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Composite Shallow & Deep Foundation in Karst Geology for the Countryside Christian Center New Sanctuary Clearwater, Florida

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COMPOSITE SHALLOW & DEEP FOUNDATION IN KARST GEOLOGY FOR THE COUNTRYSIDE CHRISTIAN CENTER NEW SANCTUARY CLEARWATER, FLORIDA

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ABSTRACT

Evaluation, design, construction, and monitoring of foundations in karst geology are challenging tasks. The random presence of karst features, the variation in size, extent, and depth of karst features, and the different origin and geological characteristics of karst features make site characterization and investigation difficult. A balance between non-intrusive filed tests is useful to improve the site characterization. Non-intrusive field tests which provide multi-dimensional mapping such as Electrical Resistivity Imaging (ERI) or Ground Penetrating Radar (GPR) can provide spatial coverage instead of point data. Non-intrusive field tests which are not sensitive to moisture such as shear wave velocity measurements can better characterize the qualitative variations observed in ERI or GPR imaging. Intrusive field tests such as SPT and CPT can provide detailed characterization and quantitative measurements for design at targeted locations which are selected by pre-screening of non-intrusive test data rather than random choice of test locations.

If the site characterization indicates the presence of karst features such as voids or raveling zones, alternative foundation options should be studied to see which option or combination of options can be suitable. Consequence of failure can be critical in determining the extents of the foundation deign for the presence of karst features and costs associated. Foundation elements should be designed to handle “manageable risk” scenarios. Possible loss of support and importance of redundancy should be taken into deign consideration and the random nature of loss of support can be taken into account as part of an assessment with and without a factor of safety evaluation.

At least a case history (Countryside Christian Center) will be presented to demonstrate a foundation design in karst geology using intrusive and non-intrusive field measurements and with “manageable risk”. Evaluations resulted in recommending a shallow foundation / slab assuming possible loss of soil support in a limited area under the shallow foundation (slab) and also deep foundation elements taking into account possible loss of lateral support or loss of a limited number of piles.

This paper encourages implementation of a smarter targeted field investigation rather than randomly punching holes in the ground and missing the voids and raveling zones. The extent and the level of the sophistication of foundation design are subject to the consequence of failure. Redundancy becomes important cost may by reduced by checking to see if the foundation can satisfy ultimate rather than service design condition when addressing the random loss of soil / rock support.

INTRODUCTION

Evaluation, design, construction, and monitoring of both foundations in karst geology are challenging tasks. A typical geotechnical engineering design / analysis involves geology, soil mechanics, and applied mechanics. A successful design / analysis is a result of sound science, reliable engineering judgment, art, and economy.

The variable nature of geology in karst areas makes the collection and the evaluation of data required for the design / analysis more challenging than usual. A proper site characterization plan, while economical, shall capture geological variations. It is not sufficient to only characterize the weak soils and rocks as in many engineering cases, it may be the contrast and distance between the weak and the strong zones that are the controlling design element. A successful site characterization program should provide a detailed qualitative spatial profile of the site for detection purpose and detailed quantitative soil / rock engineering properties at points of interest.

Following a comprehensive site characterization program, the on-site and off-site information should be used to make the engineering judgment about the geotechnical and structural engineering design of the foundation system. Even if no active sinkhole is detected at the site, judgment shall be made about formation and size of a potential sinkhole in future. Judgment shall also consider the impact from loss of ground support at the service criteria level or the ultimate strength criteria level. A foundation system shall be chosen that is not only economical but also can optimize the consequences of a potential failure by using a risk based geotechnical engineering approach and increasing the redundancies in the foundation. Also, the impact of sinkhole formation and loss of ground support (frictional, bearing or both) on structural design, response, and behavior of foundation elements shall be evaluated.

In this paper, the site characterization program and design / analysis are discussed. Information from the site investigation and deign of the 125,000 square feet sanctuary for the Countryside Christian Center in Clearwater, Florida is used as the primary example.

SITE CHARACTERIZATION PROGRAM

It is neither economical nor practical to merely rely on intrusive and penetration point tests regardless of how sophisticated the test is. The subsurface geology in karst environment can be drastically different within less than 8 feet distance under a given footing / slab / pile cap. In order to detect subsurface features, the engineer needs to use fast and economical tests that can provide spatial image of subsurface conditions and its variations. Tests such as the spectral analysis of surface waves (SASW), electrical resistivity imaging (ERI), or ground penetration radar (GPR) can cover a large area relatively fast and significantly cheaper than comparable number of penetration tests required for a similar spatial coverage.

