Development of Sinkhole Risk Evaluation Program

(BDV24 TWO 977-17)

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Presentation Outline

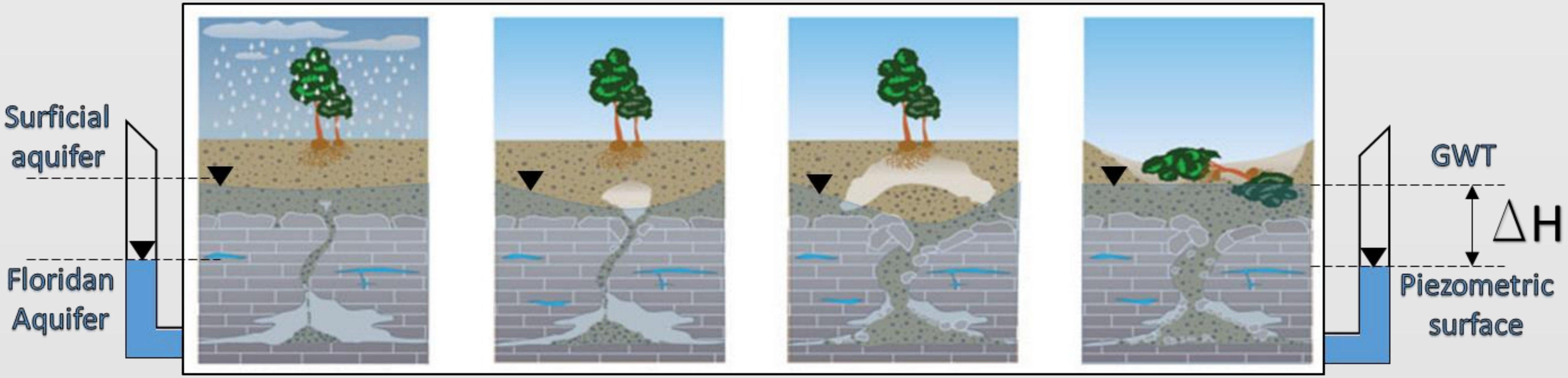
- **Introduction**
- **Project Subject Background**
- **Project Objectives**
- **Task Outline**
  - Task 1 – In-situ groundwater monitoring experiment
  - Task 2 – High-resolution groundwater recharge map
  - Task 3 – Improved identification method for detecting raveled zone
  - Task 4 – Develop the sinkhole stability analysis
- **Summary of Research Conclusions**
- **Recommendations**

Introduction

- **Research Goal:**
  - To develop a systematic and practical sinkhole vulnerability evaluation program by common experimental and numerical tools.

- **Research Methodology:**
  - CPT => vulnerability index
  - Piezometer installation and monitoring => identify points of groundwater recharge
  - Finite difference (FD) numerical analysis => high-resolution groundwater recharge model and map
  - Finite element (FE) numerical analysis => sinkhole stability analysis and charts

Project Subject Background



Product of soluble, porous, carbonate based bedrock.

Result of internal erosion in overburden soil (Soil Raveling)

- Natural recharge of aquifer.
- ‘Man-made’ influences.
  - Leaking pipes.
  - Concentration of runoff.
  - Excessive pumping/dewatering

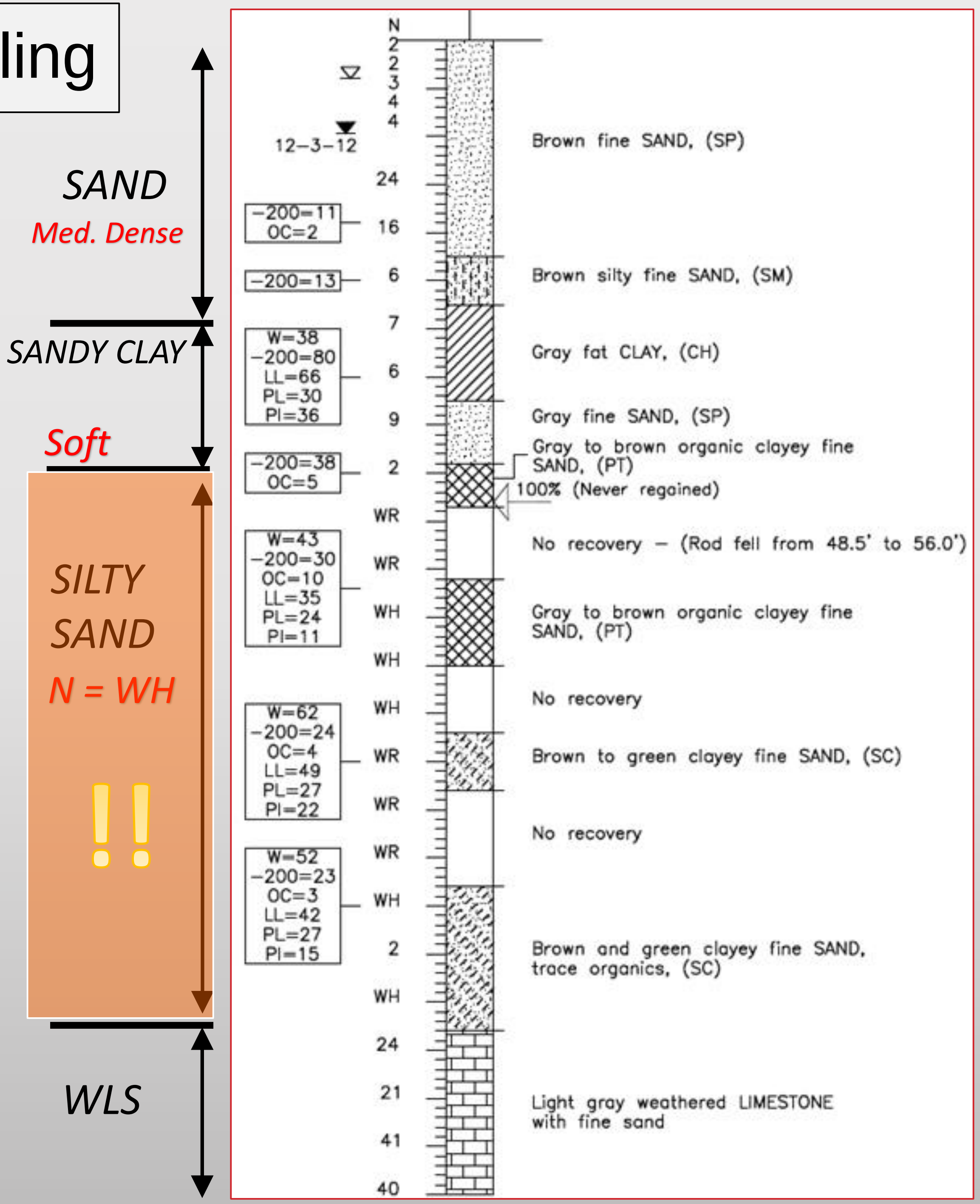
Progressive Process: *Increase Soil Raveling → Increase Potential of Sinkhole*

Image source: Florida Geological Survey

Detection of Soil Raveling

Subsurface testing encounters abnormally low strength soils above bedrock

Encountered **WH/WR** conditions above limestone in *sandy* (low -200) layer



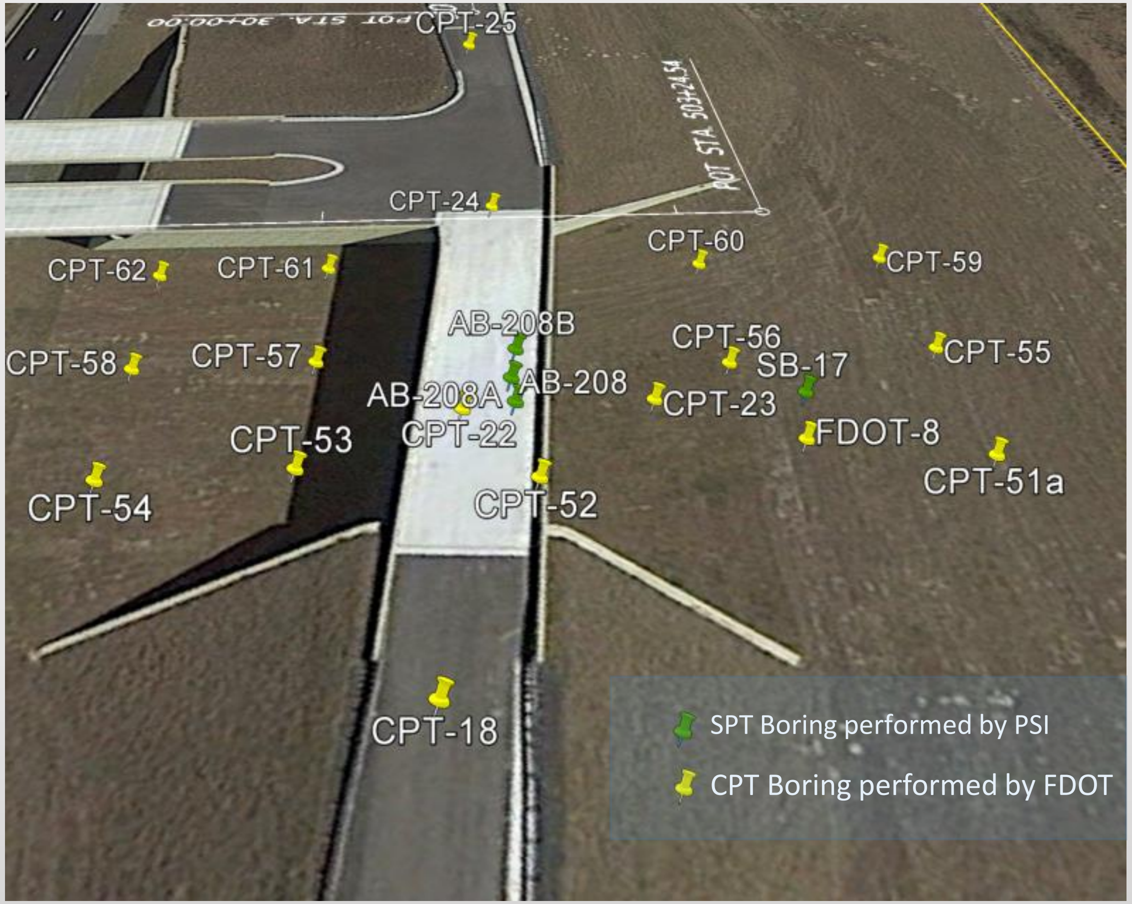
Project Objectives

1) To explore in-situ groundwater sensing & monitoring to identify points of recharge (considered as sinkhole source) => Task 1
2) To develop a high-resolution recharge map to identify the locations of high potential raveling (due to soil internal erosion) => Task 2
3) To develop a procedure to quantify the severity level of sinkhole raveling by using CPT => Task 3
4) To develop a numerical modeling procedure to evaluate sinkhole stability and also to construct the stability charts => Task 4

Task 1. In-situ groundwater monitoring experiment

Wekiva Parkway Project – Site Description

- Lake County
- About 40 minutes North of Downtown Orlando.
- Focus Section: North end of SR 46 to Mt. Plymouth Rd connector toll road.
- Located north of wekiva springs and south of Seminole springs. Numerous relic sinkholes.
- Interchange consists of 3 bridges, 4 earth-embankment ramps

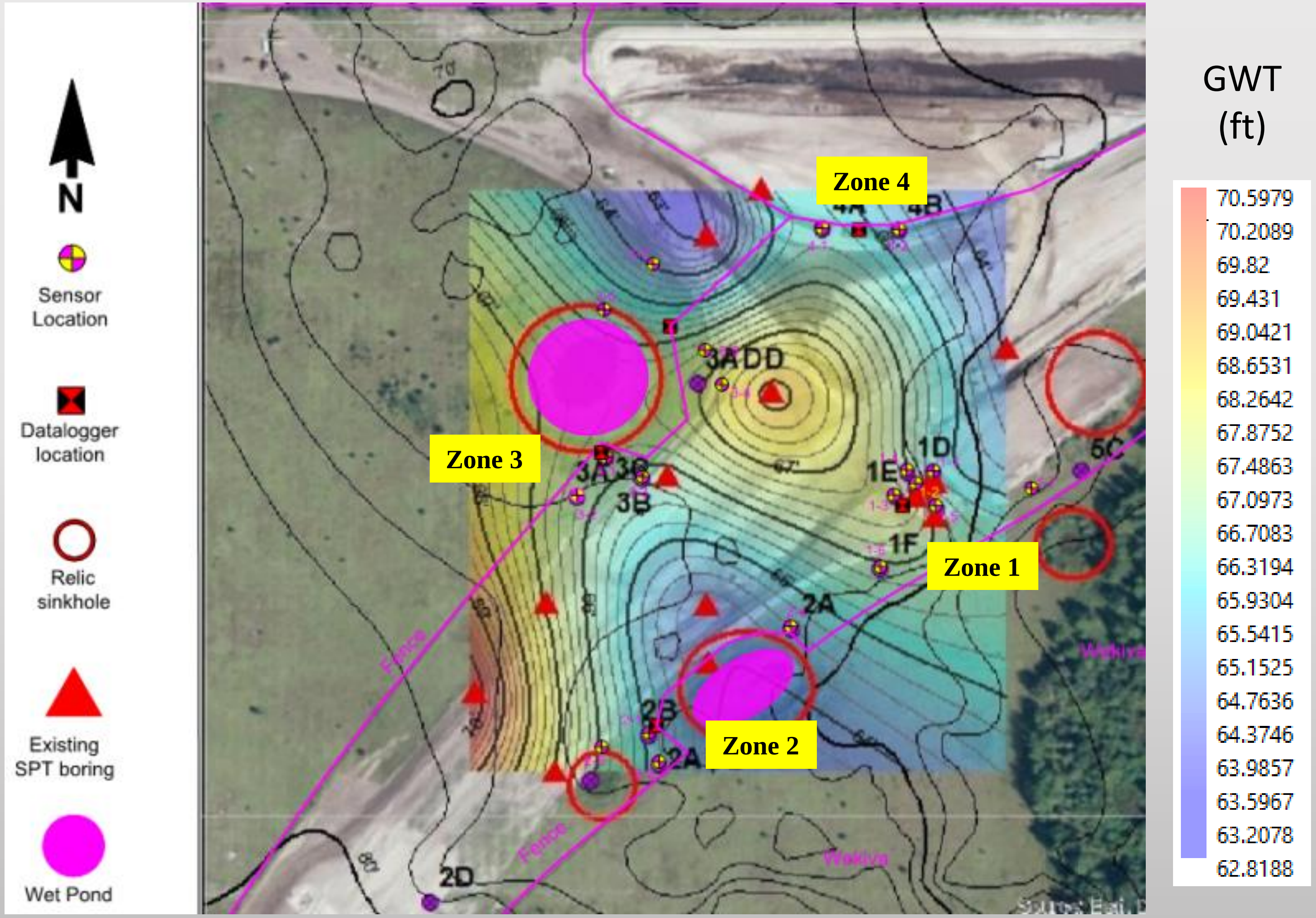


Field investigation performed by FDOT and Professional Services Inc.

- 74 CPT soundings performed till refusal
- 14 SPT borings through performed till
- Depth to Limestone varies from 60 to 130 feet.
- Borings show very loose soil (WH/WR & Tip resistance < 10 TSF) directly above the limestone bedrock.

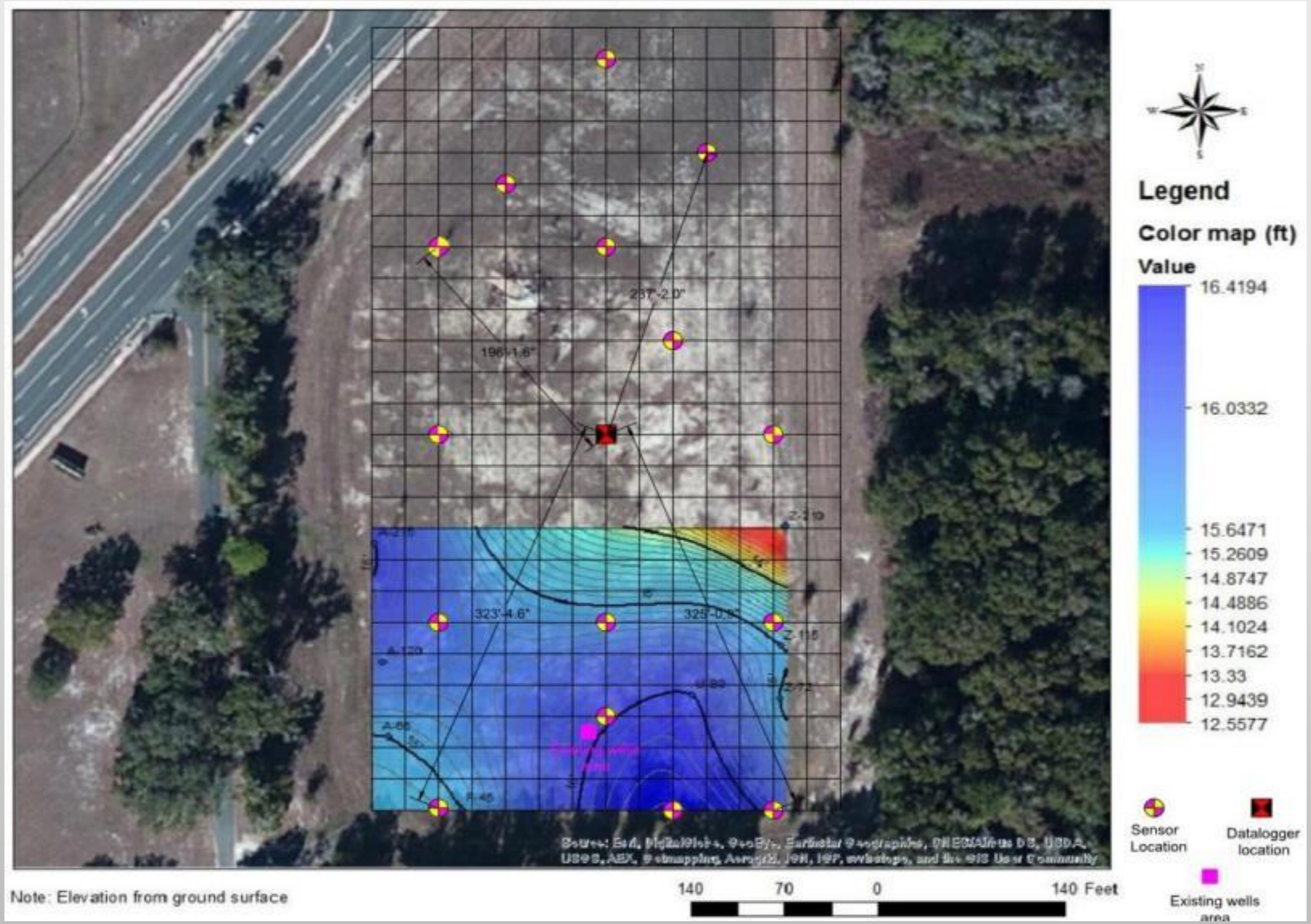
Sensor layout for Wekiva pkwy

- Ground water table from MSL
  - Low: 63 feet
  - High: 70.5 feet
- Number of Zones: 4
  - zone 1: 7 sensors
  - zone 2: 4
  - zone 3: 7
  - Zone 4: 2
- Type of sensor: 4500S-350kPa
- Number of Datalogger: 5
  - 4-channel datalogger: 4
  - 16-channel datalogger: 1
- HOBO Rain gauge (zone 3)



Sensor layout for Newberry retention pond

- Ground water table
  - Low: 13.5 ft
  - High: 16 ft
- Number of sensor: 16
- Type of sensor: 4500S-350kPa
- Number of datalogger: 1
- Type of datalogger: 16-channel



Equipment

- Piezometer sensor
- Make: Geokon
- Model: 4500S-350kPa
- Resolution: 0.025% F.S
- Accuracy:
  ±0.1% F.S.

- 4-Channel datalogger
- Make: Geokon
- Measurement Accuracy: ±0.05% F.S.
- Data Memory: 320K EEPROM
- Storage capacity: 10666 arrays

- 16-Channel datalogger
- Make: Geokon
- Measurement Accuracy: ±0.05% F.S.
- Data Memory: 320K EEPROM
- Storage capacity: 3555 arrays

Sensor preparation and installation

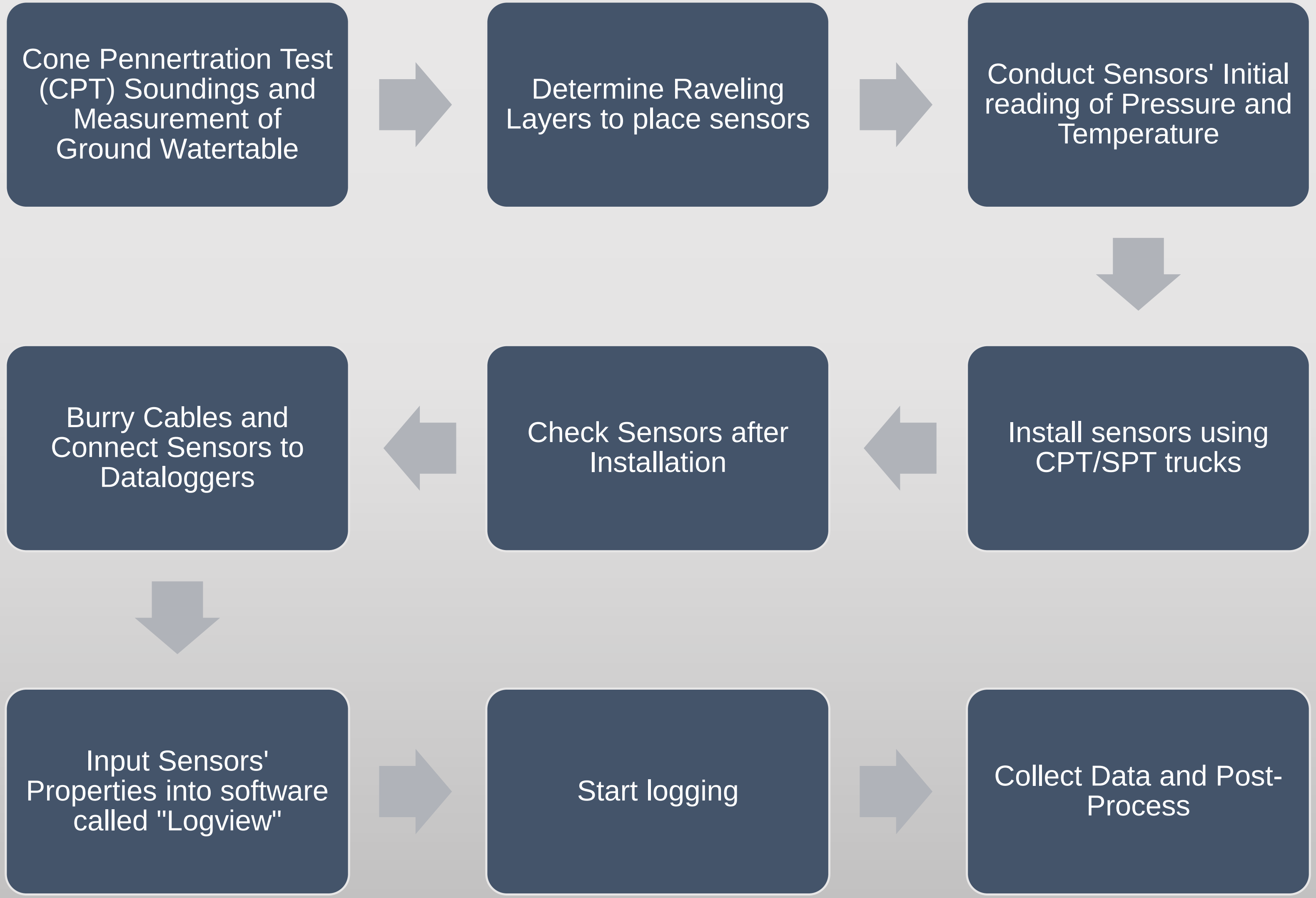
Step 1: Checking sensors and dataloggers in lab

