Site Characterization and Sinkhole Potential Evaluation using CPT-based Index Analysis

51st Southeastern Transportation Geotechnical Engineering Conference

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Presented by:

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The Sinkhole-CPT Saga

IFCEE 2018 — March 5-10 — Hilton Orlando Buena Vista Palace, Orlando, Florida — www.ifcee2018.com

"Development of a Point-Based index for Sinkhole vulnerability Evaluation in Central Florida."

Raveling Index (RI)
Sinkhole Resistance Ratio (SRR)

Geo-Congress 2019 — Philadelphia, Pennsylvania | March 24–27, 2019

"Sinkhole Vulnerability Assessment Using Groundwater Monitoring and Internal Raveling Analysis"

Geo-Congress 2020 — Minneapolis, Minnesota | February 25–28, 2020

"Probabilistic Field Assessment of Sinkhole Occurrence Using the Raveling Index"

IFCEE 2021

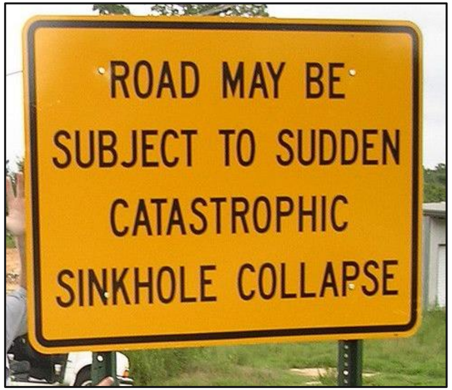
"An Empirically Developed CPT-Based Assessment Method for Characterization of Sinkhole Vulnerability in Florida Karst"

FDOT

- BDV24-977-17 : "Development of a Sinkhole Risk Evaluation Program"
- BDV24 977-41: "Validation and Update of the Sinkhole Index"

Outline

- **Background**
  - Karst
  - Sinkholes in Florida
  - Cone Penetration Testing
- **Assessment Tools**
  - Raveling Identification Chart
  - Vulnerability Indexing
    - Raveling Index
    - Sinkhole Resistance Ratio
    - *Empirical* Indices
- **Application & Recommendations**



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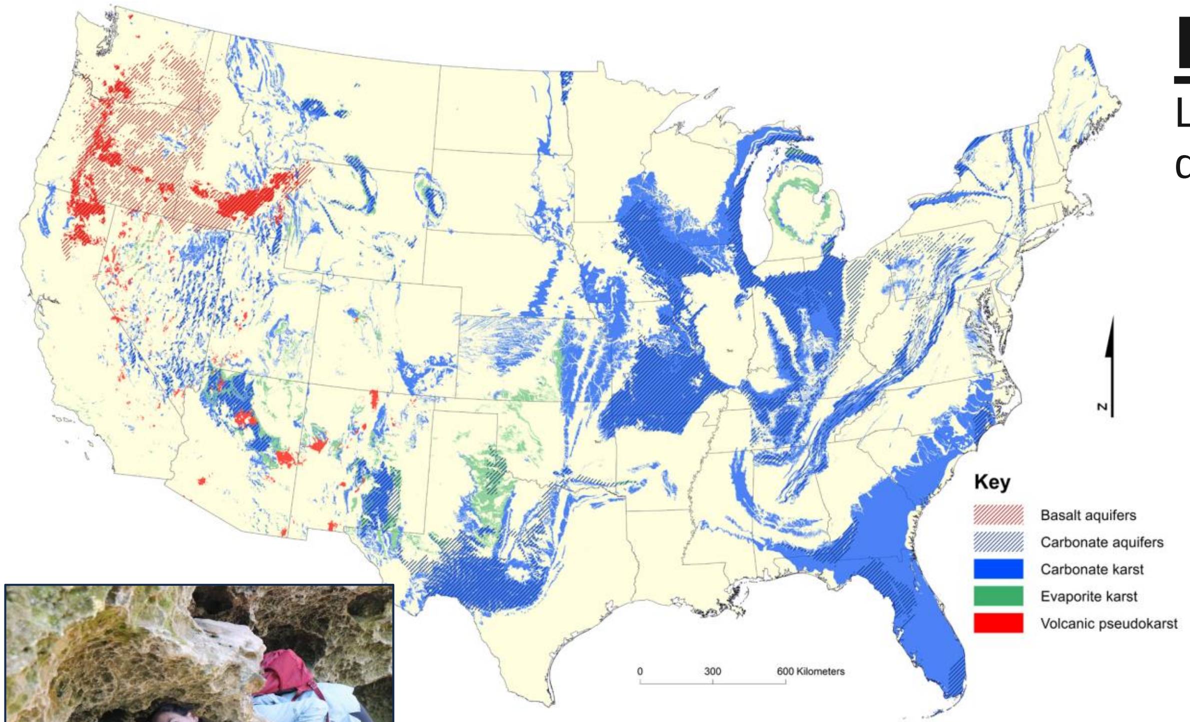
Karst:

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: Kirill Egoro (KUR)

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

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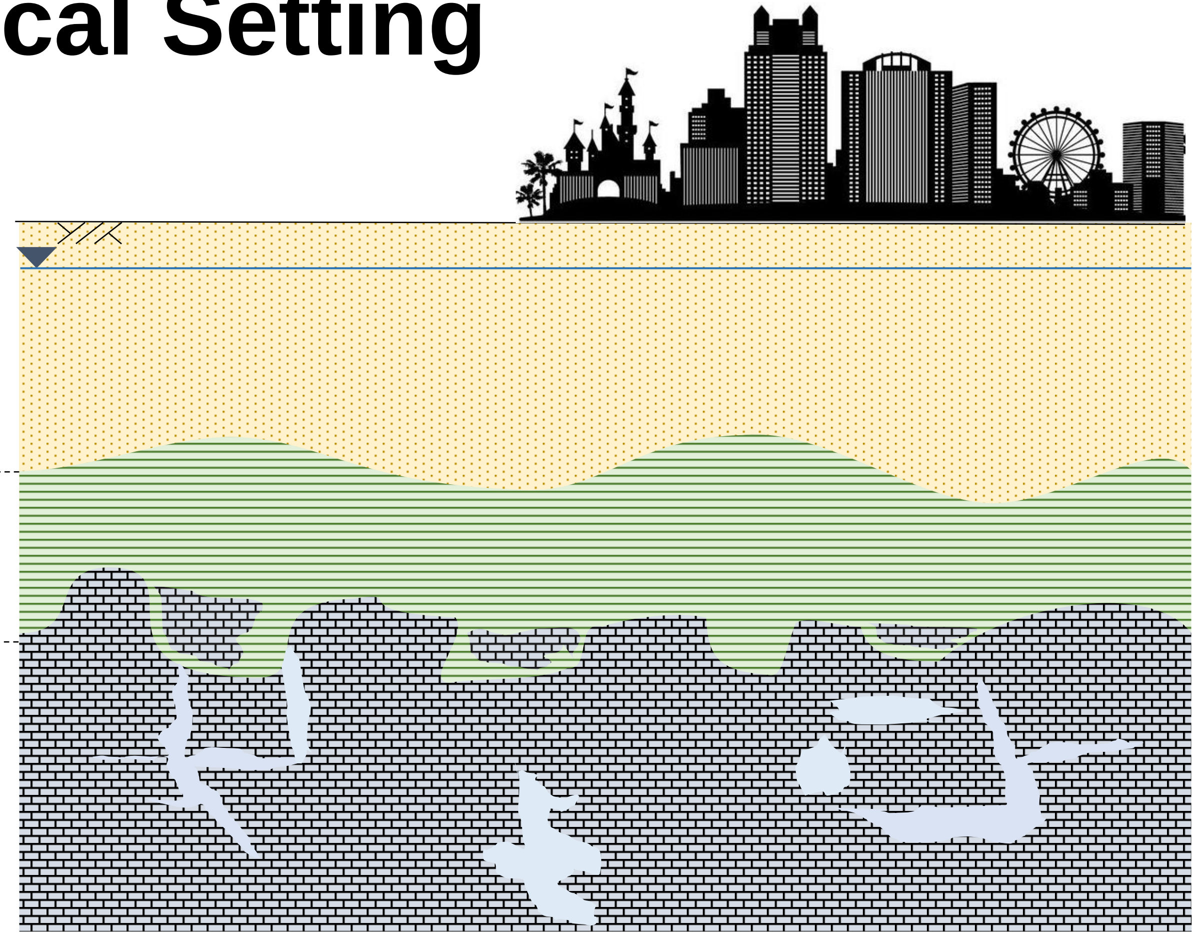
Geological Setting

Central Florida



Mixed Sands and silts
(Holocene to Pliocene)
recent – 5.3 Mya

10 – 20 m

Silts, Clays, mess
Hawthorn Group (Miocene)
5.3 – 23 Mya

20 – 60 m

Cemented Silts and Sands, Limestone & Dolostone
Ocala Limestone (Eocene)
34 – 50 Mya

No Scale

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

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Geological Setting

Central Florida

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

Hydro-geological

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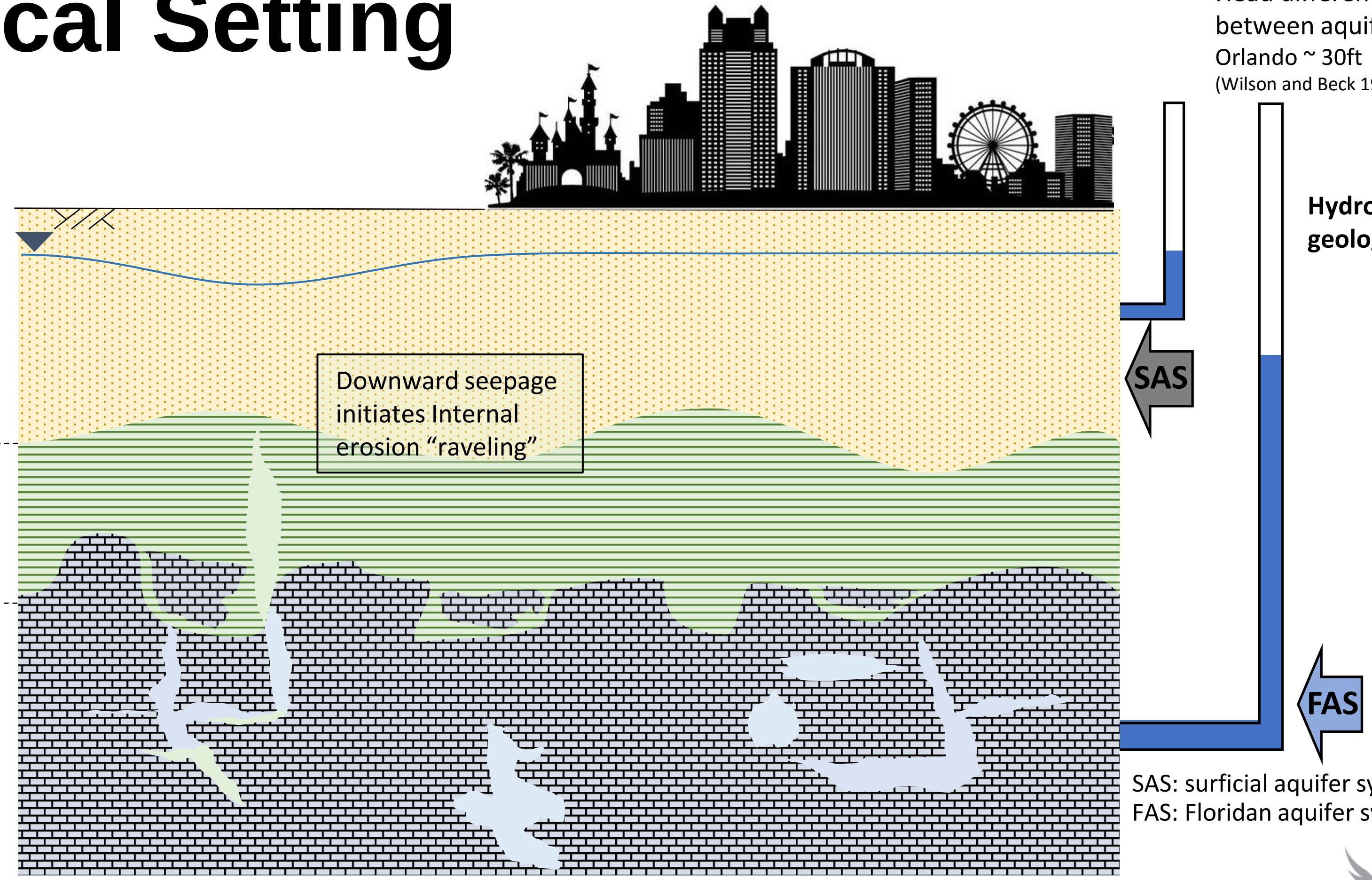

