

Central Florida Sinkhole Evaluation

By Kathy M. Gray¹

Abstract: This paper presents a discussion of sinkhole risk evaluation in Central Florida. It is the culmination of more than 33 years of practice in this area. But, rather than being the experience of one engineer, it is more a collaboration with all the engineers who have freely shared their knowledge and experience over the years. For many Central Florida engineers, these evaluations are almost a daily activity. The risk must be considered to some degree for just about every site and project. The paper discusses the sinkhole development process, the distribution of sinkhole occurrences and the relationship to groundwater recharge. Also covered is the isolated nature of sinkhole anomalies and the resultant subsurface exploration challenges. Finally, the risk evaluation process and some common risk mitigation measures are reviewed. Case histories and examples are provided to illustrate the concepts and typical conditions.

Introduction

According to Merriam-Webster, a sinkhole is “a low area or hole in the ground that is formed especially when soil and rocks are removed by flowing water.” Sinkholes are a fact of life in Florida. They occur in many areas of the State at varying frequencies. However, they are not evenly distributed throughout the State. Some areas have considerable numbers of sinkholes while other areas have none. Areas affected by sinkholes have a distinctive type of topography known as Karst. The number of sinkholes is unknown. However, based on the relatively short time records have been kept and review of topographic maps, the numbers are likely in the tens of thousands, if not greater.

There is nothing such as a typical sinkhole. They come in all sizes and shapes. Some are as small as 1/3-meter (1 ft.) in diameter while others are more than 100 meters (330 ft.) in diameter. The depths of the holes and the rates of development are equally varied. The only thing consistent about them is their lack of consistency. Their characteristics are determined by the soil, geologic and hydro-geologic factors where they occur. These factors are quite variable across the State.

One thing that is definite about sinkholes is, if one occurs under a structure susceptible to the loss of support, the consequences can be disastrous. As of December 2013, there has only been one documented case of a fatality caused by a sinkhole. They usually occur slow enough that people can get out of the way. Buildings do not have this advantage and thus many commercial and residential structures have been damaged by sinkholes over the years. This sometimes results in complete destruction of the structure. Other times the sinkhole merely causes damage which is repairable after the ground is stabilized.

Geologic Setting

Most of Florida is underlain by hundreds of meters (thousands of feet) of Limestone and Dolomite formations. These formations have many water filled solution channels and interconnected cavities which produce most of the water supply for the State. The Limestones and Dolomites are overlain by various layers of interbedded sand and clay soils. The soils vary in consistency from clean sands to silty/clayey sands, sandy clays and lean to plastic silts and clays. The soil cover varies in thickness from less than 1/3-meter (1 ft.) to more than 100-meters (hundreds of feet).

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In the sinkhole active areas of the State, the groundwater profile consists of two aquifers separated to varying degrees by a clayey aquiclude. The upper, unconfined aquifer is primarily contained in the near surface strata of sandy soils. The lower, confined aquifer is in the underlying cavernous Limestone formations. The two aquifers are hydraulically connected in localized areas where the aquiclude is breached or non-existent. In these areas, there is a downward gradient of flow which feeds the lower aquifer. This downward flow of groundwater is referred to as Recharge.

There is a significant relationship between groundwater recharge and sinkhole activity. In general, the greater the recharge, the greater the sinkhole activity. Figure 1 is a Poster prepared by the Florida Geological Survey showing the locations of sinkholes reported as of 2004. Figure 2 shows these sinkholes plotted on a Recharge Map prepared by Stewart (1980). There is a clear trend. Figure 3 shows the relative distribution of the sinkholes by Recharge Area Category:

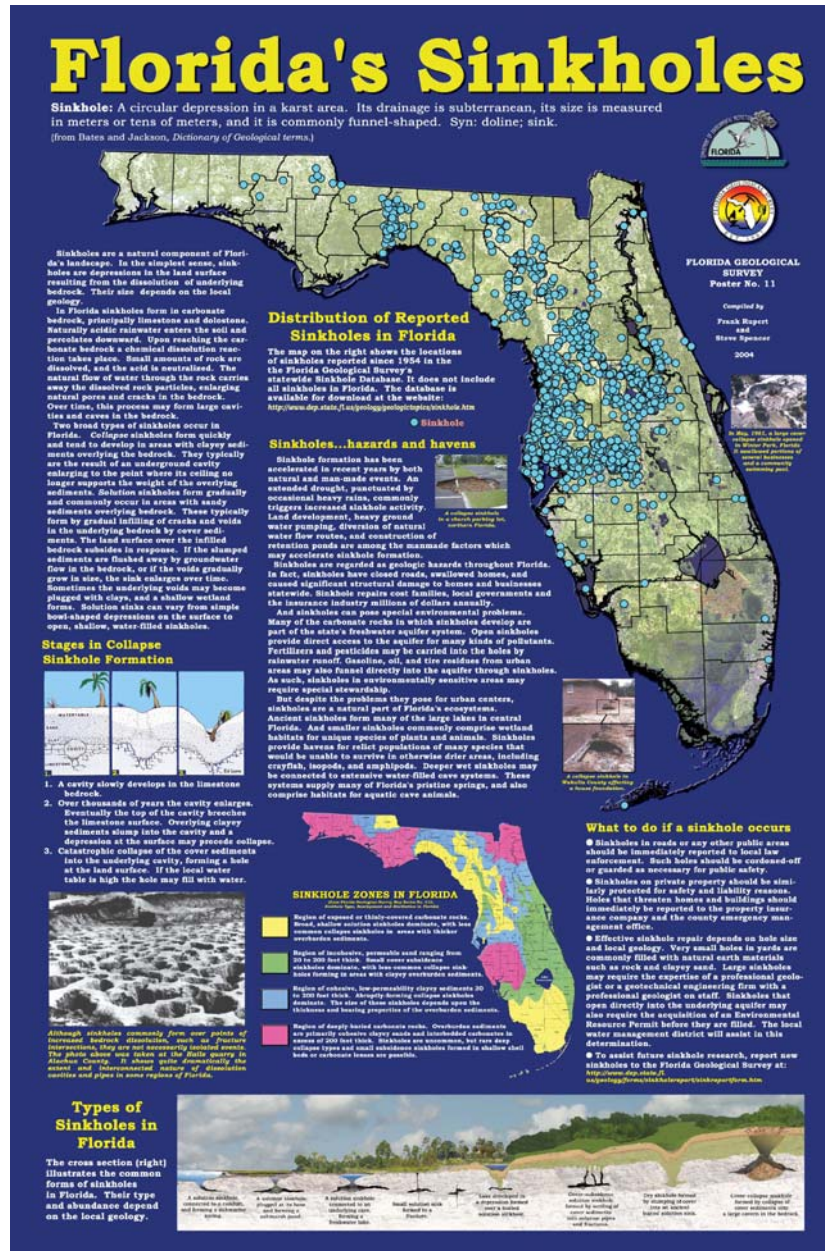


Figure 1, Florida Geological Survey Poster No. 11 Reported Sinkholes (2004)

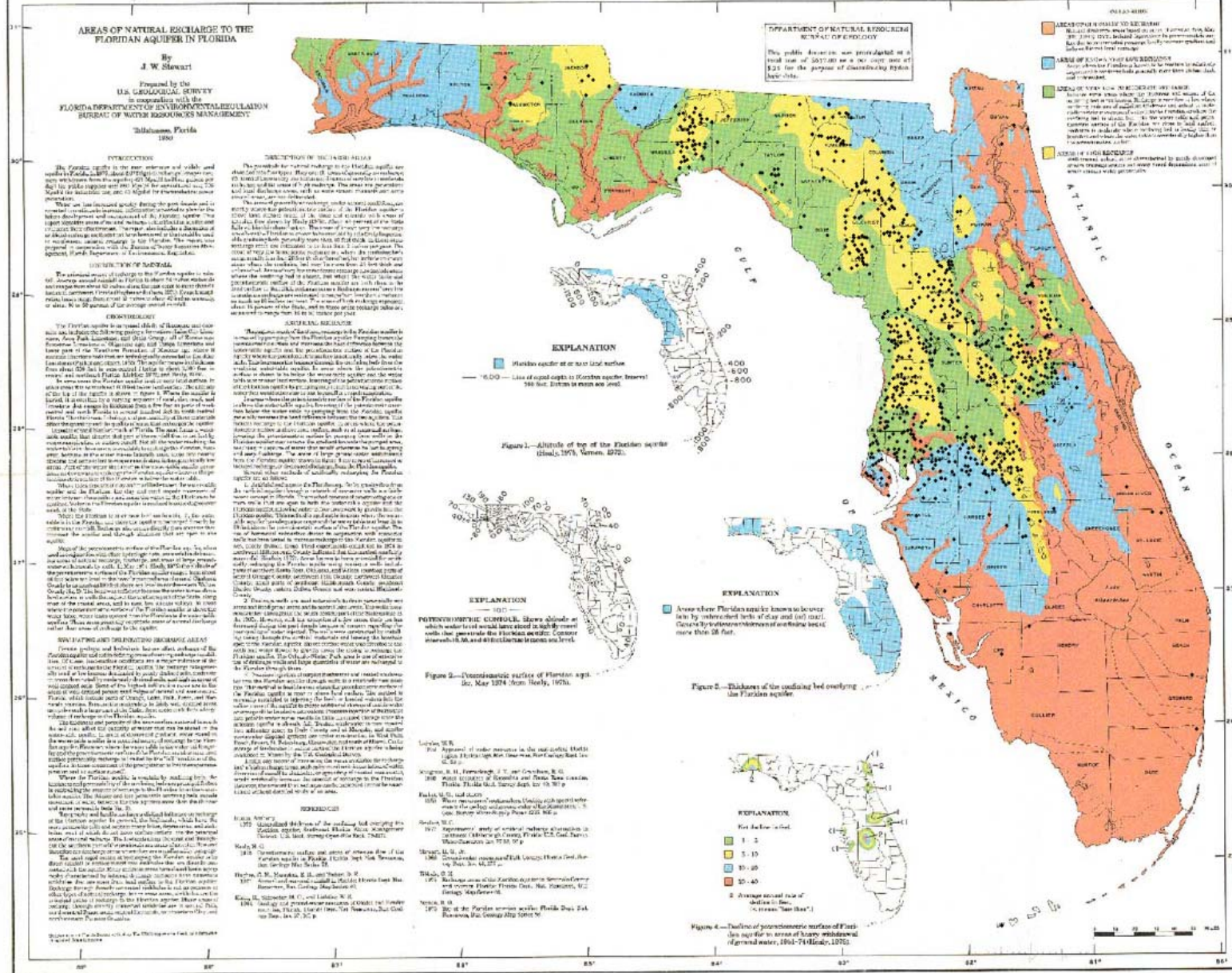


Figure 2, Florida Geological Survey Reported Sinkholes (2004) plotted on Recharge Map by Stewart (1980)