In many cases, the owner / project manager directs that the geotechnical site investigation program to be carried out prior to preparation of the site development plan. In karst geology, even with spatial geophysical profiling, such action can lead to missing potential key geological features under or in the vicinity of key load bearing structural elements. It is crucial to educate the owner / project manager about potential increased cost and / or risk if the geotechnical test locations will not correspond to the critical structural elements after the site plan is developed.

Figure 1 shows the site plan for the 125,000 square feet sanctuary for the Countryside Christian Center in Clearwater, Florida. Series of multi-electrode ERI tests were carried out to characterize the subsurface condition especially along key load bearing structural elements. Figure 2 shows one of the ERI profiles which was performed along the eastern side of the structure. Contrast in electrical resistivity implied potential non-uniform presence of weak / soft / loose soil pockets and also possible raveling zone in the rock. Review of other ERI profiles at the site showed a similar trend under the west side of the structure especial east and northeast. SPT borings within the potential raveling zones confirmed presence of a 20 to 30 feet thick void (cavern) over soft / fractured limestone.

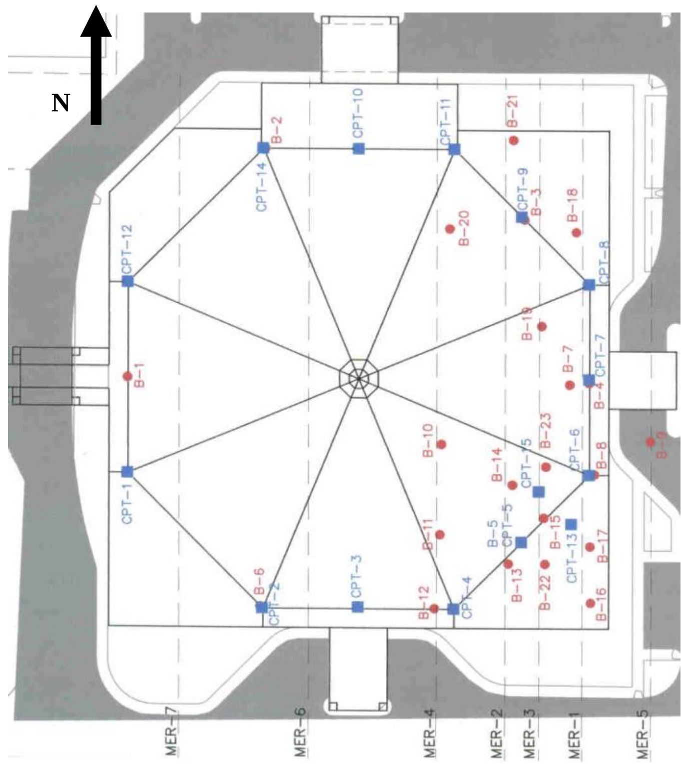

Fig. 1 –Site Characterization Plan – New Sanctuary of the Countryside Christian Center

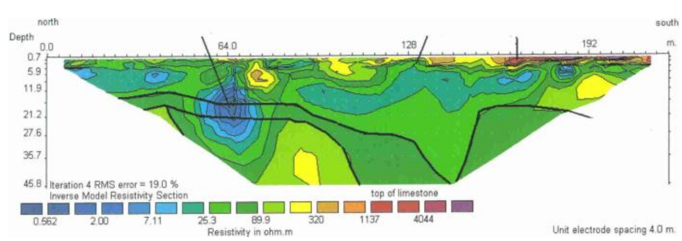

Fig. 2 – ERI Profile MER-1 - New Sanctuary of the Countryside Christian Center

Unfortunately while such tests cover a large area and are very useful in providing a spatial picture of the relative contrast between different features in the subsurface geology, they are not capable of providing reliable qualitative assessment and definitely not suitable for quantitative assessment of the engineering properties which are critical for design / analysis by both the geotechnical and the structural engineers. Referenced methods are good tools to give us a “contrast” indication of variations in soils and rocks over a large area of interest rather compared with point data obtained from penetration tests. Author has frequently encountered cases in which ERI or GPR testing predicted the presence of fine grain soils but further detailed penetration testing has revealed that the layer was coarse grain soils. In addition, the author has observed in many cases that ERI or GPR fail to detect detailed inter-layers within a soil / rock layer. Further investigation using penetration tests has detected and characterized sub-layers. The most significant short coming of ERI and GPR in providing reliable qualitative assessment and certainly any sort of quantitative information is due to their inherent dependence on electrical characteristics of the subsurface soil / rock. A given soil / rock with a specific physical characteristics (soil density, aging, stress history, etc.) can have a diverse response to ERI or GPR as degree of saturation (moisture content) or chemical characteristics (for example salinity of groundwater) of the soil / rock or groundwater changes.