SAS: surficial aquifer system
FAS: Floridan aquifer system

No Scale

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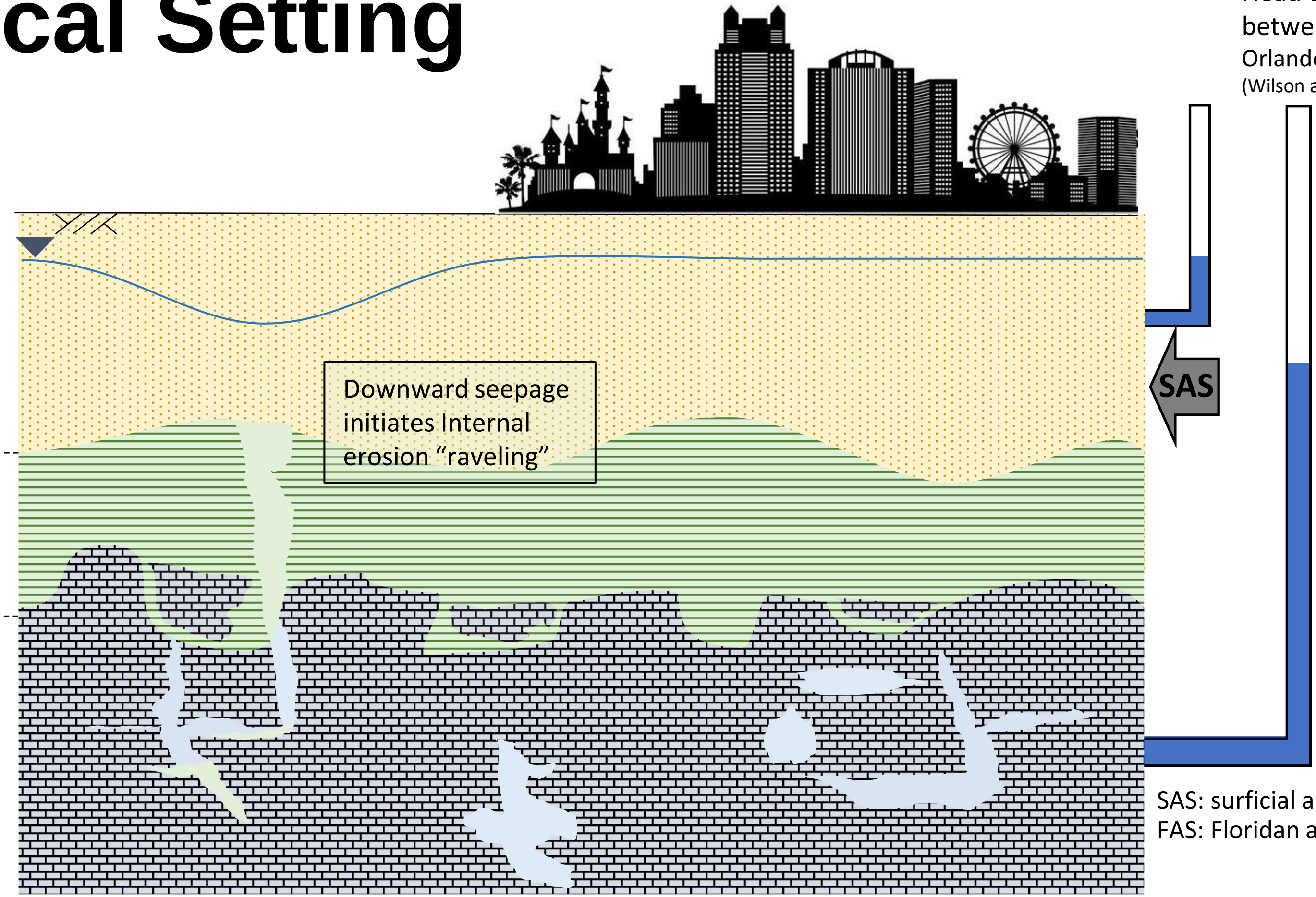

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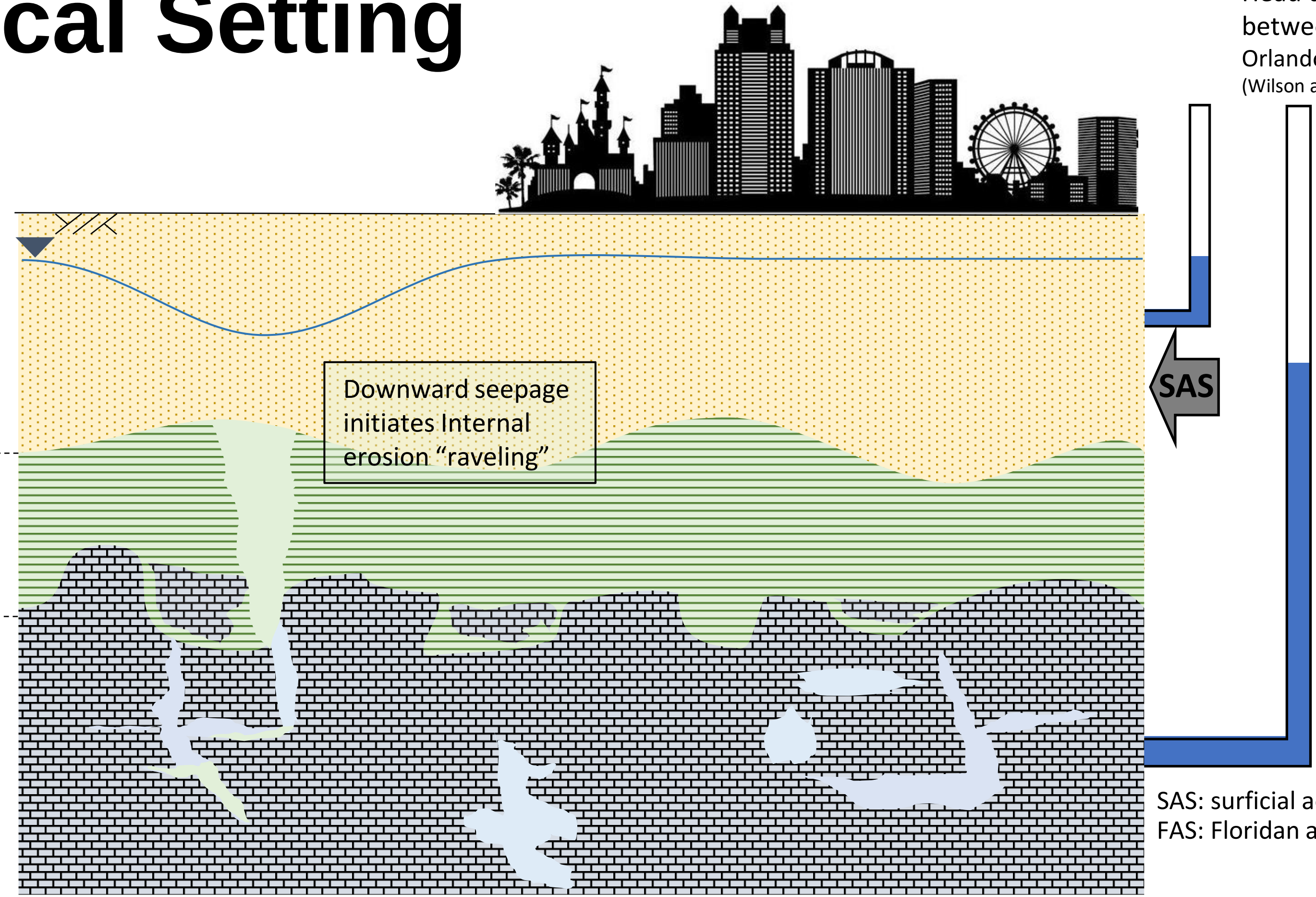

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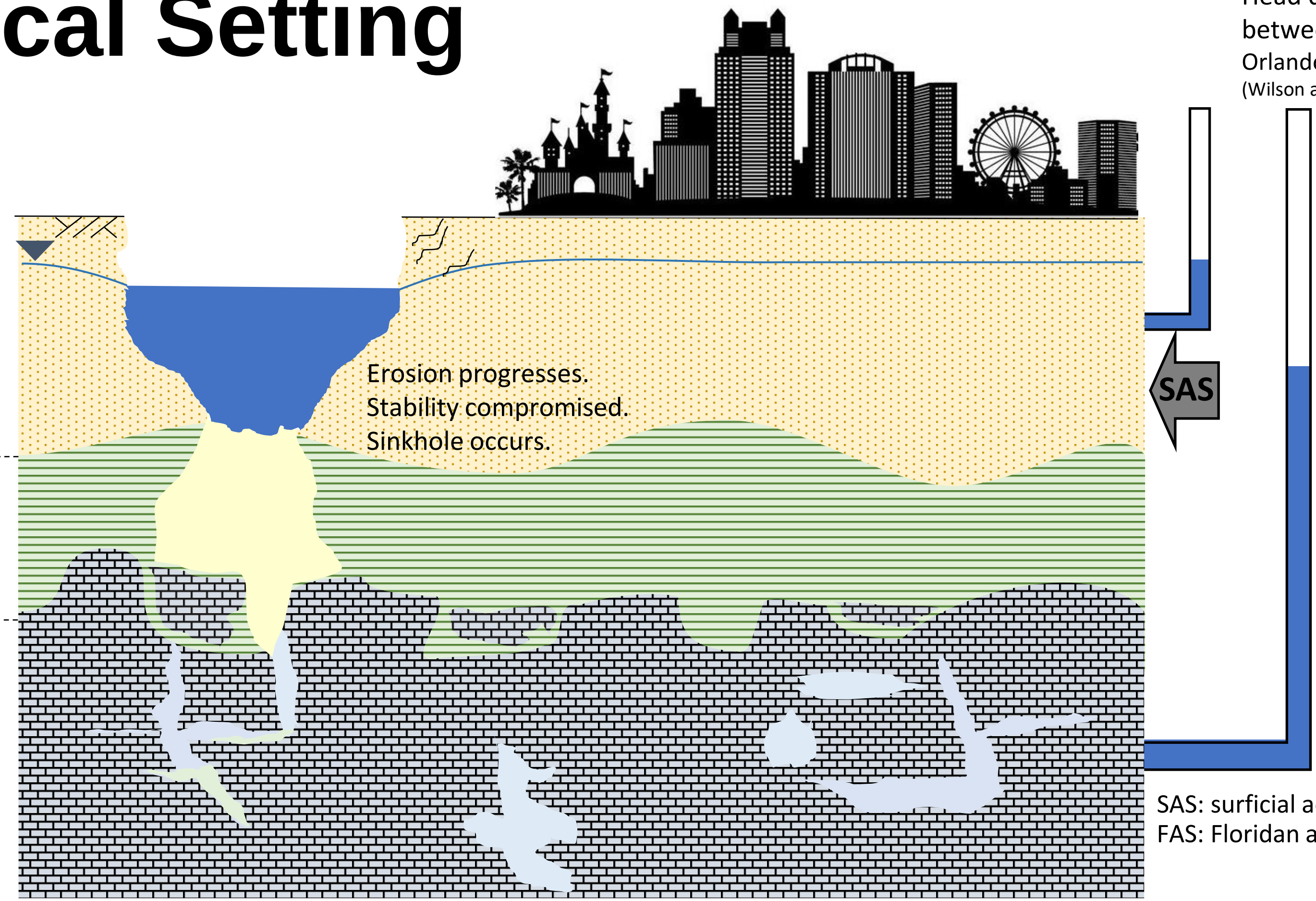

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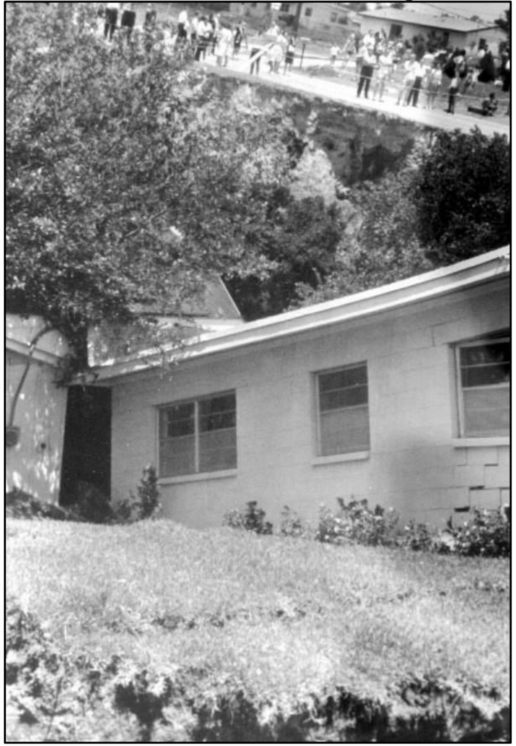
Sinkholes: in the media … and behind the scenes

Note the background



1962 Debary (FGS state archives)

2004 Deltona (FDOT)

2002 Pine Hills (GEC)

2004 Deltona (FDOT)

Hernando County (photo: Sam Upchurch)

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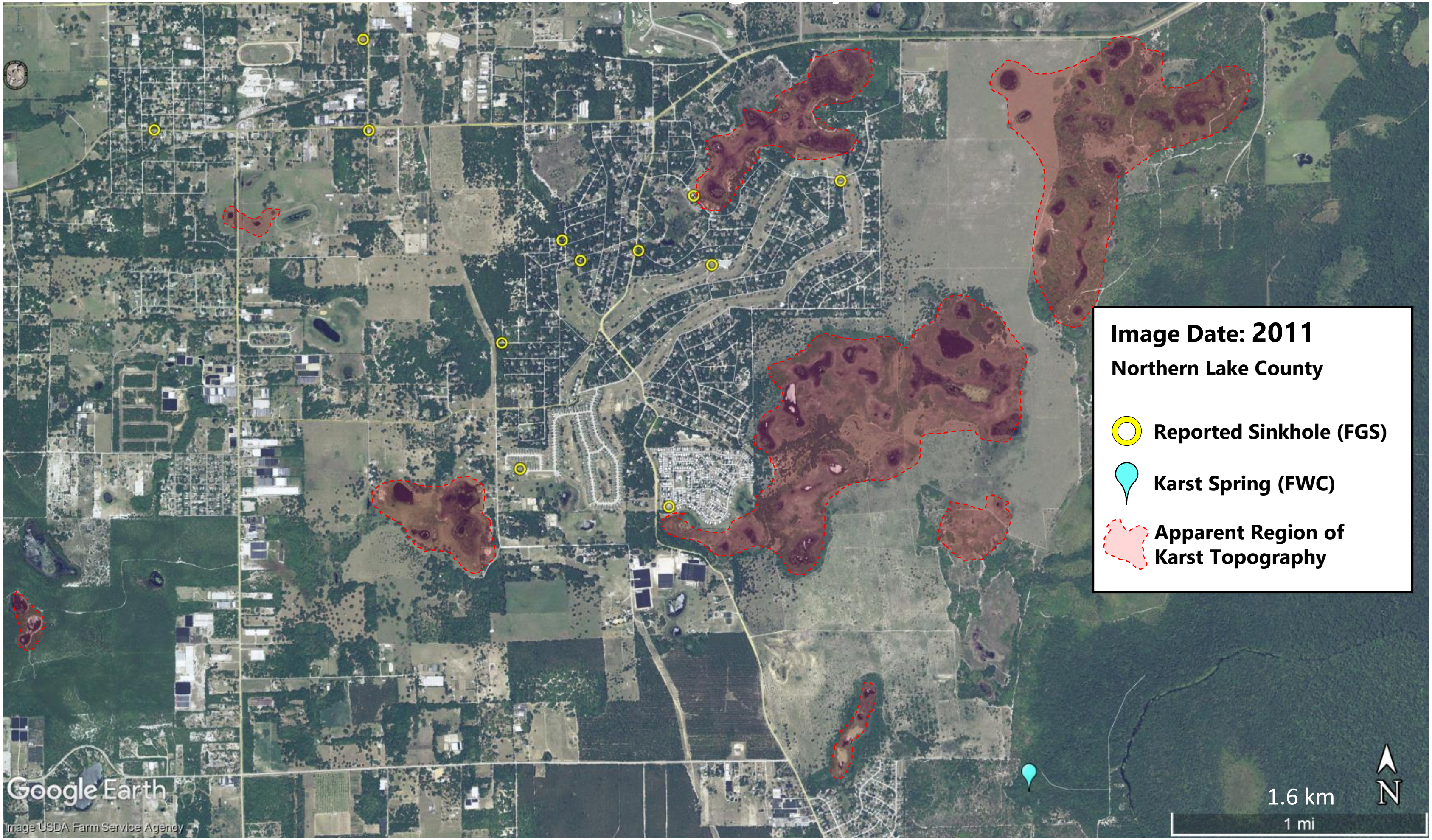
Karst Terrain



