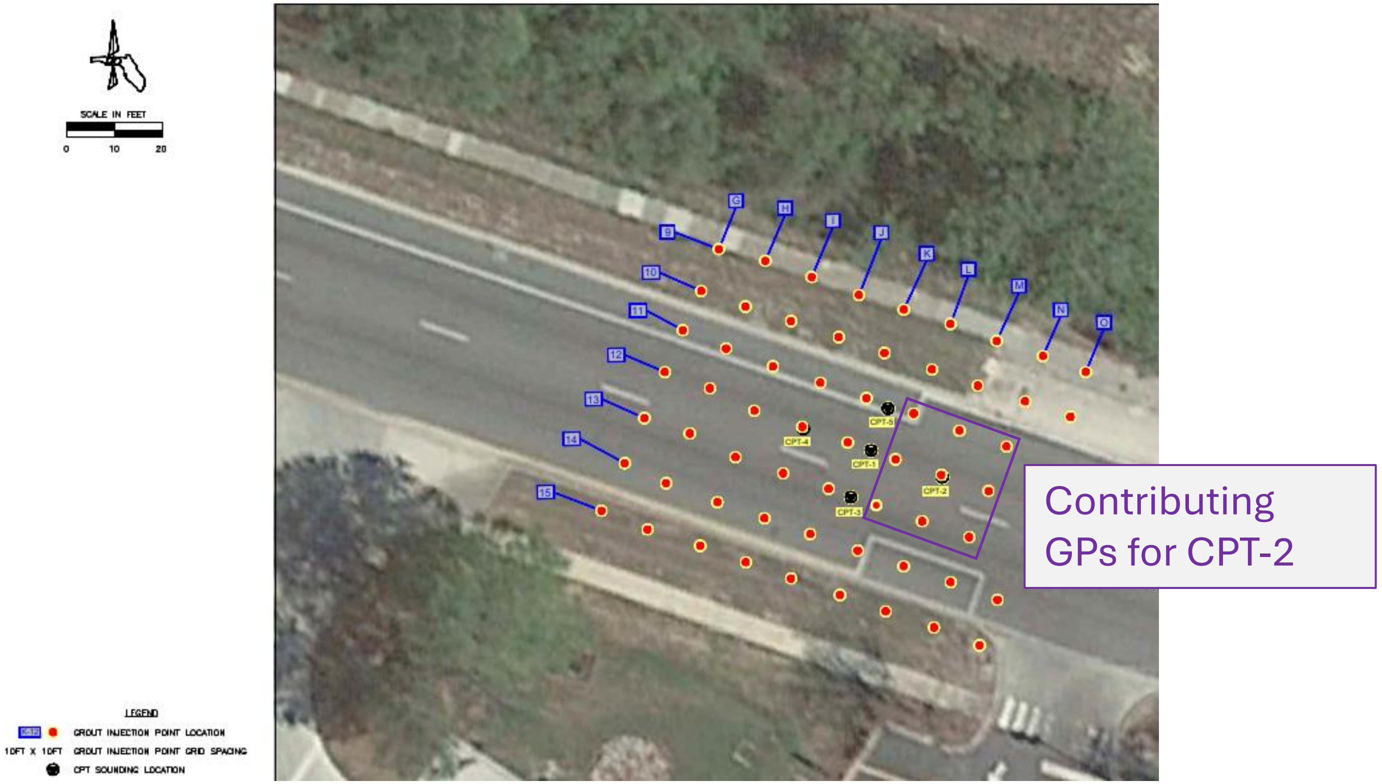


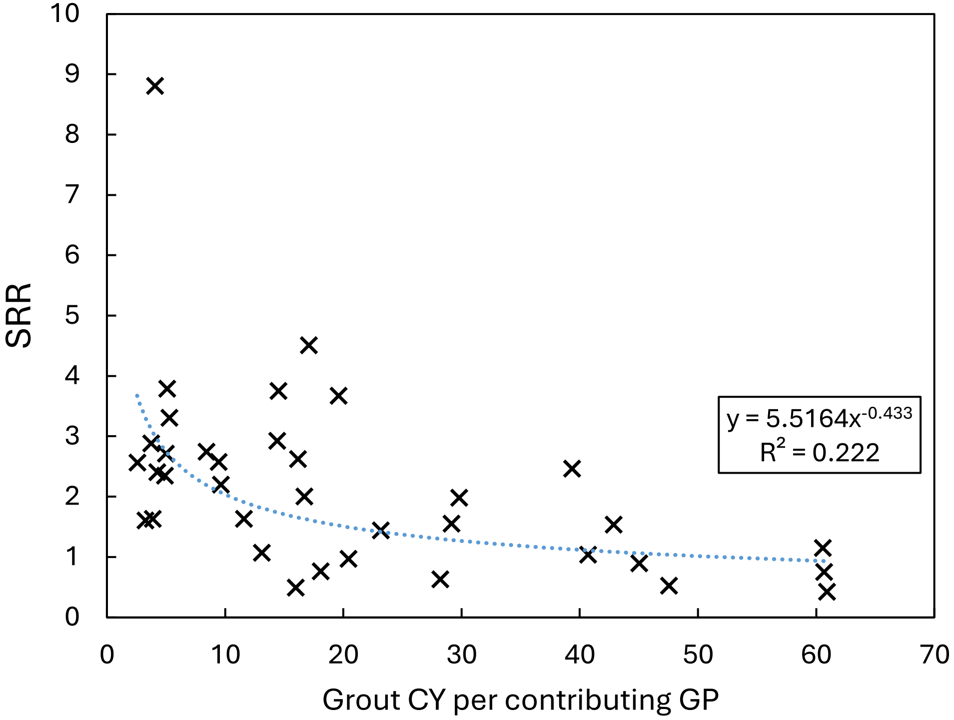


2. Correlation between SRR and the grout-take volume.

Approach 2: Individual CPT-based assessment (n = 36)

- SRR calced from individual CPT
- Summation of Grout Volumes from within *vicinity* of CPT.
  - Nearest Neighbor
  - Even Split
  - Tributary Distance





Ongoing:

- Tributary Distance and Area?
- Grout Take as function of depth / stratigraphy?

Summary of Progress

Critical conditions (Numerical Model)

- Field data from Cover Collapse sinkholes suggests $SRR_{critical}$ = 2.0
- 115 FEM stability to find SRR simulated in various soil and geometry conditions.
- Bottom-end $SRR_{FS=1.0}$ between 0.3 - 0.5
- Stability Style Chart shows promise when comparing $SRR_{FS=1.0}$ to field data

Critical conditions (Laboratory)

- Viable method determined to test SRR using large scale soil box with simulated void and failure.
  - PANDA DCPT → q_d
- Failure mechanism will be observed and SRR_{Lab} will be measured at various stages.
- Testing to occur Fall 2024

Additional Analysis Potential (Grout Take Statistics)

- Field Data shows grout take highly variable in karst conditions
- Site-based assessment shows best trend with limited dataset to estimate a range of V_{grout} per GP at project given averaged SRRs.
- Depth of grout takes need to be considered.

Thank you!

Question?

Ryan.Shamet@unf.edu

Project Timeline

Deliverable # / Description as Provided in Scope (Associated Task)	Anticipated Date of Deliverable Submittal Month/Year	Estimated Progress
Project Kickoff Teleconference/Presentation	Dec 2023	Completed
Deliverable 1: A written report on the findings from Task 4, including (a) testing procedure and (b) results of physical model tests of sinkhole raveling using the LSSB	August 2024	30% **Delayed till July 1**
Deliverable 2: A written report on the findings from Task 5, including: (a) severity criteria of the SRR, (b) correlation of the SRR to other indices (RI, factor of safety), and (c) evaluation of the effects of grout-take.	August 2024	85%
Deliverable 3a: Draft Final Report	September 2024	15%
Deliverable 3b: Closeout teleconference and PowerPoint presentation	Dec 2024	-
Deliverable 4: Final Report	Dec 2024	-