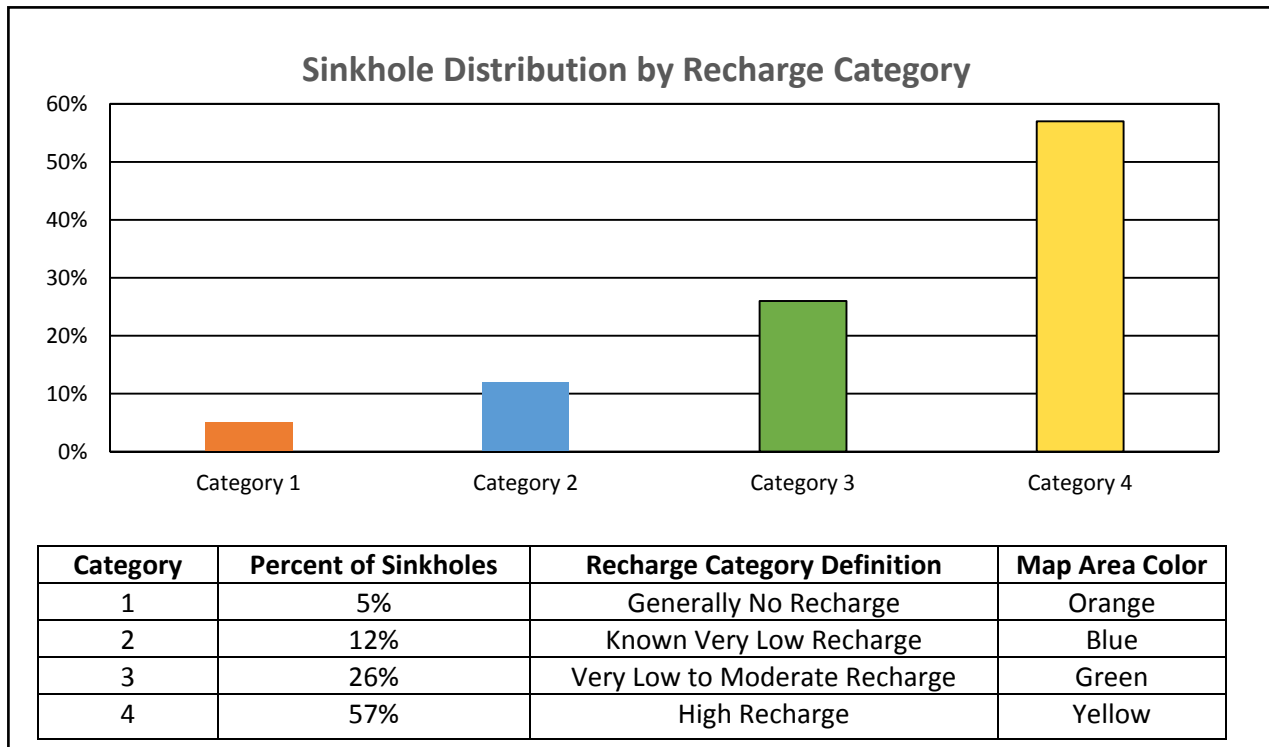


Figure 3, Statewide Sinkhole Distribution by Recharge Area

The map shows the locations of over 700 sinkholes reported to the Florida Geological Survey as of 2004. Based on this data, 83% of the reported sinkholes are located in the two highest Recharge Areas. And, only 17% are located in the two poorest Recharge Areas.

Sinkhole Development

Sinkholes in Florida are believed to be caused by either Soil Raveling or Cavern Collapse. The Soil Raveling phenomenon manifests itself in two primary ways. Either as a Cover Subsidence or a Cover Collapse. The processes are discussed in more detail below.

The Soil Raveling Concept refers to a process whereby the soil profile deteriorates from the bottom up. The theory is that this is caused by breaches in the clayey aquiclude above the Limestone Aquifer which allows groundwater to flow downward into solution channels and cavities in the rock. This downward flow of water into the aquifer is known as Recharge. As indicated in Figure 2, groundwater recharge occurs throughout many areas of the State to varying degrees. It is believed this flow of groundwater internally erodes soil particles into the underlying Limestone voids. As time progresses, this process unravels the soil structure upward until a subsidence or collapse of the surface occurs.

A Subsidence Type sinkhole would occur if this process plays out in a soil profile composed primarily of non-cohesive sandy soils. Somewhat similar to the way a depression forms in the sands of an hour-glass. The Cover Collapse version of this type sinkhole would occur in situations where there is a near surface layer of clayey or cemented soils (i.e. hardpan, etc.) which temporarily “bridge over” the deteriorating profile. As the raveling process continues it eventually exceeds the ability of the “bridge” to span it and the surface collapses. Sometimes suddenly without warning. If the “bridge” soils are strong enough, it is possible in this case to have an actual void develop. Cover Collapse sinkholes on the verge of failure can be suddenly triggered by heavy rainfall, vibration or other external affects. Figure 4 provides illustrations of the Cover Subsidence and Cover Collapse Concepts by Tihansky (1999).

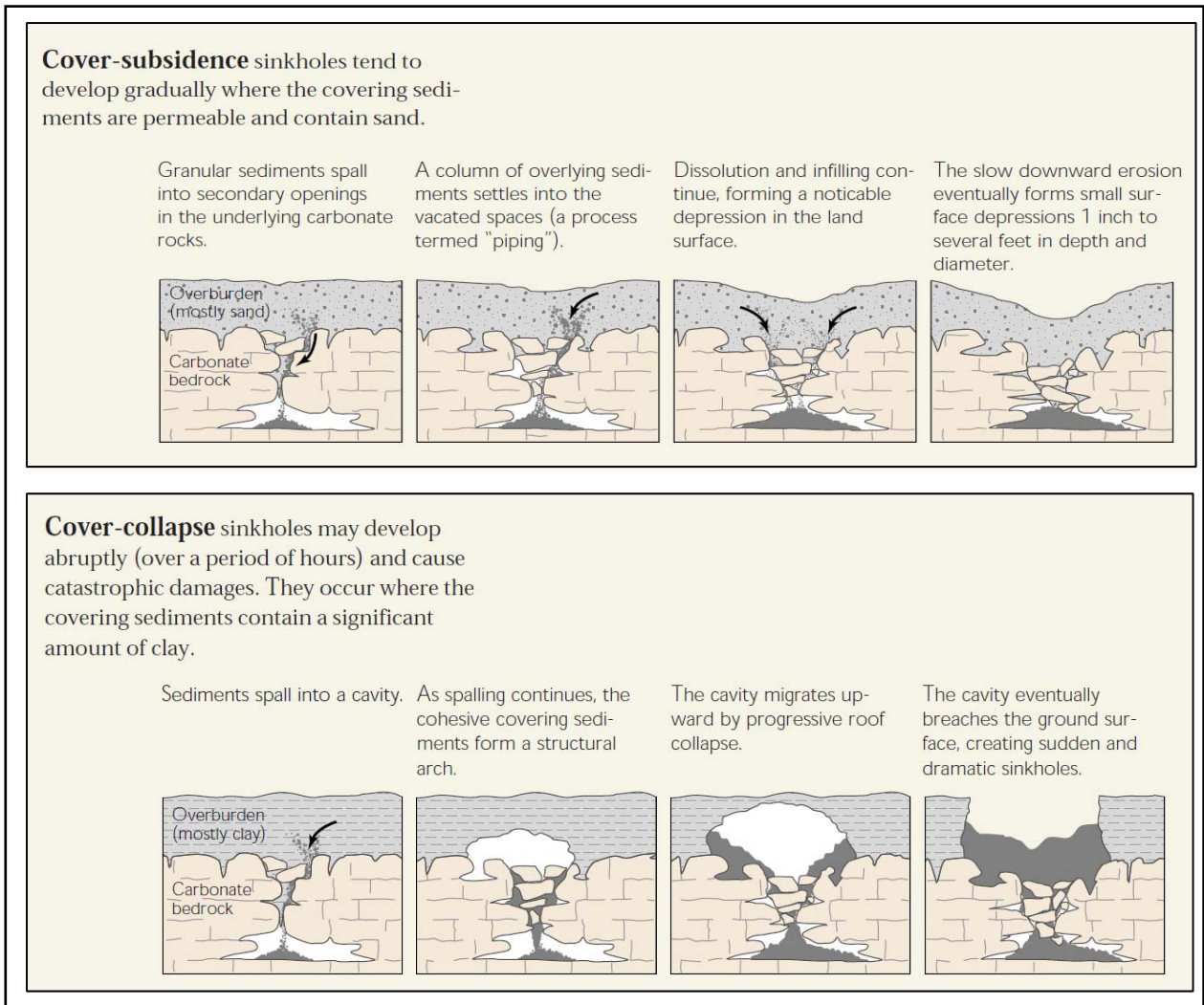


Figure 4, Illustrations of Cover Subsidence and Cover Collapse Concepts by Tihansky (1999)