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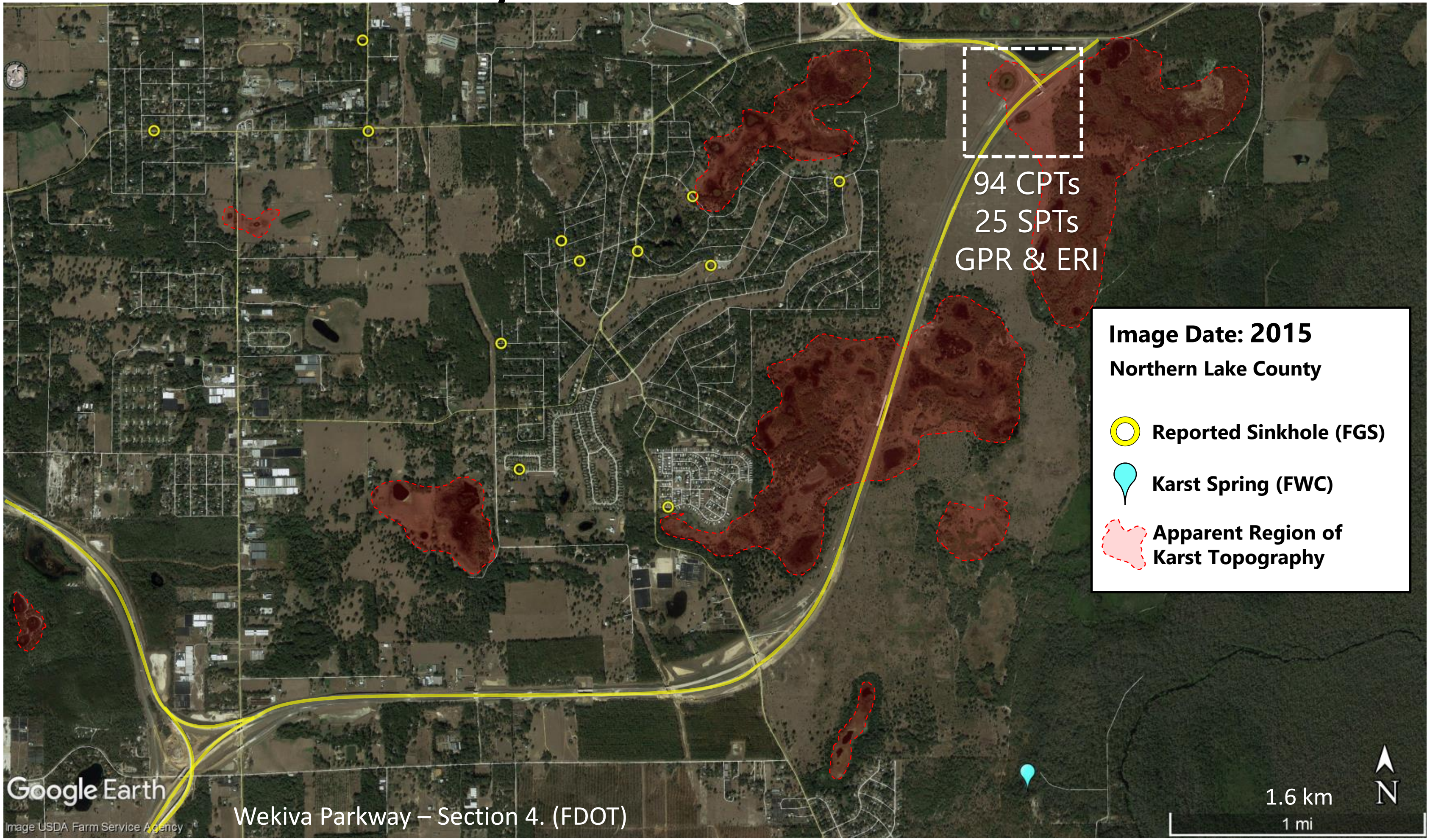
Karst Terrain - Wekiva Parkway – Section 4



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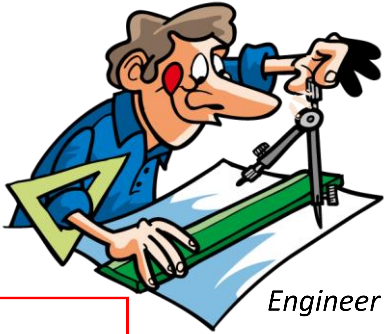
"Assessment" Components



Sinkhole contributing factors: (Upchurch 2019)

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

During typical subsurface investigation in karst:

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

Objective:

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

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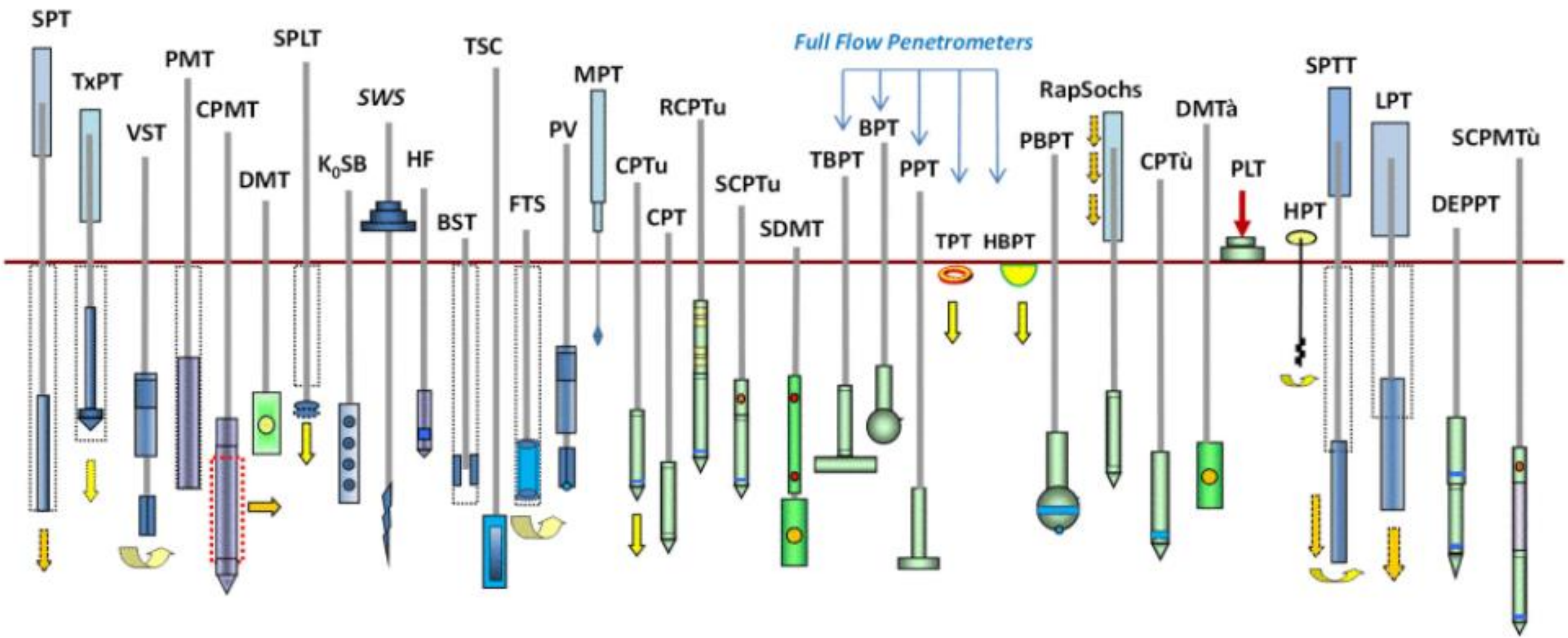
Geotech's "TLA" Subsurface Investigation Techniques

TLA = Three Letter Acronym



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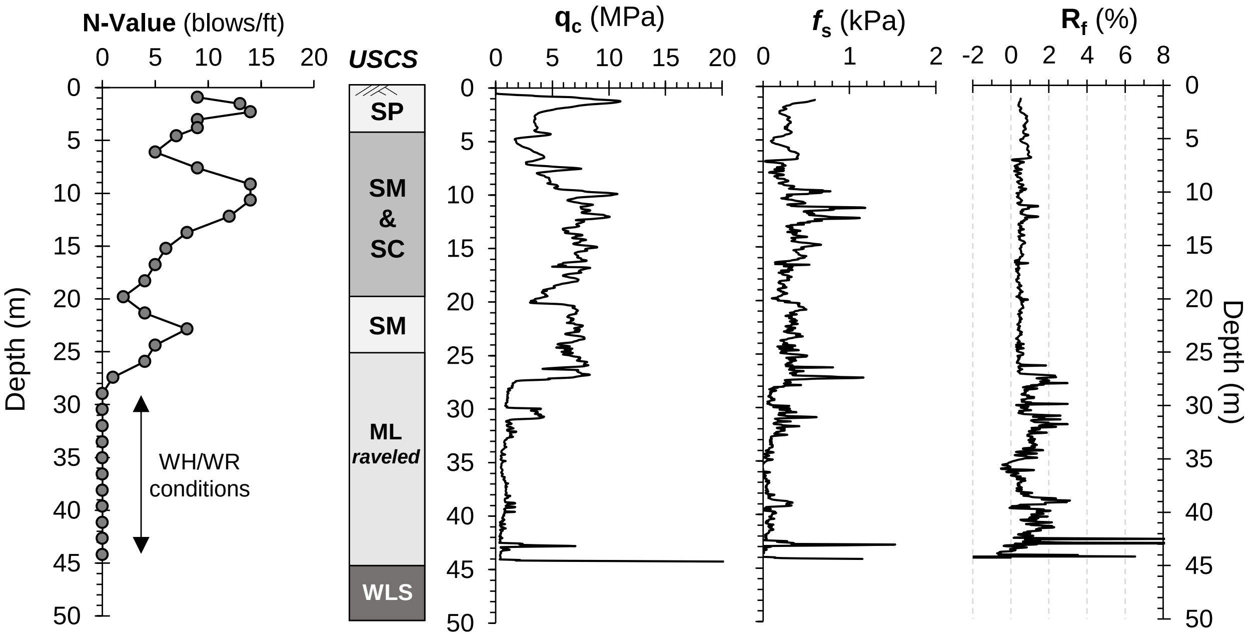
Courtesy of Dr. Paul Mayne

Cone Penetration Test (CPT)

ASTM D5778-12

SPT



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**]

Important for ground verification

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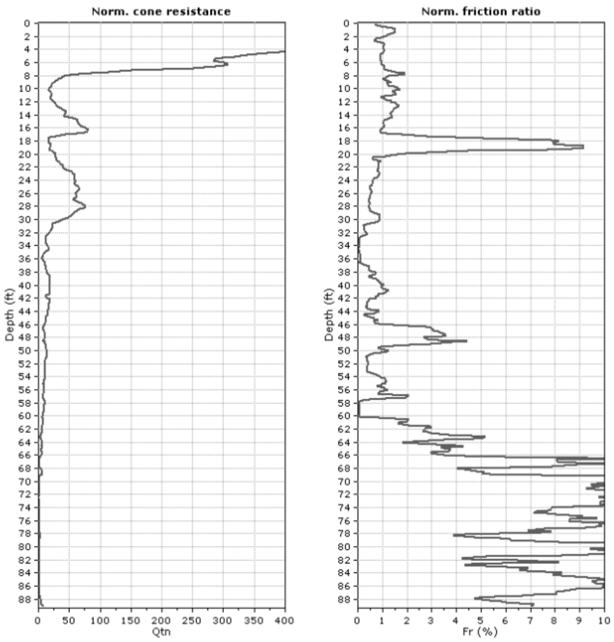
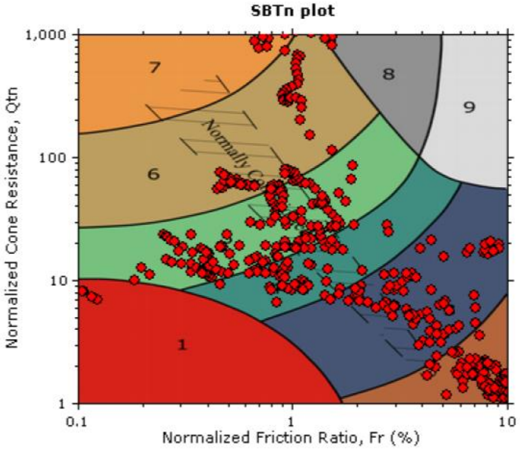
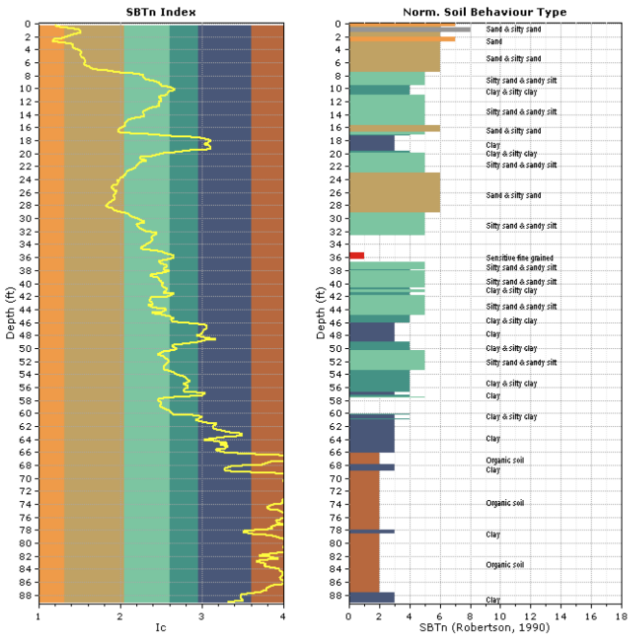
Cone Penetration Test (CPT)