Step 2: Install sensor using CPT/SPT trucks

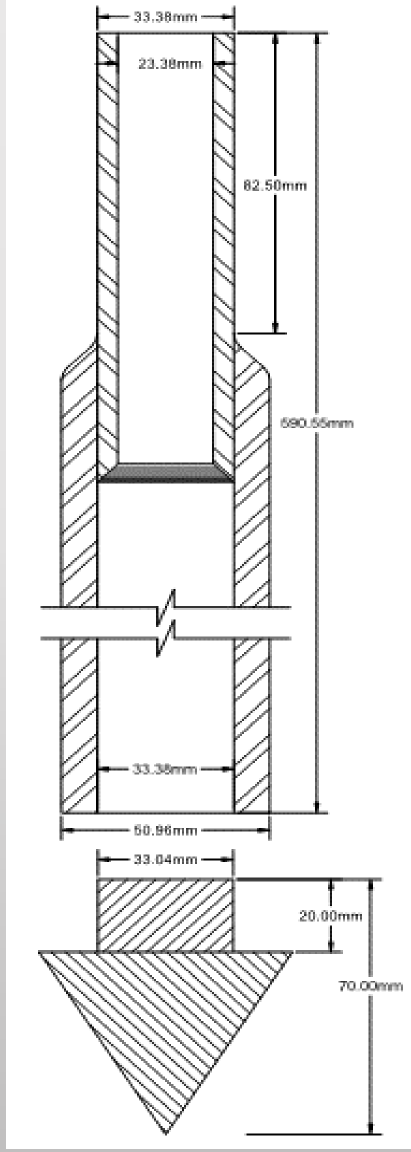
Step 3: Use trencher to bury cables safely to datalogger

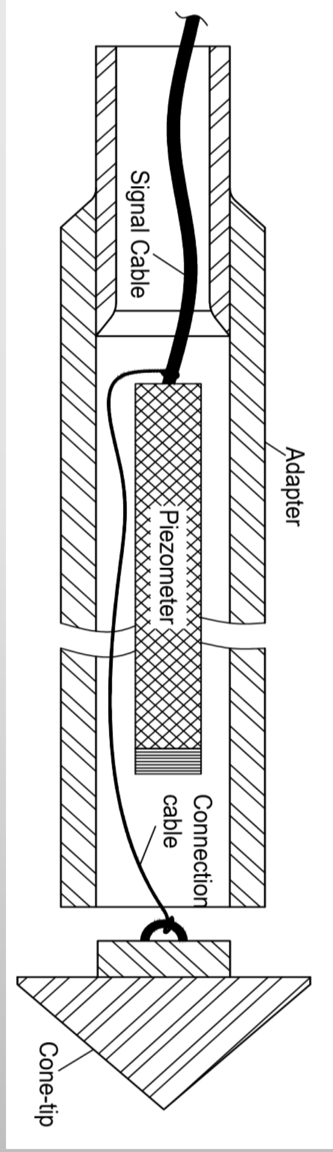
Step 4: Connect sensors to datalogger and start logging

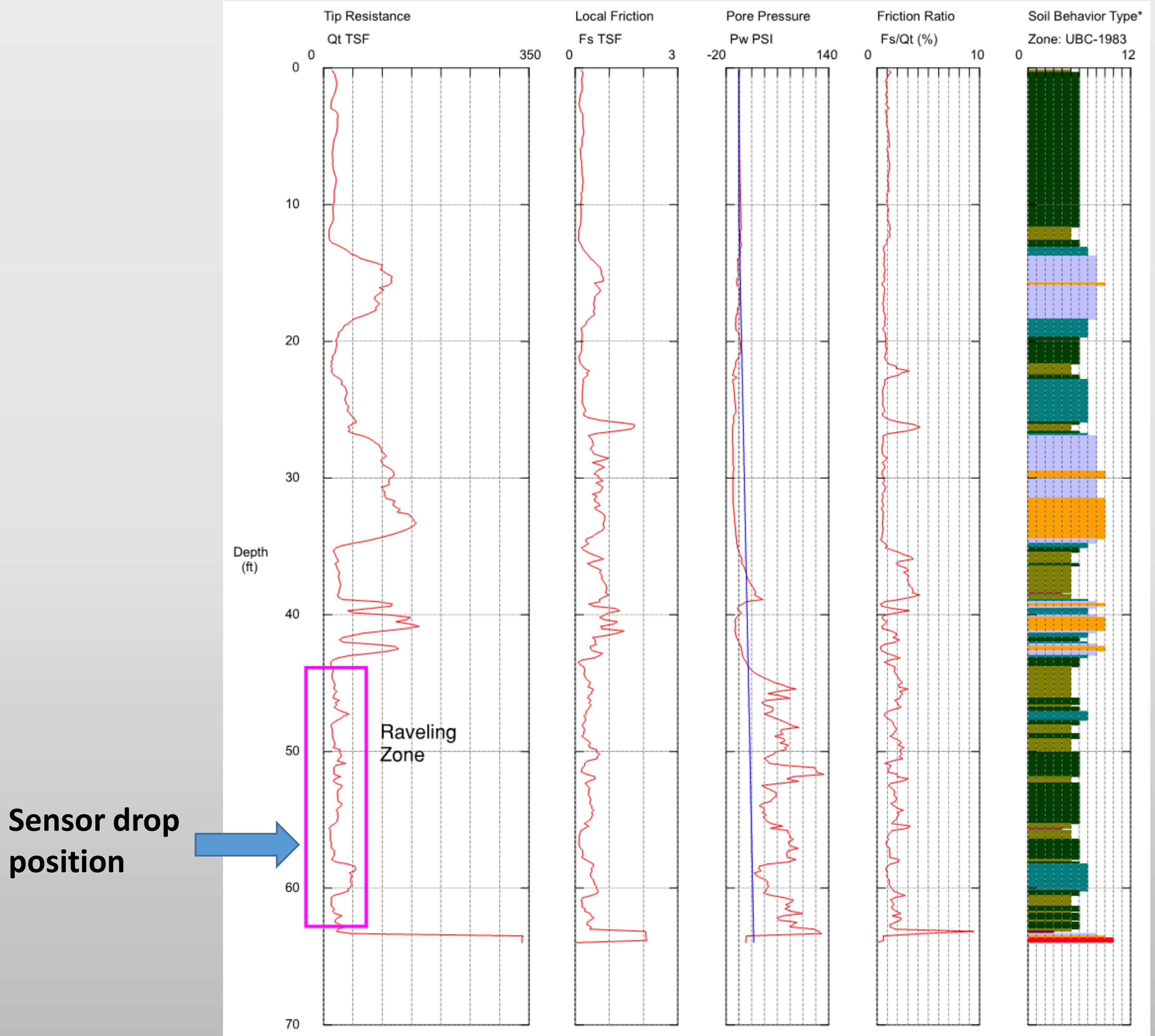
Process of sensor Installation



Adapter and Sacrificial cone-tip

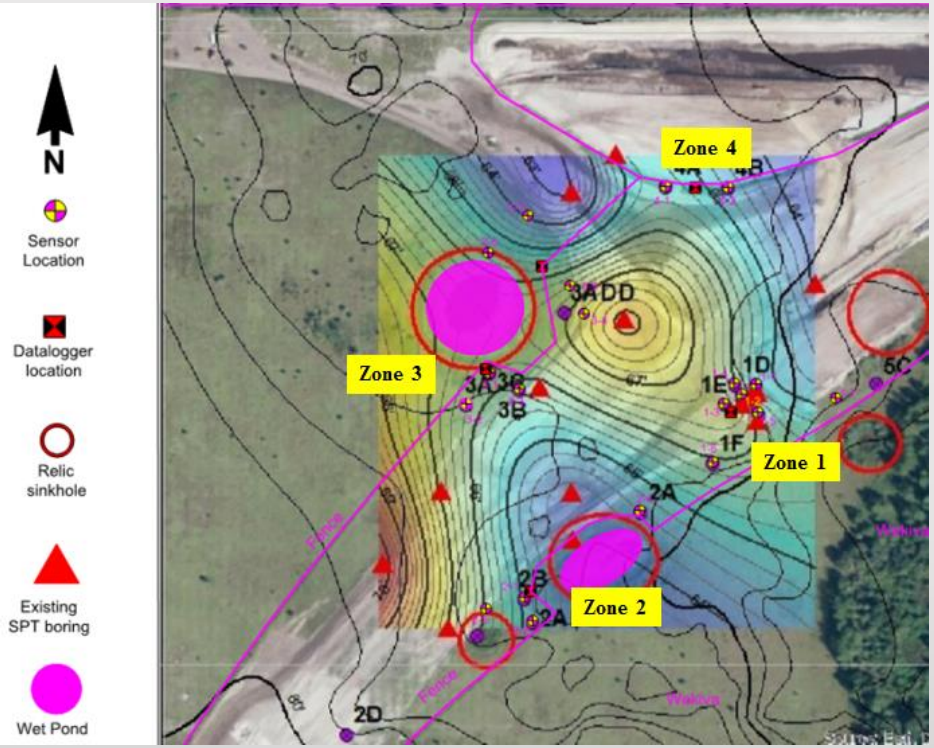


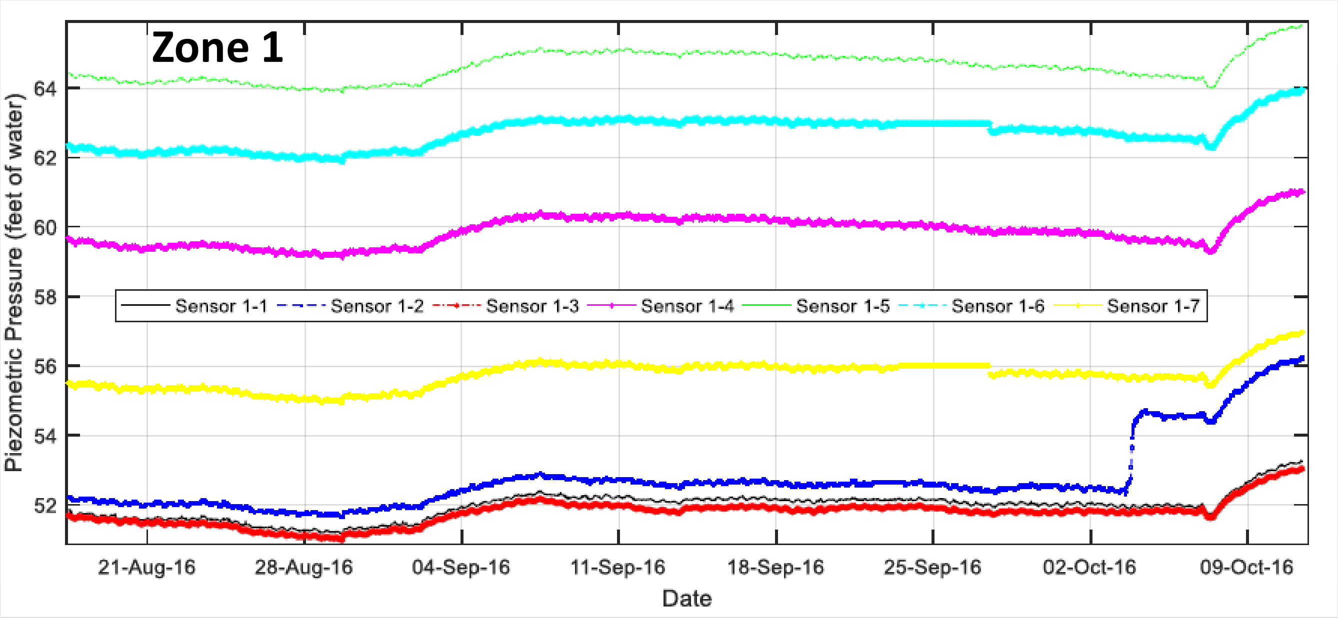


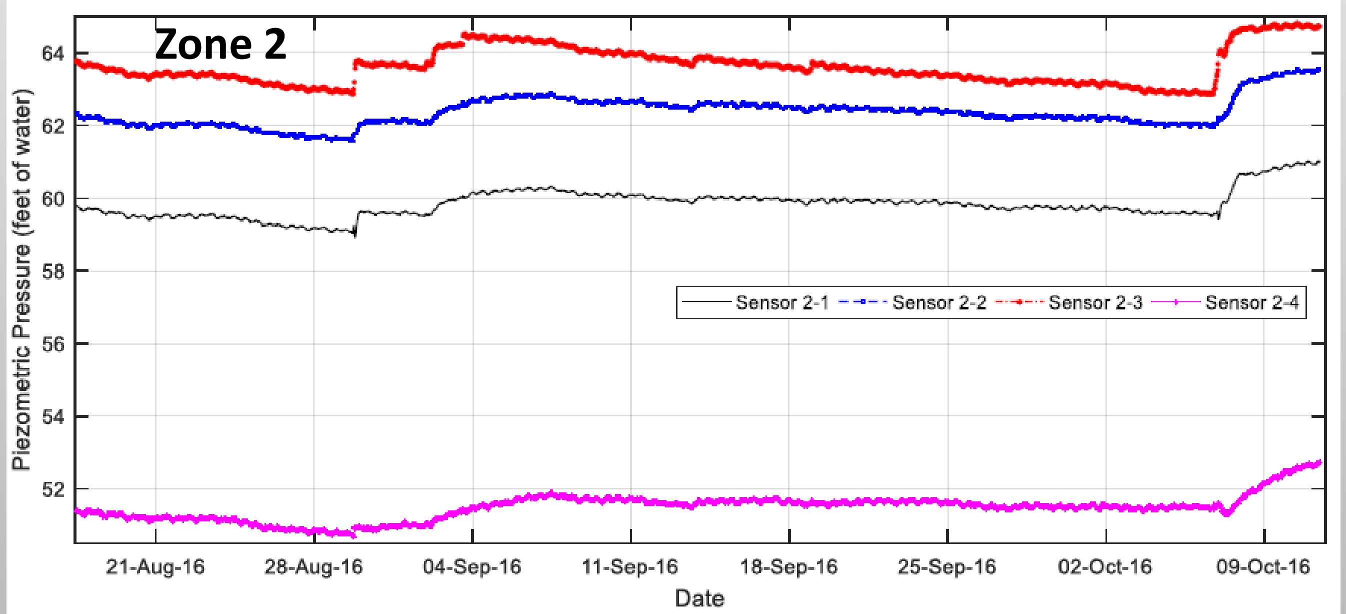


Tip Resistance
Qt TSF
0
350
Local Friction
Fs TSF
0
3
Pore Pressure
Pw PSI
-20
140
Friction Ratio
Fs/Qt (%)
0
10
Soil Behavior Type*
Zone: UBC-1983
0
12
Depth
(ft)
0
10
20
30
40
50
60
70
Raveling
Zone
Sensor drop
position

Example of piezometer data monitoring

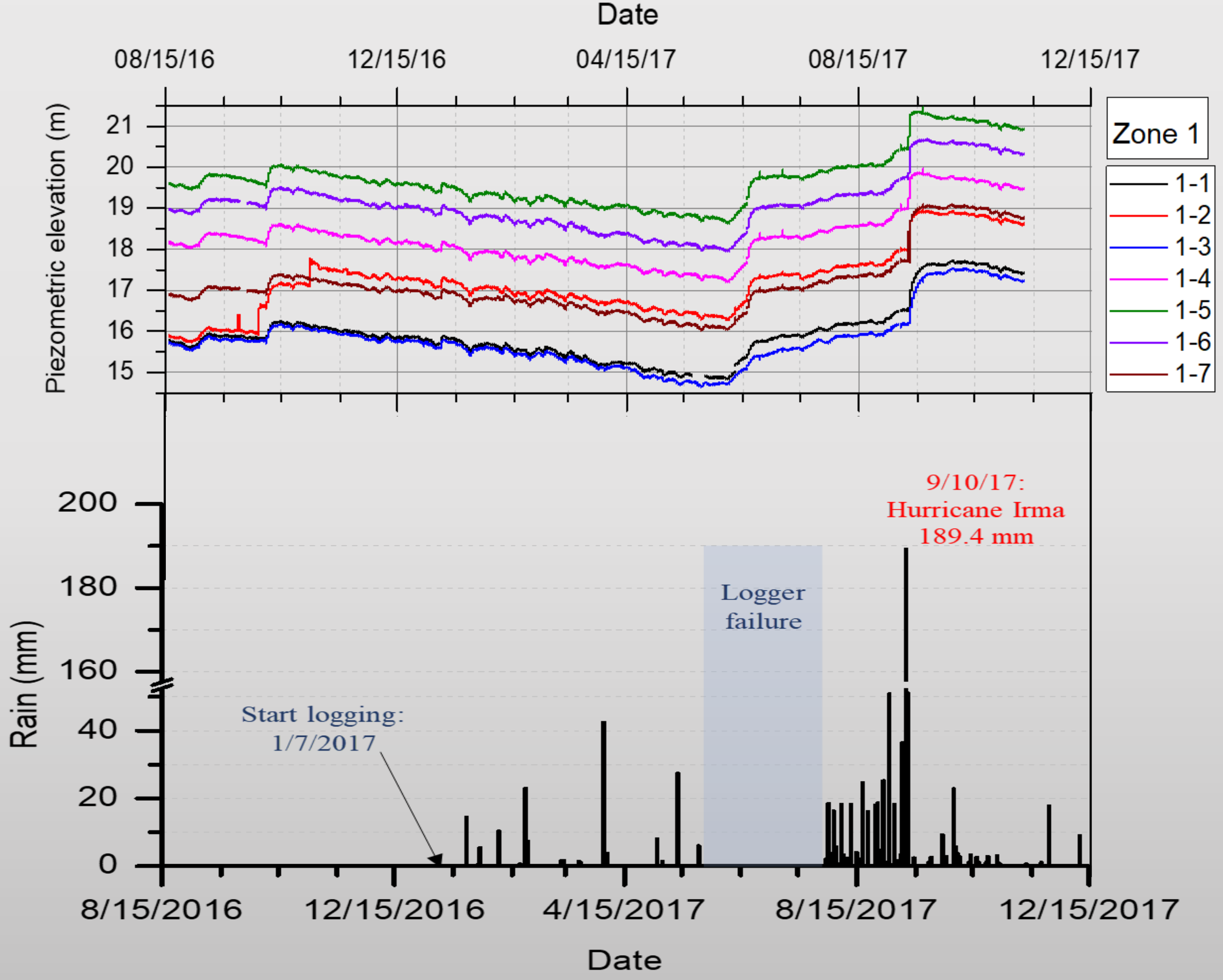






(Tu 2016)

Zone 1



- Strong correlation with extreme rainfall events

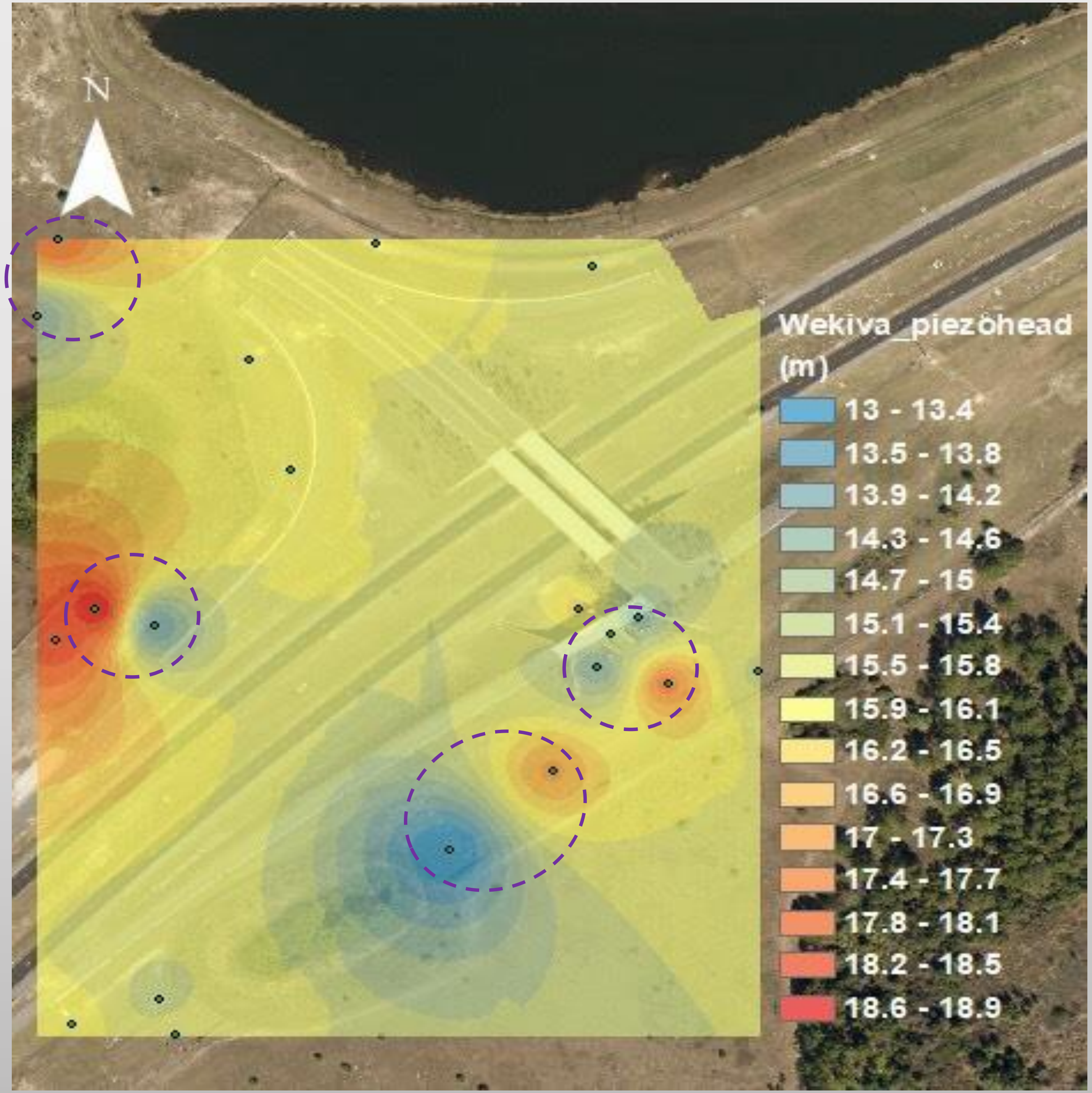
Groundwater Contours

High head difference with close proximity may indicate large hydraulic seepage gradients.