So, what is the evidence supporting the Raveling Sinkhole Concept? There is quite a bit actually. First, from Figure 2 it is clear there is a definite relationship between the degree of Groundwater Recharge and sinkhole activity. Secondly, there is the soil boring evidence. Figure 5 from the Winter Park Sinkhole Report (1982) presents the results of 7 Standard Penetration Test (SPT) borings, ASTM D-1586, done near known sinkholes. The borings found very low SPT N-values and extensive zones where the drilling tools "Fell by weight of rod and hammer". This is commonly referred to as "Weight of Rod" (WR) or "Weight of Hammer" (WH) by other drillers. The borings also encountered several locations where the drilling fluid used to clean out the cuttings and stabilize the hole was lost. This is commonly referred to as "circulation loss". Soil conditions such as these are frequently encountered in sinkhole active areas. The severity of the deterioration varies considerably from location to location. It occurs in both sandy and clayey soil profiles. When extensive zones are encountered in the soils above the Limestone, they indicate a seriously deteriorated soil structure. Falling rod/hammer and circulation losses are common in the underlying cavernous Limestone. This is to be expected and does not usually cause serious problems unless there is a connection and deterioration of the overlying soils.

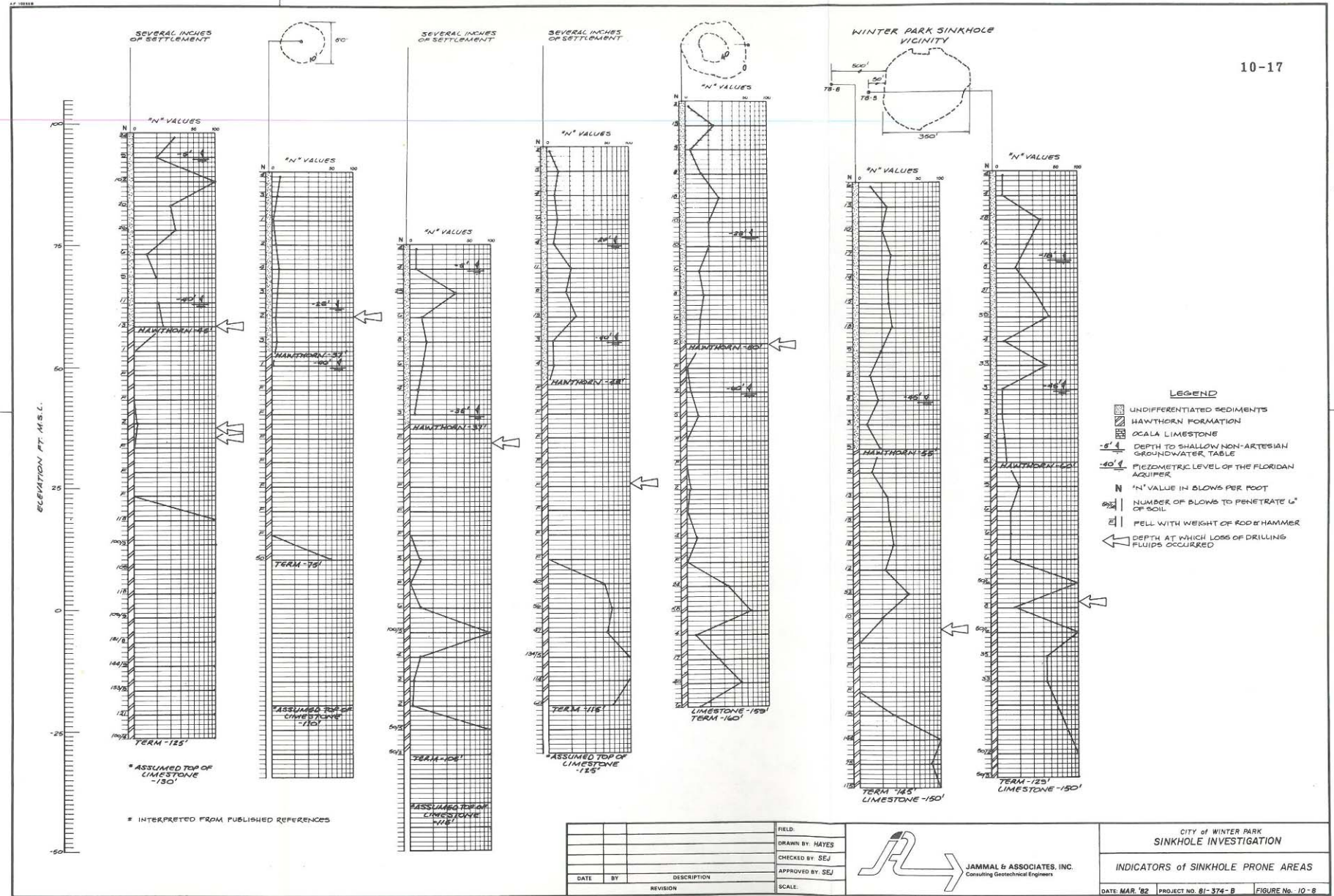


Figure 5, Indicators of Sinkhole Prone Areas, The Winter Park Sinkhole Report by S.E. Jammal (1982)

Another soil exploration test used in Florida is the electronic Cone Penetration Test (CPT), ASTM D-5778. This is a test where a 60-degree conical tip is hydraulically pushed through the soil at a constant rate. The resistance to penetration of the tip and along a friction sleeve are measured with electronic sensors. Figure 6 presents the results of a CPT Sounding performed at a sinkhole active location in Longwood, Florida. The CPT encountered deteriorated soils from depths of about 14 meters (45 ft.) to 21 meters (70 ft.). Tip resistance readings less than 10 kg/cm² (10 tsf) are typical of raveled soil conditions. This location was stabilized by cement pressure grouting. It took 32 injections and 473 m³ (619 cy) of grout to stabilize a 230 m² (2,500 ft²) area.

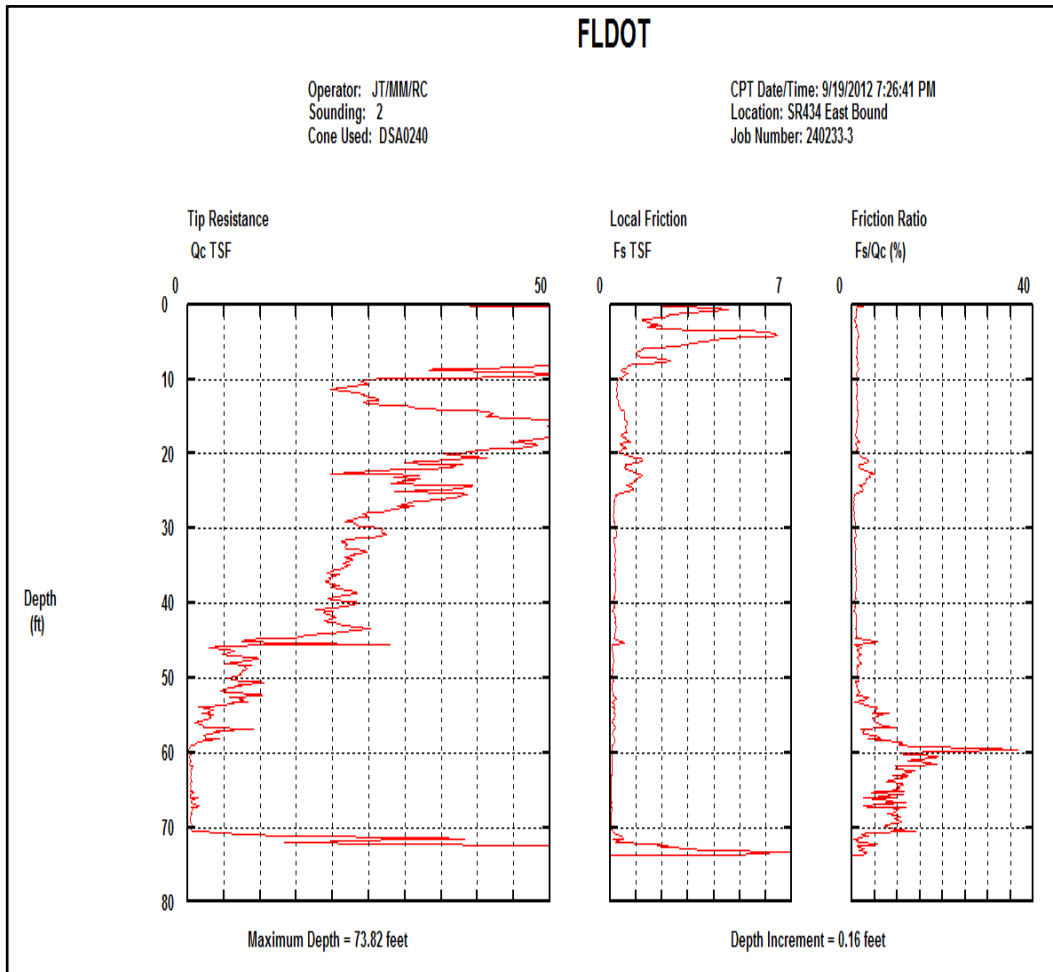


Figure 6, Case History: Cone Penetration Test (CPT) result at a Sinkhole Active Location

Another example of Soil Raveling is presented in Figure 7. This shows an SPT boring, P-5 (SB-13), and a CPT Sounding (FDOT - 5) done for Section 4B of the Wekiva Parkway Project in Lake County, Florida. The SPT boring found extensive soil raveling and drilling fluid circulation loss between depths of about 18 m (60 ft.) to 34 m (110 ft.). This is indicated by the WH and WR symbols where the drilling tools sank under their own weight. Cone Penetration Test Sounding FDOT - 5 was performed 1.5 m (5 ft.) from P-5 (SB-13) for comparison. In the zone of raveled soils, the lowest CPT Cone Tip Resistance was about 4 kg/cm² (4 tsf). The CPT Sounding showed this zone of raveled soils was not a void, but just abnormally soft soils. The soil type indicated by the SPT boring is Clayey Fine Sand, Unified Soil Classification Type SC.