While electrical resistivity based geophysical tests such as ERI or GPR are capable of showing a relative contrast between subsurface soils / rocks within large areas of interest very fast, other non-intrusive tests are recommended to spatially and quantitatively characterize zones of interest before detailed penetration tests are carried out at limited targeted points. Shear wave velocity can characterize an area of the subsurface geology as a non-intrusive (non-destructive) test by sequential surface point measurements and creating a cross sectional profile. Shear wave velocity is a great quantitative assessment of the small strain soil modulus and density and is not influenced by degree of saturation (moisture content) or chemical characteristics (for example salinity) of the soil / rock / groundwater. Performing tests that can provide shear wave velocity measurements such as SASW can provide extensive spatial evaluation of subsurface geology, both quantitative and qualitative, without any penetration at relatively fast pace within areas of interests detected in ERI or GPR profiles. It can locate abnormal soil / rock conditions, sudden change in rock elevation, rock quality, and raveling zones. It also provides valuable quantitative modulus data, which can be used by both geotechnical and structural engineer in design / analysis.

Applications of shear wave velocity measurements to quantify features observed in ERI profile and reduce cost of penetration and laboratory testing is demonstrated in Fig. 3 and 4. Figure 3 shows an ERI profile from a site investigation program in Anguilla, British West Indies. The author was skeptical that low values of resistivity may not be due to solution channels or raveling zones but a combination of salinity of groundwater, carbonate based mineral soil / rock, and highly fractured rock. Shear wave velocity measurements within the low electrical resistivity area resembling a solution channel / raveling zone is shown in Fig. 4. Correlations between shear wave velocity and subsurface soil / rock condition, as recommended by both Uniform Building Code (UBC) and International Building Code (IBC), is used. The results did not show any indications of presence of voids / solution channels / raveling zones. It is noteworthy that a limited large diameter (8-inch) rock coring showed continuous presence of poor quality weathered / fractured / porous low density rock with presence of 20% to 40% rock fragments. Shear wave velocity measurements significantly reduced the amount of penetration testing required and a limited rock coring plus limited SPT testing provided all necessary data required for design. Performing an extensive rock coring and SPT boring, followed by laboratory testing, would have been not only very costly but also very time consuming.

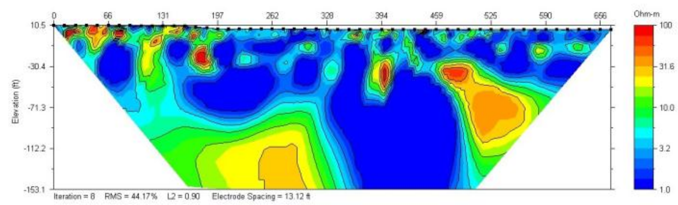

Fig. 3 – ERI Profile P6 – Anguilla, British West Indies

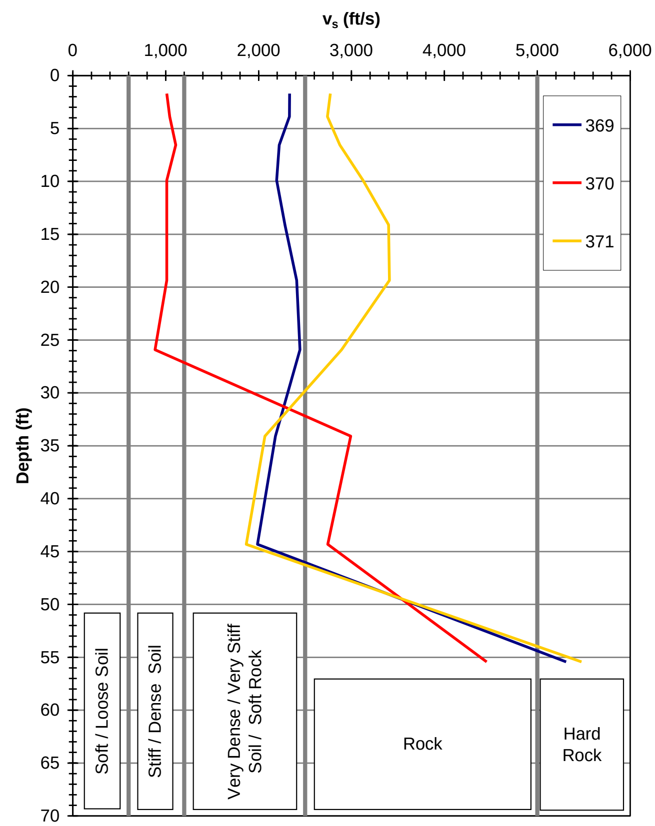

Fig. 4 – Shear Wave Velocity Variations over Low Electric

Resistivity of ERI Profile P6 – Anguilla, British West Indies

Following spatial profiling of the subsurface geology using geophysical tests, limited but targeted focused intelligent penetration field testing such as SPT, CPT, or both plus laboratory testing of soil / rock (if needed) can be carried out to