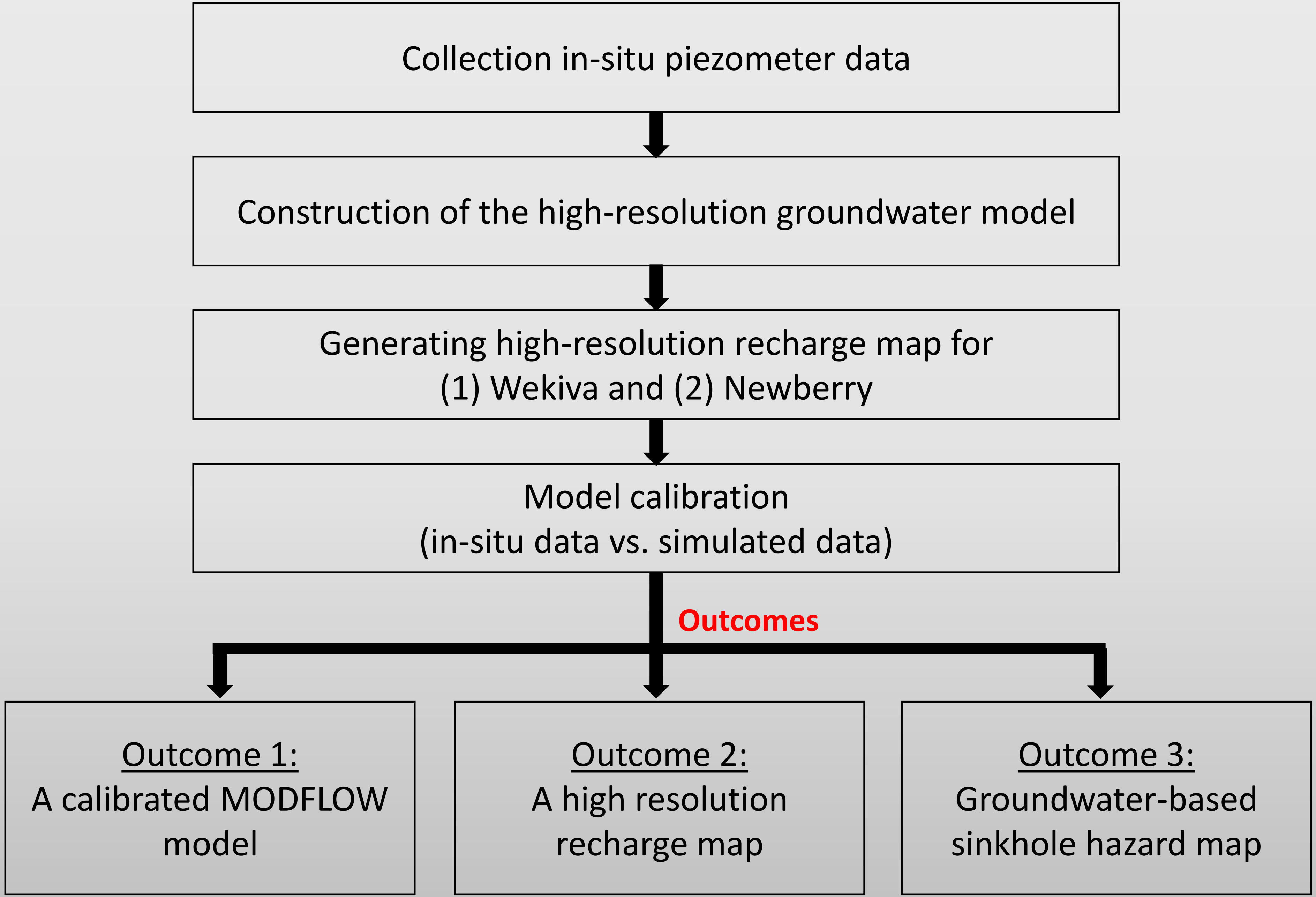
$$i = \Delta H/L$$

$$q = ki$$

Approximate recharge points nearby



Task 2. High-resolution groundwater recharge map


Collection in-situ piezometer data
Construction of the high-resolution groundwater model
Generating high-resolution recharge map for
(1) Wekiva and (2) Newberry
Model calibration
(in-situ data vs. simulated data)
Outcomes
Outcome 1:
A calibrated MODFLOW
model
Outcome 2:
A high resolution
recharge map
Outcome 3:
Groundwater-based
sinkhole hazard map

Procedures of High Resolution Groundwater Modeling

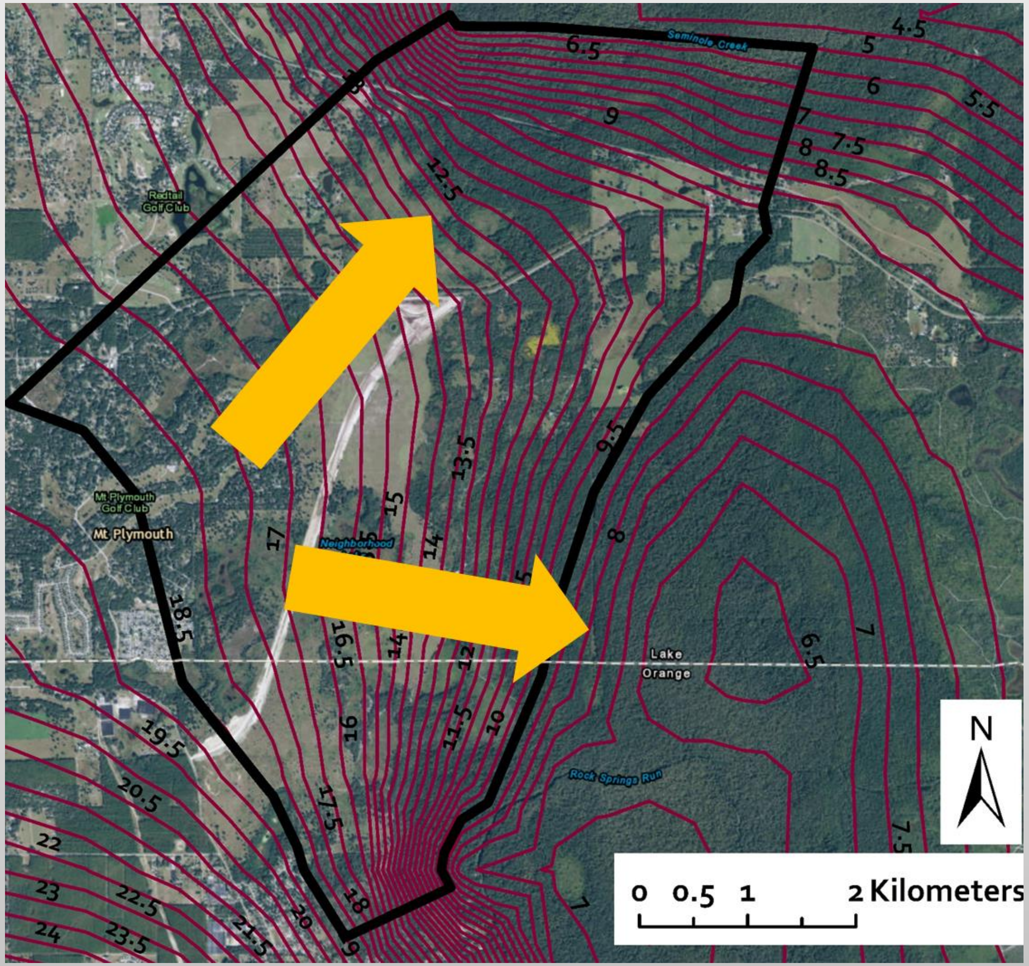
- Step 1 – Selection of study area
- Step 2 – Model domain identification
- Step 3 – Discretization
  - Horizontal
  - Vertical
- Step 4 – Boundary condition
- Step 5 – Local-scale model setup
  - Same procedure from Steps 1 through 4 for the local-scale model
- Step 6 – Calibration of numerical model
- Step 7 – Recharge map generation

Step 1 – Study Area

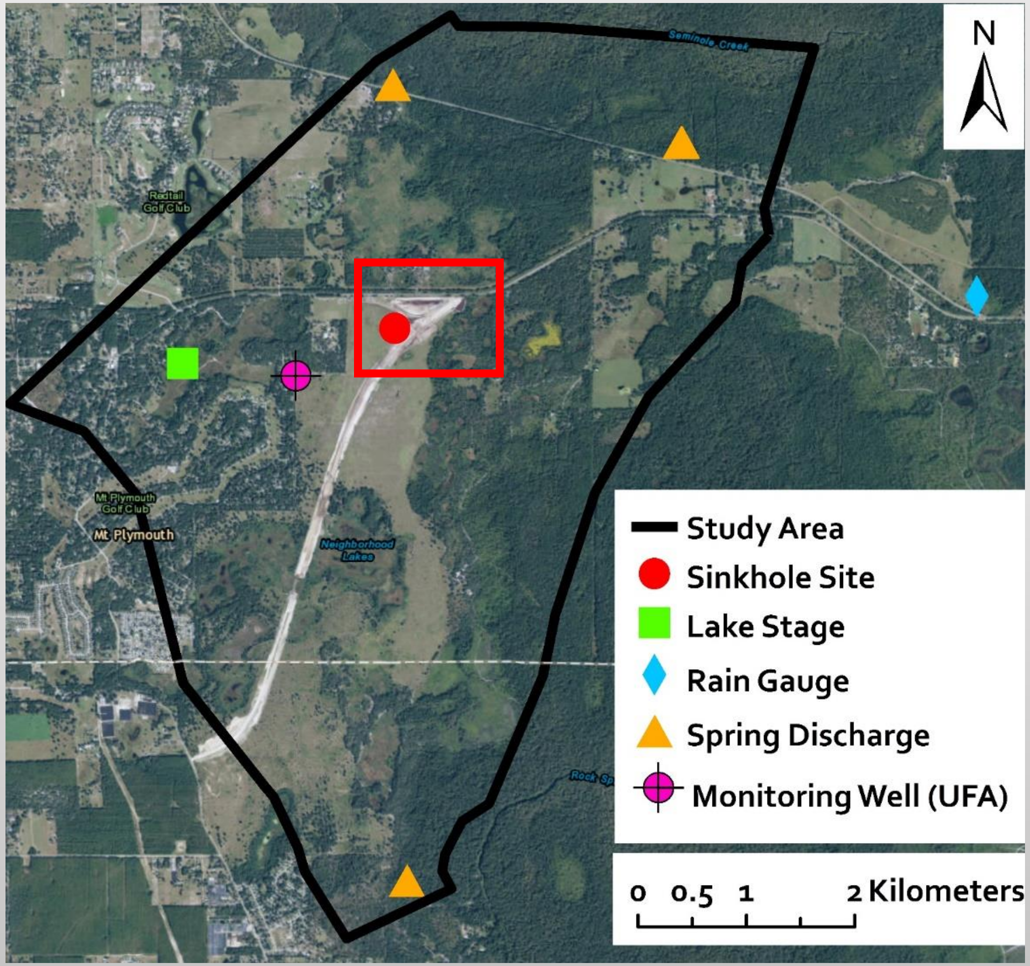
- Construction site located at the Wekiva Parkway Bridge at Mt. Plymouth, Florida **Site 1**

- FDOT drain basin site located at the detention pond at Newberry, Florida **Site 2**

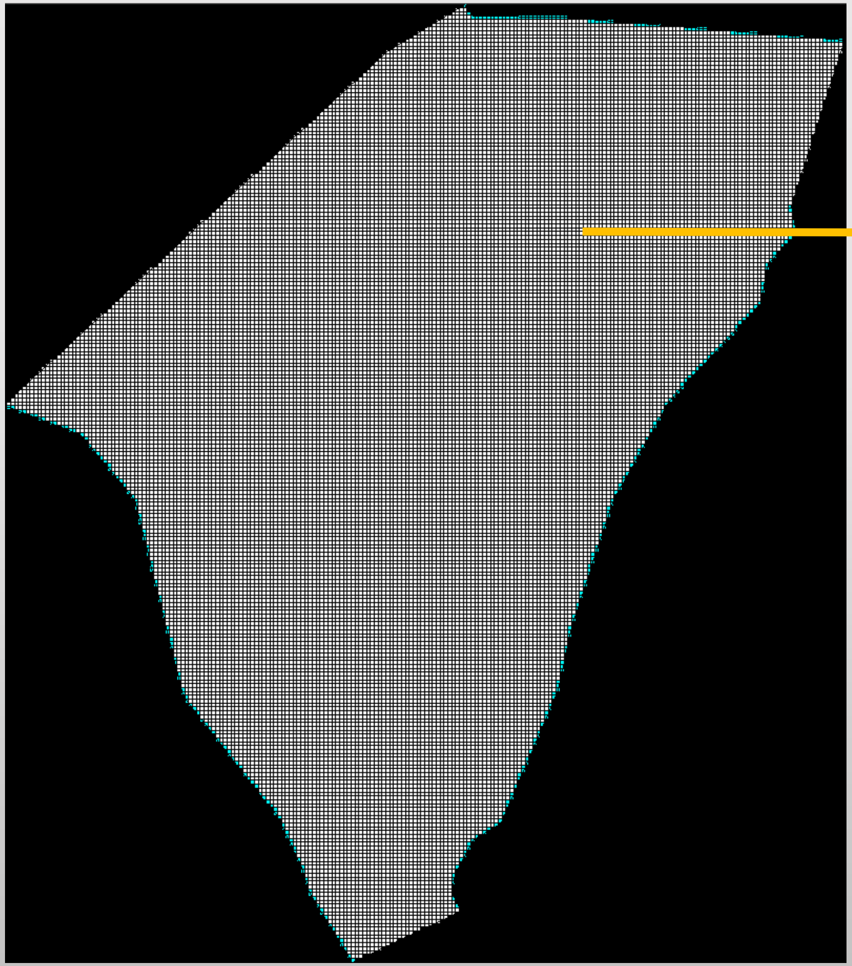
Step 2 - Model Domain Identification

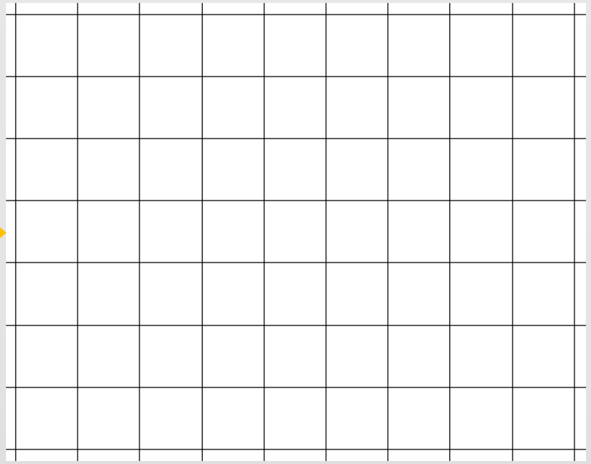


Water Table Contour 2010
(SJRWMD Special Publication SJ95-SP7)



Step 3 – Model Horizontal and Vertical Discretization





248 Rows and 218 Columns => 54,064 elements

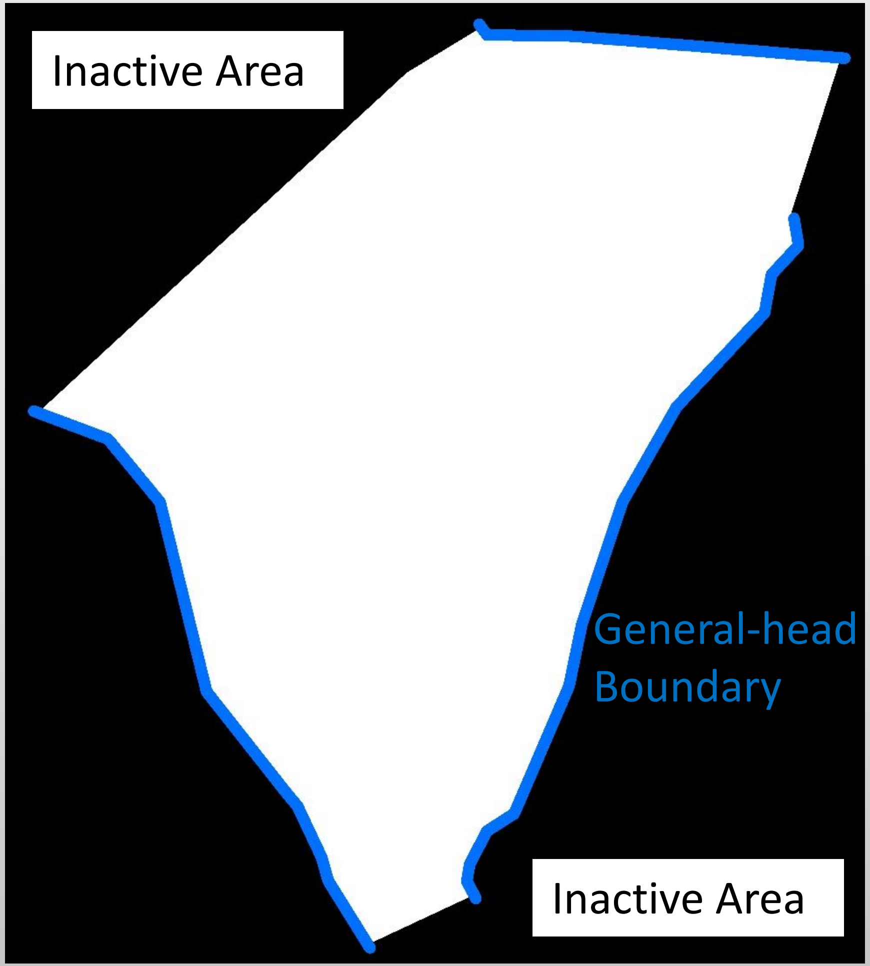
Grid Size: 30 m x 30 m

Surficial Layer (Surficial Aquifer)
Primarily composed of sand

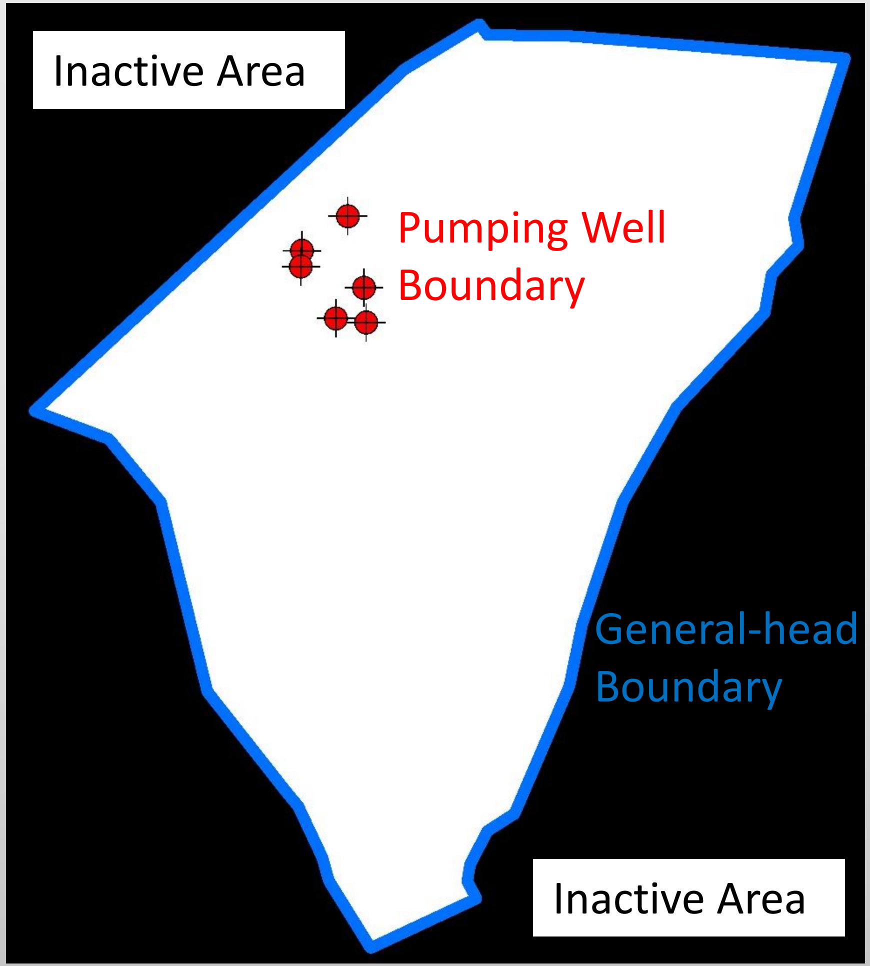
Clay Layer (Upper Confining Unit)
Primarily composed of clay

Limestone Layer (Floridan aquifer)
Primarily composed of limestone and dolostone

Step 4 – Boundary conditions



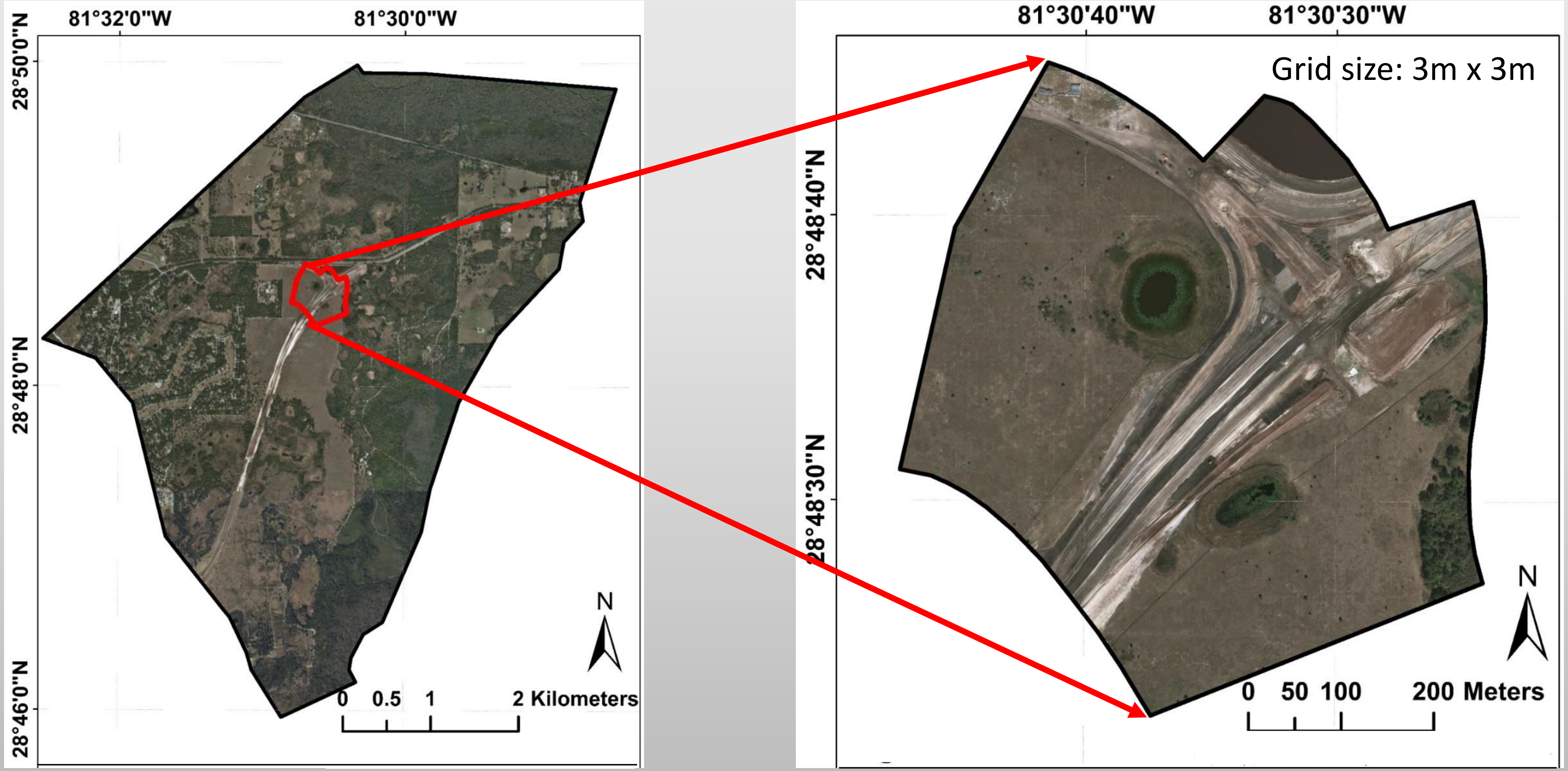
Surficial Layer



Limestone Layer

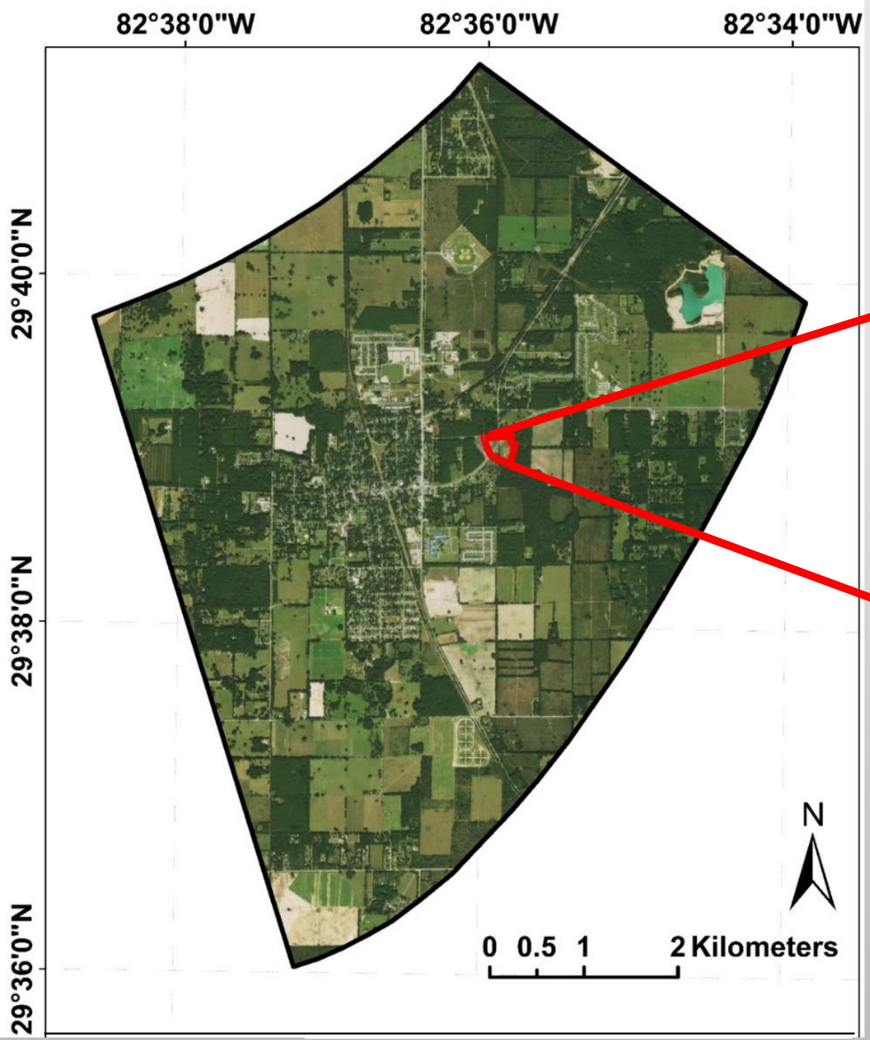
Step 5 – Local-scale model setup (Wekiva Site)