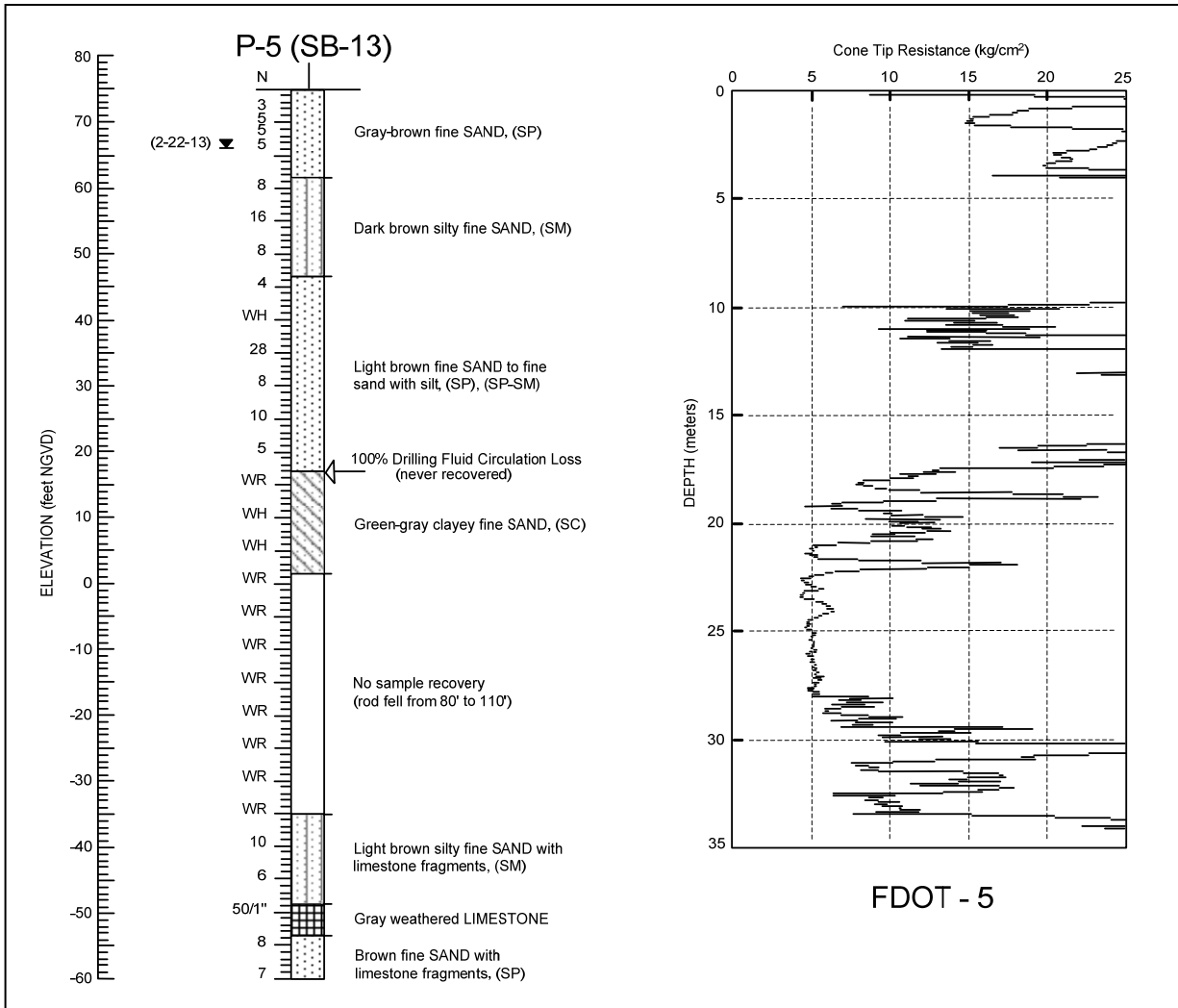


Figure 7, Case History: SPT Boring and CPT Sounding showing Raveled Soil Conditions

The Cavern Collapse Theory of sinkhole development is based on the fact that slightly acidic groundwater can dissolve Limestone. The assumption is that this water flows through caverns in the Limestone and slowly dissolves the rock. At some point the dissolution process expands a cavern until the roof collapses under the weight of the overlying soils. The evidence for this theory is weak. While it is true that most of the State is underlain by cavernous Limestone. White (1988) estimates the dissolution of Limestone in a tropical environment, such as Florida, at only about 1 to 2 inches per thousand years. There have almost certainly been cavern collapses throughout geologic history. Especially before the current overlying soils were deposited and the rock was exposed to intense weathering. However, this process does not appear to be the predominant mechanism at this time and there are few, if any, cases of proven cavern collapse in the record.

A popular Cavern Collapse theory often repeated is that sinkholes occur during times of drought because the groundwater table and the aquifer potentiometric levels drop. As the theory goes, failure occurs because the effective weight of the overlying soils increases at the same time the internal cavern water pressure decreases. It is true that a lower groundwater table increases the effective weight of soil. And most Limestone caverns are filled with water under a pressure. However, if these factors were

the cause of sinkholes, there should be a relatively even distribution of sinkholes throughout the State because the entire peninsula is underlain by cavernous limestone. But, as shown in Figure 45, sinkholes are not evenly distributed throughout the State. The higher Recharge areas have a higher concentration of sinkholes and the lesser Recharge areas have much fewer. And, sinkholes occur during both wet and dry seasons, not just during droughts.

Another problem with the Cavern Collapse Theory is what comes first. Dissolution of the Limestone is believed to be most intense at the point of recharge where the acidic water first enters the system. As the water reacts with the rock the acidity should be neutralized and less dissolution should occur downstream. So which material is more susceptible to the deteriorating effects of the water? The Limestone rock or the soils overlying the entrance to the system. The rock has much more cohesive strength than the soils. Thus the soils are much more susceptible to erosion than the rock. If there is a point of recharge, there is almost certainly soil erosion and raveling occurring at a much faster rate than the slow dissolution of the rock. Therefore, it is more likely for a sinkhole to occur due to raveling than cavern roof collapse.

Exploration Issues

Traditional field exploration methods for sinkhole evaluations consist of aerial photo review, topographic map review, Soil Survey review, site visits and the performance of soil borings. Most often these are Standard Penetration Test (SPT) borings and/or Cone Penetrometer Test soundings (CPT). Sometimes, Geophysical Surveys such as Ground Penetrating Radar (GPR) and/or Electrical Resistivity (ER) are used to supplement or guide the SPT and CPT testing. All of these methods prove useful at times to varying degrees. And, they all suffer from inherent limitations. The biggest limitation of the boring and sounding methods are the isolated nature of the information they provide. They can only reveal what they encounter within the diameter of the hole they create. They don't give much information about what is between the borings. This can be a significant problem because sinkhole activity tends to be vertically oriented. Borings are good at finding horizontal layers. They are not good at detecting relatively narrow, vertical anomalies. Figure 8 is a Case History where two borings were done at a known sinkhole location. The boring in the middle of the sinkhole (TB-1) had extensive raveled soils and drilling fluid circulation losses while the boring only 7.5 m (25 ft.) away (TB-2) had no raveled soils or circulation losses.

When used in conjunction with SPT borings and CPT soundings, Geophysical surveys such as Ground Penetrating Radar and Electrical Resistivity Imaging can sometimes be useful. The problem with these surveys are the accuracy and reliability of the interpretation. When the ground conditions are favorable, it is possible to get good results. However, as shown in Figures 9 and 10, the results are not always reliable. This is a case history from the Wekiva Parkway Project in Lake County, Florida. Ground Penetrating Radar (GPR) and Electrical Resistivity Imaging (ERI) surveys were done. The investigator identified anomalous GPR and ERI areas. The GPR anomalies were categorized as either Level A or Level B. With Level A being the most severe condition. Figure 9 also shows some recommended test boring locations. Boring location P-5 (SB-13) is in a GPR survey area Level A. Boring location P-8 (SB-24) is in a GPR Level A and an ERI anomaly area. As can be seen from Figure 10 the boring at location P-5 (SB-13) found significant raveled soil conditions. However, the boring at location P-8 (SB-24) showed no issues. Even though both testing methods at that location indicated there should be a problem. This is a common problem with geophysical surveys. The technology may develop to the point where it is reliable in all ground conditions. And someday, it may even become the primary tool for exploring sinkhole active areas. But, more research and development is needed.