- validate the projected subsurface condition as depicted in geophysical profiling, and
- obtain the engineering properties needed by the geotechnical and structural engineers.

In karst geology, a sequential and progressive site investigation procedure, as stated here, starting with continuous profiling using fast electrical resistivity based geophysical methods, followed by spatial but slower tests such as shear wave velocity measurements within a targeted zone, then boring at specific points can overcome many shortcomings of a site investigation which is solely based on random borings, borings on a pre-determined grid, or boring under the center of a footing (or pile cap). By providing crucially needed spatially subsurface profiles / information to both the geotechnical and the structural engineers, we can reduce probability and consequences of expensive remedial actions and repairs resulted from sinkhole, raveling, subsidence, or large differential settlements. It can also reduce the probability of catastrophic failures by giving a full detailed image of the subsurface condition that can be taken into consideration in foundation design. A detailed progressive site investigation program, as stated here, may usually be more expensive but it will lead to a greater overall cost effectiveness if it results in reduction of the number of expensive borings and laboratory testing. It may also lead to optimized foundation design rather than an over-conservative design to accommodate uncertainties.

MANAGEABLE RISK AND FOUNDATION DESIGN

While a targeted and focused site investigation plan reduces the probability of missing karst features during the field work, the critical element of foundation design / analysis will be how the information are used to better design and construct the foundation and manage the risk associated with construction in karst geology. Foundation design in karst geology is function of the consequences of failure as it relates to:

- economic loss – Economic loss is not about either a structure is residential or industrial, etc. The author occasionally encounters scenarios that the architect / owner / project manager questions the rationale behind a more sophisticated foundation by stating that it is merely a single family residential house. The distinction shall not be the application of the structure rather it should be the economic loss due to collapse / failure For example, collapse of a $2,000,000 single family residential house can justify extra measures to enhance the foundation while it may not be justifiable to implement the same measures for a $100,000 small starter residential house or a $250,000 commercial / industrial structure. Obviously, it is not rational to spend an additional $50,000 to $100,000 to put a $100,000 house on piles. It is noteworthy that there are simple improvements which do not represent significant cost but can reduce the risk even for less expensive structures. This subject is elaborated further later in this paper;
- loss of life - The potential for major loss of lives resulting from sinkhole activities, raveling, and subsequent collapse at gathering places such as places of worship and sport centers is larger than in a single family house; and
- strategic significance of the structure - The consequences of failure due to sinkhole activities, raveling and subsequent collapse is more significant to a community when the structure is for example the hospital rather than an individual residence.

A reasonable and economic approach to foundation in karst geology is a risk based geotechnical engineering approach. The extent of the site characterization program and the level of the design sophistication are function of the level of risk acceptable for:

- possible failure occurrence;
- severity of possible failure; and
- consequence of failure.

In karst geology, formation of karst feature and related subsidence are not matters of if but when and at what rate. The formation, rate of occurrence, and rate of expansion are functions of many chemical and physical processes and characteristics including soil / rock mineralogy and chemistry, groundwater flow rate and pressure, and groundwater chemistry. The author is not aware of an engineering geological procedure / analysis / method that can reliably predict the occurrence and expansion rate of karst features. A given feature can form or expand in size leading to subsidence within the service life of a structure or it may take place over geological times (hundreds or thousands or years).

If the area is susceptible to sinkhole activities but the site characterization program does not demonstrate the presence of sinkholes / raveling zones / solution channels at the site, the author recommends designing the structure (foundation) to withstand potential future sinkhole occurrence and its impact using risk based geotechnical engineering. Based on consequences of failure (economic loss and loss of life) and importance of the structure, the structure can be designed for a given potential future sinkhole occurrence at critical location. The size of a potential sinkhole for the design purpose is function of the frequency of sinkhole occurrences in the area and their statistical size distribution.