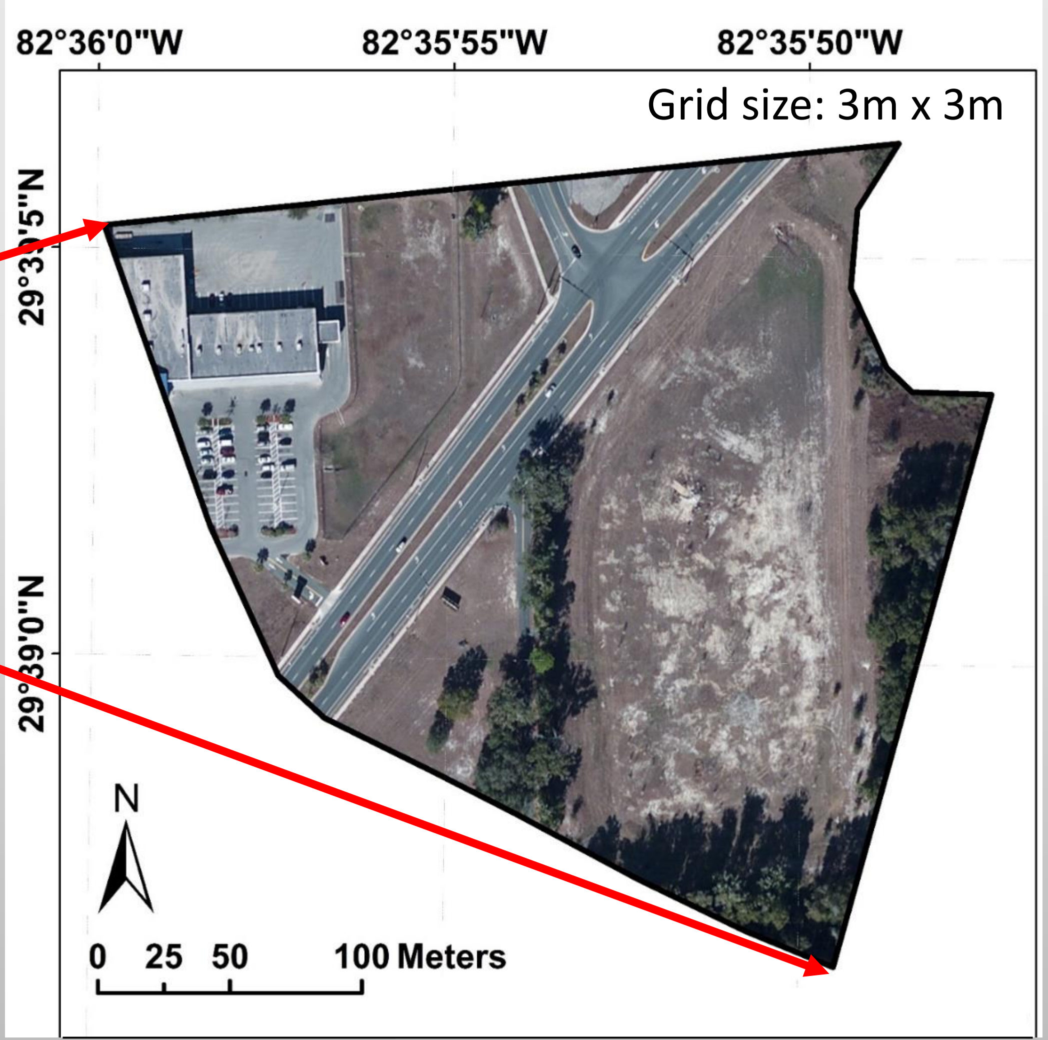
Substep 5.1 – model domain for the local-scale model



Step 5 – Local-scale model setup (Newberry Site)

Substep 5.1 – model domain for the local-scale model





Step 5 - Local-scale model setup

Substep 5.2 - Discretization

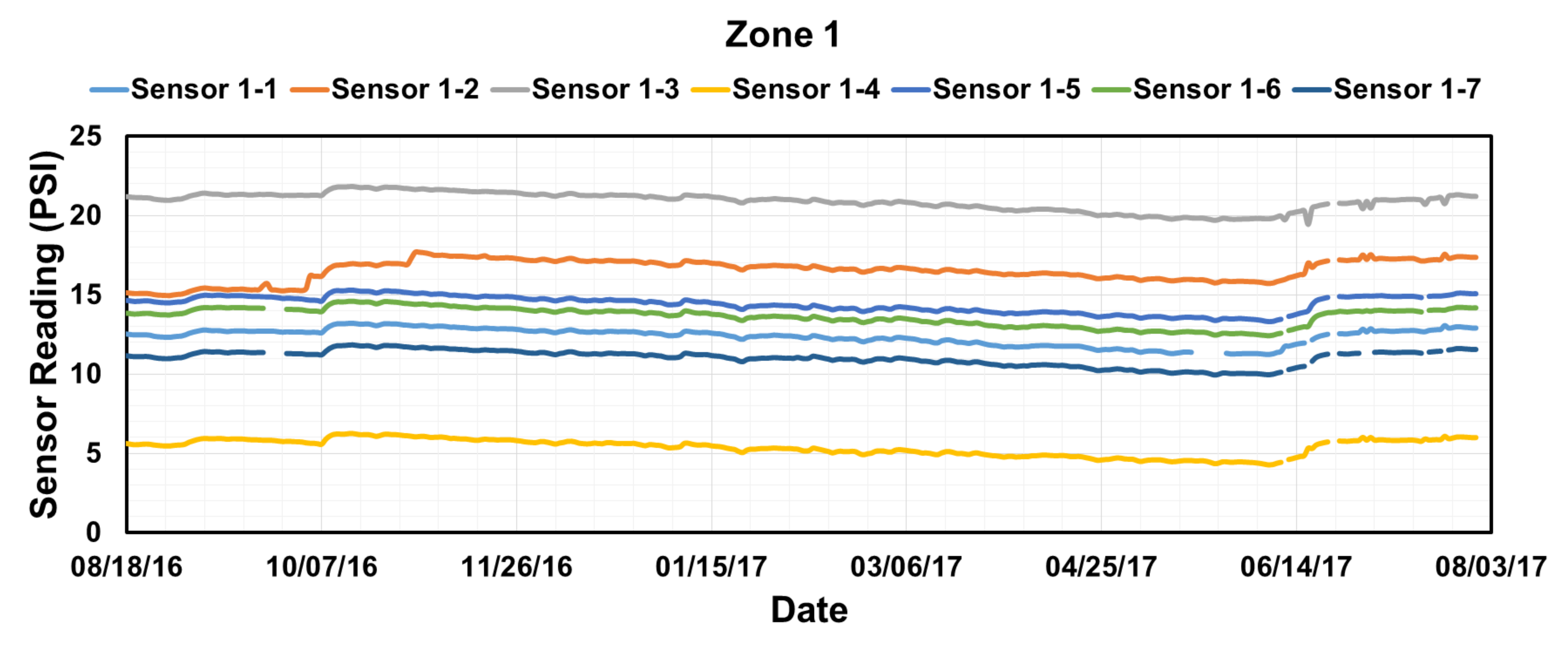
- Site 1 (Construction site at the Wekiva Parkway Bridge)

Fine Sand
Silty Fine Sand
Clayed Fine Sand and Clay
Silty fine sand and clayed fine sand
Weathered Limestone

- Site 2 (Drain basin site at the detention pond)

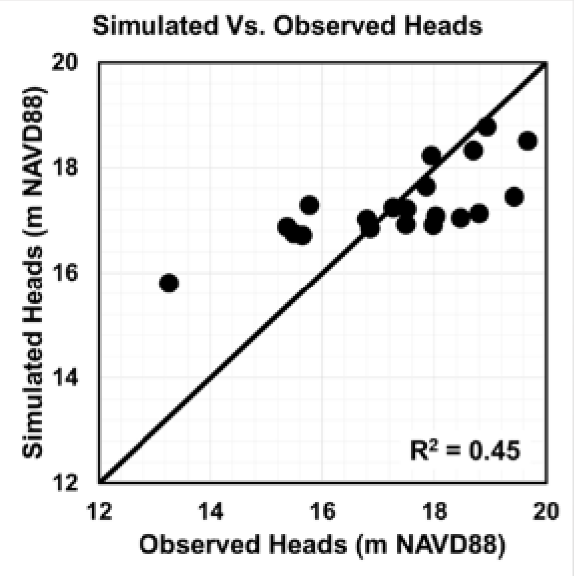
Sand, Sandy Clay, Clay
Soft to Medium Dense Limestone

Monitored Data for the Model Calibration (Site 1 – Zone 1)

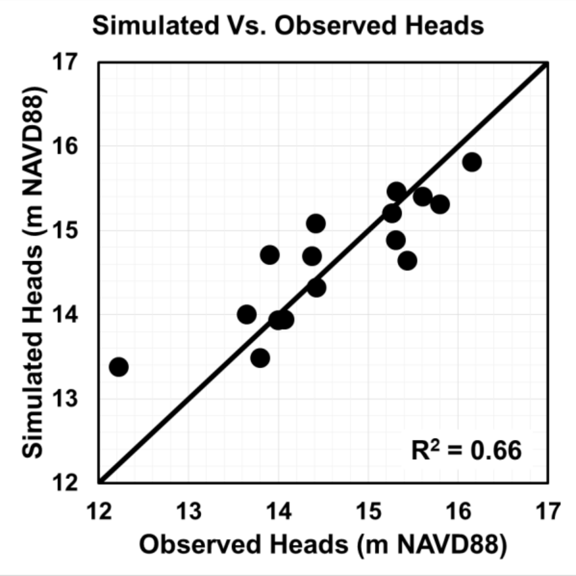


Model Calibration

- Methodology:
  - Hydraulic conductivity (k) of each layer (including soil layers and limestone layer) is adjusted and the groundwater levels are simulated accordingly
  - A trial-and-error method is used to compare the simulated groundwater levels and the observed groundwater levels and determine the difference between them