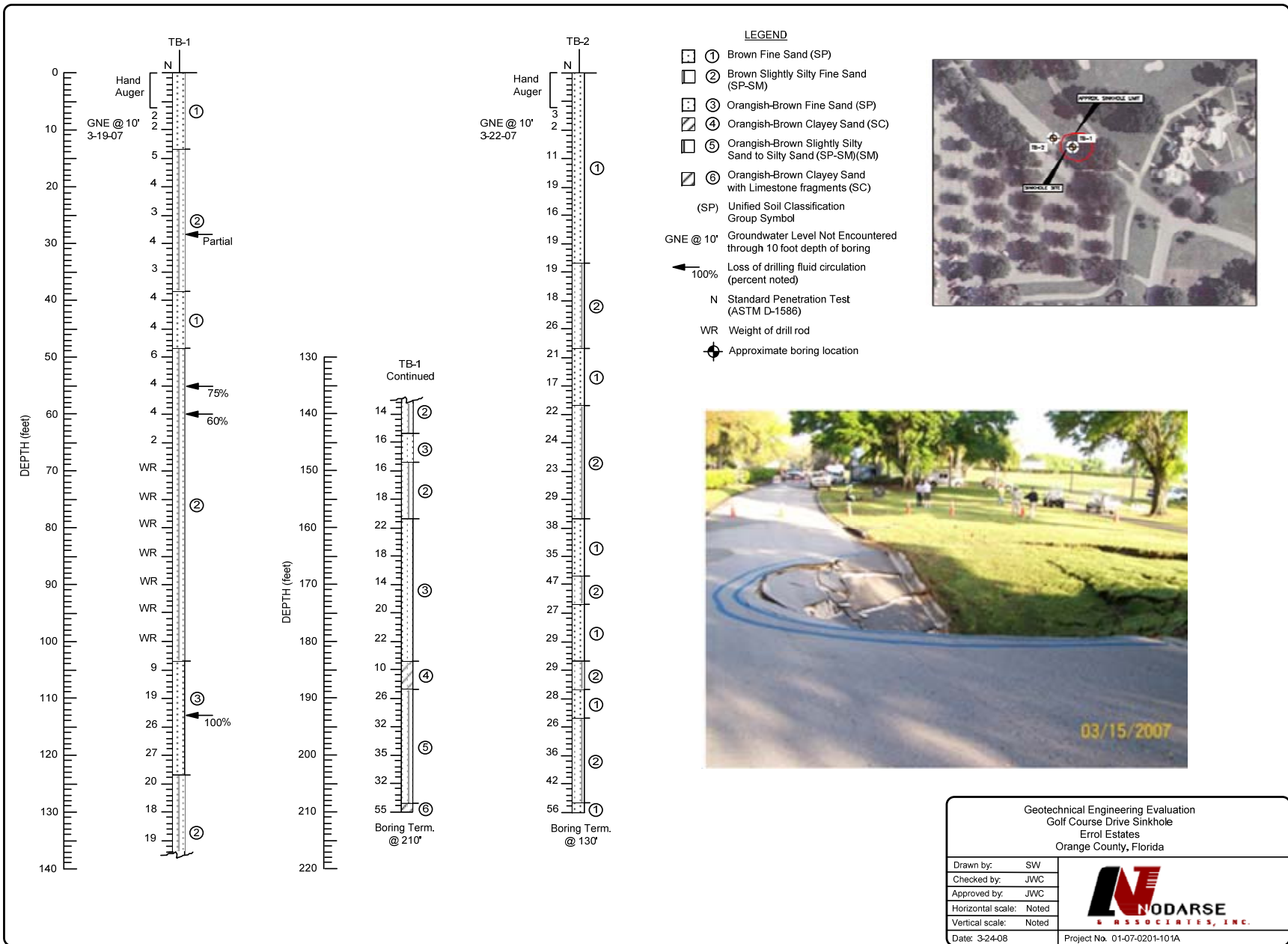


Figure 8, Case History: SPT Boring variability at a known Sinkhole Location

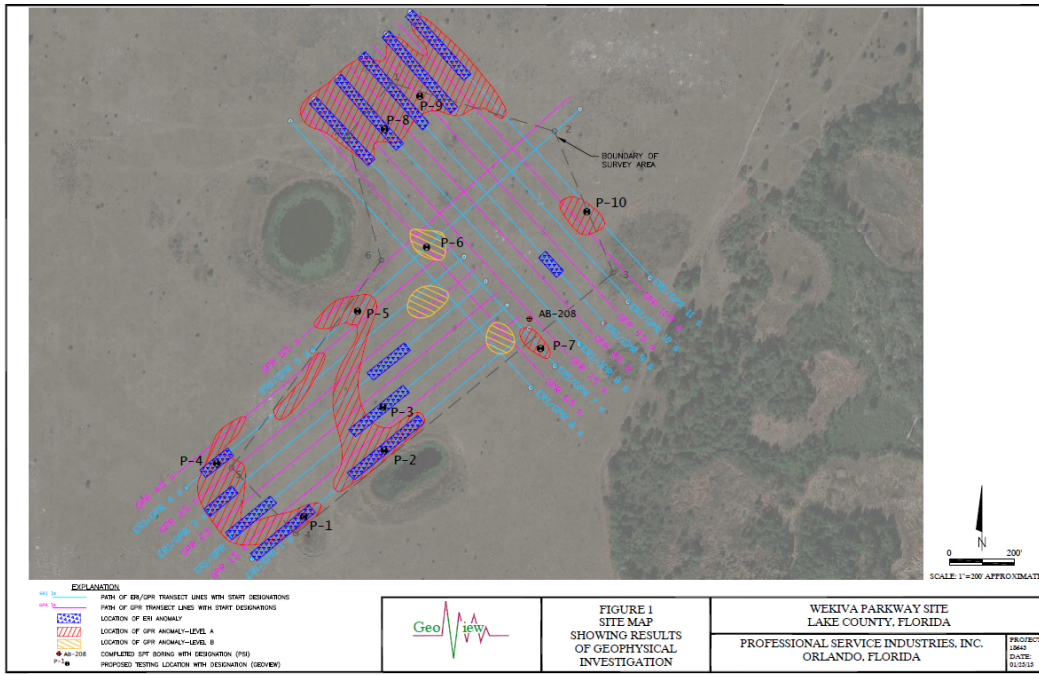


Figure 9, Geophysical Testing Site Map from Wekiva Parkway Project, Lake County, Florida

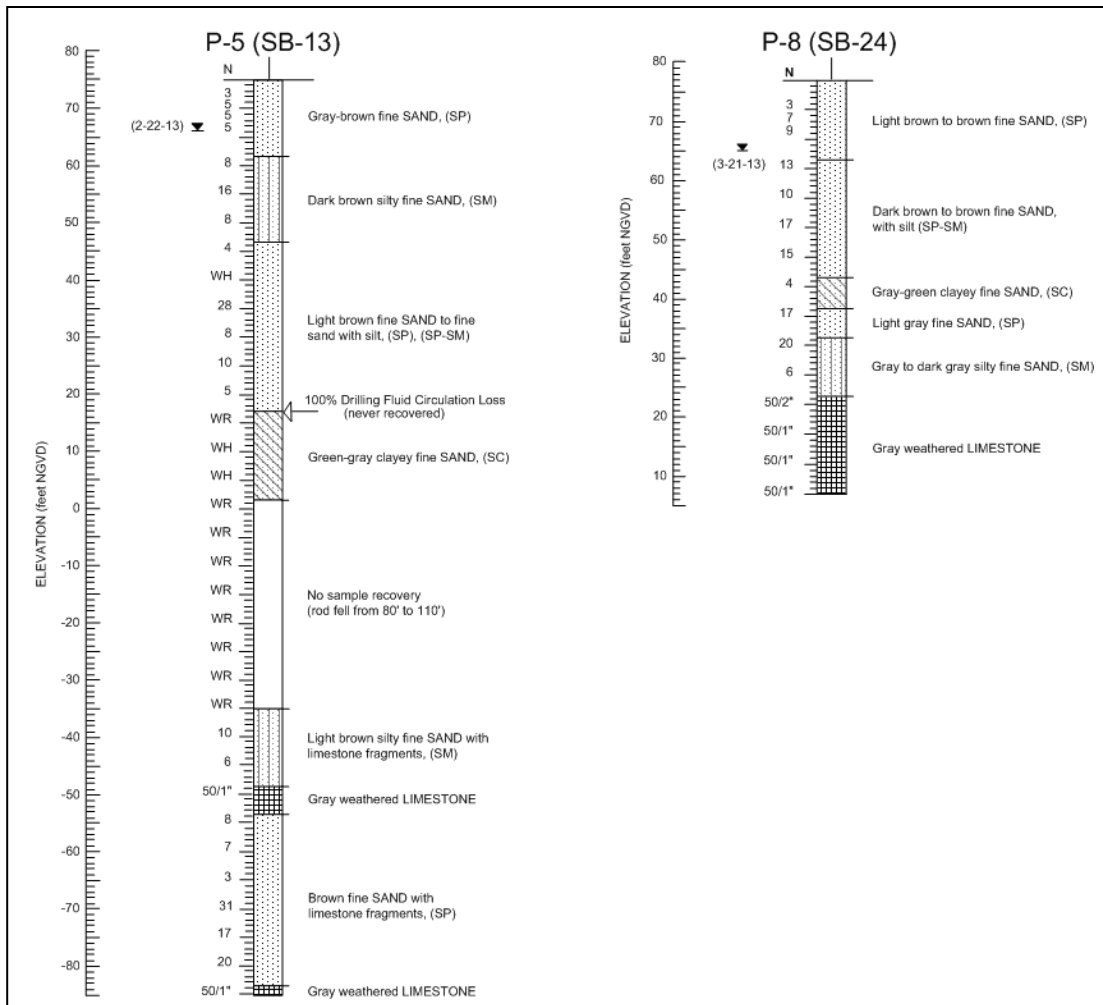


Figure 10, Case History: SPT Borings in Geophysical Testing "Anomolous" Areas.