A structure may experience three level of distress:

- cosmetic or architectural / non-structural distress - These distresses typically occur at stress levels below serviceability stress levels (similar to un-factored load design levels);

- serviceability level structural distress – These stresses are due to experience of load beyond serviceability stresses but less than ultimate strength stress levels. These distresses typically occur above working stress levels (un-factored load design level) but below the ultimate strength stress levels (factored load levels). While these distresses are structural distress (non-cosmetic / architectural), if remedial actions are implemented, they do not propagate and do not lead to total failure / collapse. Usually, there is time to implement a corrective action / remedial plan and avoid propagation and total failure; and

- ultimate state level structural distresses – These distresses are those beyond ultimate strength levels. These distresses typically occur when the structure experiences loads beyond designed factored loads. In these cases, the structure usually experience permanent damage which leads to failure / collapse. It is either impractical or costly to repair the structure. These kinds of distresses can also result in sudden and catastrophic failure and loss of life.

A structure is designed for both serviceability criteria and ultimate strength criteria. If a structure is in karst geology but site characterization program does not show the presence of any sinkhole / raveling zone solution channel at the site which can influence the structure, it is probably too extreme to design the foundation for possible future formation of a sinkhole for both serviceability and ultimate strength criteria. The geotechnical and structural engineer have the final say in decision making based on their engineering judgment and they can choose to:

- ignore the risk of any sinkhole formation during the service life of the structure or to choose to design the foundation for a possible future formation of a sinkhole / raveling zone / solution channel during the service life of the structure;

- if they choose to take the possibility of formation of karst features into consideration in the design, they have to choose a reasonable size for a potential karst feature. The size will be function of a typical sinkhole in the area. Obviously it is not practical to design for extreme cases. It is also function of additional construction cost versus consequences of the failure; and

- if they choose to take the possibility of formation of karst features into consideration in the design, they have to decide whether to include the possible presence of a karst feature in the design for only the ultimate strength criteria or for both the serviceability and the ultimate strength criteria. In other words, engineers can decide whether take into consideration the presence of a potential future sinkhole only in the design for the ultimate strength criteria (i.e. prevent collapse in case of a possible occurrence) or in the design for both the serviceability and the ultimate strength criteria (i.e. the structure remains functional even if a comparable sinkhole occurs). If the engineer chooses to design for a potential future sinkhole formation for the ultimate strength criteria, one approach is designing the foundation with applicable safety factors while ignoring potential sinkhole formation and then design / evaluate the foundation with inclusion of the presence of a potential future sinkhole while reducing safety factor or using safety factor of one.

A general review (observation) of available information in Tampa Bay, Florida for frequency and size of sinkhole related ground raveling occurrences shows that a usual typical sinkhole has a surface opening of 10 feet to 20 feet. Therefore designing the slab / footing for the formation of a potential future sinkhole with 15 feet diameter ground opening will probably protect the structure from ultimate failure / collapse against most sinkhole related raveling. It is probably not economical / reasonable to try to protect a structure with no strategic significance against formation of larger sinkholes.

In addition to risk based conservative design for a potential future sinkhole formation, there are also redundancy criteria that can significantly improve the foundation performance if sinkhole formation / raveling / subsidence occurs.

In karst geology, it is a sound design criterion to use smaller size foundation elements at larger quantities rather than large size elements at fewer numbers to create redundancy regardless of whether the engineer chooses to include design for possible formation of karst features.

In design of slab / footing system, it is better to use footings not just under the load bearing walls but also in a grid formation to increase the stiffness (deformational characteristics) and the load transfer capability of the slab / footing system. Such configuration helps the foundation to withstand a loss of support if a sinkhole opens in future.

If a deep foundation is used as part of the foundation design, the engineer can increase the redundancy by implementing the following as they may be applicable or practical:

- in the case of slab / pile system, at least for the ultimate strength criteria, design the slab assuming loss of some piles resulting from sinkhole formation;

- use smaller size piles but more piles;

- piles can be designed with applicable safety factors for both tip bearing and side friction without taking into consideration formation of a potential future sinkhole. Subsequently, the influence of potential future sinkhole formation can be implemented by ignoring the side friction contribution and designing the pile as a tip bearing pile for the ultimate strength criteria and with reduced safety factor or safety factor of one. Many engineers ignore the side friction contribution all together and design the pile as a tip bearing pile with applicable safety factor. It is a matter of risk based geotechnical engineering and the engineering judgment; and

- When designing assuming the potential for a future sinkhole formation, it is noteworthy that the pile design involves a critical structural engineering design component which may end up being the controlling design criteria. If a sinkhole is present or probable to form in future, pile shall be structurally designed for the lateral buckling. In pile design for the lateral buckling, the expected unsupported length is the length of pile which is not confined laterally by soil / rock due to presence of voids / sinkhole / raveling zone / solution channel.