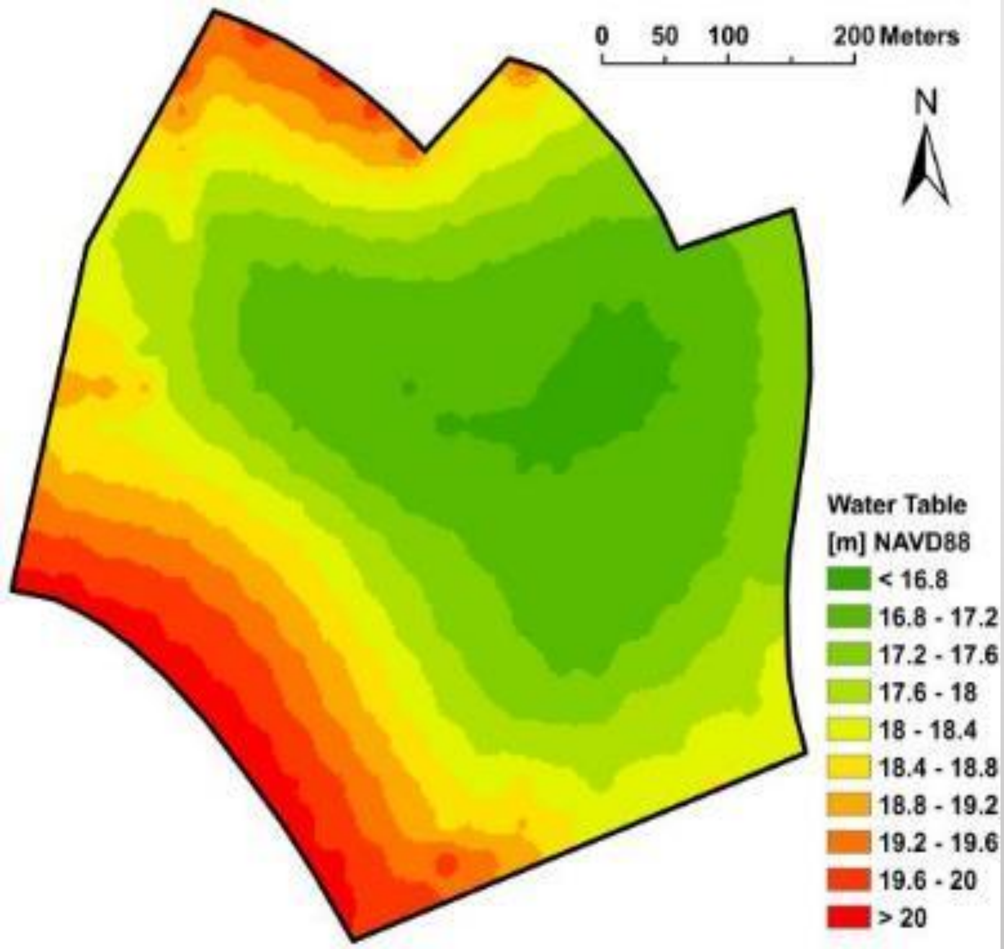


Wekiva Pkwy Site

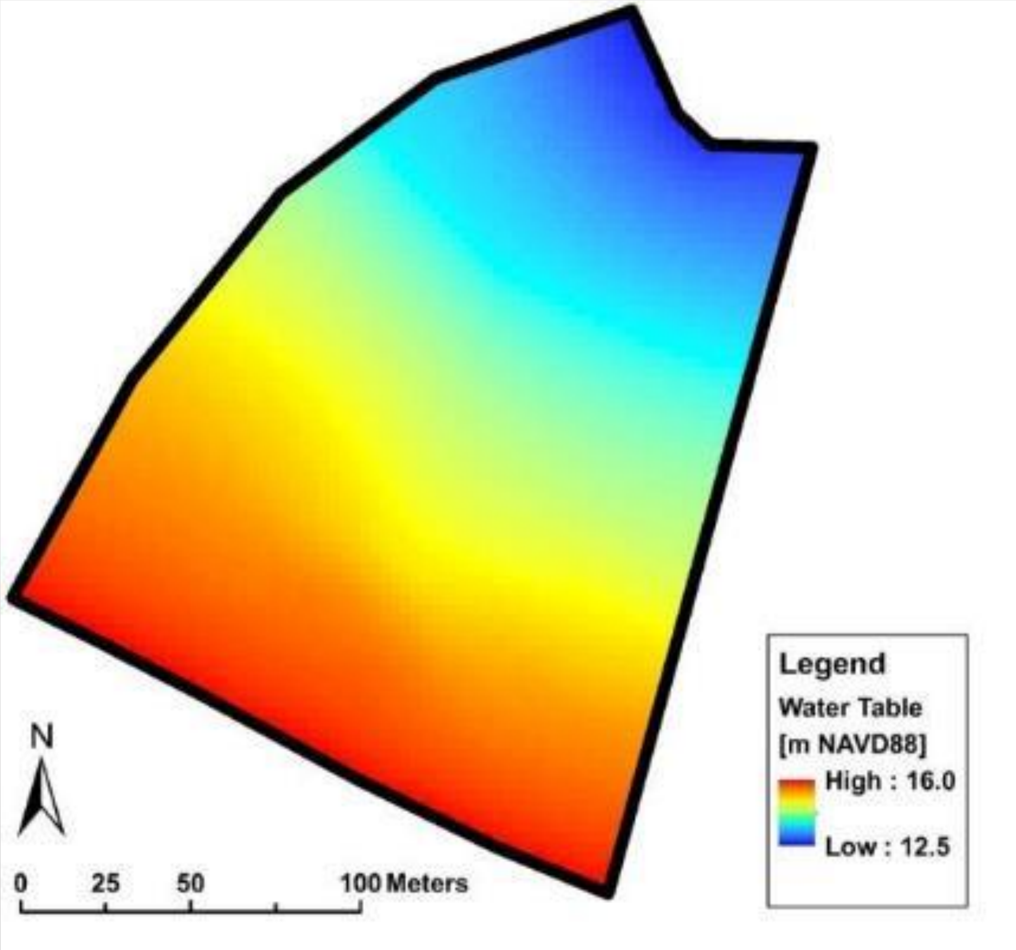


Newberry Pond Site

Results - Calibrated Groundwater Table

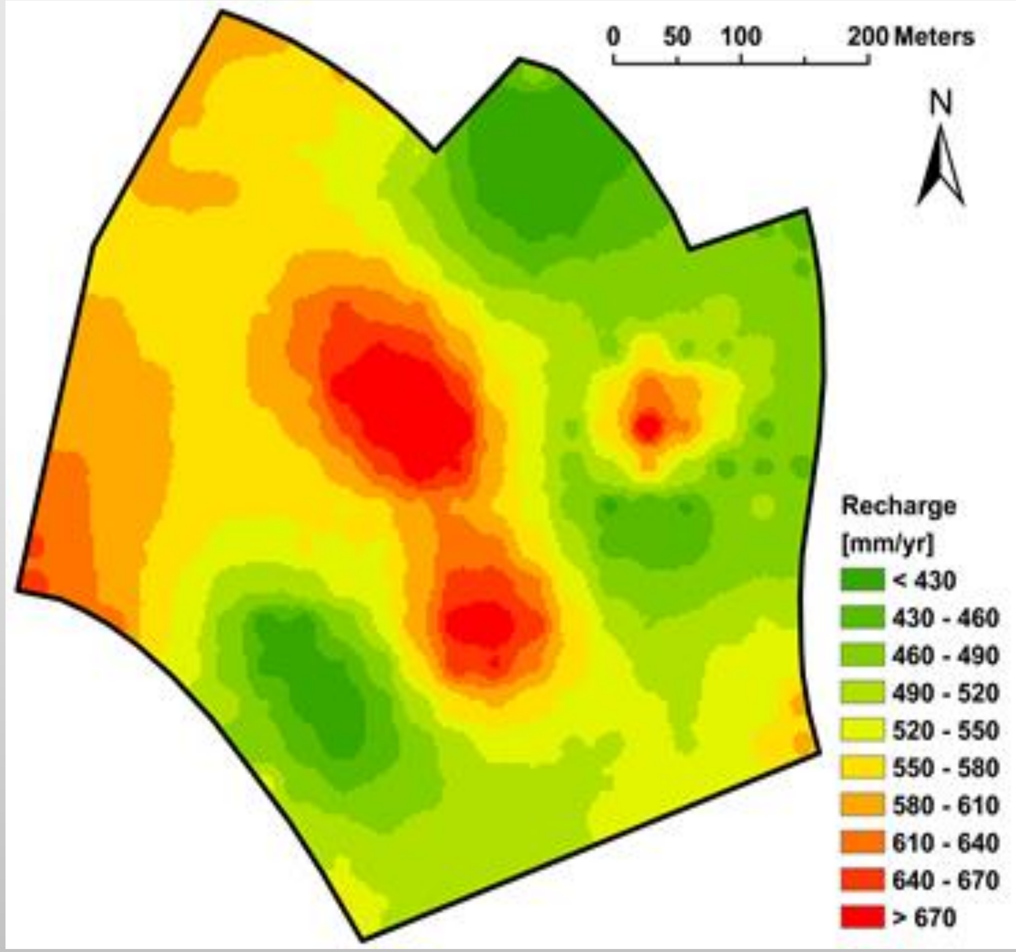


Wekiva Pkwy Site

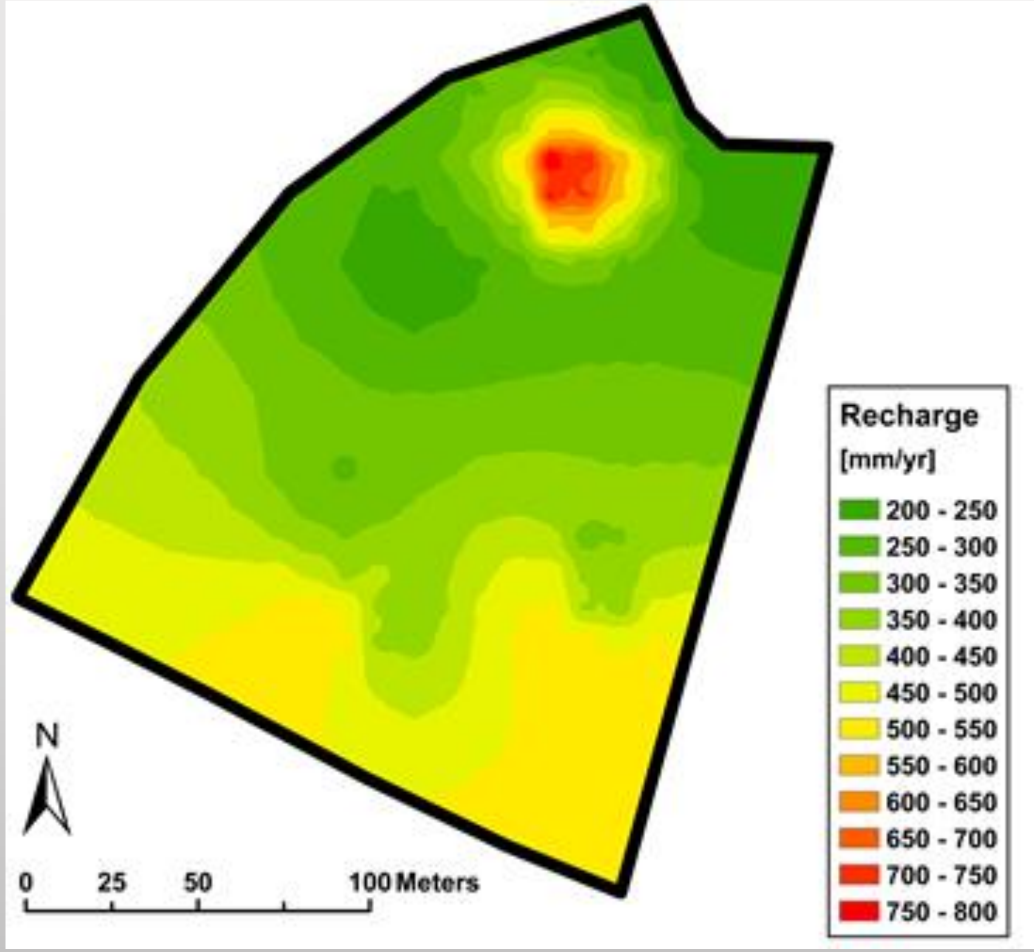


Newberry Pond Site

Results – Calibrated Groundwater Recharge Map

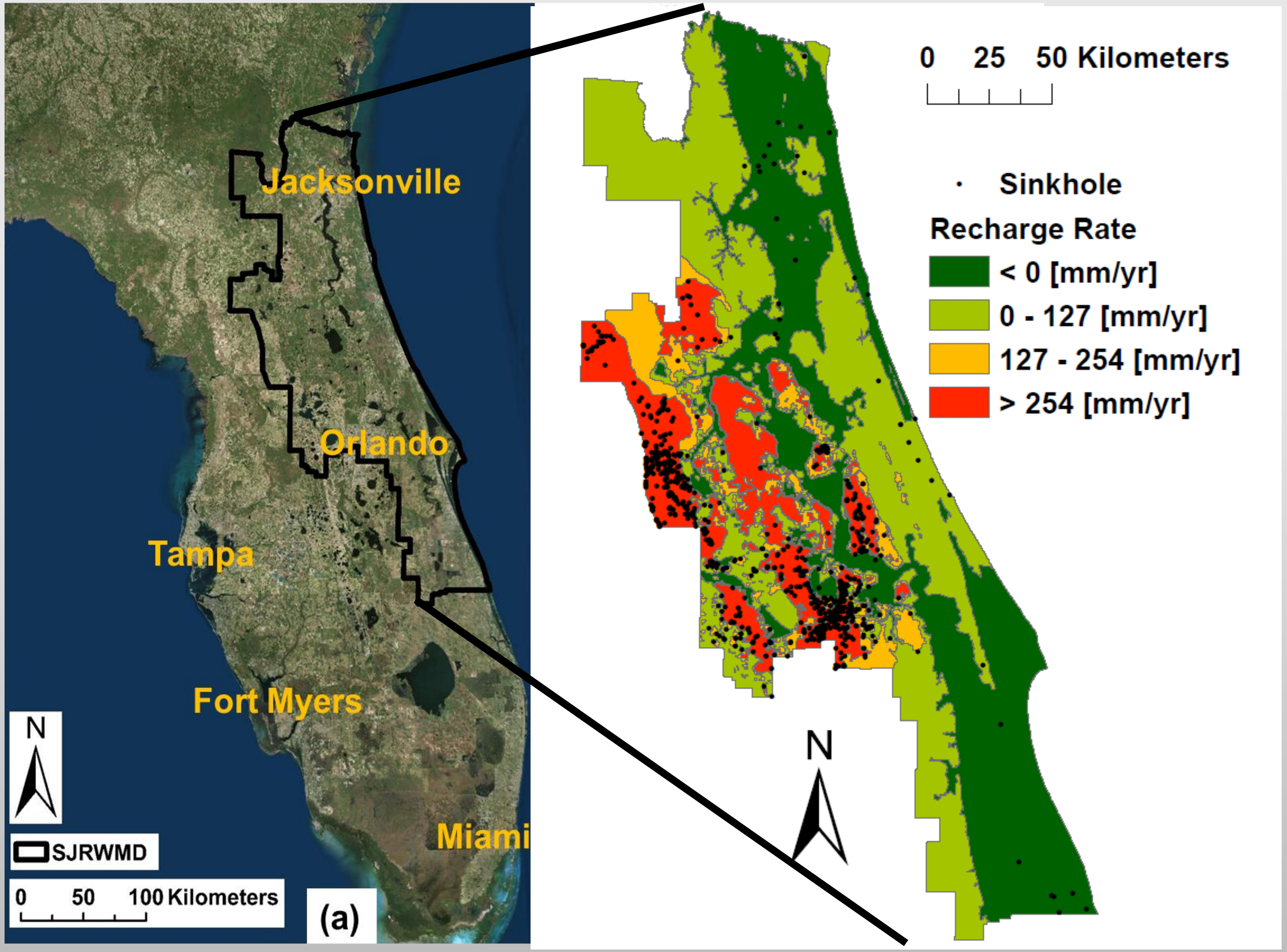


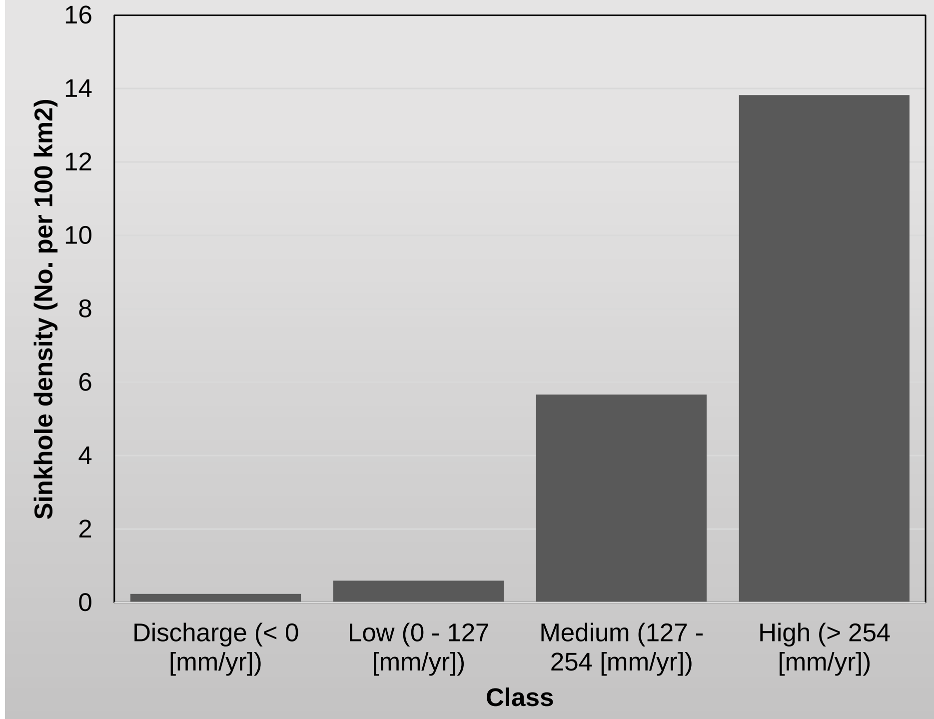
Wekiva Pkwy Site



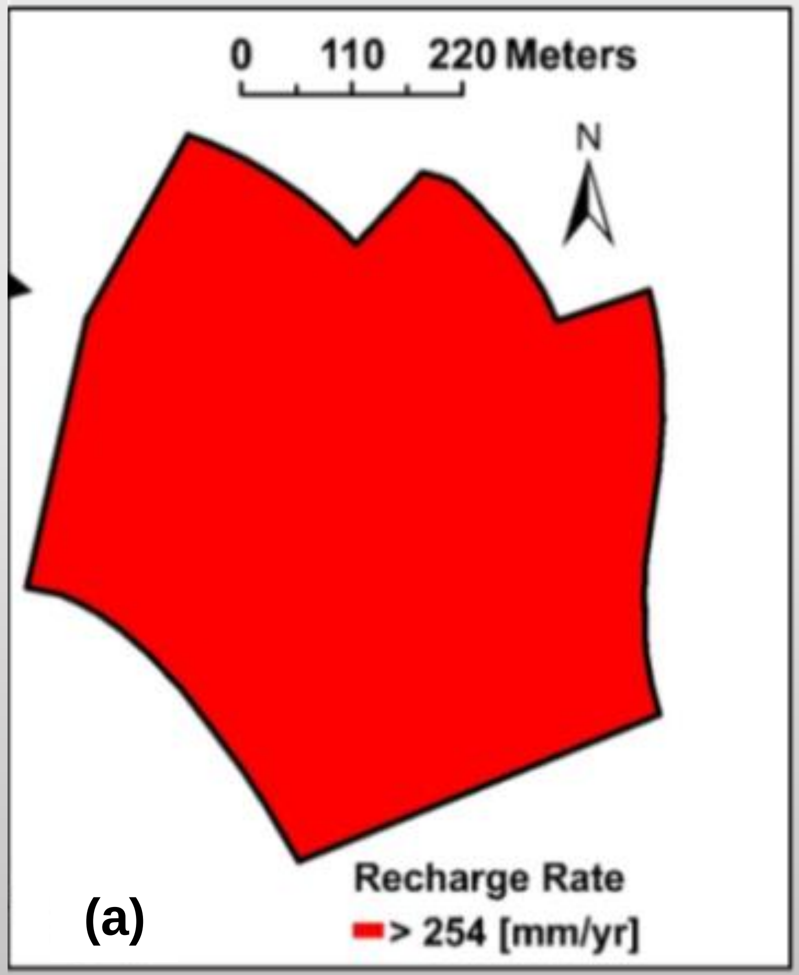
Newberry Pond Site

Development of sinkhole risk category

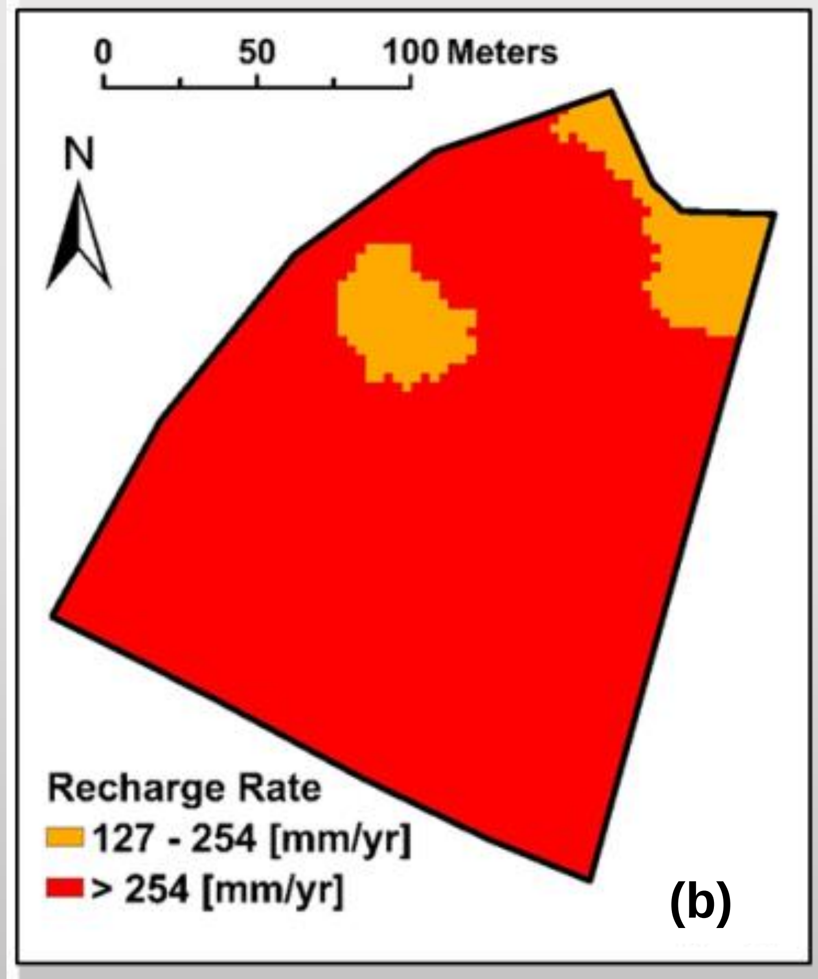




Groundwater Based Sinkhole Risk Map



Wekiva Pkwy Site



Newberry Pond Site

Task 3. Improved identification method for detecting raveled zone

Existing methods

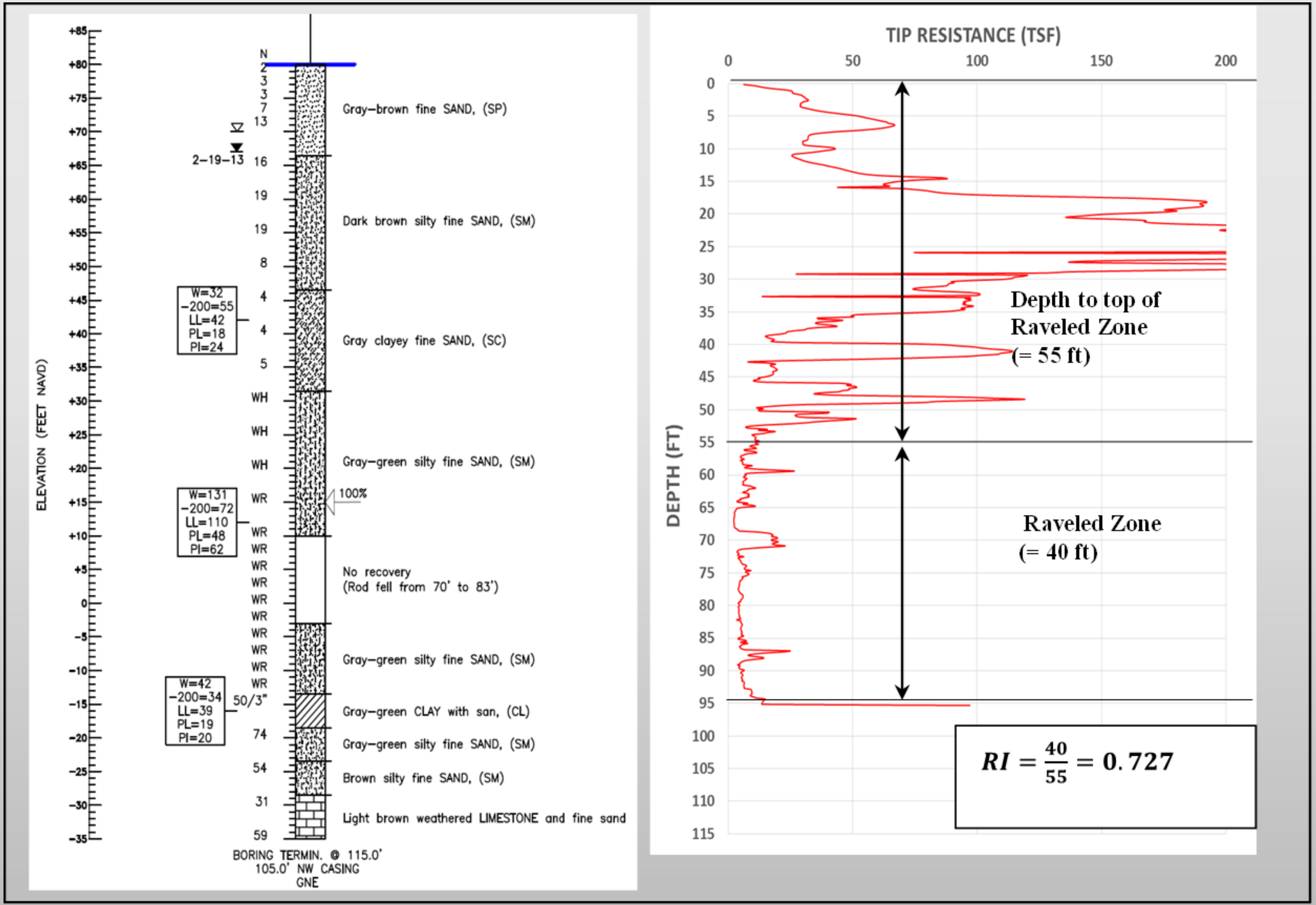
- Raveling criteria:

CPT tip resistance $q_t < 10$ TSF (?)

- Raveling Index (RI)

Proposed by Gray and Bixler (1994), the raveling index is the ratio of thicknesses of raveled soil to harder “undisturbed” overburden soil. Best when calculated using CPT data because of high resolution of data.

$$RI = \frac{Thickness\ of\ raveled\ zone}{Depth\ to\ top\ of\ raveled\ zone}$$

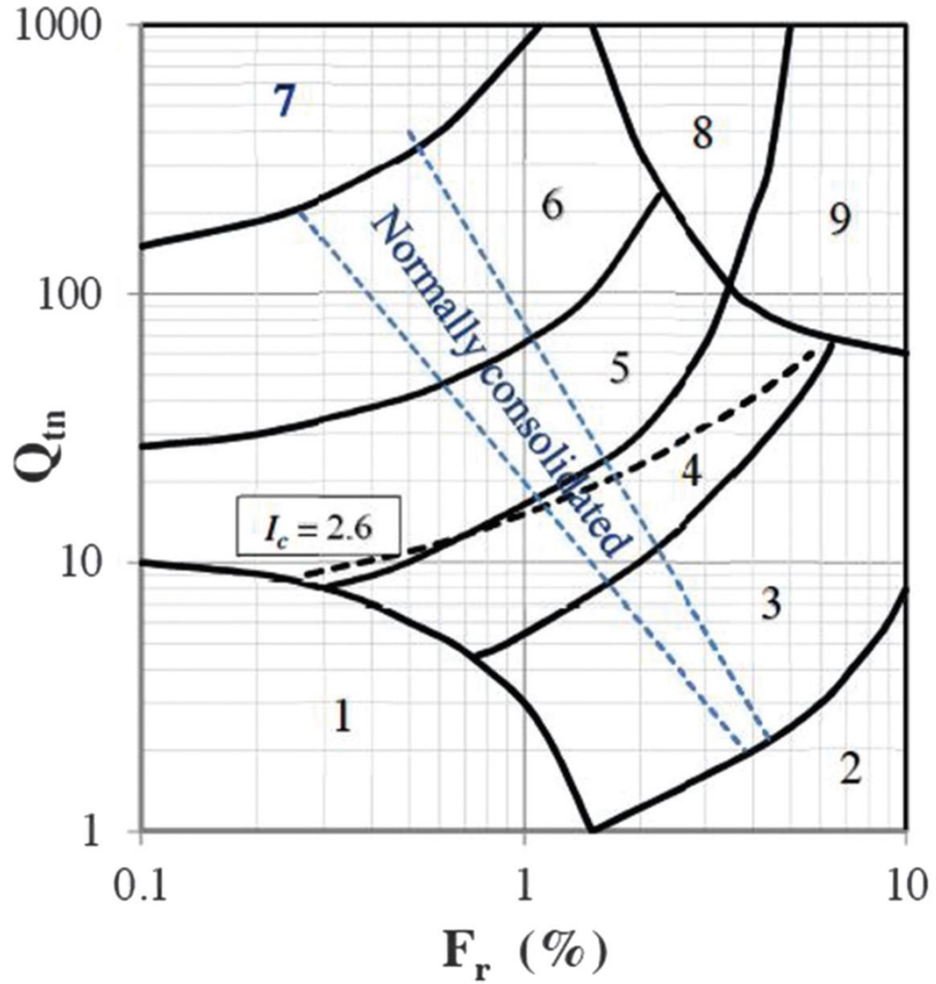


Cone Penetration Testing

<u>Correlations</u>:

- Newest Correlation Chart (Robertson 2016)

- Commercially available software applies the chart to measured CPT data “real-time” providing estimated soil stratigraphy from each test

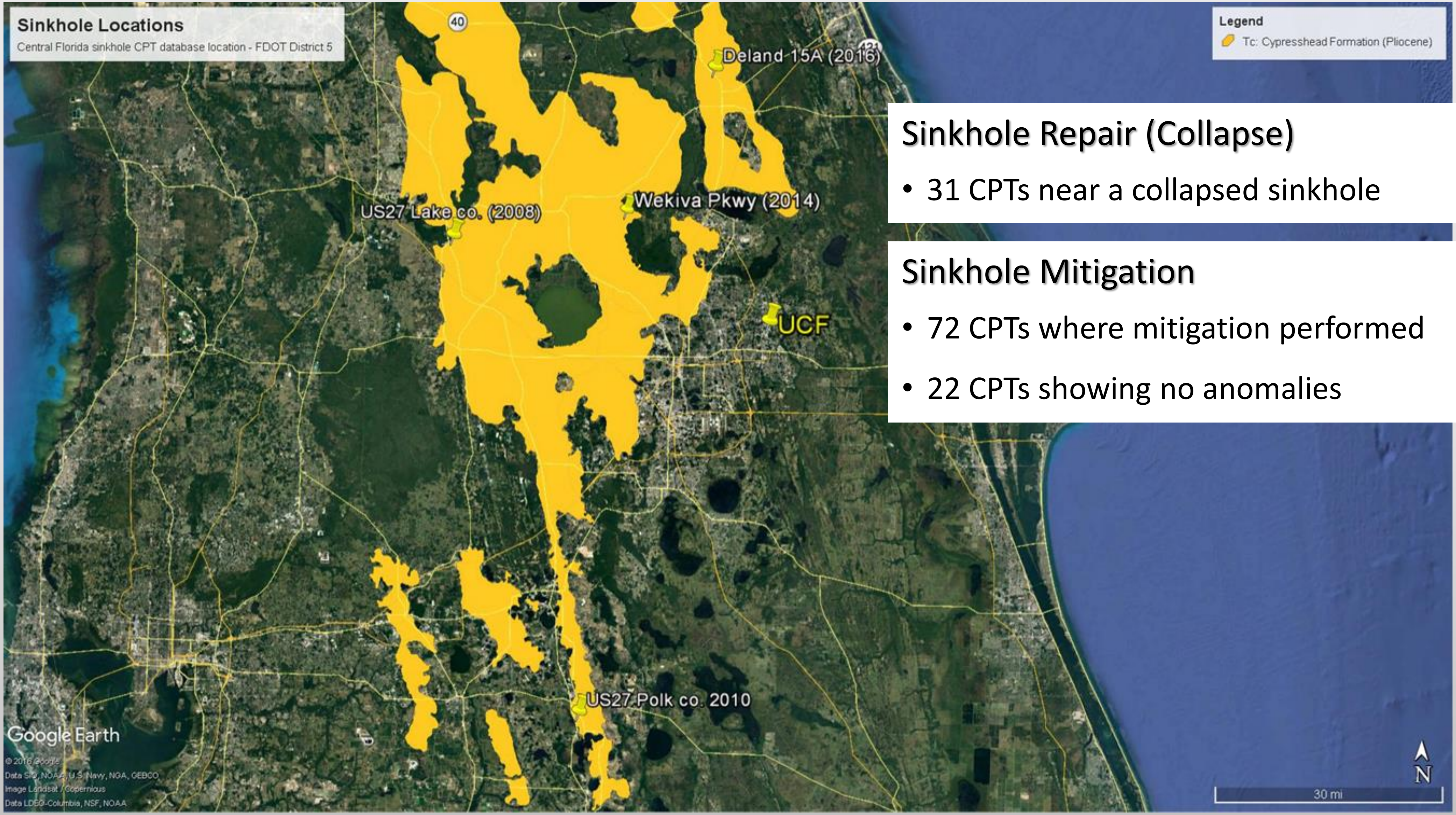


1 Sensitive fine-grained
2 Organic
3 Clay
4 Silt-mixtures
5 Sand-mixtures
6 Sand
7 Gravelly sand to sand
8 Very stiff sand to clayey sand
9 Very stiff fine-grained

$$Q_{tn} = \frac{q_c - \sigma_{vo}}{\sigma'_{vo}}$$

$$F_r = \left[\frac{f_s}{q_c - \sigma_{vo}}\right] * 100\%$$

Central Florida sites: Data Collection

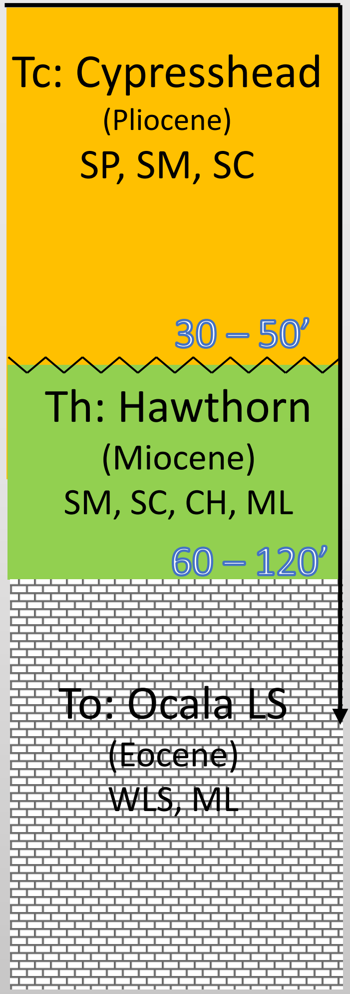


Sinkhole Repair (Collapse)