Since there is good correlation between groundwater recharge and sinkhole development, another technique for detecting sinkholes is to see if there are any points of recharge within the influence of a proposed structure or facility. This can be done with arrays of deep, pore-water pressure sensors. Once the sensors have stabilized, the pore pressure readings at each point can be converted to elevation head and plotted as a contour map. If there is a point of recharge (cone of depression), the contours should converge around a piezometric low. Figure 11 shows an example of this technique used at a site on State Road 434 in Longwood, Florida. This site had experienced long term subsidence problems. An array of 20 pore pressure sensors were installed at depths of about 20 m (65 ft.) and monitored. The sensors were installed with Cone Penetrometer equipment using the Bixler Probe. Monitoring showed a difference in piezometric head of about 5 m (16 ft.) between the outside and inside contours. The site was stabilized later with cement pressure grouting. It took about 880 m³ (1,150 cy) of grout.

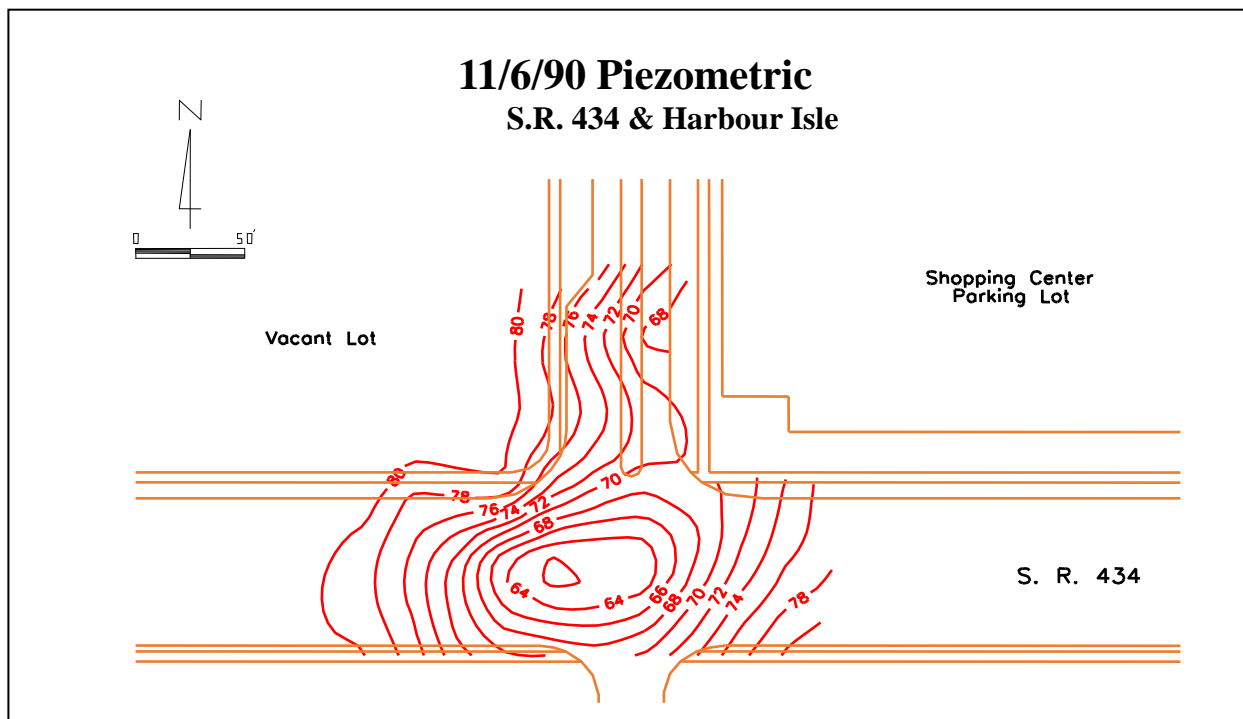


Figure 11, Case History: Pore Pressure Sensor Elevation Head Contours

Sinkhole Risk Evaluation

Many factors must be considered when evaluating sinkhole risk. Some of the more important ones are:

1. Recharge Area Category
2. Past History
3. Raveled Soil Indicators (WH/WR)
4. Drilling Fluid Circulation Losses
5. Topography
6. Vegetation Indicators
7. Stratigraphy
8. Aquifer Potentiometric Level vs Groundwater Table
9. Raveling Index
10. Structure Type & Public Safety

The first four items (i.e. Recharge Area Category, Past History, Raveled Soil Indicators and Drilling Fluid Circulation Losses) have been discussed previously. Other considerations include the site topography, vegetation indicators, Potentiometric levels vs groundwater table, structure type and public safety.

Sinkhole activity creates a distinctive topography known as Karst. It is characterized by significant elevation change, closed drainage basins and circular depressions. The drainage is predominantly vertical and the terrain is typically well drained. Figure 12 is an example of Karst. Conversely, areas less prone to sinkhole activity have flatter terrain with little elevation relief. They typically have well developed surface drainage systems (i.e. creeks, streams, etc.). Drainage is primarily horizontal, but because of the flat topography they are poorly drained. Figure 13 is an example of this topography.

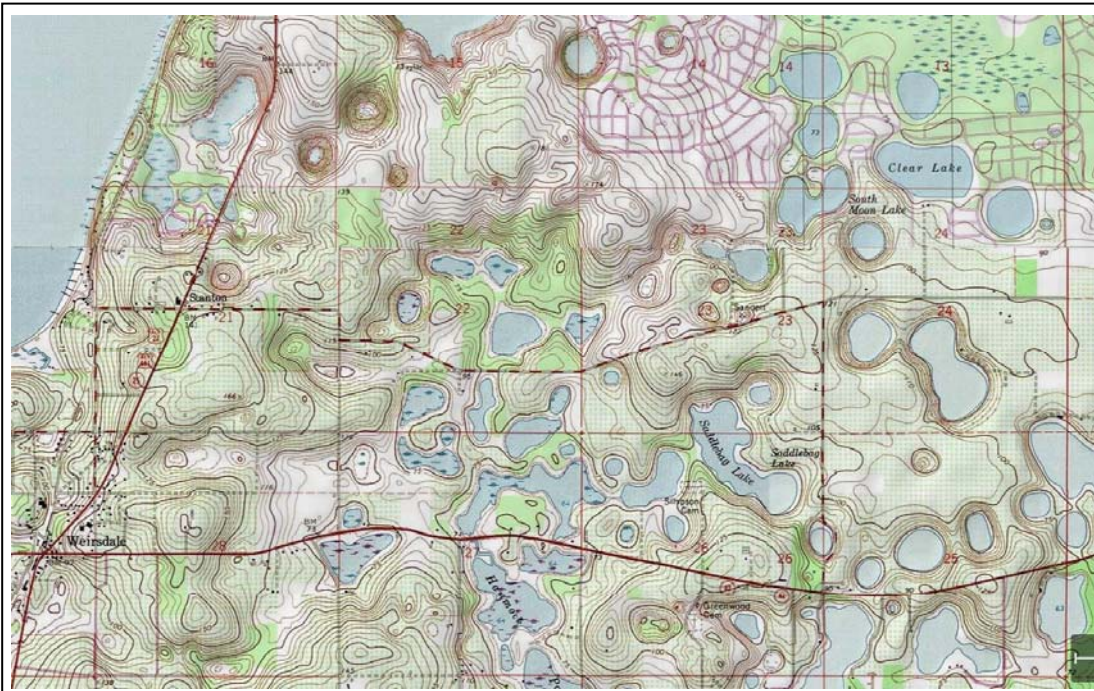


Figure 12, Example of Karst Topography

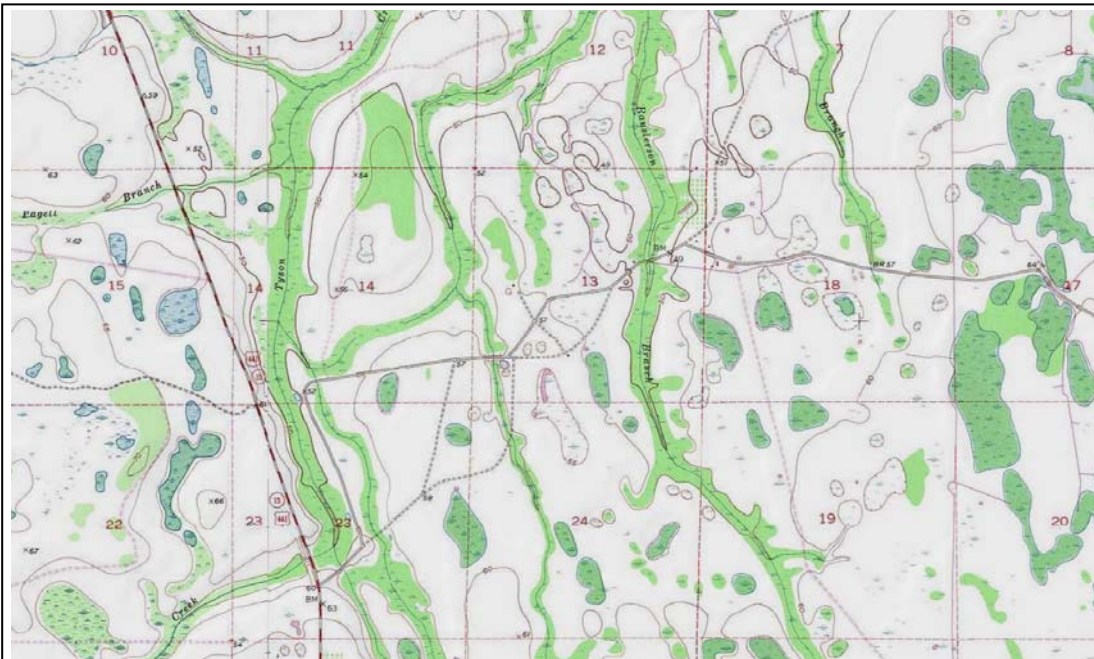


Figure 13, Example of non-Karst Topography

Another potential indicator of sinkhole activity is vegetation that is stressed. Such an area would have an isolated patch of brown or dying trees, bushes or grass surrounded by healthy green vegetation. This could be an indicator of a groundwater table that is being depressed by a point of recharge.