If the area is susceptible to sinkhole activities and site characterization program demonstrate the presence of sinkholes / raveling zones, solution channels / voids, the structure (foundation) shall be designed to take into account presence and impact of such features. The engineer should compare the karst features observed at the site with those representatives of the area. If karst features in the general area are more severe than those observed at the site, it is a matter of engineering judgment and level of acceptable / manageable risk for the engineer to decide either to design for featured observed at the site or for more critical cases observed in the area.

Some of above mentioned discussions / ideas were used in design of the 125,000 square feet sanctuary for the Countryside Christian Center in Clearwater, Florida. Following geophysical field testing at the site using a multi-electrode ERI, eight SPT borings (boring B-1 through B-8 in Fig. 1), fifteen CPT borings (borings CPT-1 through CPT-15 in Fig. 1), and fifteen exploratory drilling without any SPT measurements and spooning (borings B-9 through B-23 in Fig. 1 to investigate extent and nature of karst features and to establish depth to reliable rock layer) were performed. Subsurface soil stratigraphy, depth to rock lenses, depth to reliable rock, extent of kart features such as buried sinkholes, and strength and deformational engineering properties were evaluated and estimated using data collected and empirical correlations.

Based on observations made during the site characterization program and based on evaluation of data collected about presence of karst features and soil / rock properties, it was decided to design the foundation as shown in Fig. 5. Main 100 kips column loads were transferred to bed rock using piles. No active sinkhole was detected in the west side and the foundation was designed as a structural slab with potential for withstanding potential limited loss of ground support. On the east side, karst features were detected. The foundation was designed as a combination of structural slab and pile system.

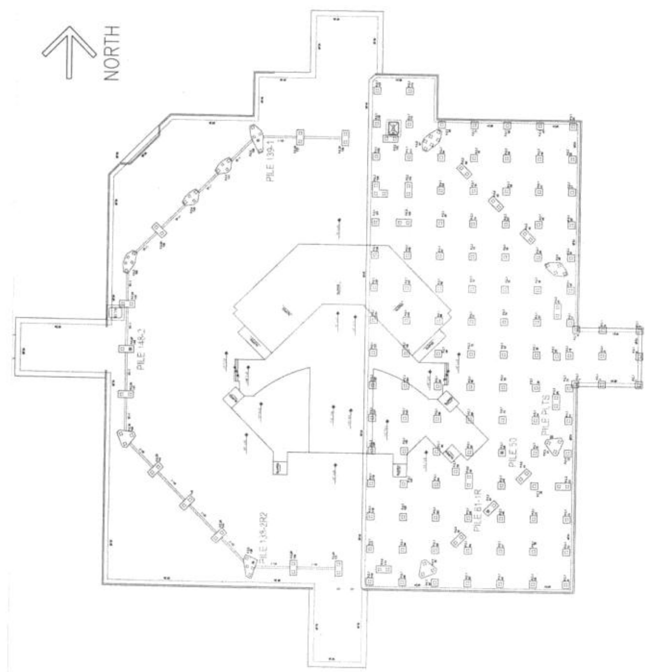

Fig. 5 - Foundation Plan – New Sanctuary of the Countryside Christian Center

Among processed information, a relationship between depth and minimum, average, and maximum CPT tip bearing resistance at a given depth was developed as shown in Fig. 6. Data presented in Fig. 6 in conjunction with LCPC method was used to establish design information for pile design. Relationships between cumulative pile side friction and depth were developed for both auger cast piles and precast driven piles with different cross sectional dimensions using data shown in Fig. 6. Because of the presence of severe sinkhole condition and a 20 to 30 feet thick void (cavern) contribution of side frictional capacity was taken into consideration cautiously. A sample correlation for 18” x 18” precast driven pile is shown in Fig. 7.

Use of a few alternative pile options were evaluated. Auger cast pile had the advantage of drilling to depth and within reliable rock but the disadvantage is significant grout flow in existing subsurface karst features. Use of cased cast in place piles can prevent such a dilemma but it is more expensive. Precast driven pile does not have the problem with flow of grout / concrete into karst features but in presence of rock lenses with soil layers, it may sit on a rock lens rather than reliable rock or it may be damaged during driving when penetrating through rock lenses. In the end, client chose to proceed with precast driven piles as the optimum technical and economic choice. The chance of damage due to excessive hammering was minimized by careful monitoring of the pile driving process and following hammering recommendations. The risk of false refusal and sitting on rock lenses was minimized by extensive geophysical and penetration field testing to establish the reliable bed rock. During construction, if a pile did not reach the expected reliable bed rock, additional sister piles were added.