Soil behavior identification

- *Soil Behavior correlation* ➡ Software (Geologiskimi CPeT)







- CPT Soil Behavior Type (SBT) charts are not accurate in karst topography
- Schmertmann (1978) and Sowers (1996) conclude karst terrain often follows “inverse soil profile”

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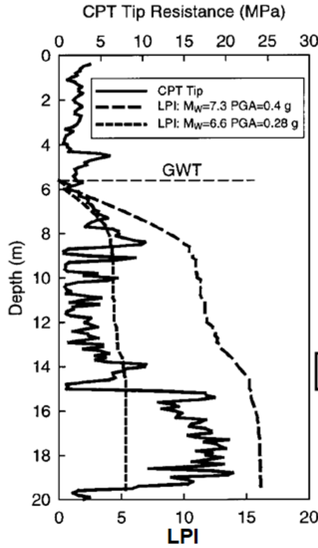
Cone Penetration Test (CPT)

Geo-hazard vulnerability

- *Liquefaction Potential Indexing* (LPI)



$$LPI = \int_0^{20m} \left(1 - \frac{CSS}{L}\right) * W(z)dz$$

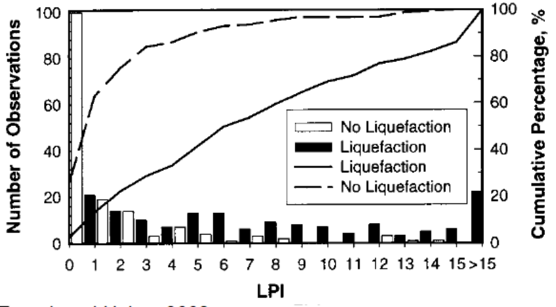
Where:

CSS = Cyclic Shear Strength

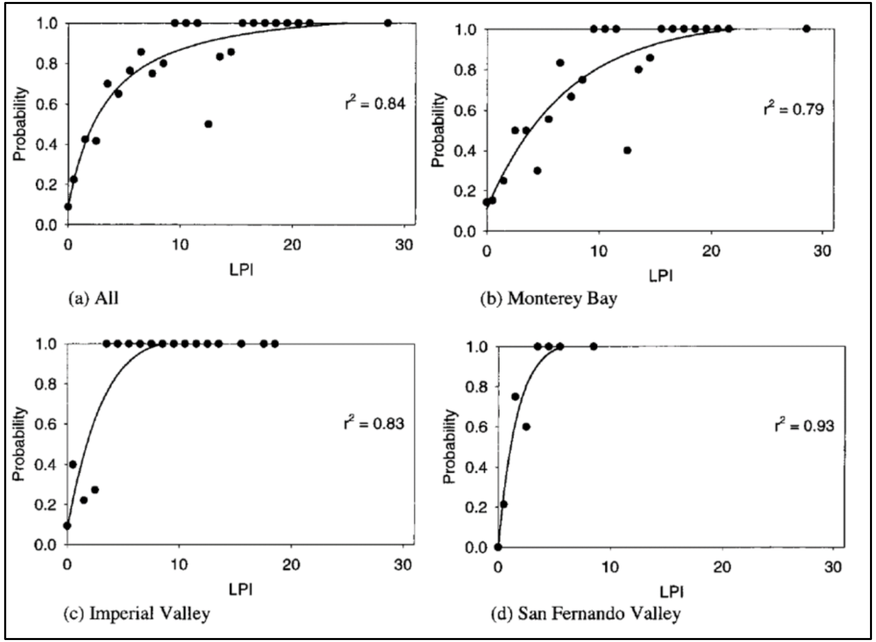
L = Dynamic Load induced

W(z) = 10 - 0.5*(depth in m)

From: *Iwataska et al. 1978*



From: *Toprak and Holzer 2003*



Toprak and Holzer (2003):

- 5 EQ
- 27 sites
- 314 CPTs
- 156 = Liquefied
  158 = NO liquefaction

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CPT-Based Sinkhole Assessment

GOAL:

Subsurface characterization for *BETTER* decision making in Florida's karst

Cone Penetration Test (CPT):

- ✓ Fast(er)
- ✓ Near continuous data
- ✓ Repeatable and reliable
- ✓ less "dynamic"

Point-based identification → **Site-based characterization** → **Regional comparison**

1. **CPT-based raveling chart**
2. **Vulnerability quantification from CPT**
   - **-Raveling Index**
   - **-Sinkhole Resistance Ratio**
   - **-Empirical indices**

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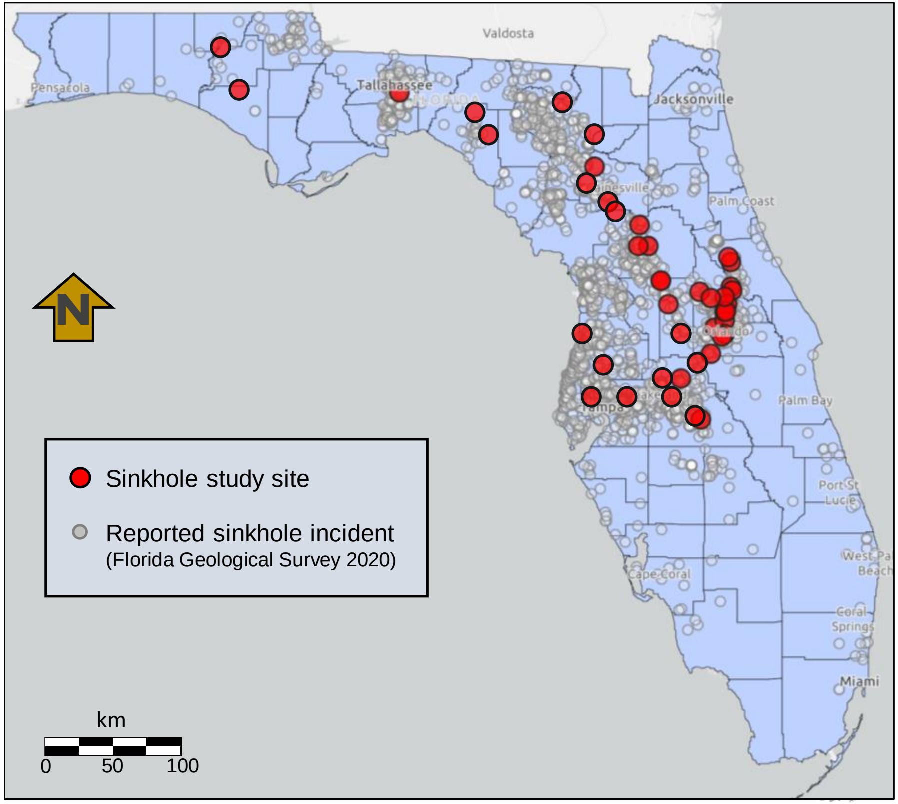
The Database

49 locations **237** CPTS

Data Criteria:

- Verified karst sinkhole activity
  - Internal erosion identified at limestone/soil interface (nearby SPT)
- *Collapse* mechanism observed
  - Cover collapse vs. solution vs. subsidence
- Trustworthy CPT data
  - Detailed testing layout
  - Apparent calibration of CPT



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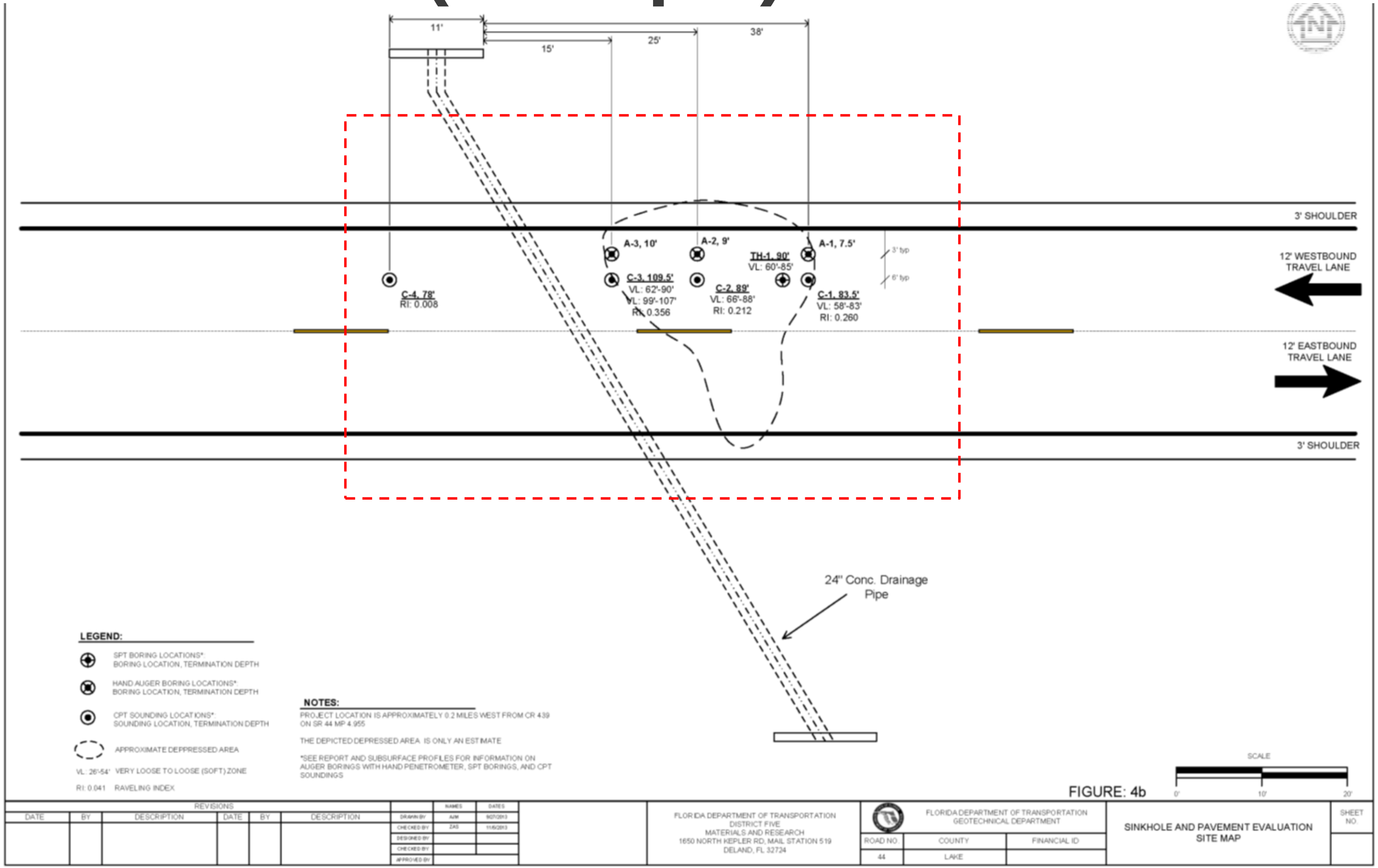
The Database (example)



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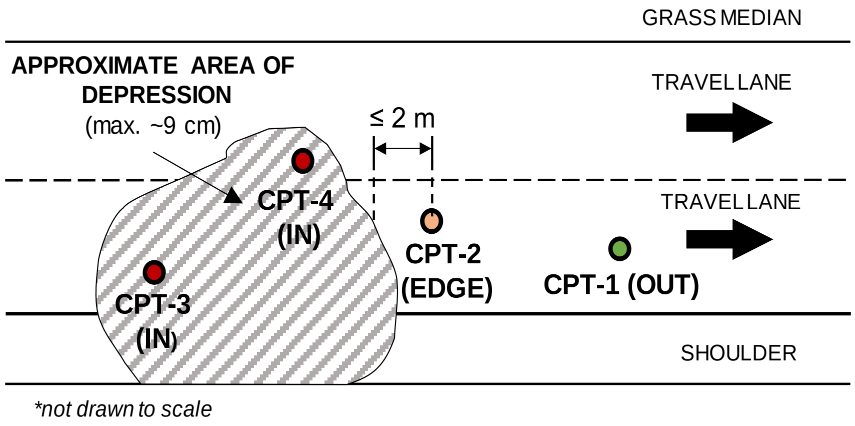
The Database (CPT categorizing)



“INSIDE” = Most Vulnerable conditions
“EDGE” = Vulnerable conditions
“OUT” = Least vulnerable conditions

49 Project Sites		
Total # of CPTs	“IN”	30
	“EDGE”	60
	“OUT”	76

Assuming:

- Distance ∝ Disturbance
- Closer to center of sinkhole is more representative of **severe** conditions.
- Subsurface conditions < 2 m from observed sinkhole still effected by internal erosion.
- > 2m: less disturbed

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CPT-based Raveling Chart

From database: What is CPT resistance criteria for raveled soil?