The Soil Profile in sinkhole active areas is typically quite variable. Often, there will be little to no consistency in layering from boring to boring. Frequently the depth to Limestone or other stable bearing layers may vary radically in relatively short distances. And, the clayey confining beds typically overlaying the Limestone are often breached or non-existent.

Another consideration in the evaluation is the relationship between the aquifer Potentiometric Level and the shallow groundwater table. In order to have downward flow of water and recharge of the aquifer, there must be a downward hydraulic gradient. Thus, the shallow groundwater table must be above the Potentiometric Level. If the Potentiometric Level is above the groundwater table there can be no recharge. In fact, that is the definition of an artesian condition or a spring. The U.S. Geological Survey in cooperation with the Water Management Districts maintain aquifer Potentiometric Maps similar to the below Figure 14.

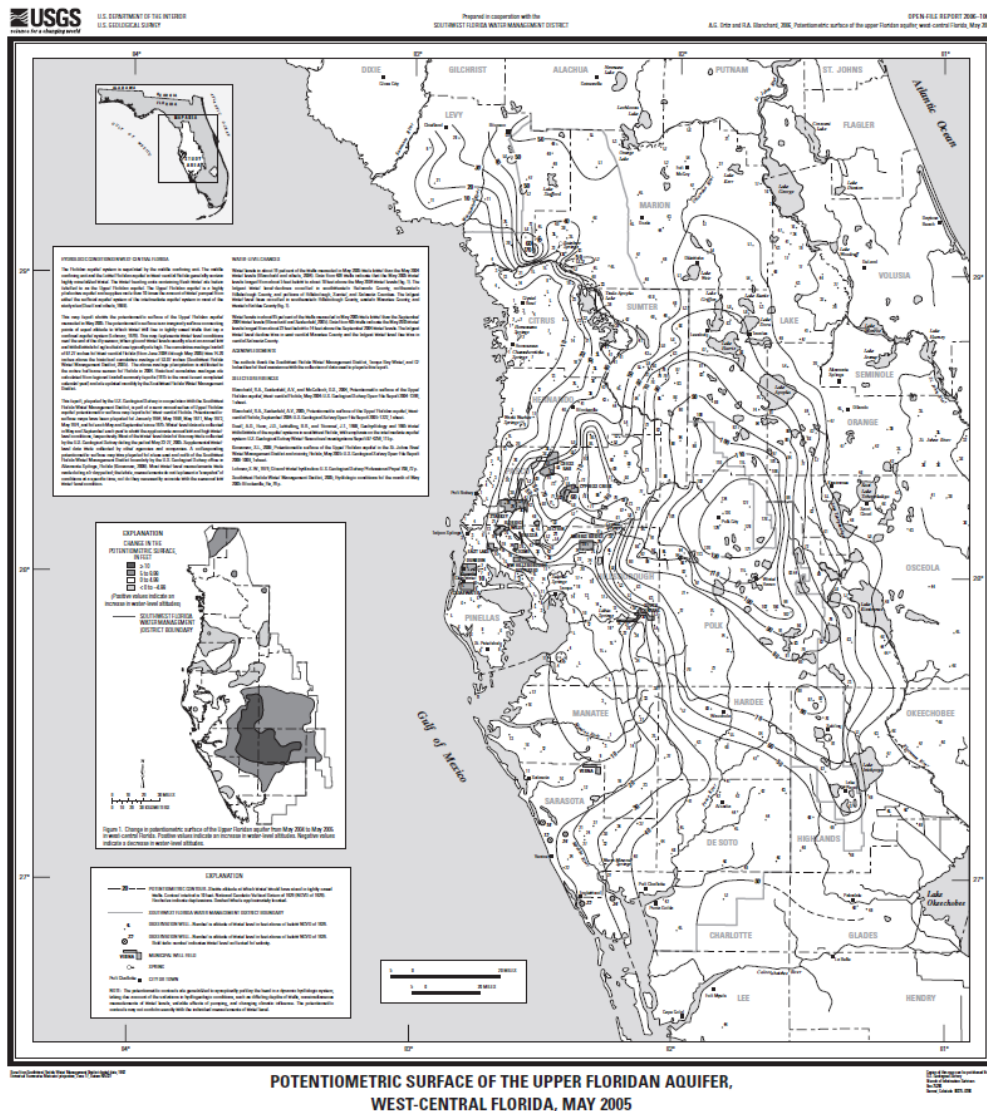


Figure 14, Example of Potentiometric Surface Map

The Raveling Index is another tool which can be helpful with the evaluation of sinkhole risk. The Index is defined as the thickness of the raveled soil zone divided by the depth to the top of the raveled zone. This ratio gives a relative indication of the degree of internal soil erosion. The lower the number the less the deterioration and the lower the risk. Based on experience, ratios less than about 0.1 to 0.2 are considered lower risk. Ratios greater than 0.3 to 0.6 are considered relatively serious. Such conditions would likely require mitigation. An example of the Raveling Index calculation is presented in the below Figure 15.

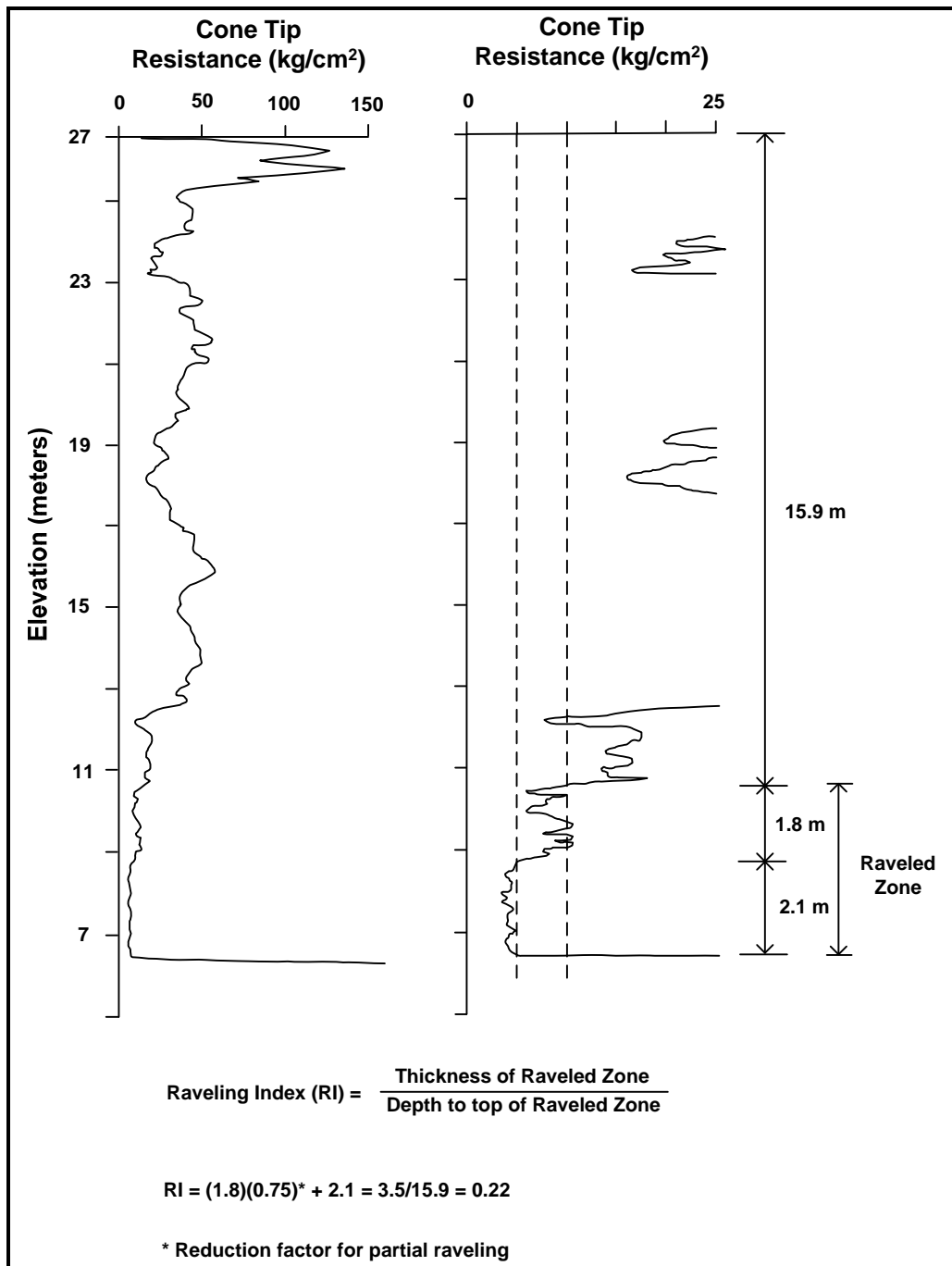


Figure 15, Example Raveling Index Calculation

Finally, the risk evaluation and degree of conservatism applied should also consider the type of structure involved and the risk to public safety. Some structures are more susceptible to the effects of an isolated loss of support than others. Buildings have a relatively large “footprint” and are thus better able to withstand a small to moderate sized sinkhole without experiencing a sudden collapse. In most cases, the failure of buildings in this situation is progressive and there is time for people to evacuate. Conversely, structures such as highway bridges and overpasses are less able to withstand even a moderate sized sinkhole. Bridges are special types of structures because of their public safety aspect and their relatively isolated points of foundation support. This makes them more susceptible to sudden failure. If a bridge pier settled suddenly without warning, people traveling at highway speeds would not have time to react. Serious accidents and loss of life are probable. Thus, a higher level of conservatism is justified for bridges.