- 31 CPTs near a collapsed sinkhole

Sinkhole Mitigation

- 72 CPTs where mitigation performed
- 22 CPTs showing no anomalies



Central Florida sites: Data Preparation

Normalized: based on Robertson and Wride (1998)

$$Normalized\ Cone\ Tip\ Resistance: \quad Q_{tn} = \left(\frac{q_c - \sigma_{vo}}{P_a}\right)\left(\frac{P_a}{\sigma'_{vo}}\right)^n$$

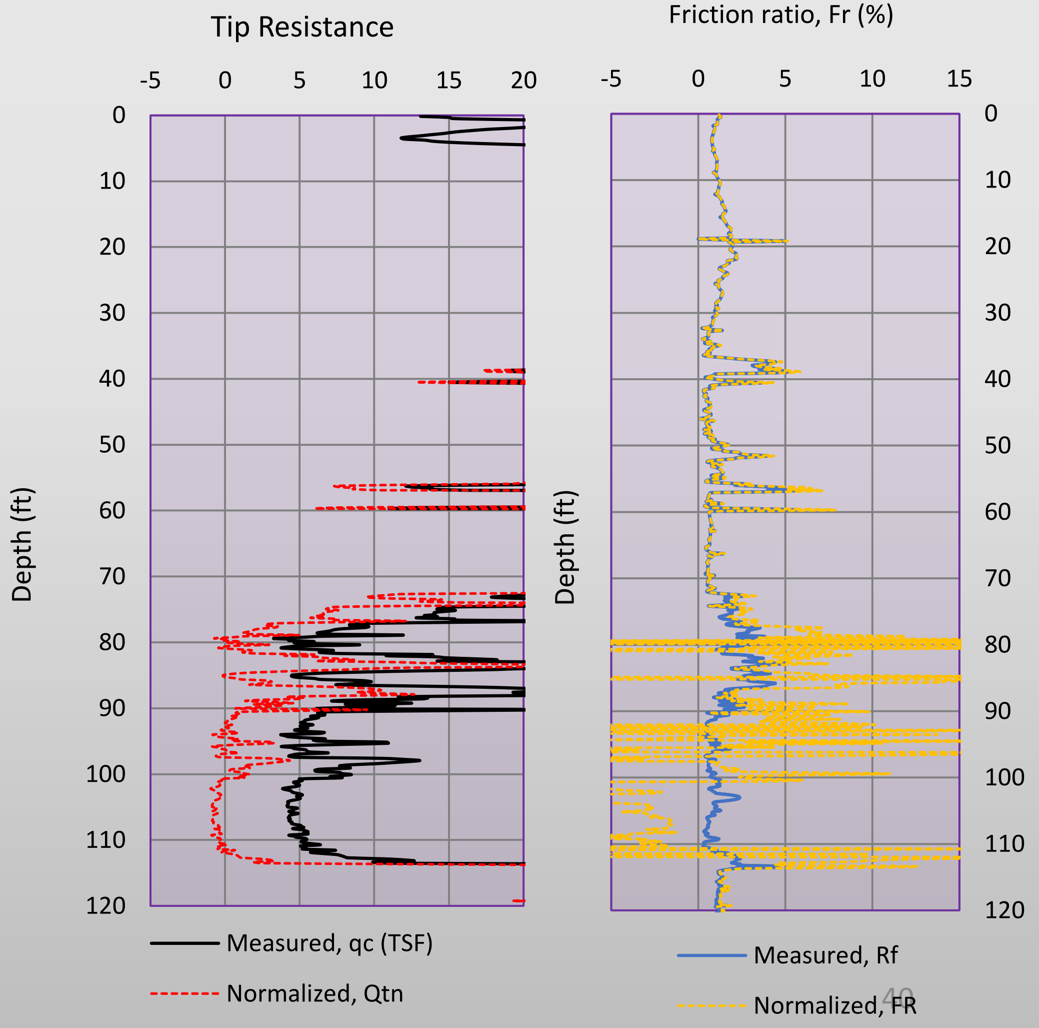
$$Normalized\ Friction\ Ratio: \quad F_R = \frac{f_s}{q_c - \sigma_{vo}} * 100\%$$

Where:

- q_c = measured tip resistance (TSF)
- f_s = measured sleeve friction resistance
- σ_{vo} & σ'_{vo} = total and effective vertical stress created from overburden soil (TSF)*
- P_a = atmospheric pressure (~1.06 TSF)
- n = stress exponent [0.5 in sands, 1.0 in clays] (assumed 0.65)

Spiking F_R may be indicative of raveling/soil arching (??)
But,
Only Normalized tip resistance (Q_{tn}) and Sleeve friction (f_s) used

CPT-55: Raveled

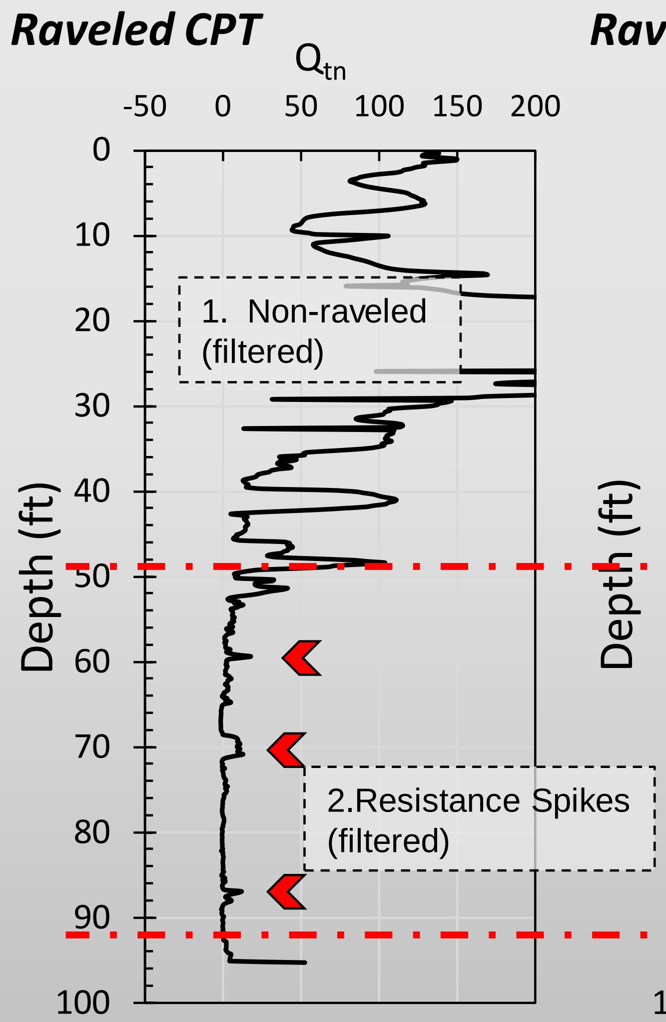


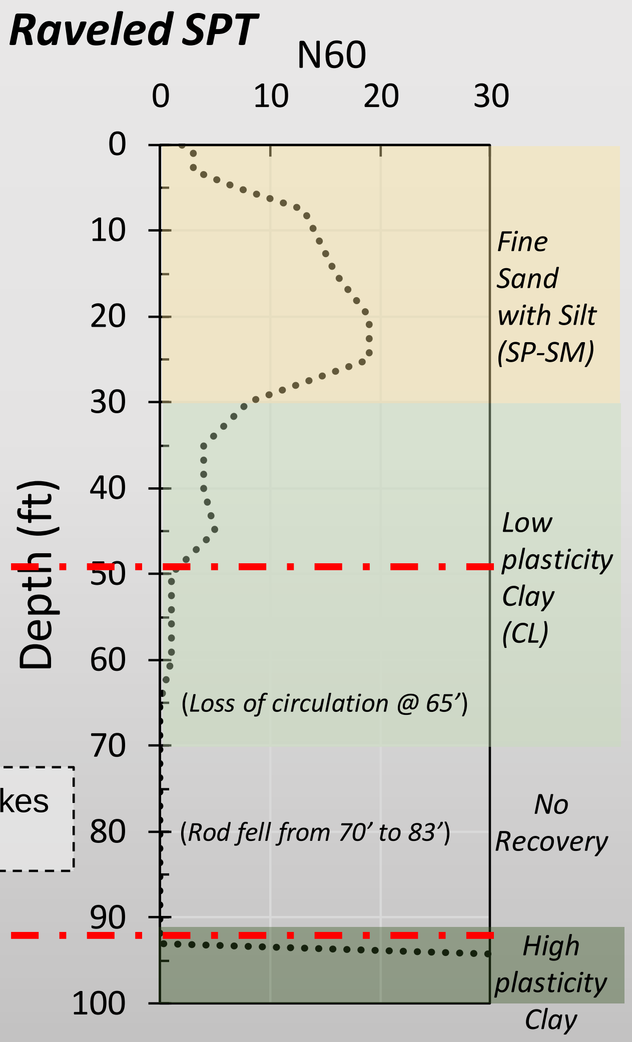
Central Florida sites: Data Preparation

Filtering Data: 2 stages

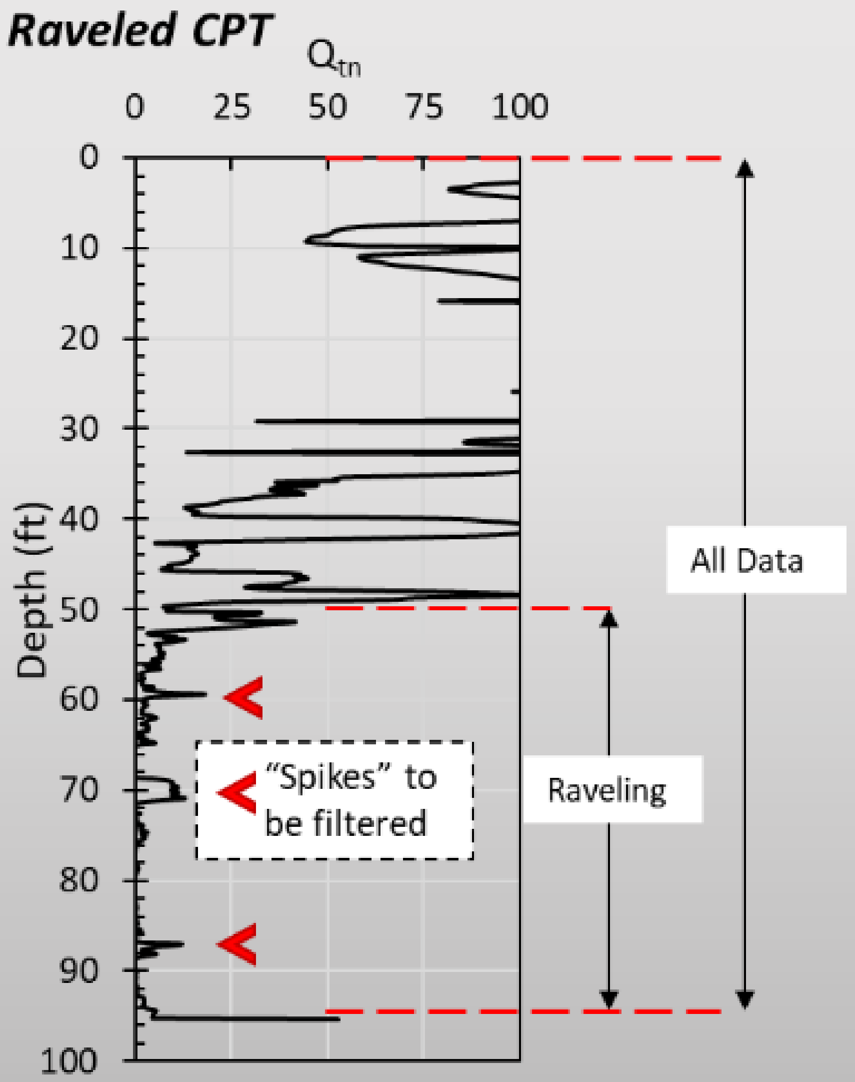
1) Filtered out residual (overburden) soil data ranges
- Raveling depths only
- Verified by nearby SPTs or proximity of collapse

2) Abnormal Spikes of q_c within Raveled zone
- Caused by phosphates, lenses of stiffer material, horizontal raveling, operator or cone error, etc.
- May affect "severity" of raveling, but not needed in criteria development

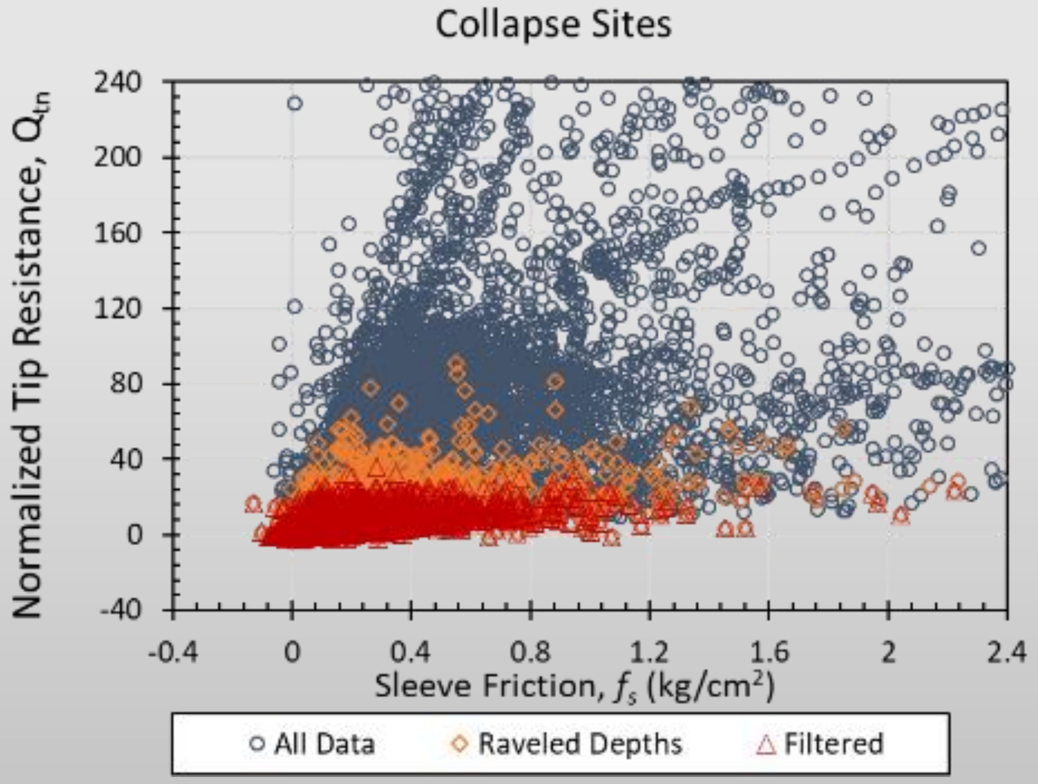




Central Florida sites: Data Preparation



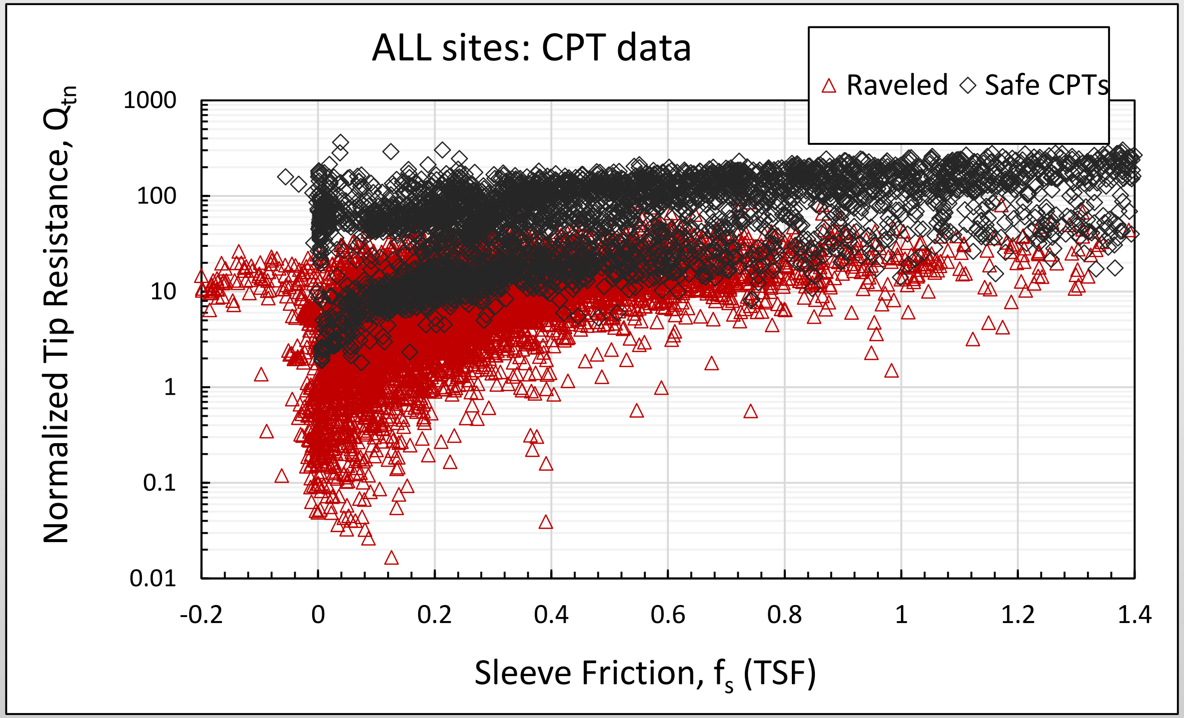
Abnormal Spikes of tip resistance within raveled zone.

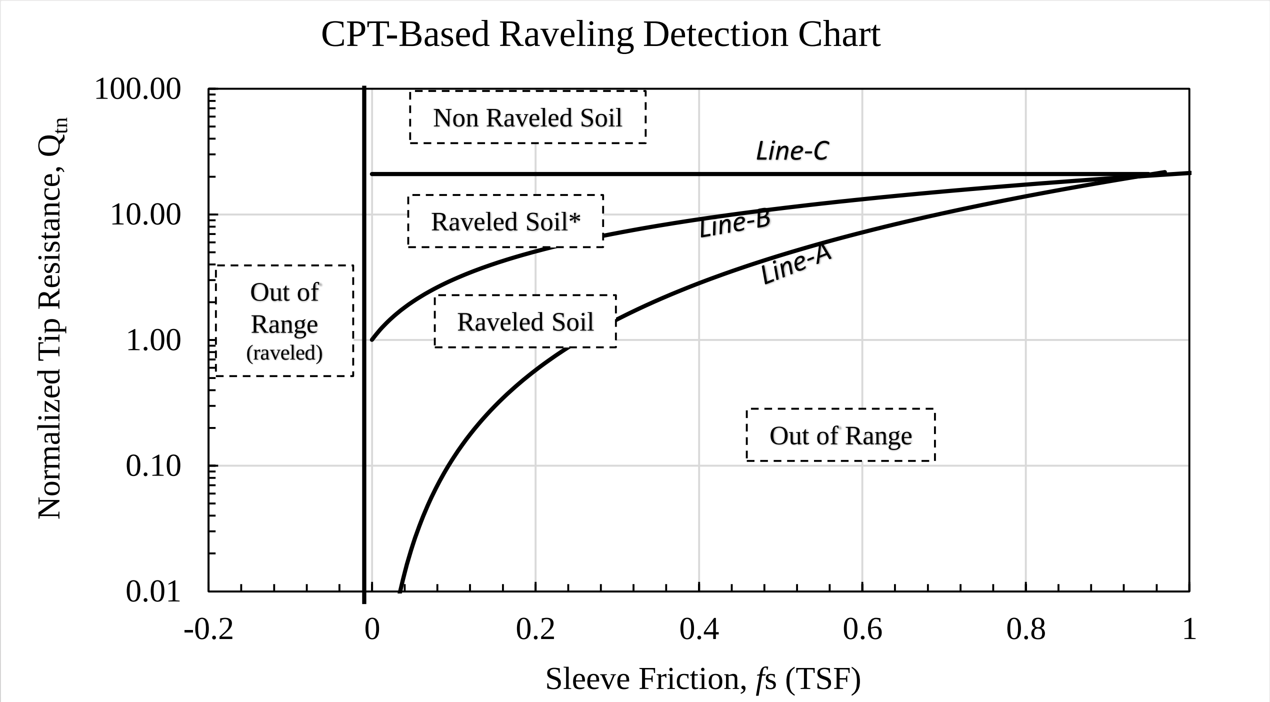


Filtering Process lowers Q_{tn} and f_s.

Results

- Updated Raveling Detection Criteria (CPT-based scatter plot)

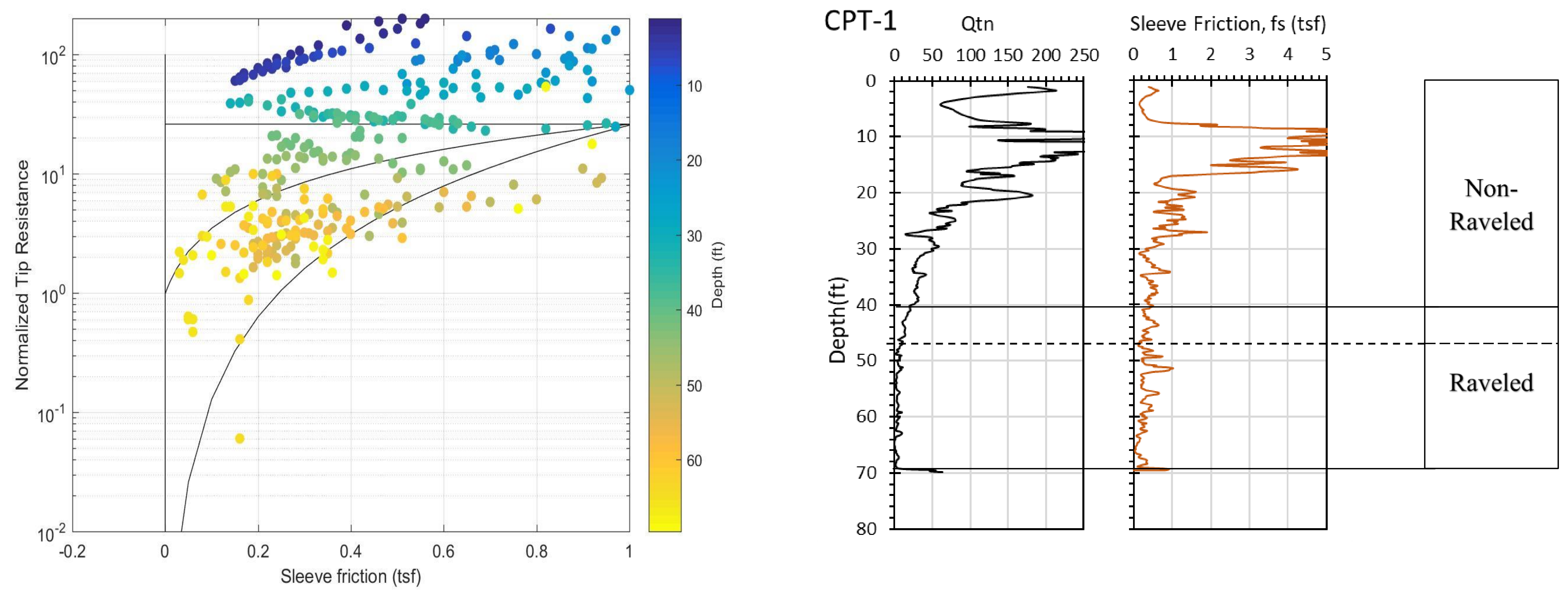




- Empirically developed from 125 CPTs in CFL soils suspected of cover collapse sinkholes

Line	Threshold function
A	$Q_{tn} = 23.341 * (f_s)^{2.2989}$
B	$Q_{tn} = 25.00 * f_s + 0.984$
C	$Q_{tn} = 26$

Results (implementation)



Assessment of Sinkhole Hazard by CPT

- This chapter presents techniques used as tools for assessing potential Sinkhole hazards during site characterization.