✓ "SBT-style" chart to identify depths experiencing raveling when investigating in karst.

✗ Detect sinkhole activity universally in any geological conditions.

Methodology:

Data correction ⇨ categorization ⇨ filtering ⇨ Statistical criteria ⇨ Severity contours ⇨ CPT-based Raveling Chart

Provide a standard method to identify depths of potential internal erosion

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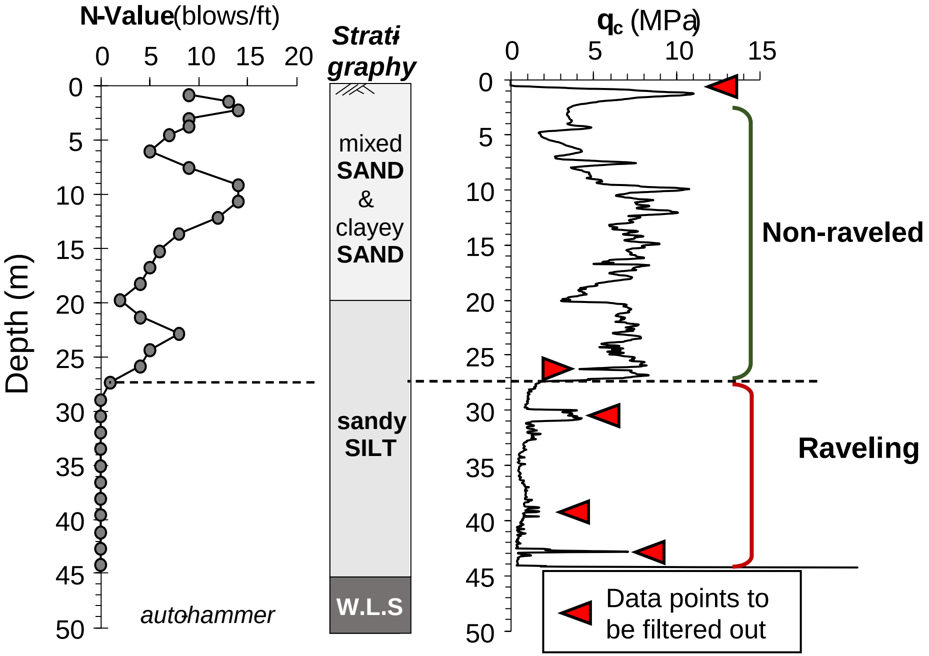
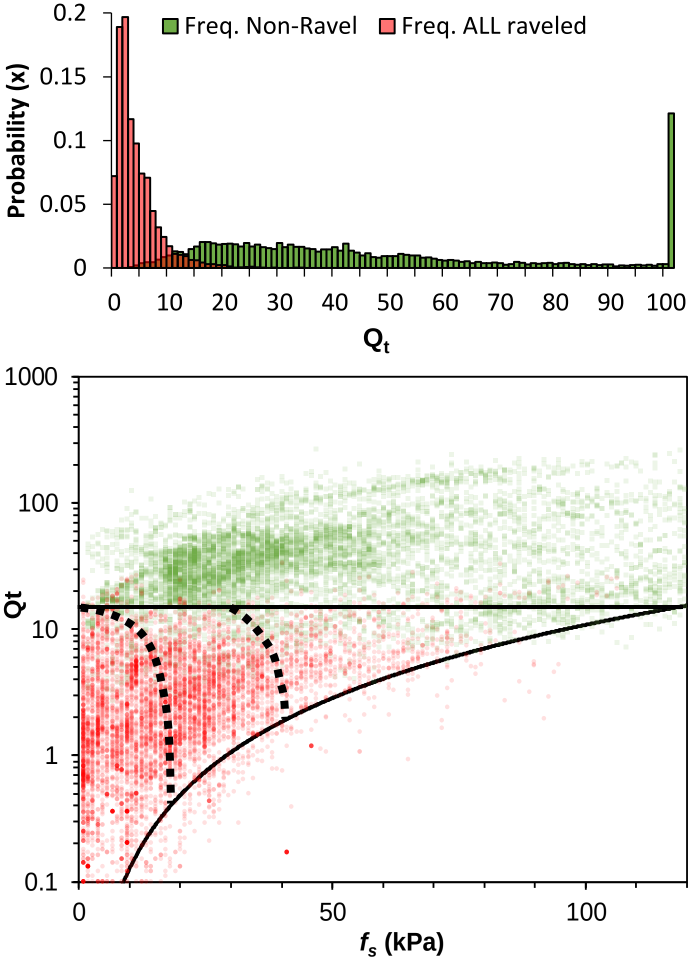
CPT-based Raveling Chart

Data categorization & Filtering:



SPT performed ~3m NE *of sinkhole* *CPT performed* ~0.5m *from SPT*



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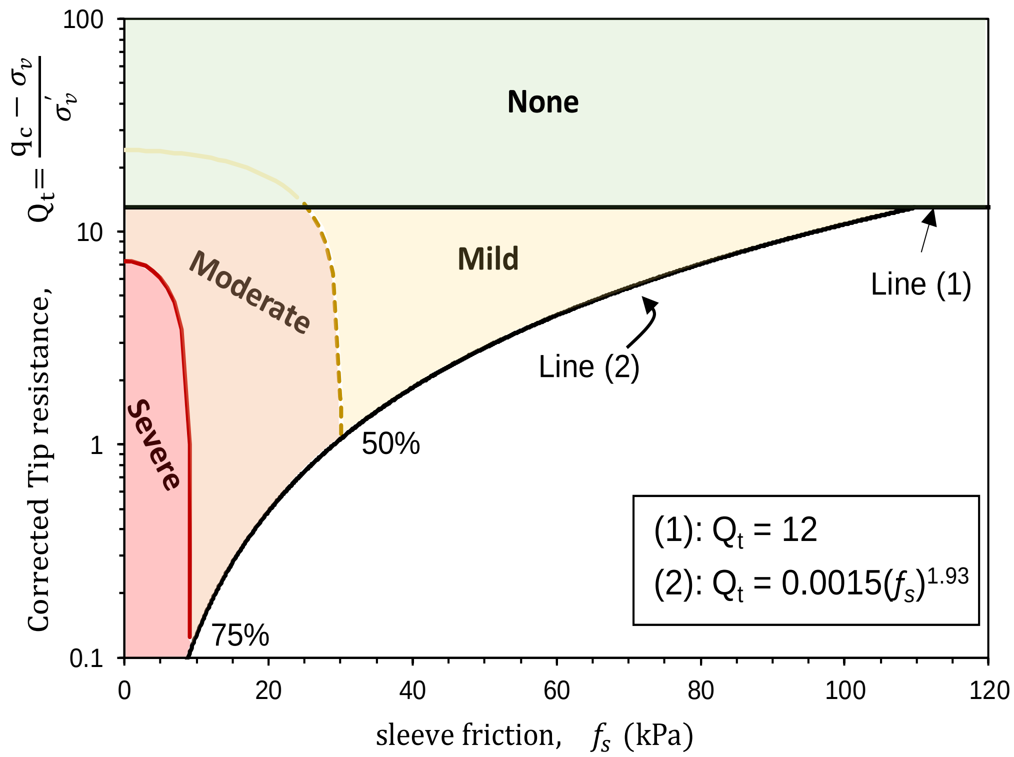
1. CPT-based Raveling Chart

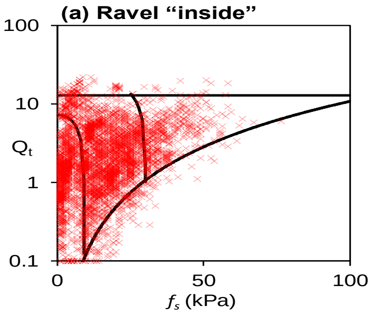
Generalized chart:

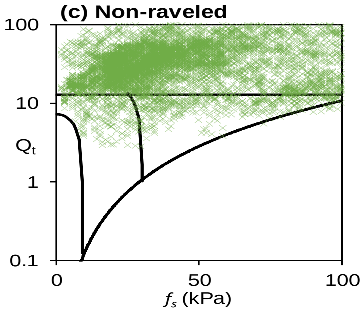
Probability that encountered resistance value is from most critical (raveled "inside") data set



Zone	critical raveling[×]	raveling
	probability of encountered behavior	
Severe	> 75%	100%
Moderate	50 - 75%	95%
Mild	< 50%	95%
None	< 1 %	< 5%

[×]within collapsed feature





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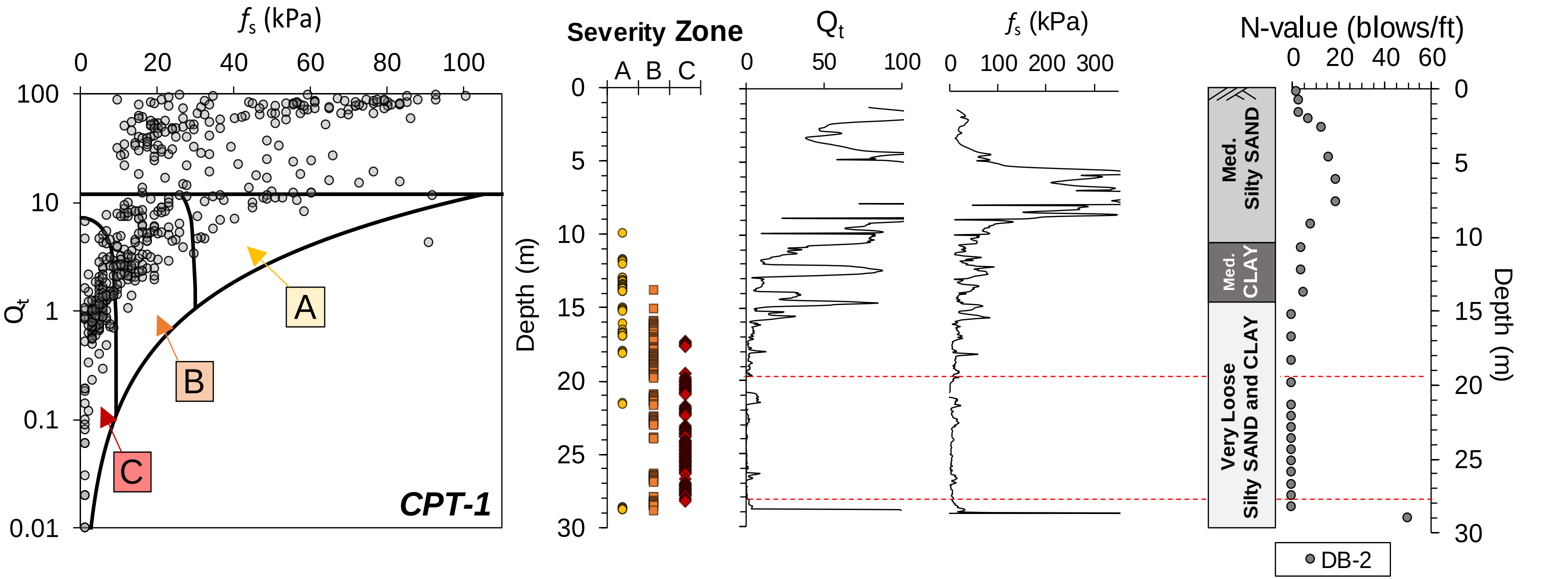
CPT-based Raveling Chart – Example

Application

- Provides a standard to identify depths which soil exhibits similar resistance values to those found in sinkhole active sites.
- Identify most-critical depths more precisely when compared to SPT.
- Applicable in central Florida <u>when investigating in a karst landscape</u>



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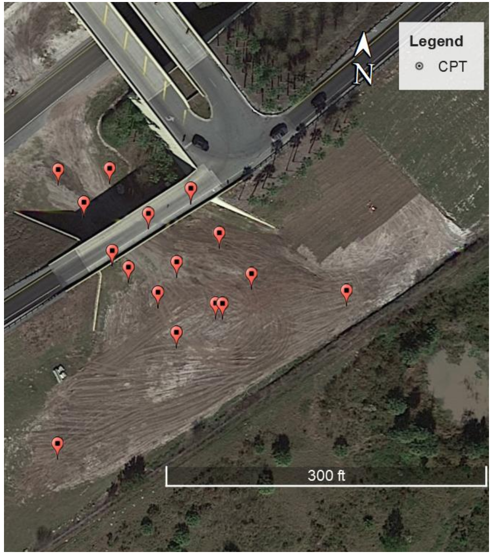
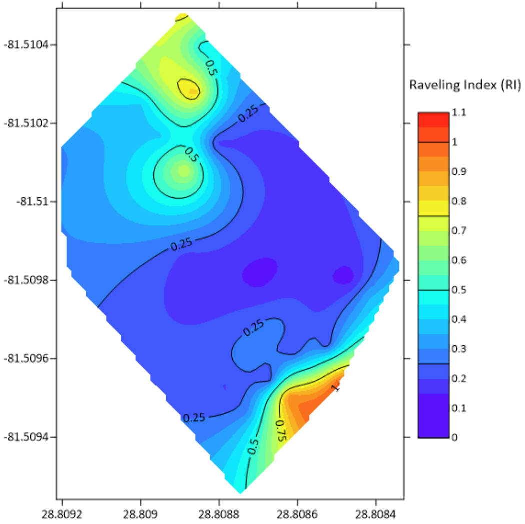
Assessment Indices (practical)

<u>Raveling Index (RI):</u> Simple comparison index to assess the progression of internal erosion encountered. (Foshee and Bixler 1994)

$$\mathrm{RI} = \frac{t_{\mathrm{ravel}}}{t_{\mathrm{over}}}$$

- Quantifiable!
- Associated with risk assessment
- Comparison over time





Updates to the Raveling index to include:

- ✓ Encountered soil resistance
- ✓ Depth of encountered raveling and potential ground-surface collapse