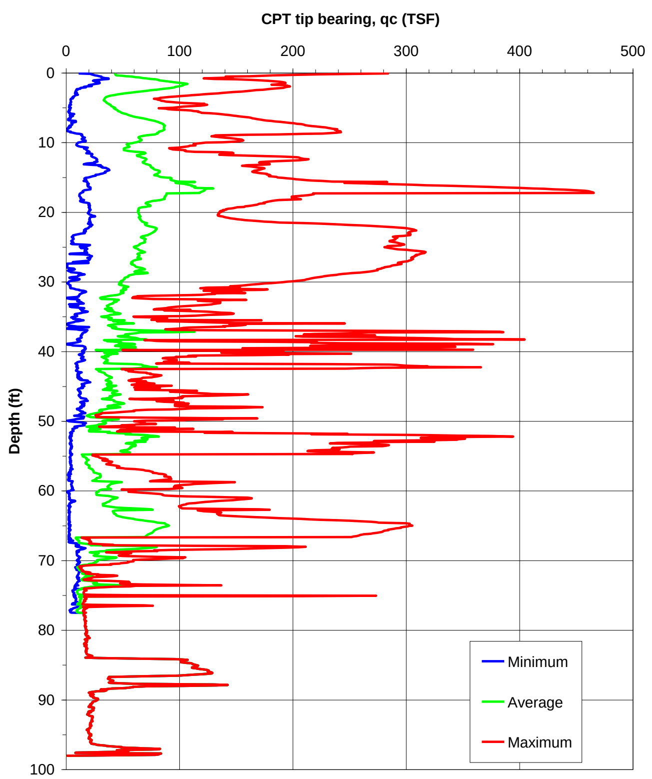

Fig. 6 - CPT Tip Bearing Resistance - New Sanctuary of the Countryside Christian Center

Karins Engineering Group carried out the structural engineering design of the foundation system. The foundation design went through several iterations when considering how to best configure the structure and minimize the risk of damage from karst features. A few design options were considered:

- a structural slab fully pile supported
- a soil supported slab minimizing contact pressure and reinforced to span over areas with existing karst features; and
- a composite system utilizing aspects of both above mentioned concepts.

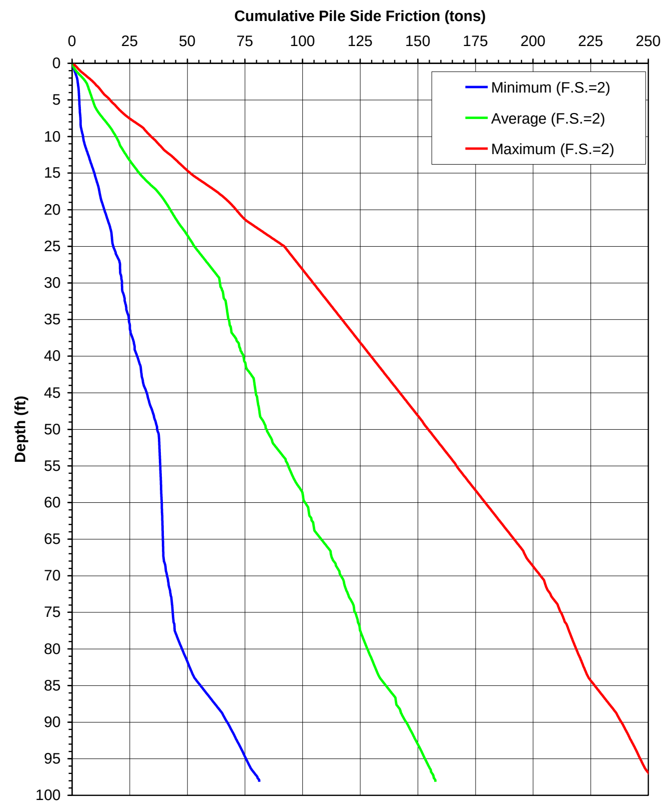

Fig. 7 - Cumulative Pile Side Friction (18" x 18" Precast Driven Pile) - New Sanctuary of the Countryside Christian Center

Pile caps for the critical locations such as key columns with 100 kips loads are supported with multiple piles not only due to required capacity but also to increase redundancy.