1. Point-based method (1D, single test)
2. Profile-based method (2D, multiple tests)
3. Area-based methods (comparative)
   - Current Raveling Index (RI)
   - Proposed Sinkhole Resistance Ratio (SRR)

Sinkhole Resistance Ratio (SRR)

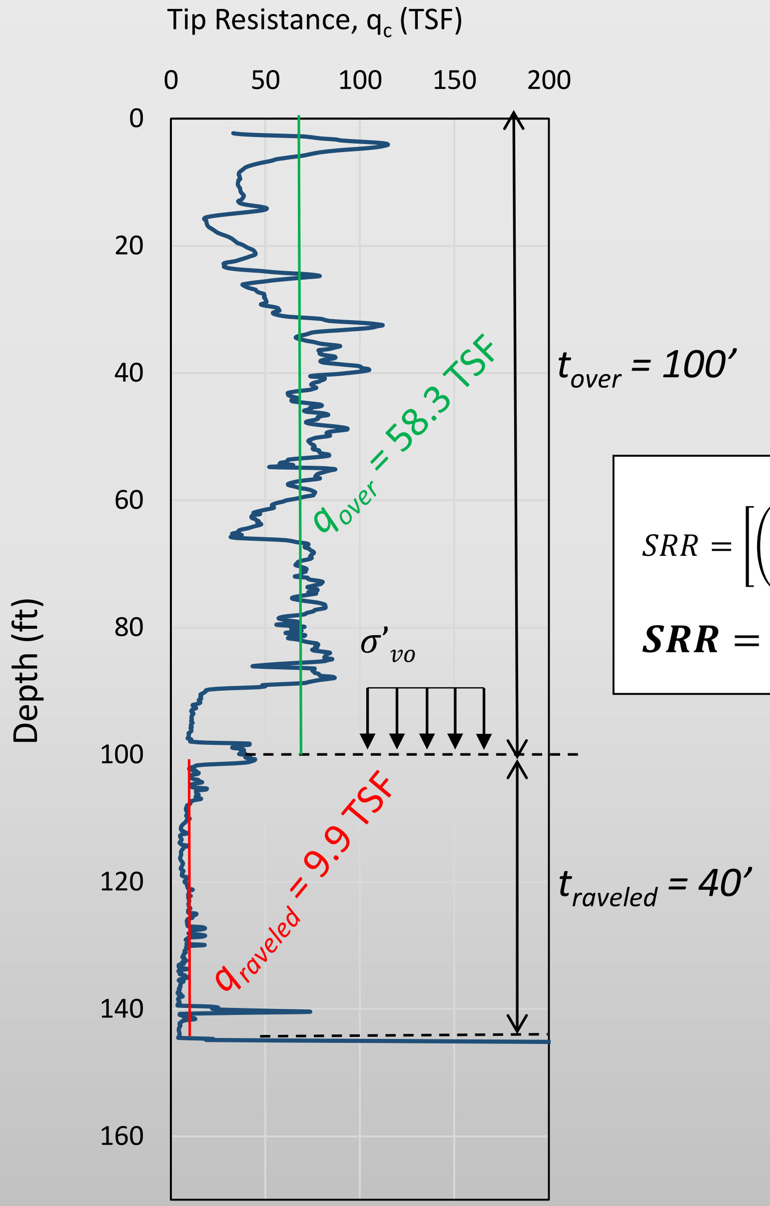
$$\mathrm{SRR} = \left(\frac{q_{over} + q_{ravel}}{100 * \sigma'_{vo}}\right)\left(\frac{t_{over}}{t_{ravel}}\right)$$

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)

Effective stress calculated using estimated unit weight: (Robertson and Cabal 2010):

$$\gamma_{sat} = \gamma_w[0.27[\log(R_f)] + 0.36\left[\log\left(\frac{q_c}{P_a}\right)\right] + 1.236] * \frac{G_s}{2.65}$$



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

$$\boldsymbol{SRR = 0.622}$$

Index Comparison – Wekiva Pwky site

Zone 3 - Bridge Area	*Thickness (ft)*		*Measured q_c (TSF) average*		σ_v' *(TSF)*	RI [4]	SRR [5]
CPT	*Overburden*	*Raveled*	*Overburden*	*Raveled*			
CPT-51a	55.94	51.67	99.35	13.60	1.86	0.92	0.66
FDOT-8	68.41	54.46	134.51	25.84	2.14	0.80	0.94
CPT-23	67.42	46.26	129.55	14.13	2.17	0.69	0.96
CPT-55	72.83	40.69	121.94	9.60	2.41	0.56	0.98
CPT 1-1	44.78	21.82	133.22	21.22	1.37	0.49	2.31
CPT 1-2	51.67	21.66	82.42	19.79	1.73	0.42	1.41
CPT-62	37.73	14.93	128.55	16.62	1.40	0.40	2.62
CPT 1-4	43.14	16.74	165.77	26.43	1.34	0.39	3.70
CPT 1-6	43.80	15.26	86.73	13.72	1.36	0.35	2.12
CPT-24	42.32	13.95	112.70	18.80	1.34	0.33	2.98
CPT-53	48.72	14.60	95.80	8.01	1.65	0.30	2.11
CPT 1-3	54.30	16.24	115.59	33.92	1.74	0.30	2.87
CPT 1-7	35.76	9.68	119.11	17.17	1.42	0.27	3.55
CPT-58	37.57	9.35	112.64	17.72	1.33	0.25	3.95
CPT-54	39.21	9.51	122.96	21.39	1.43	0.24	4.15
CPT-61	42.65	10.01	104.91	10.93	1.48	0.23	3.32
CPT-52	58.23	12.31	104.48	14.68	1.95	0.21	2.88
CPT-18	50.52	9.68	80.84	24.81	1.69	0.19	3.26
CPT-56	65.94	12.14	129.68	25.32	2.23	0.18	3.78
CPT-22	52.49	7.71	88.80	27.30	1.70	0.15	4.64
CPT-60	51.02	7.21	115.04	17.54	1.73	0.14	5.42
CPT-57	42.32	4.76	123.07	13.62	1.49	0.11	8.13
CPT-59	58.23	6.40	100.86	22.35	1.94	0.11	5.77

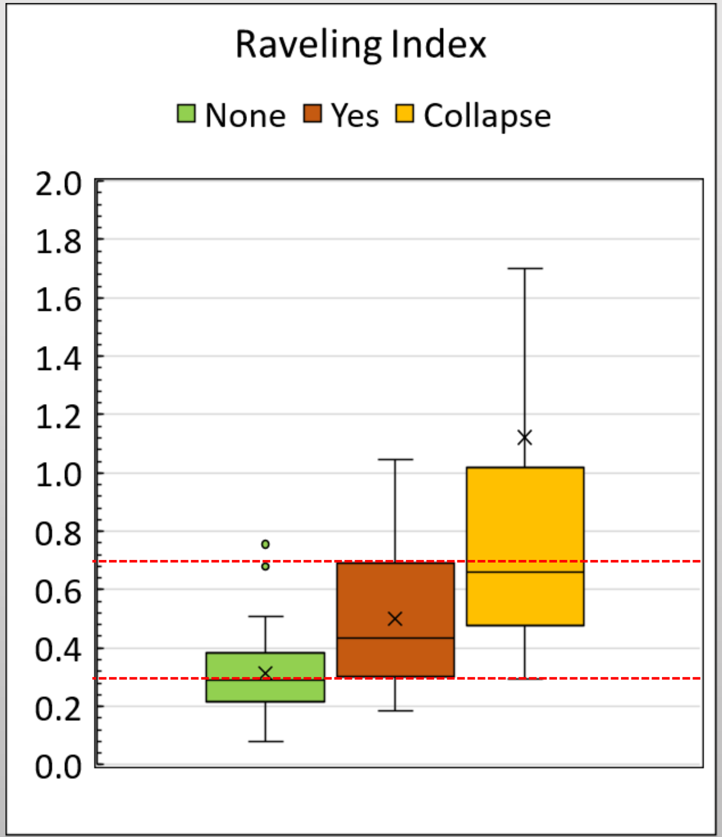
Index Comparison – SRR vs. RI

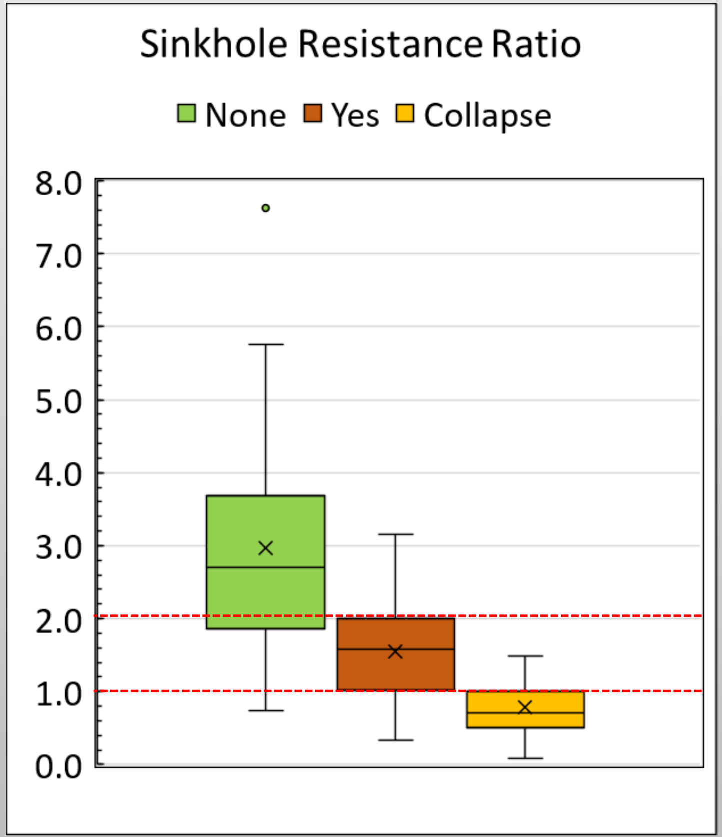
74 Total CPTs from suspected Sinkhole Active sites in Central Florida

- Mitigation required [YES] (N_{yes} = 23)
- No severe raveling [NONE] (N_{none} = 51)

27 Total CPTs from Sinkhole Collapse repair sites in Central Florida

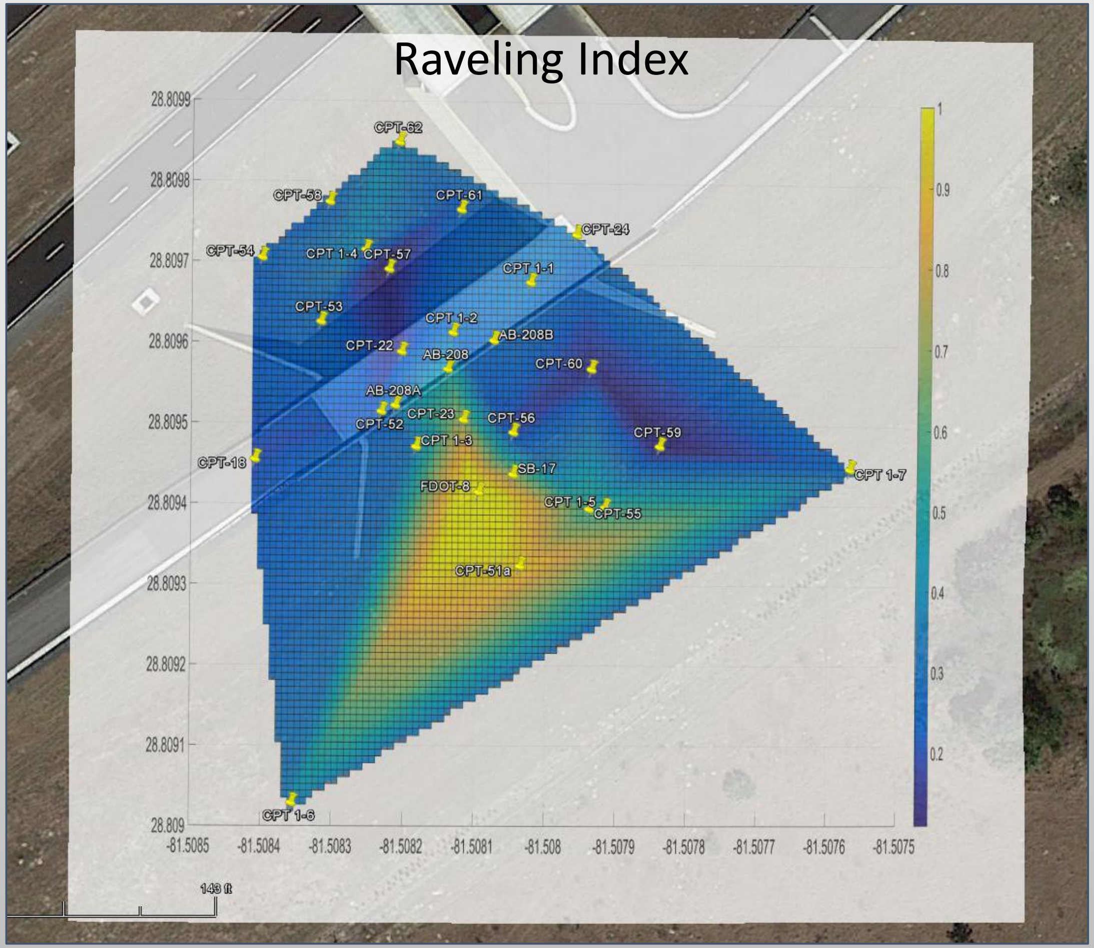
— Same geological formation as above sites! (Cypress head formation)

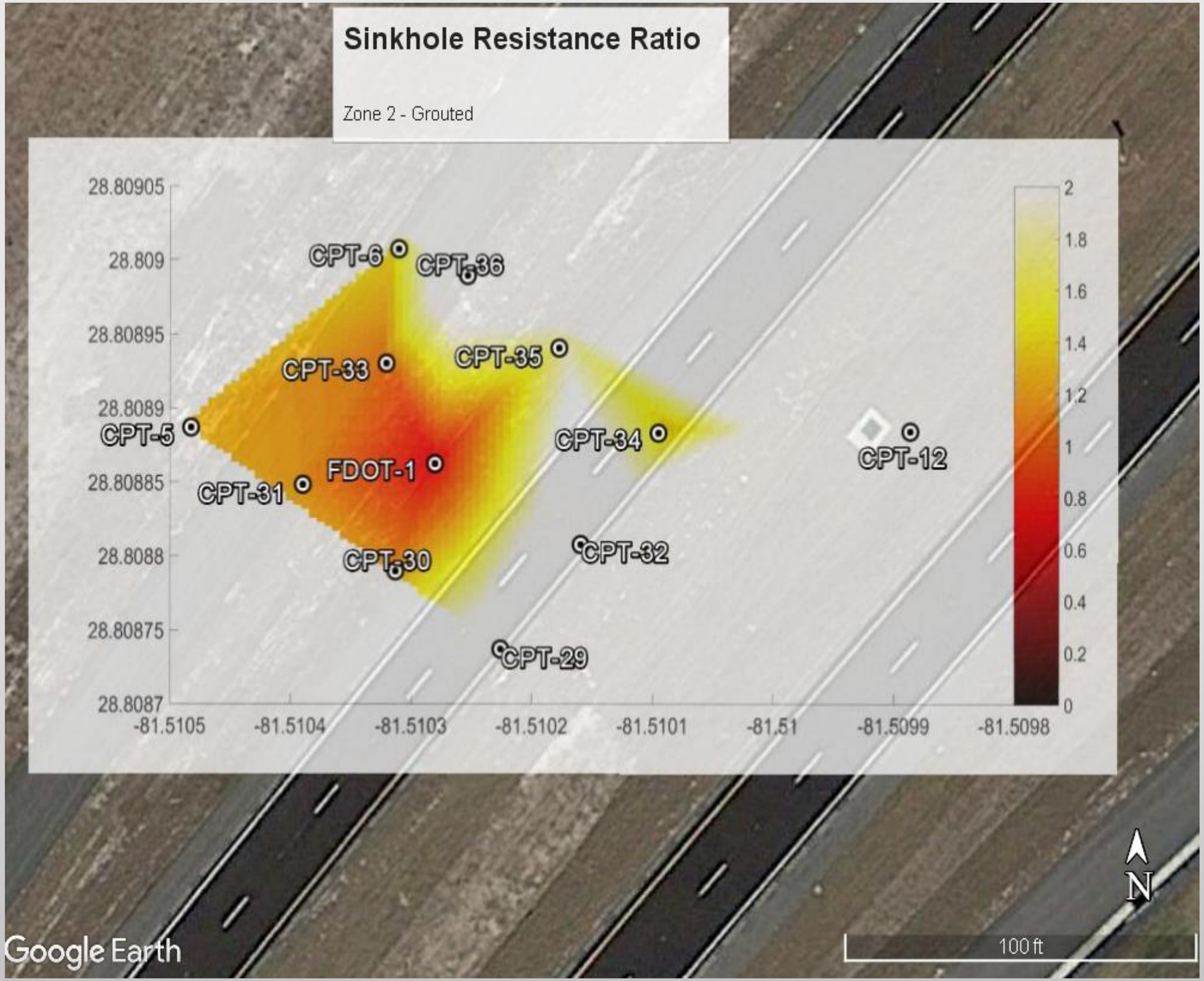


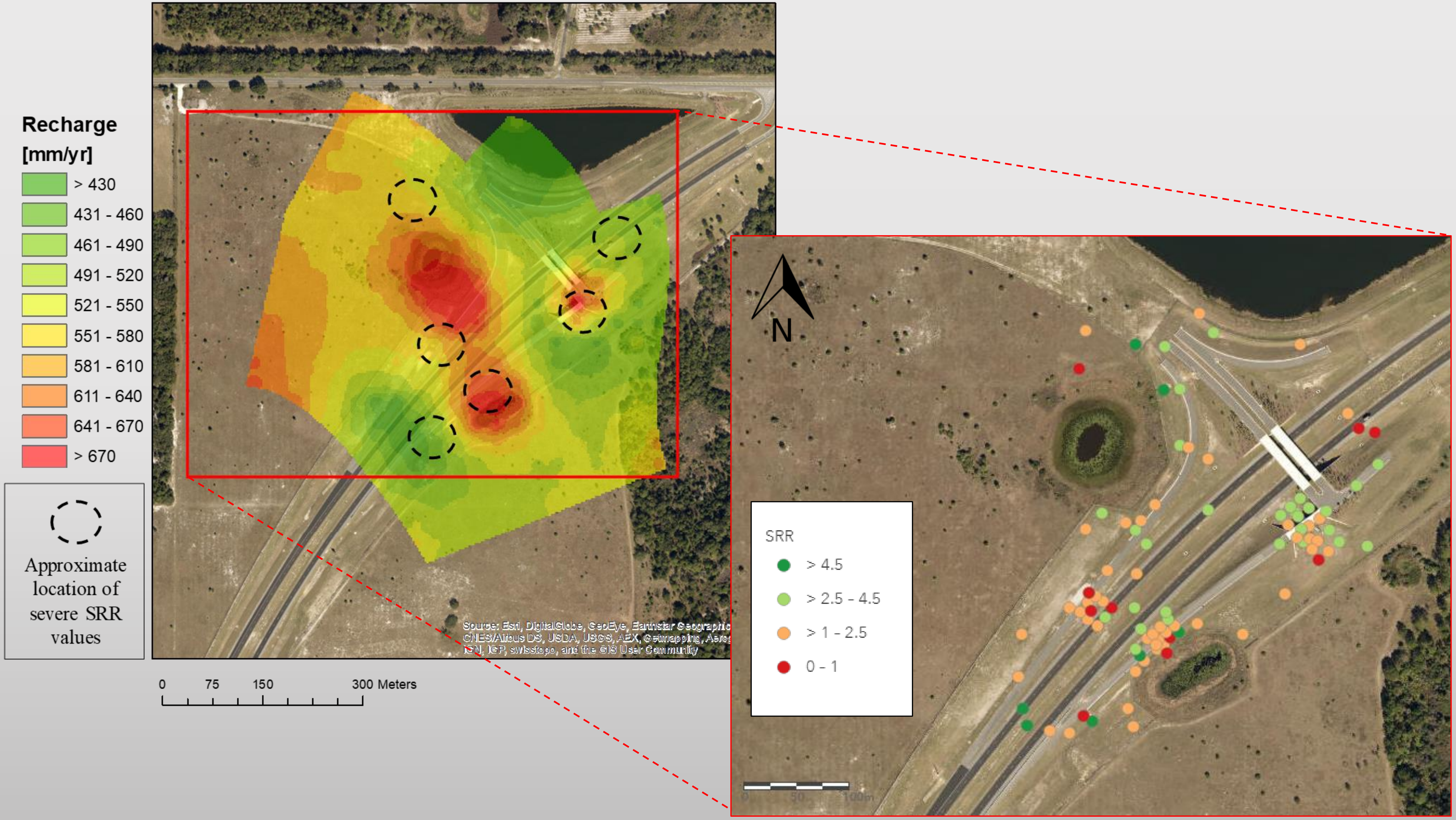


Index Contouring

Help estimate volume of mitigation technique required (grout or geogrid)







Recharge
[mm/yr]
> 430
431 - 460
461 - 490
491 - 520
521 - 550
551 - 580
581 - 610
611 - 640
641 - 670
> 670
Approximate location of severe SRR values
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
0
75
150
300 Meters
N
SRR
> 4.5
> 2.5 - 4.5
> 1 - 2.5
0 - 1

Task 4 – Develop the sinkhole stability analysis

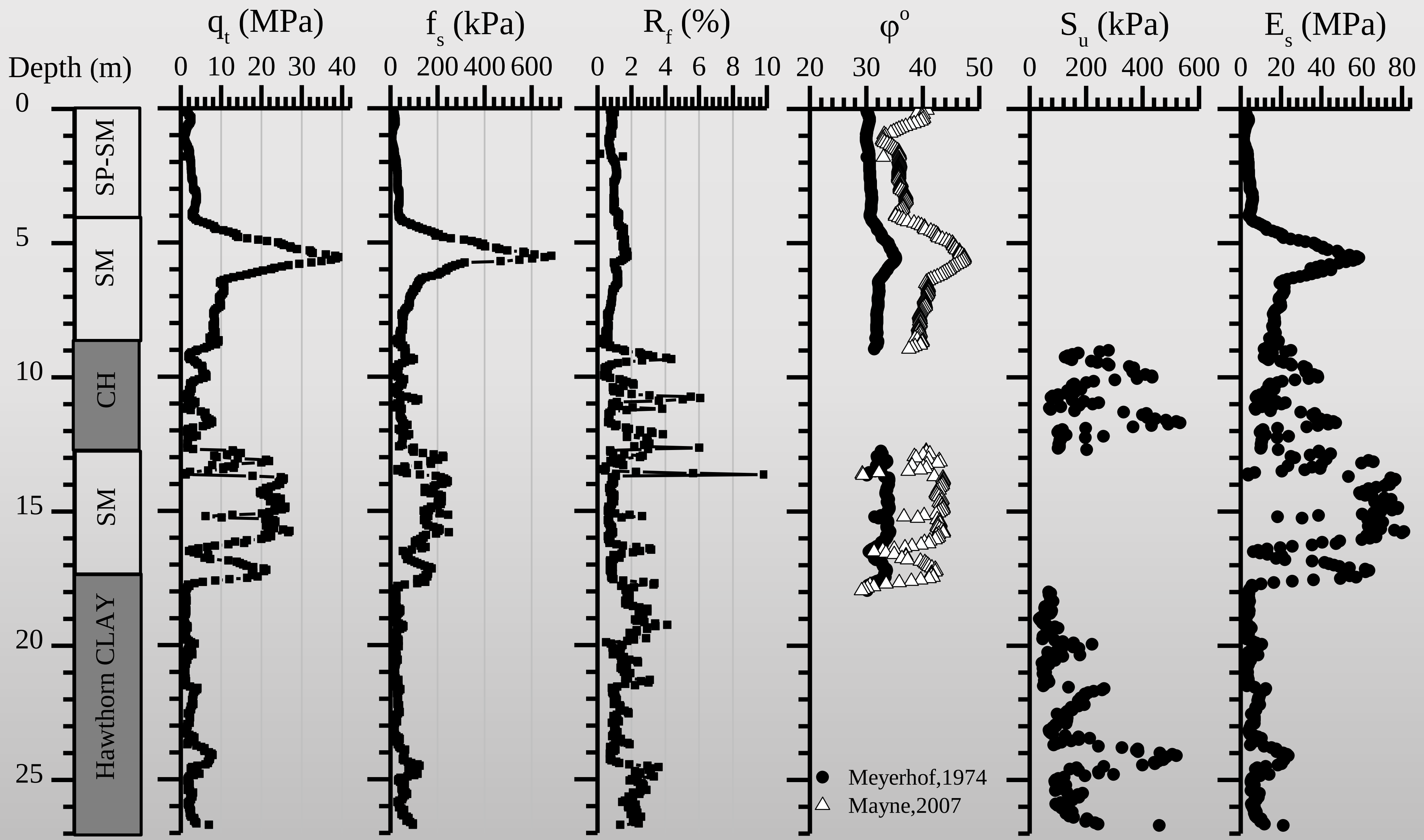
Overview of Numerical Simulations

- FE Commercial Software
  - Plaxis2D
- Constitutive Soil Model
  - Hardening Soil Model
- Two case studies
  - Wekiva Pkwy site (active raveling site)
  - US-441, Marion County (collapsed site)
- Stability charts (in terms of factor of safety)