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Assessment Indices (theoretical)

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- Quantifiable!
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- Comparison over time

Updates to the Raveling index to include:

✓ Encountered soil resistance
✓ Depth of encountered raveling and potential ground-surface collapse

Sinkhole Resistance Ratio:

$$SRR = \left(\frac{\mathrm{t_{over}}}{\mathrm{t_{ravel}}}\right) * \left(\frac{\bar{q}_{t_{\mathrm{over}}} + \bar{q}_{t_{\mathrm{ravel}}}}{100 * \sigma'_{\mathrm{v}(ravel)}}\right)$$

[stress: tsf]

- Theoretically-based
- Including sinkhole resisting soil factors obtained from CPT
- Still can be quickly calculated for each CPT

Nam, Shamet, Soliman, Wang, and Yun (2019) “Development of a Sinkhole Risk Evaluation Program.” *Technical Report.* Florida Department of Transportation No. 166 BDV24-977-174

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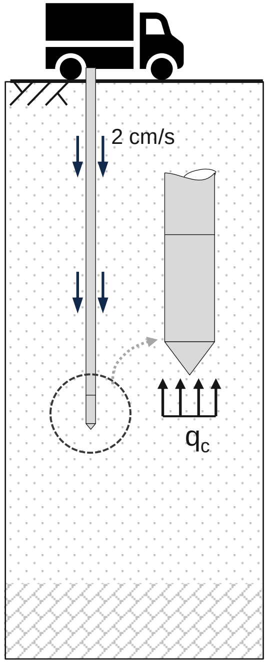
Assessment Indices (theoretical)

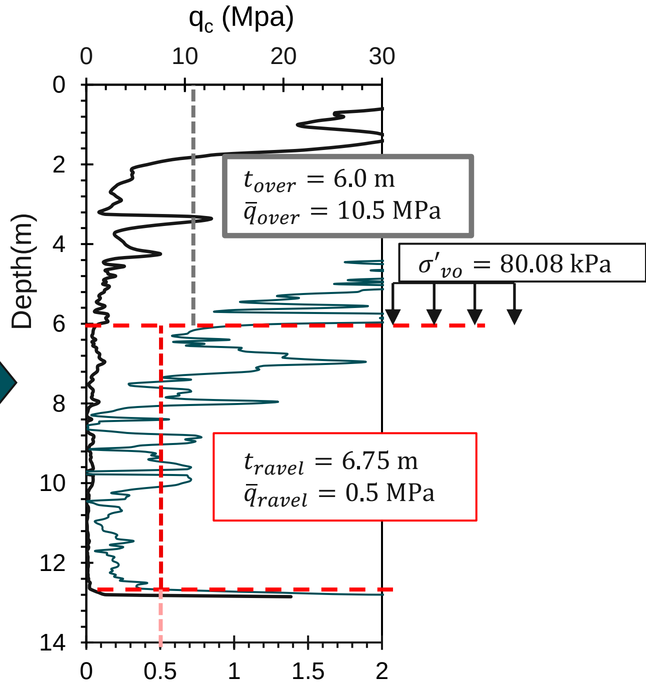
Sinkhole Resistance Ratio:

$$SRR = \left(\frac{t_{over}}{t_{ravel}}\right) * \left(\frac{\bar{q}_{t\,over} + \bar{q}_{t\,ravel}}{100 * \sigma'_{v(ravel)}}\right)$$

Where:

t_{over} = thickness of non-raveled soil
t_{ravel} = thickness of raveled soil
$\bar{q}_{t\,over}$ = average cone tip resistance of non-raveled soil
$\bar{q}_{t\,ravel}$ = average cone tip resistance of raveled soil
$\sigma'_{v(ravel)}$ = effective stress at top of raveling





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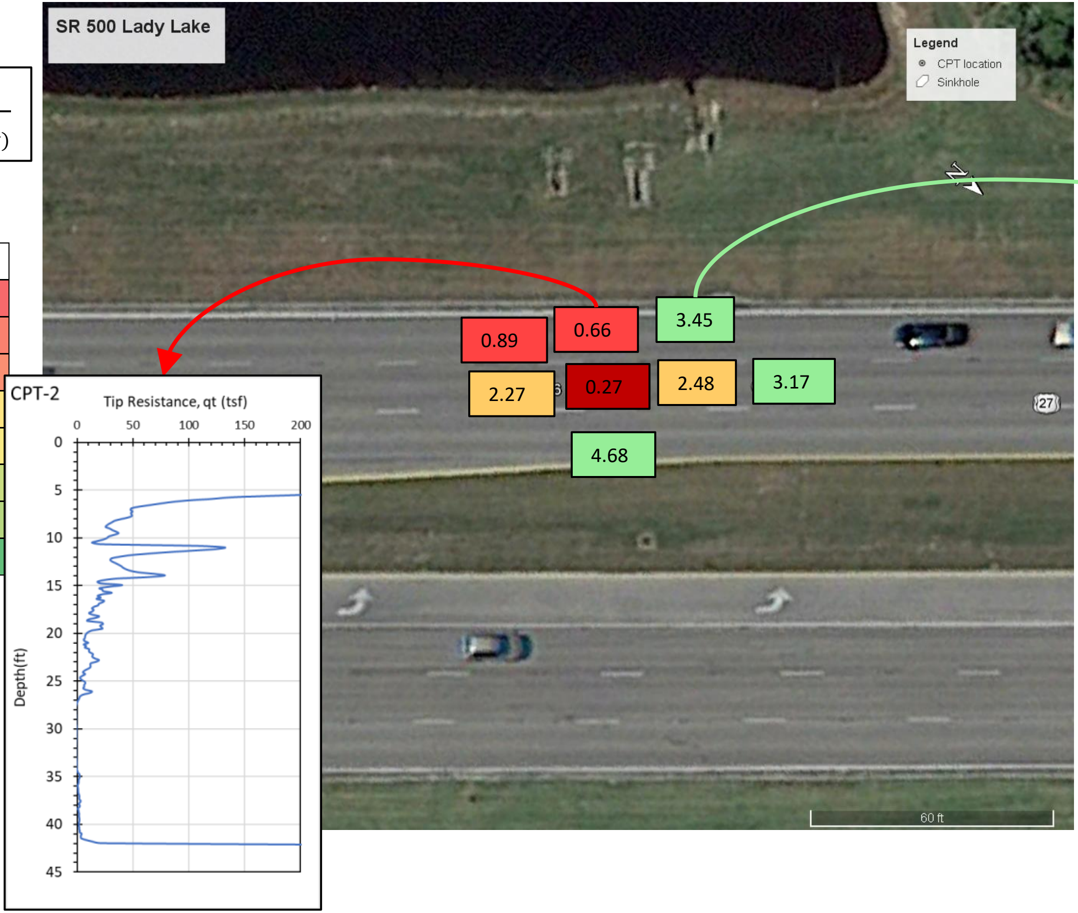
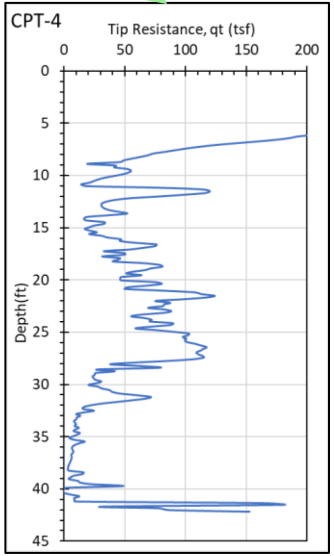
Nam, Shamet, Soliman, Wang, and Yun (2019) "Development of a Sinkhole Risk Evaluation Program." *Technical Report.* Florida Department of Transportation No. 166 BDV24-977-174

Vulnerability Quantification - Example

$$SRR = \frac{t_{over}}{t_{ravel}} * \frac{q_{ravel} + q_{over}}{100 * \sigma'_{v(top\ of\ rav)}}$$

Test location	SRR
CPT-3	0.27
CPT-2	0.66
CPT-7	0.89
CPT-6	2.27
CPT-4	2.48
CPT-5	3.17
CPT-8	3.45
CPT-1A	4.68





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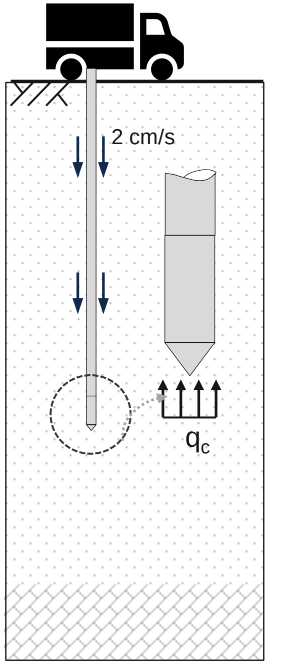
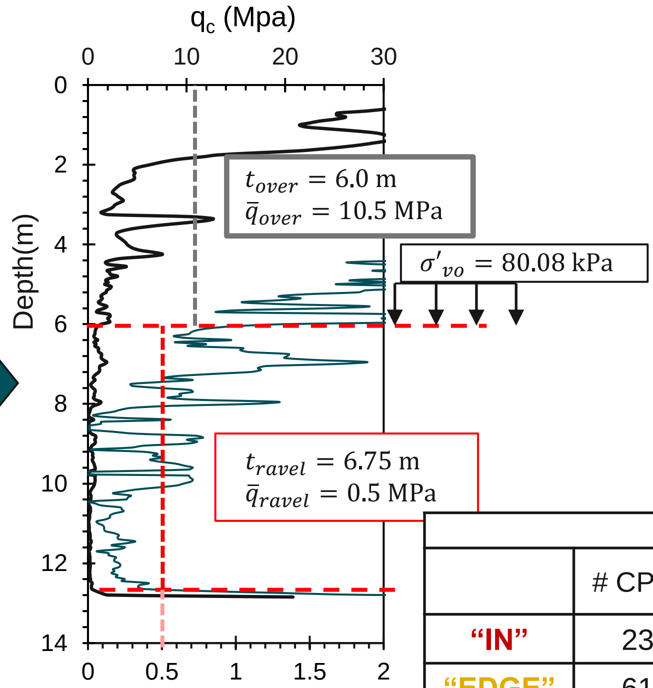
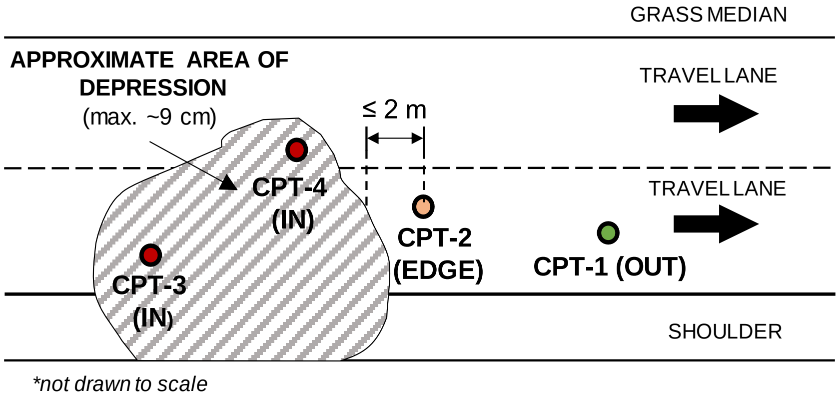
Subsurface Parameters





CPTs categorized



averaged values						
	# CPTs	t_{over} (m)	t_{ravel} (m)	σ'_{vo} (kPa)	$\bar{q}_{over}$ (MPa)	$\bar{q}_{ravel}$ (MPa)
"IN"	23	8.9	13.0	125.4	3.9	0.8
"EDGE"	61	13.1	6.8	159.7	7.3	1.7
"OUT"	71	14.5	4.5	148.9	8.8	1.9

Data Driven index for certain geologic conditions?

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Empirically-based index

Database of CPTs in Karst → t_{over}, t_{ravel}, $q_{c,ravel}$, $q_{c,over}$

Assign *initial* severity value (VI_o)
- Inside = 7
- Edge = 5
- Out = 1

higher # more severe

CPT parameter correlation to *initial* severity (Pearson coeff.)

Determine Resistance and Geometry Variable
- Resistance: $f(q_c)$ → VAR_R
- Geometry: f(thickness) → VAR_G

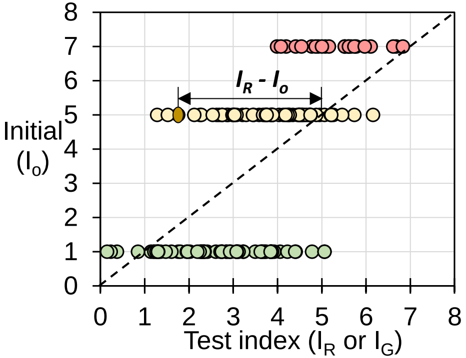
Set equation type for new index (VI_R or VI_G) and set coefficients.

Example:

$$VI_R = \mathbf{a} * (\mathrm{VAR_R})^{\mathbf{b}} + \mathbf{c}$$

Iterate to find constants which minimizes error between initial severity value (blind) and new index (with CPT parameters)

Find: $\mathbf{a}, \mathbf{b}, \mathbf{c} \rightarrow \sum(VI_o - VI_R)^2 \Rightarrow 0$



New Index Value **relating severity** and **CPT parameters** following equation format.

Plot $\mathbf{VI_G}$ vs. $\mathbf{VI_R}$.
Statistically determine "critical" conditions using contouring.