Risk Mitigation

There are a variety of means to mitigate the risk of sinkhole activity. The measures taken should consider the type of structure involved as well as the economic and public safety consequences. In cases where the risk appears relatively low and the structure is more resistant (i.e. buildings, etc.), standard shallow foundations may be appropriate. If the risk is higher, Mat Foundations, Structurally Connected Footings, Deep Foundations and/or Ground Stabilization (i.e. cement pressure grouting, etc.) could be appropriate for a building.



When dealing with more sensitive structures such as a highway bridges, both the level of effort put into the evaluation (i.e. exploration, analysis, etc.) and the design factor of safety should be increased. Special designs appropriate for bridges include Deep Foundation Minimum Tip Elevations, Foundation Redundancy and/or Ground Stabilization (i.e. cement pressure grouting, etc.). Due to the limitations discussed previously with the various exploration techniques, the minimum consideration for a bridge located in one of the two highest recharge areas should be Minimum Tip Elevations. The concept is to extend deep foundations to a bearing layer resistant to the sinkhole raveling process. If a sinkhole occurs, the bridge may experience some structural damage, but the risk of catastrophic failure would be reduced.

A common method for repairing sinkholes as well as trying to prevent their formation is cement pressure grouting. This involves installing a grid of injection pipes. The pipes are usually 50 mm (2 in.) to 100 mm (4 in.) inside diameter. And, are extended to the top of rock or other raveling resistant strata. Grout is then pumped under pressure to seal the rock interface and fill/compact the upper loose, raveled soils. The grouting operation is both exploratory and treatment at the same time. Based on the grout intakes, injection points are added, moved or deleted until the area is sufficiently stabilized. This sometimes requires secondary and tertiary grids of injections subdividing the primary grid spacing. The grout usually consists of cement, sand, water and cementitious materials (i.e. fly ash, pozzolan, etc.). Additives such as water reducers or bentonite are sometimes used to improve cohesiveness and pumpability. The grout slump normally varies between about 100 mm (4 in.) to 230 mm (9 in.) depending on how well it is flowing and how well the grout is plugging the point of recharge. Grout quantities can be as small as a 100 m³ (130 cy) to more than 1,000 m³ (1,300 cy). Estimating the grout quantity required is more of an art than a science. The Total Volume Method (TVM) of estimating has been found about as useful as anything. The next two figures explain the Method and how to use it. As shown in Figure 17, the TVM% varied from 19.3% to 36.7% (average 26%) on eleven projects.

Total Volume Method of Grout Estimating

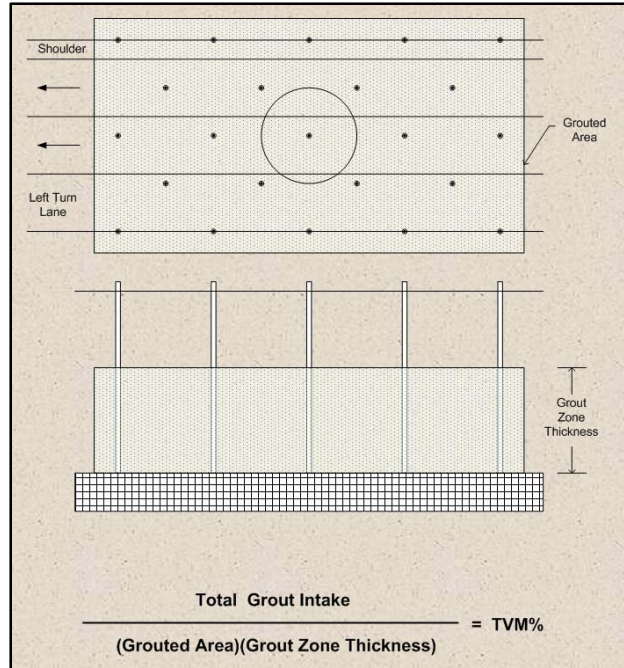


Figure 16, Illustration of Total Volume Method

Date	Project Number	Description	County	Approximate Sinkhole Dimensions		Total Grout Intake (cy)	Number of Grout Injections		Average Primary Injection Depth (feet)	Thickness of Grouted Zone (feet)	Estimated Area Grouted (square feet)	Total Volume Method (%)
				Dia. (feet)	Depth (feet)		Primary (> 5 cy)	Secondary (≤ 5 cy)				
11/21/94	77120-3518	SR 434/Harbour Isle Way Longwood, FL	Seminole	10	0.3	1,153	40	14	62	11.2	14,000	19.8%
1/9/95	11906-9048	US 441 Southbound near Lady Lake	Lake	20	15	594	15	3	68	21.2	3,750	20.2%
11/27/97	75906-9018	Maitland Blvd. WB @ Summit Blvd.	Orange	30	22	818	18	0	70	16.4	4,900	27.5%
4/8/98	Maintenance	SR 44: 2,068' West of County Road 437	Lake	20	18	670	14	3	65	18.0	3,200	31.4%
7/9/98	36002-3503	US 301 Northbound ~ 2 miles S. of Citra	Marion	2	2	81	3	2	61	31.8	187	36.7%
7/26/00	75060-3504	State Road 50 ~ 400 feet W. of Dean Rd.	Orange	60	0.5	2,165	13	3	120	56.7	4,900	21.0%
5/30/02	243865-1	I-4 WB ~ 1,064' South of Lake Mary Blvd.	Seminole	15	7	1,535	24	2	68	32.6	7,200	17.6%
3/13/03	242702-1	I-4 EB Deltona ~ 2,000' N. of Dirksen Dr.	Volusia	5	0.5	526	17	14	53	20.0	2,750	25.8%
7/22/04	Maintenance	US 441 Southbound Ocala	Marion	8	8	149	13	7	32	10.5	1,060	35.9%
8/17/04	Maintenance	US 301 Southbound ~ 3 miles S. of Citra	Marion	14	3	296	9	9	54	19.1	1,800	23.2%
9/9/04	Maintenance	SR 414 (Maitland Blvd.) WB @ Keller Road	Orange	10	4	694	20	25	77	32.4	3,000	19.3%
Averages:				18.4	8	753	15	7	67	26	3,275	26%

Figure 17, Case Histories of Grout Quantity Intake

Conclusions

The following key points can be discerned from the available information on sinkholes:

1. Sinkhole distribution in Florida is not random.
2. There is a good relationship between sinkhole activity and groundwater recharge.
3. Cover-subsidence and Cover-collapse seem to be the predominant mechanisms.
4. Many sinkholes seem to develop as relatively narrow, vertically oriented anomalies.
5. Standard borings and soundings are not good at detecting developing sinkholes.
6. Geophysical Testing methods are not reliable enough yet in all ground conditions.
7. Pore-water pressure sensor arrays may have the ability to locate developing sinkholes.
8. Many factors must be considered to evaluate sinkhole risk.
9. The Raveling Index can indicate the degree of internal soil erosion and degree of risk.
10. Bridge foundations require special consideration and a higher factor of safety.
11. Minimum pile tip elevations are a prudent, cost effective way to mitigate bridge foundation risk.
12. Cement pressure grouting can be used to stabilize and prevent future sinkhole activity.
13. The Total Volume Method is useful for estimating the grout quantity required for stabilization.

Acknowledgments

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References

1. Rupert, F. & Spencer, S (2004), Florida's Sinkholes, Poster 11, Florida Geological Survey, Florida Department of Environmental Protection, Tallahassee, Florida.
2. Stewart, J. W. (1980), Areas of Natural Recharge to the Floridan Aquifer in Florida, Map Series 98, Bureau of Geology, Florida Department of Natural Resources, Tallahassee, Florida.
3. Tihansky, A. B., (1999), Sinkholes, West-Central Florida, in Galloway, Devin, Jones, D. R. Ingebritsen, S.E., eds., Land subsidence in the United States: U.S. Geological Survey Circular 1182, p. 121-140.
4. Jammal, S. E. (1982), The Winter Park Sinkhole, A Report to the City of Winter Park, Florida, Jammal & Associates, Inc. Consulting Geotechnical Engineers, Winter Park, Florida.
5. White, W. B. (1988), Geomorphology and Hydrology of Karst Terrains, Oxford University Press, New York, NY.
6. Foshee, J. R. & Bixler, B. (1994), Cover-Subsidence Sinkhole Evaluation of State Road 434, Longwood, Florida, ASCE Journal of Geotechnical Engineering, Vol. 120, No. 11, November, 1994, Paper No. 6291.