Figure 5 shows the final design, which is a composite of soil supported structural slab and piles. In order to consider complex interactions between subsurface soil / rock and the structure as well as between different structural systems, finite element analyses were performed. Applied loads from the superstructure were considered in conjunction with those recommended by pre-engineered metal building manufacturer. A typical graphical image output is presented for one of the parameters for one set of design iterations. Several finite element analysis models were considered to optimize structural efficiency and in an effort to model occurrence of possible subsurface failures. Several additional finite element analysis models were created to determine the structure's response to possible future soil failure events. Soil supported regions were designed to span over areas of up to 30 feet in diameter if ground support would be lost. In structural pile design, loss of lateral soil bracing (support) of at least 20 feet was taken into consideration. A typical graphical image output is presented in Fig. 9 for the same output, which was shown in Fig. 8, after some piles were eliminated to assess the impact of possible partial loss of some foundation support in future. Performing these analyses allowed the team to converge on the final design configuration and design the structure on a risk based geotechnical engineering.

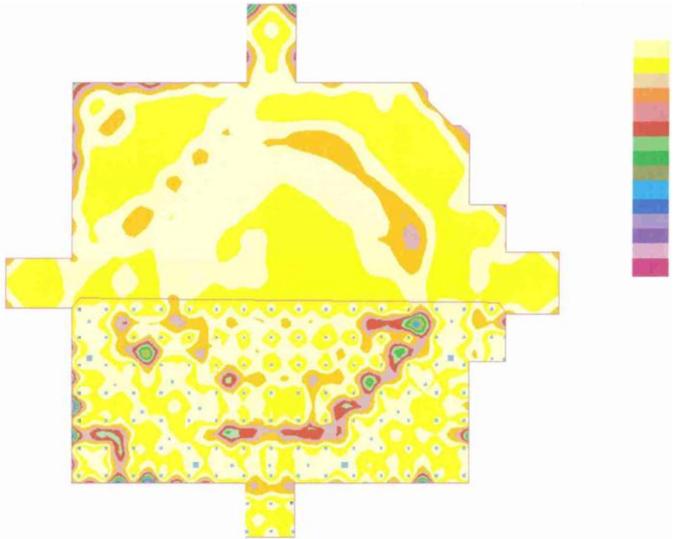

Fig. 8 - Deflections Predicted in Foundation Finite Element Modeling – New Sanctuary of the Countryside Christian Center

CONCLUSIONS

Evaluation, design, construction, and monitoring of both shallow and deep foundations in karst geology are challenging tasks. A successful design / analysis is a result of sound science, reliable engineering judgment, art, and economy. A discussion on approach to foundation design in karst geology was presented. Challenges involved in site characterization program were discussed. A case for implementing a step wise progressive site investigation incorporating sequential application of geophysical testing with capability of spatial profiling followed by targeted point penetration testing was built.

It was recommended to take into account possible future formation of karst features in design if the area is susceptible to such activities even if no such features were encountered during the site investigation. Design for such possibilities can be implemented only against ultimate strength design criteria or against both serviceability and ultimate strength criteria.

Importance of redundancy in design for minimizing possibility of collapse / failure and subsequent losses were discussed. Potential means to create redundancy were also discussed.

Sample site investigation and design were presented with implementing some of the issues which were discussed.

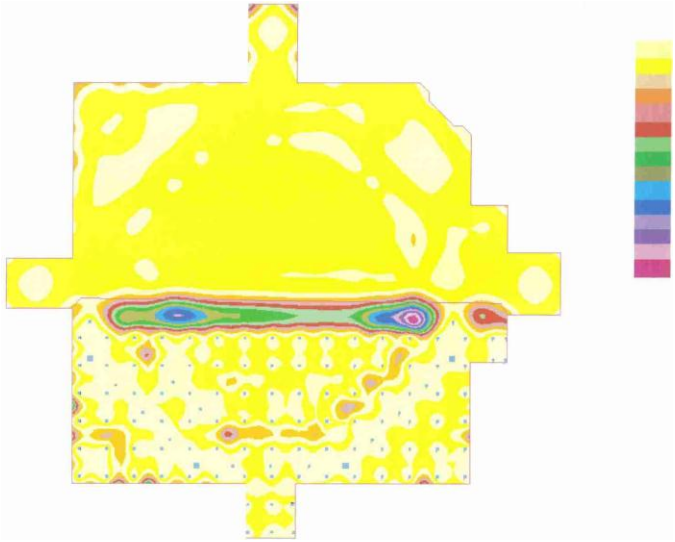

Fig. 9 - Deflections Predicted in Foundation Finite Element Modeling after Assumed Failure of Limited Number of Piles – New Sanctuary of the Countryside Christian Center

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