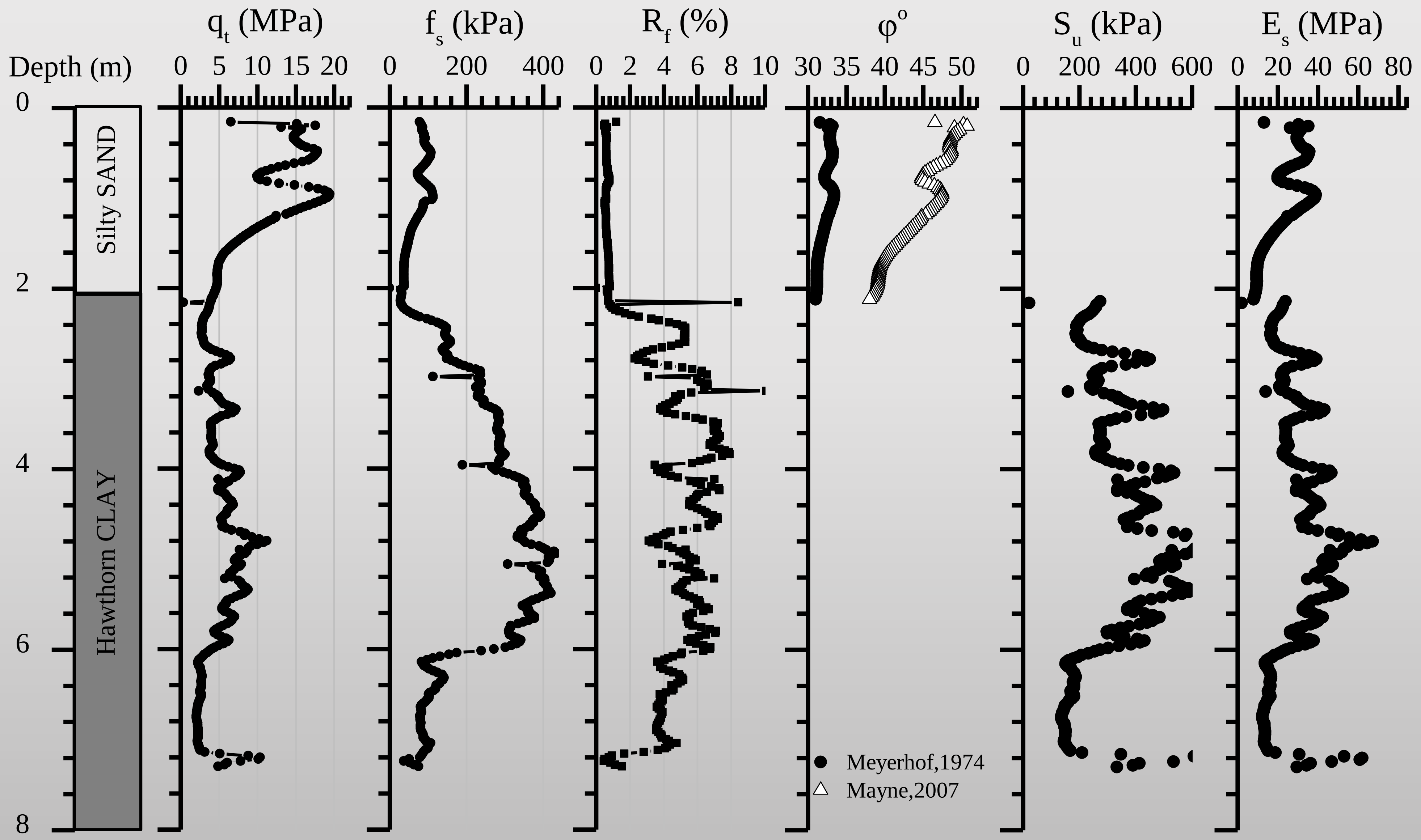
Input parameters from CPT data

Parameter	Correlation	Reference
Friction Angle	$\varphi = \tan^{-1}(0.1+0.38\log(q_c/\sigma'_v))$ σ'_v : Effective Vertical Stress	Robertson and Campanella, 1983
	$\varphi = 29^{\circ} + (q_c)^{0.5}$	Meyerhof, 1974
	$\varphi = 17.6 + 11*\log(q_c)$	Mayne, 2007
Undrained Shear Strength	$S_u = (q_c - \sigma_{v0})/N_k$ σ_{v0} : Total Vertical Stress N_k : Constant	Kulhawy and Mayne, 1990
Stiffness (Secant Modulus)	$E_s = \alpha * q_c$ α : Constant (Soil Type)	Bowles, 1988

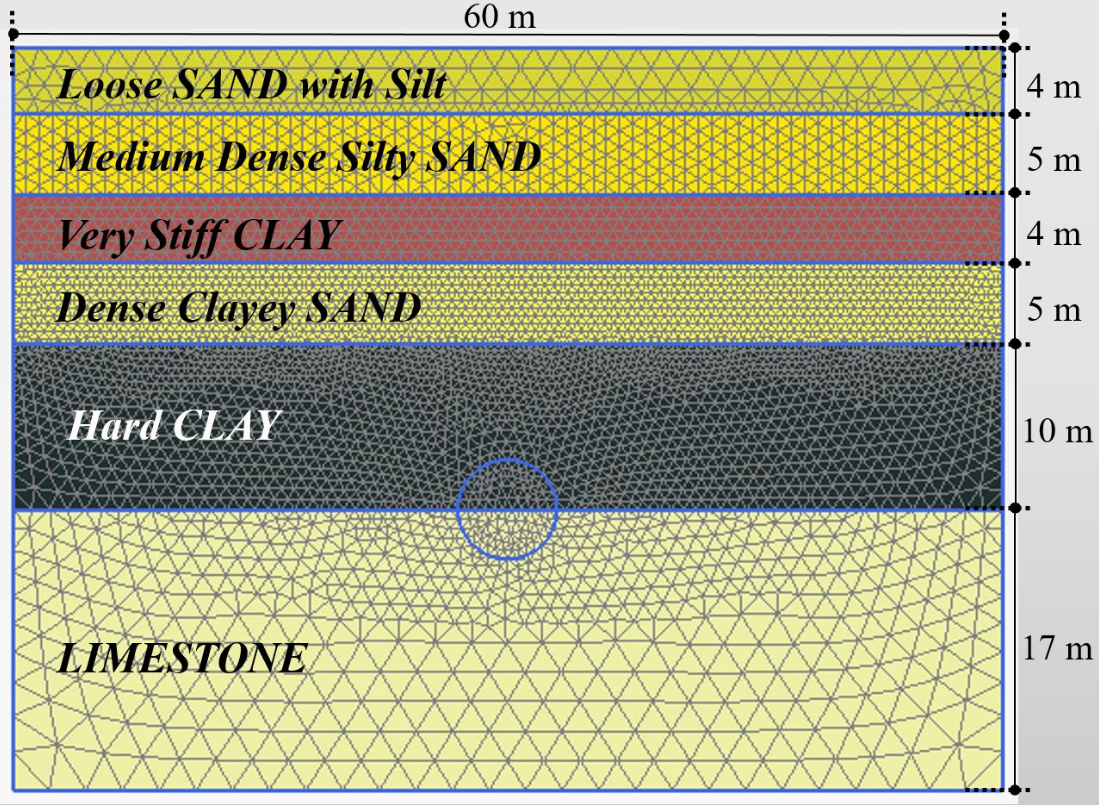
Strength and Stiffness Parameters – Wekiva Pkwy site



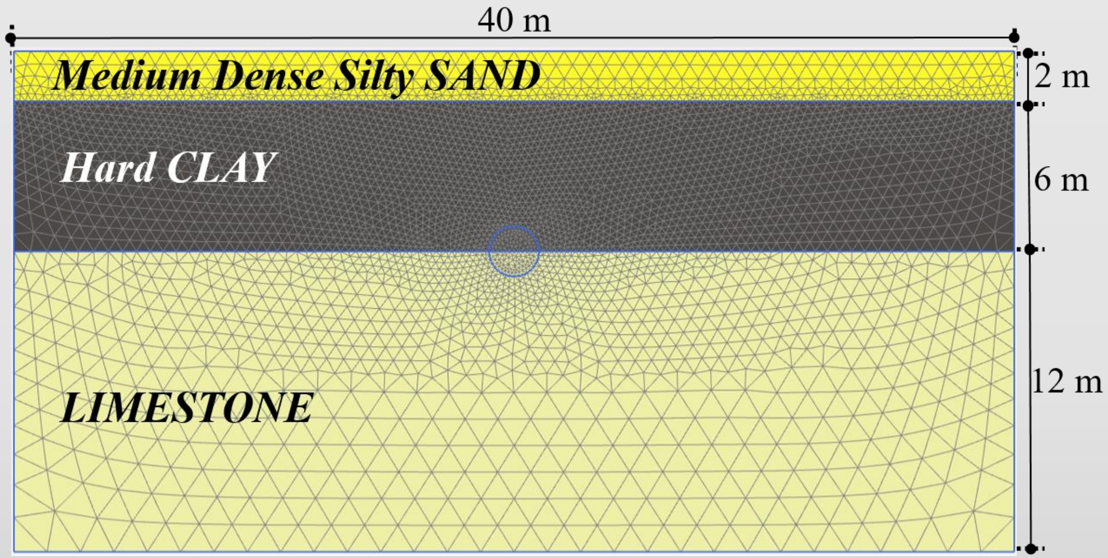
Strength and Stiffness Parameters – US 441 site



Finite Element (FE) modeling

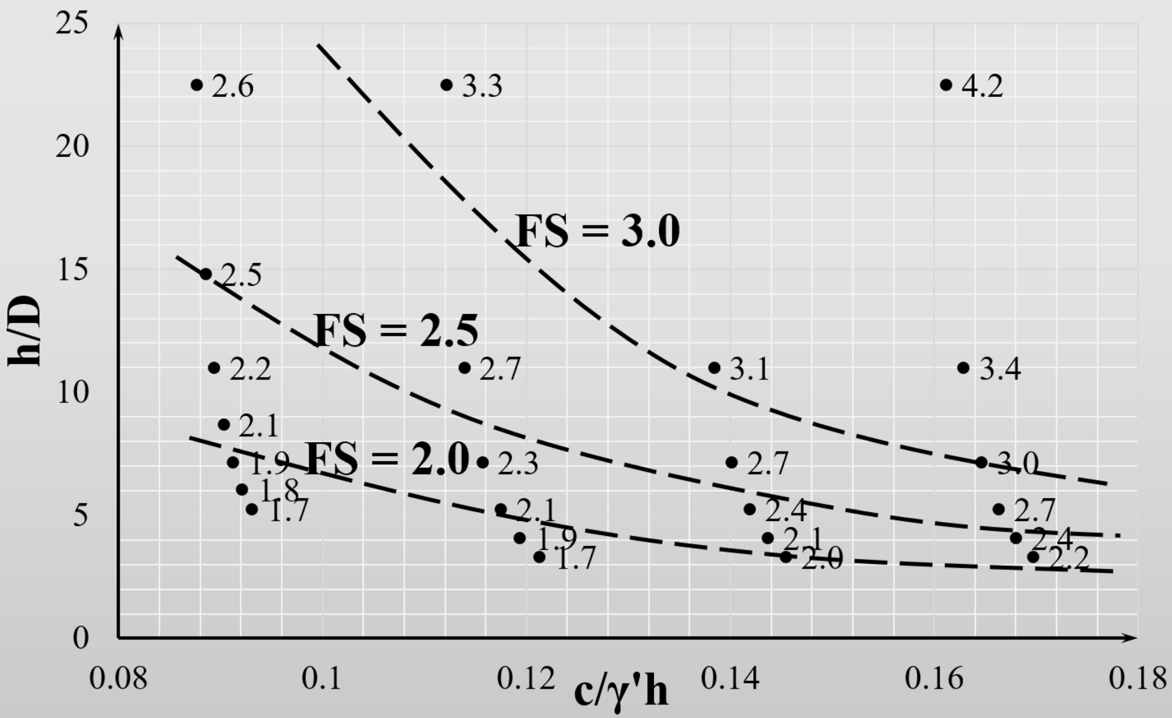


Wekiva Pkwy site

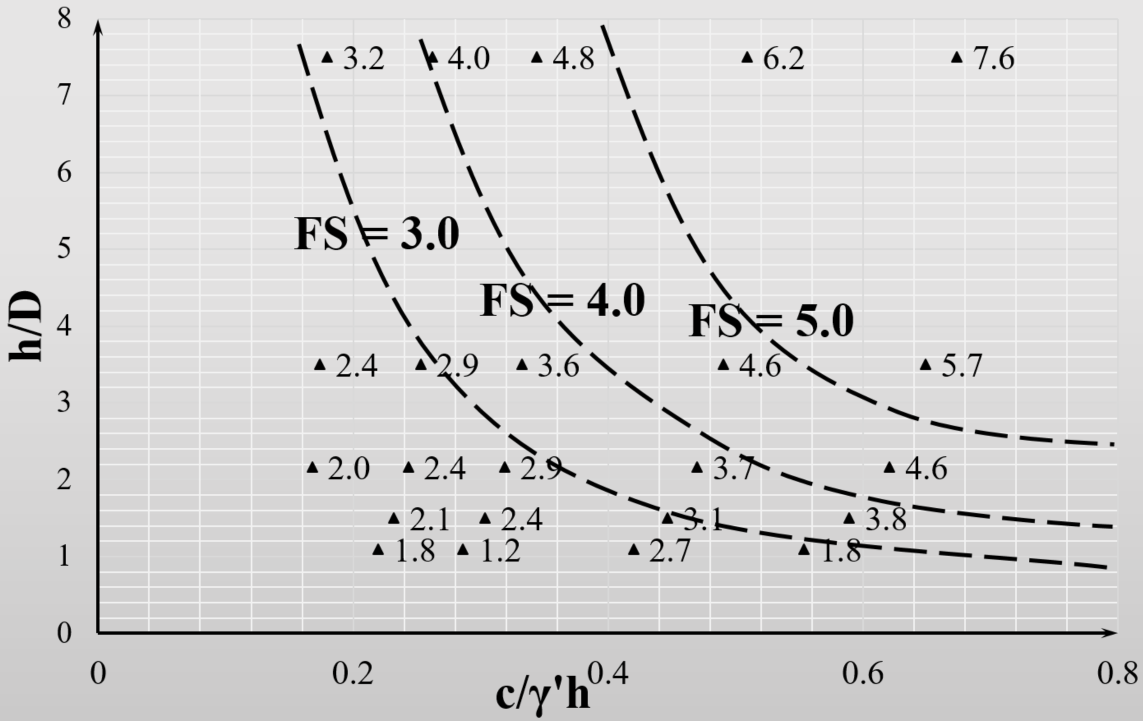


US 441 site

Sinkhole Stability Charts

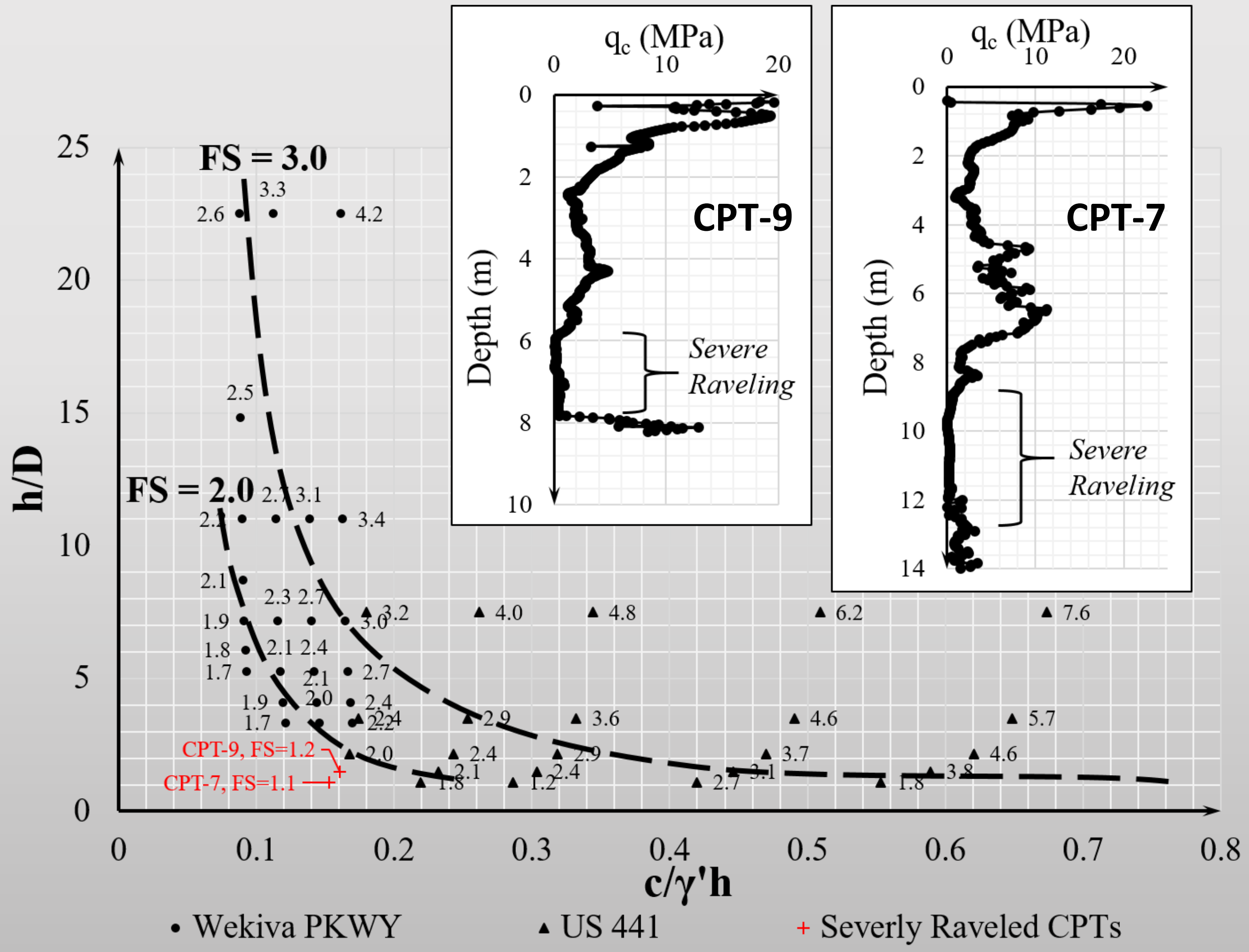


Wekiva Pkwy site



US 441 site

Combined Stability Chart



Summary of Research Conclusions

- A comprehensive sinkhole risk evaluation program was developed, including (i) identification of points of recharge by in-situ piezometer monitoring, (ii) CPT-based vulnerability assessment, (iii) high-resolution groundwater recharge map, and (iv) FE-based sinkhole stability analysis.
- CPT (one of most common subsurface exploration methods) is used to determine the vulnerability of sinkhole
  - Raveling chart can be used to identify the severity of sinkhole raveling.
  - Sinkhole resistance ratio (SRR) can be used to quantify the vulnerability of sinkhole.
- Assessment of groundwater flow can be used as a sinkhole risk evaluation means.
  - Piezometer sensors can be used to identify points of groundwater recharge that are the sources of soil internal erosion.
  - High-resolution groundwater recharge map was construct to estimate the risk level sinkhole.
- A procedure of sinkhole stability analysis from CPT test data was devised.
  - Finite element (FE) analysis results help to understand the sinkhole mechanism and the overall stability for the site of study
  - Site specific sinkhole stability charts are developed to determine the factor of safety for the site of study.

Recommendations

- (1) modified analysis method to be used in conjunction with an existing field test method (CPT) and (2) guidelines to design a field monitoring program to develop of High-Resolution Groundwater Recharge Maps to concentrate site investigations identified in high-risk areas of potential sinkhole activity.
- Both of these would be done during the design phase to identify remediation programs prior to construction; thereby, significantly reducing the cost.
- In addition, these can be performed for existing roadways (maintenance) which would assist geotechnical engineers in assessing current subsurface conditions and recommending remediation programs to protect existing infrastructure.

Thank you!

&

Questions?

Further Research Needed

- Further long-term monitoring of piezometer data are recommended to understand the raveling process. Along with piezometer monitoring, CPT sounding tests over time are also recommended.
- Piezometer sensors can be used to determine “effective” hydraulic conductivity of the site.
- It is recommended to investigate the impacts of extreme rainfall events on sinkhole formation and raveling process. CPT data on sinkhole collapsed sites after rainfall events are necessary to be further studied.
- Raveling chart and SRR index should be fine-tuned and validated throughout the state of Florida covering different hydrogeological/geotechnical environments.
- The current SRR is based on an intuitive approach and can be improved by more theoretical approaches.
- Existing condition (e.g. mechanical and/or weathering conditions) of underlying limestone bedrock may be incorporated into the current sinkhole vulnerability assessment.
- The sinkhole stability charts developed are site specific, thus the general stability charts should be developed and validated by many other sites.

Project Benefits

- **Qualitative**

Since the Department owes two CPT trucks (SMO & District 5 Materials), the Sinkhole Resistance Ratio (SRR) analysis methodology can be immediately used to associate a "risk index" to the site to know what course of action is needed (safe, immediate remediation, continued monitoring, etc.).

This is an improved monitoring methodology to provide the engineer with tangible data to make a decision when to act and develop an immediate remediation program (as well as to determine what type of remediation program is warranted) versus being reactive in an emergency situation; thereby, efficiently using existing resources.

Project Benefits (cont.)

- **Quantitative**

There is a direct cost of remedial procedures to fix facilities affected by the surface movements associated with sinkholes and the indirect costs of lane closures and associated safety of the traveling public.

Improved monitoring techniques will provide the engineer with the information to make better decisions when to act and to design a more effective remediation program, as well as to determine what type of remediation program is warranted.

In addition, if this monitoring is done during the design phase to identify remediation programs prior to construction, cost of remediation is significantly reduced (as well as minimizing the impact to the traveling public) – the cost of an emergency supplemental agreement during a construction contract is significantly higher.

The loss in construction time associated with the time needed for the supplemental site investigation.

Implementation Items

(1) Modified analysis method to be used in conjunction with an existing field test method (CPT)

(2) Guidelines to design a field monitoring program to develop of High-Resolution Groundwater Recharge Maps to concentrate site investigations identified in high-risk areas of potential sinkhole activity.

Both of these would be done during the design phase to identify remediation programs prior to construction; thereby, significantly reducing the cost. In addition, these can be performed for existing roadways (maintenance) which would assist geotechnical engineers in assessing current subsurface conditions and recommending remediation programs to protect existing infrastructure.