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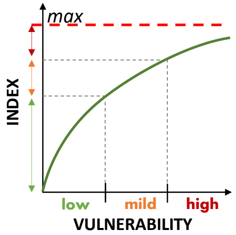
Empirically-based index



$$VI_n = \mathbf{a} * \log\left[(\mathrm{VAR_n})^{\mathbf{b}}\right] + \mathbf{c}$$

Soil Resistance

$$VAR_R = \frac{1}{q_{ravel} + q_{over}}$$

Geometry

$$VAR_G = \frac{t_{\mathrm{ravel}}}{t_{\mathrm{total}}}$$

Solve for: **a**, **b**, **c**

a = 5.19
b = 1.37
c = 17.25

a = 5.49
b = 1.20
c = 6.98

$$VI_R = 5.19\log\left[\left(\frac{1}{q_{ravel} + q_{over}}\right)^{1.37}\right] + 17.25$$

$$VI_G = 5.49\log\left[\left(\frac{t_{\mathrm{ravel}}}{t_{\mathrm{total}}}\right)^{1.20}\right] + 6.98$$

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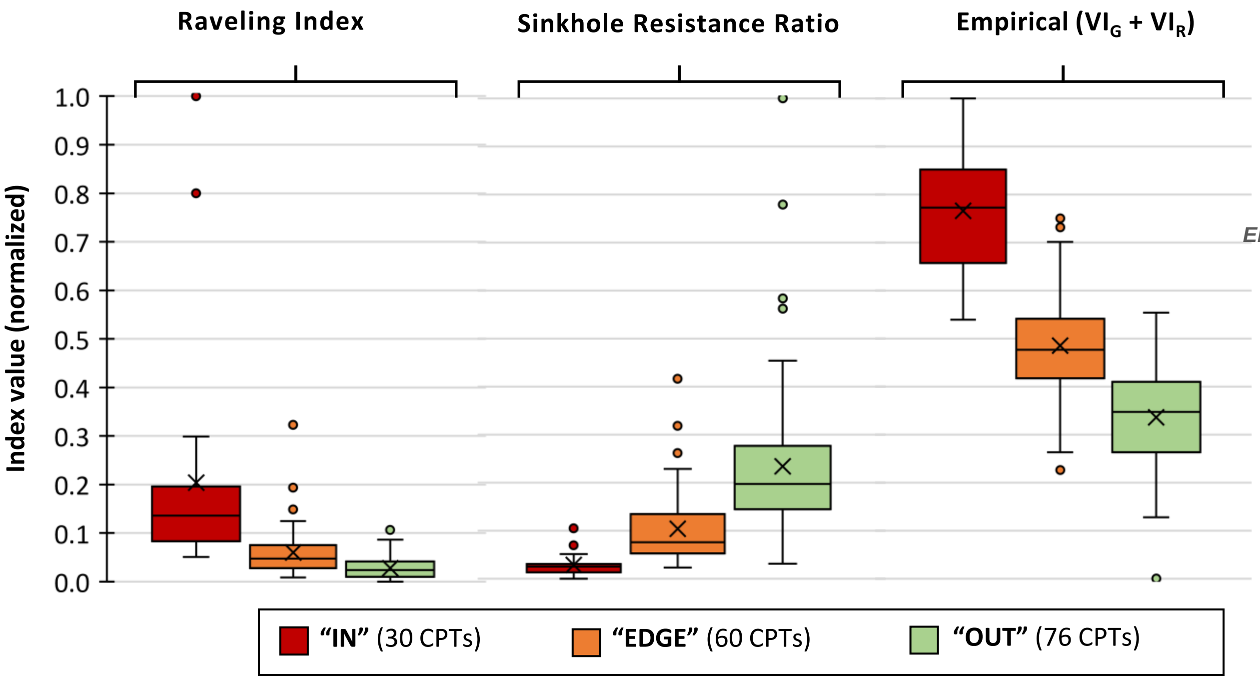
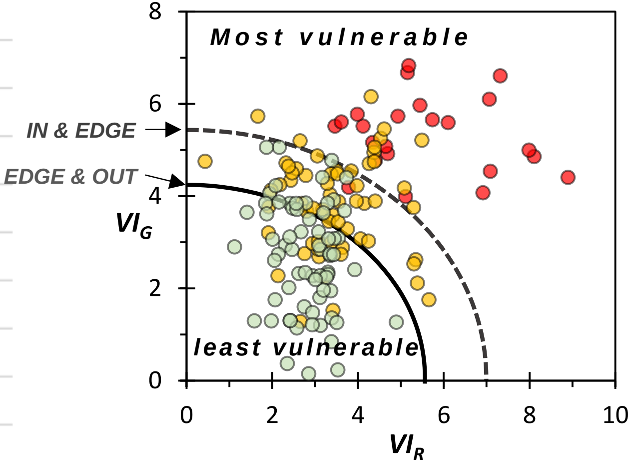
Vulnerability Indices (comparison)

RI: $\left(\frac{t_{ravel}}{t_{over}}\right)$

SRR: $\left(\frac{\mathrm{t_{over}}}{\mathrm{t_{travel}}}\right) * \left(\frac{\bar{q}_{\mathrm{over}} + \bar{q}_{\mathrm{ravel}}}{100 * \sigma'_{\mathrm{vo}}}\right)$

Empirical: $5.19\log\left[\left(\frac{1}{q_{ravel} + q_{over}}\right)^{1.37}\right] + 5.49\log\left[\left(\frac{t_{ravel}}{t_{\mathrm{total}}}\right)^{1.20}\right] + 24.23$





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Vulnerability Quantification

Tested suitability of indices to quantify relative vulnerability to sinkhole conditions from database (n = 237).

Raveling index (RI):

✓ Quick Calculation

✖ Lacks consideration of soil strength

Sinkhole Resistance Ratio (SRR):

✓ Relatively quick calculation

✖ Theoretically based, not trained on data.

Empirically updated, SRR ($VI_R + VI_G$):

✓ Statistically optimized for CPT-obtained soil parameters

✖ Requires most computation effort, only applicable for central Florida geological conditions

Statistically determined critical values from PDF intersections

accuracy & computation time →

Vulnerability ↓

	Raveling Index	*Sinkhole Resistance Ratio*	$I_R + I_G$ *
low	< 0.5	> 2.0	< 6.4
medium	0.5 – 1.0	2 – 0.75	6.4 – 8.75
high	> 1.0	≤ 0.75	> 8.75

*When bedrock is encountered > 10m

Still completing database and statistically training equation with various geologic conditions and anticipated sinkhole types

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Recommendations & Observations

When using CPTs in karst:

- Proper calibration of penetrometer is imperative.
- Use 10 cm^2 penetrometer with piezocone behind tip (u_2)
- Always correct for pwp ($q_c \rightarrow q_t$):

  Best way to distinguish between loose raveled sands and soft non-disturbed clays

When using CPT-based raveling chart:

- Only applicable in karst landscapes.
- Note changes in hydraulic pressure in CPT push ram.
- Always use when nearby SPTs can verify stratification:

  loose sands and weathered limestone.

Driving mechanism must also be considered!!

When using Vulnerability Indexing:

- Choose index best suited for associated risk of project and geologic condition.

  quick grouting vs. design-build project
- Perform and compare index values over time estimate rate of raveling.

THANK YOU

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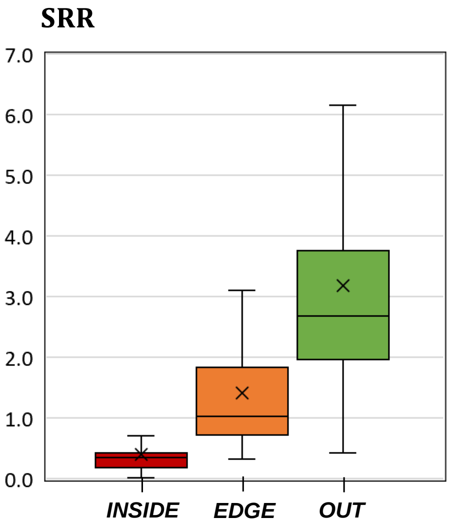
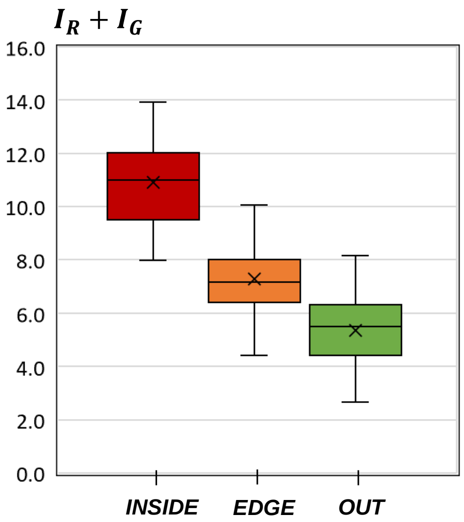
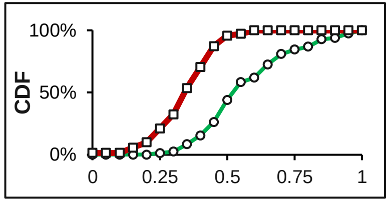
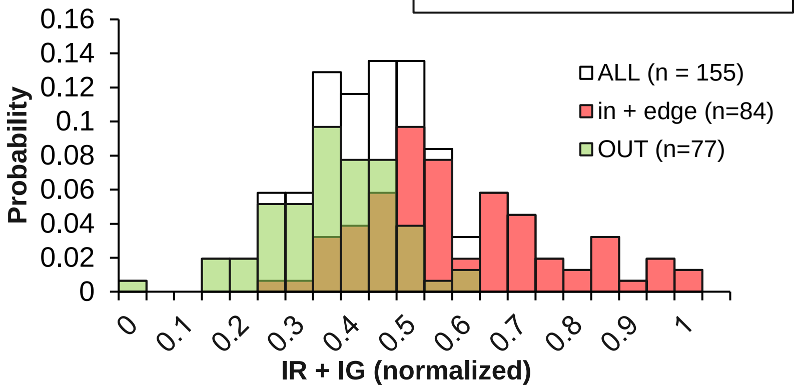
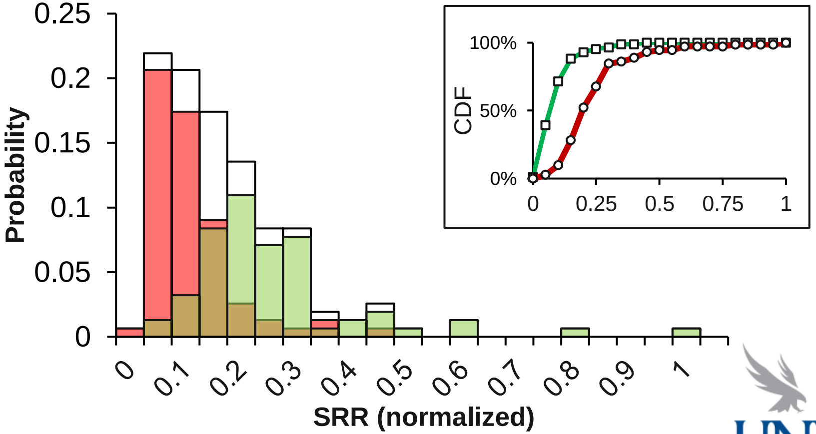
SRR (theoretical) vs. Empirical Index











- ✓ Clearer distinction between categories
- ✓ Normal distribution of values
- ✖ Requires additional analysis
- ✖ Specific geological conditions

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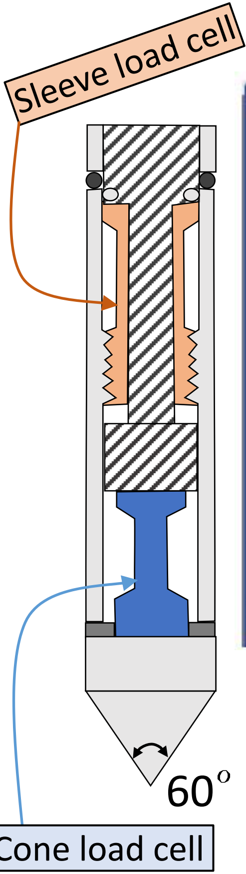
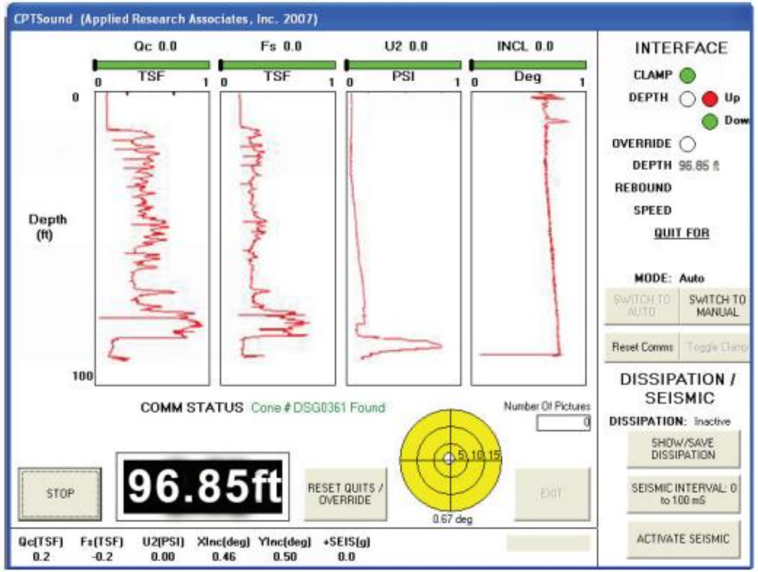
Cone Penetration Test (CPT)

ASTM D5778-12

Rate controlled:

2 cm/s





- Cone tip Resistance, $\mathbf{q_c}$
- Sleeve friction resistance, $\boldsymbol{f_s}$
- Friction ratio, $\boldsymbol{R_f} = f_s/q_c$

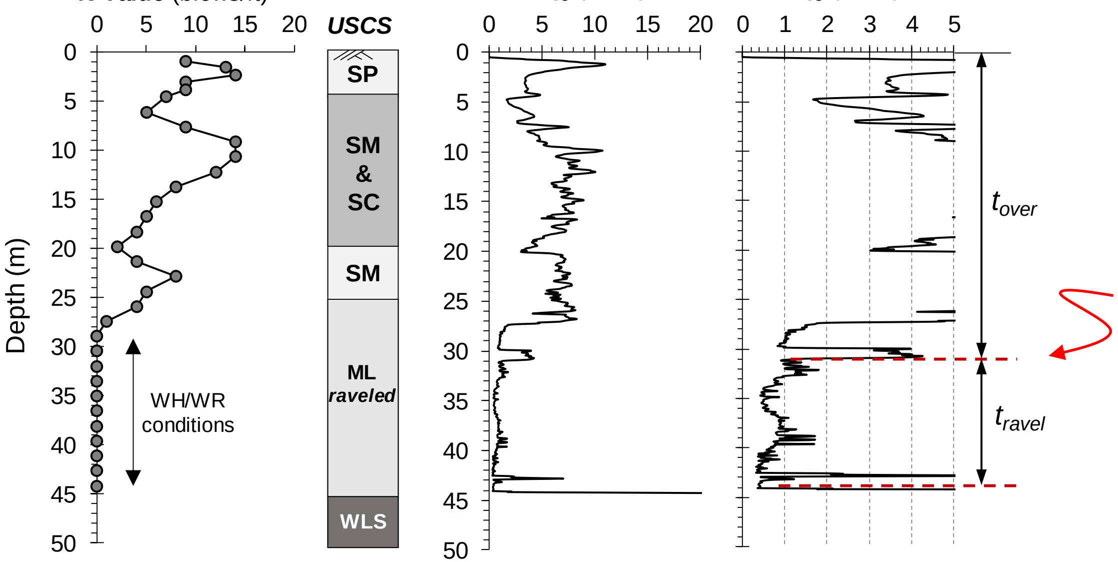
Assessment Indices (theoretical)

<u>Raveling Index (RI):</u> Simple comparison index to assess the progression of internal erosion encountered. (Foshee and Bixler 1994)

$$\mathrm{RI} = \frac{t_{\mathrm{ravel}}}{t_{\mathrm{over}}}$$

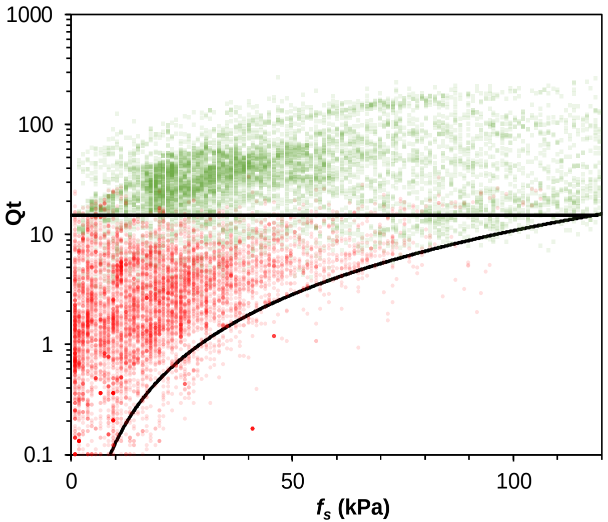
Foshee and Bixler (1994):
q_c < 10 tsf (1 MPa) in karst = raveled

Use of raveling chart



SPT performed ~3m NE *of sinkhole*

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



Nam, Shamet, Soliman, Wang, and Yun (2019) “Development of a Sinkhole Risk Evaluation Program.” *Technical Report.* Florida Department of Transportation No. 166 BDV24-977-174

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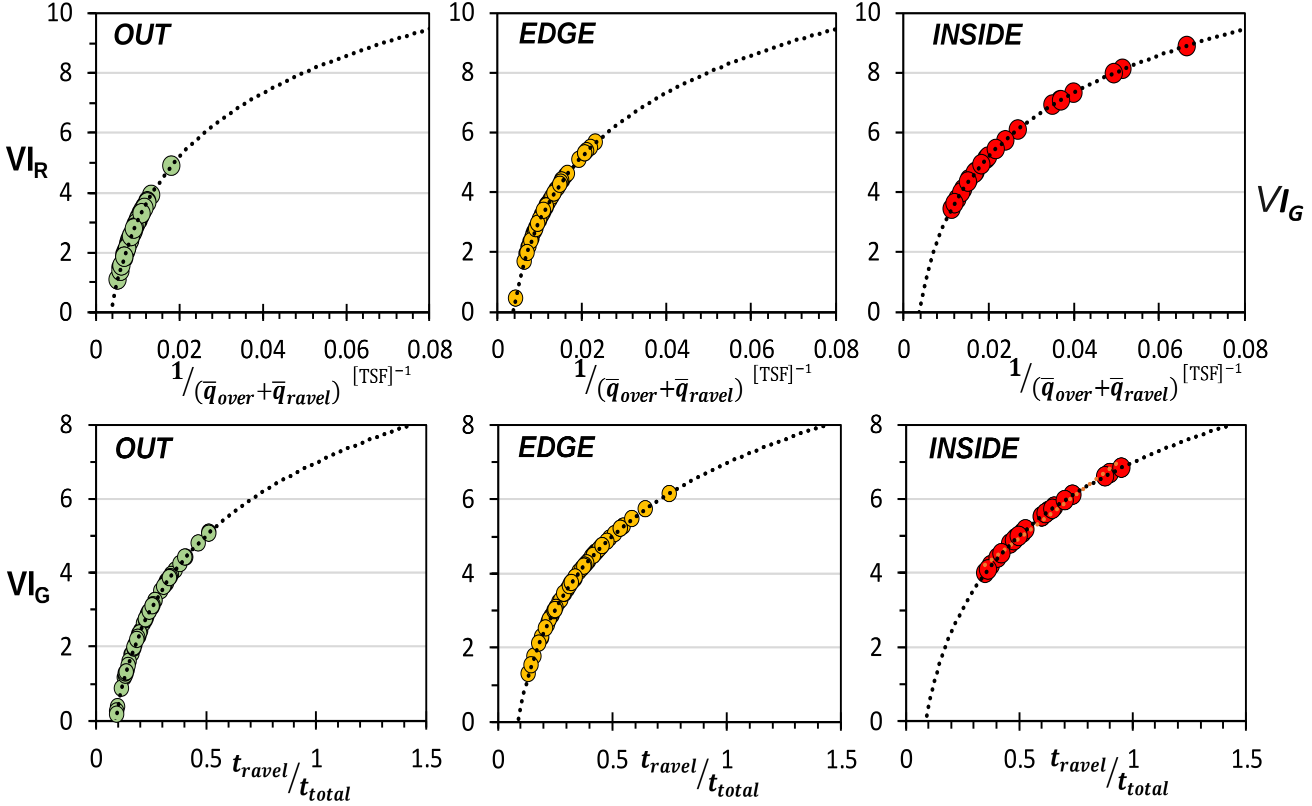
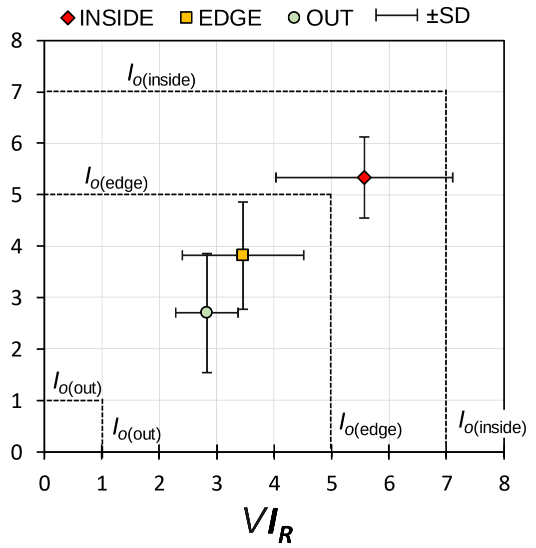
Empirical Index Procedure – Categorical Regression

$$I_n = \mathbf{a} * \log\left[(\mathrm{VAR_n})^{\mathbf{b}}\right] + \mathbf{c}$$





Impossible to match initial conditions (I_o)

✓ Desired trend is preserved

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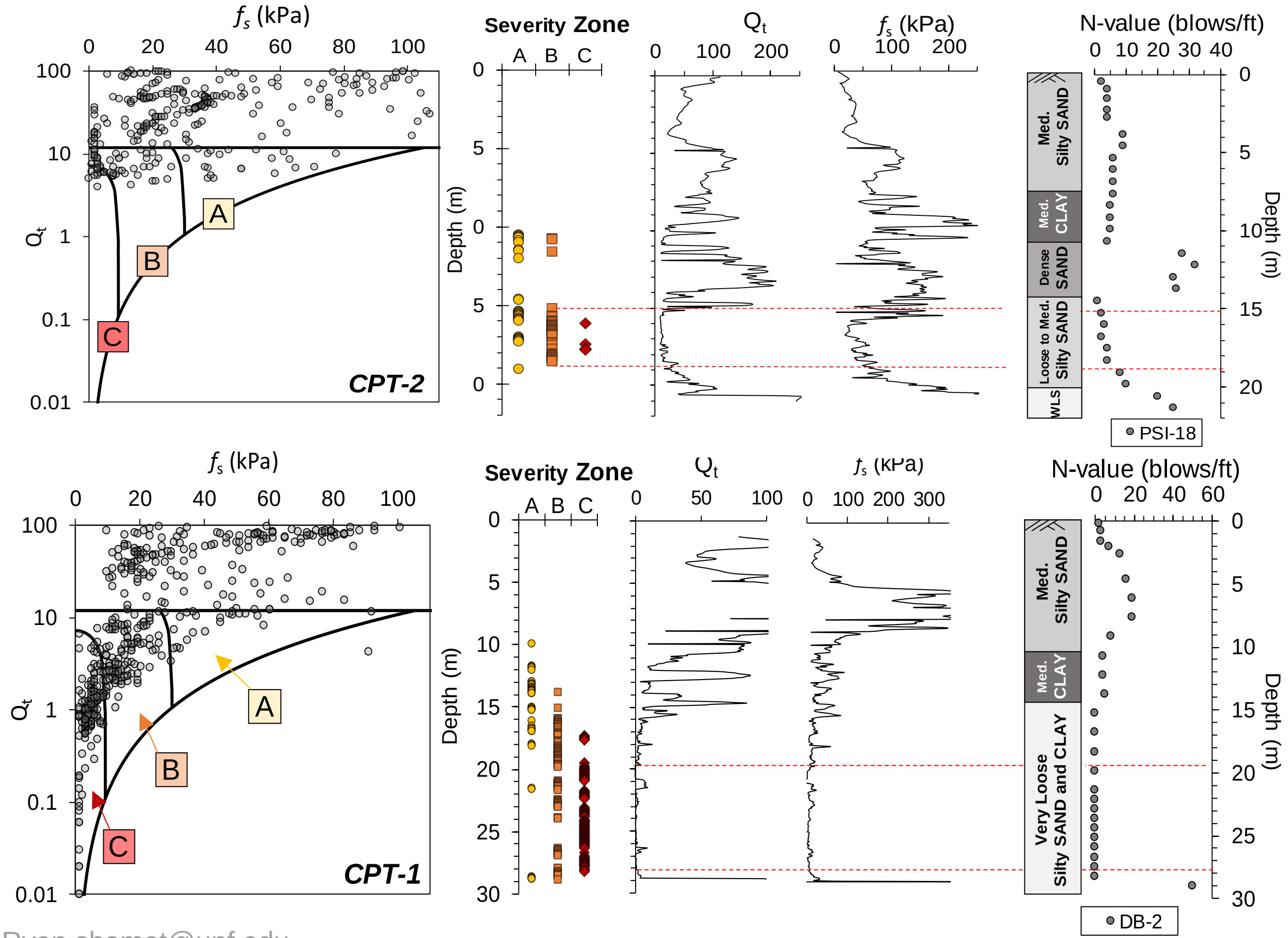

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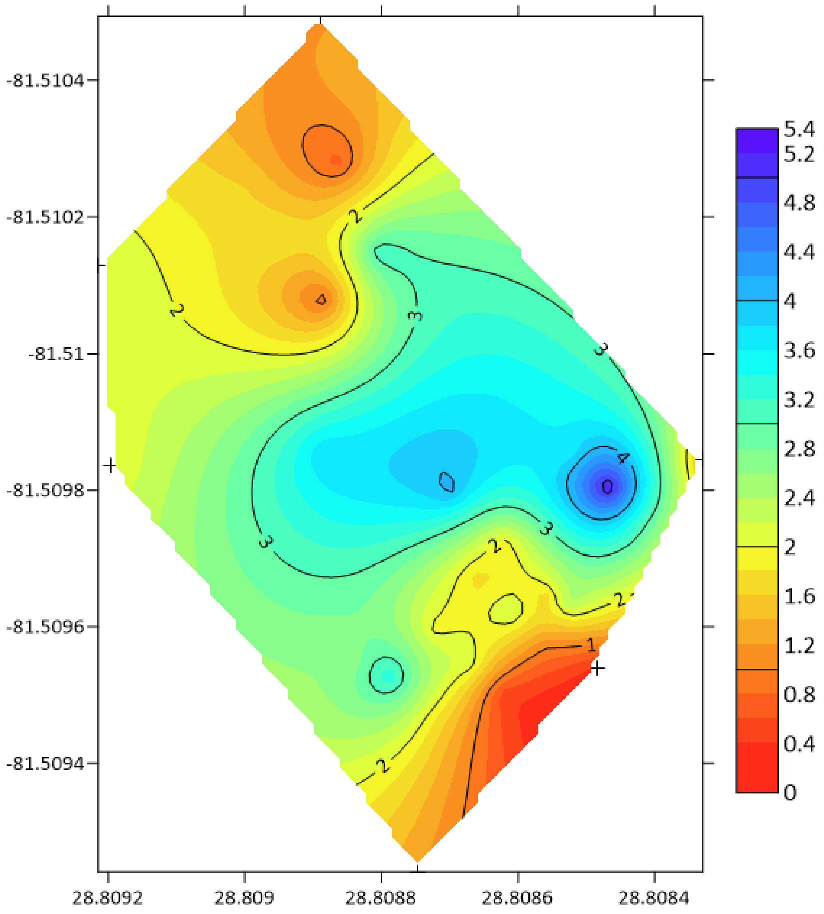

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