DEEP FOUNDATIONS IN THE CHALLENGING GEOLOGY OF CENTRAL FLORIDA

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Central Florida is among the fastest growing urban areas in the United States, and its rapid development has required the steady construction of various types of civil engineering works. The karst geologic terrain and variable geotechnical conditions, however, present special challenges to the design and construction of deep foundations.

The subsurface profile can be idealized as a surficial layer of Pleistocene sands, underlain by the highly variable Miocene-age Hawthorn Group, consisting of various combinations of sand, silt, clay, phosphate and highly weathered limestone. The Hawthorn Group is underlain by Eocene-age limestone that comprises the Floridan aquifer. Vast networks of solution cavities are present throughout the Eocene limestone, sometimes allowing downward raveling of the overlying soils and the creation of sinkholes. In some cases, the relic sinkholes can be filled with soft compressible organic soils extending to depths greater than 100 feet (30.5 m).

Driven piles are frequently employed as a deep foundation alternative, although occasionally cast-in-place piles/shafts have also been used. Piles are often driven for bearing in the weathered limestone within the Hawthorn Group, but are sometimes installed as friction piles in the upper soil and intermediate geomaterials. Dynamic pile testing is routinely performed during pre-construction test pile programs, or during production for quality control and assurance purposes.

This paper presents discussions on the design and construction aspects of deep foundations unique to Central Florida subsurface conditions and local practice. Foundation issues such as subsurface variability, soil setup, pile damage, negative skin friction, and sinkhole conditions are discussed with the aid of demonstrative case histories.

INTRODUCTION

Central Florida is among the fastest growing urban areas in the United States. The Central Florida region addressed by this paper is roughly defined in Figure 1. The region includes Orange, Osceola, Seminole, Lake, Brevard, Volusia, Marion, Sumter and Flagler counties. This portion of Florida contains the metropolitan Orlando area, the Kennedy Space Center, Daytona Beach, Walt Disney World and the other themed entertainment attractions known throughout the world. Central Florida's rapid development to accommodate its expanding economy, exponential population growth and tourism has required the steady construction of various types of civil engineering works. This paper addresses the challenging geologic/geotechnical conditions of this region of Florida and presents an overview of the local deep foundations practice.

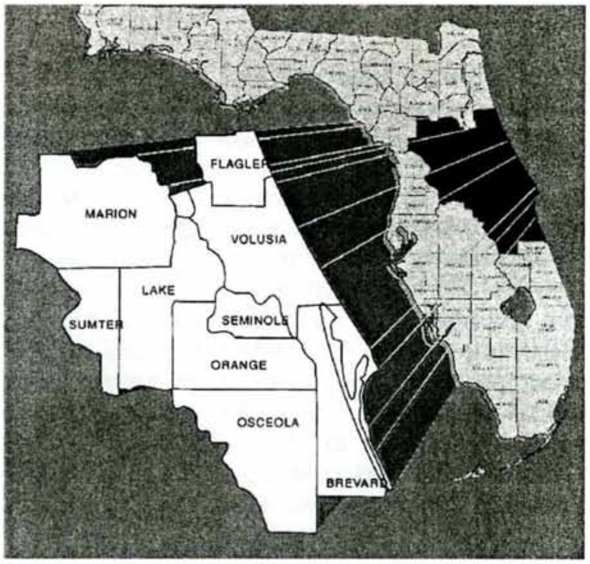

Figure 1
Map of Central Florida

Major cities: Daytona Beach, DeLand, Melbourne, Merritt Island, Ocala, Orlando, and Titusville.

Counties: Brevard, Flagler, Lake, Marion, Orange, Osceola, Seminole, Sumter, and Volusia.

GEOLOGIC PERSPECTIVE

The geology of Central Florida is quite variable in terms of the thickness and elevations of the primary geologic units. In general, the northwest area has thinner overburden soils and rock at higher elevations. Conversely, in the south and east areas, the rock tends to be deeper and the overburden thicker. The hydrogeologic interaction of the subsurface units creates the distinctive karst topography prevalent throughout much of the region.

The surficial unit of the geologic profile consists of Recent and Pleistocene quartz sands containing variable amounts of silt, clay, shell and/or organics. The thickness of this unit ranges from 0 to 200 feet (61 m). The next geologic unit in the profile is the Miocene-age Hawthorn Group. It typically has a greenish-gray or bluish-gray color and is composed of highly variable mixtures of sand, clay, silt, shell, marl, limestone, phosphate nodules and/or chert fragments. The unit is generally more clayey than the overlying surficial unit and typically ranges in thickness from 0 to 200 feet (61 m). The lower portions of the Hawthorn are often composed of very hard desiccated clays and highly weathered limestone.

The Hawthorn Group overlies a cavernous limestone unit made up of the Miocene-age Tampa Formation; the Oligocene-age Suwannee Formation and the Eocene-age Ocala, Avon Park and Lake City Formations. This limestone unit extends to depths of over 1,000 feet (305 m) and comprises the Floridan aquifer, one of the most productive aquifer systems in the world. The limestone is characterized by a vast system of interconnected channels and caverns created by dissolution of the limestone over many millions of years. Similar marine limestones, dolomite, shale, sand and anhydrite continue to about 6,500 feet (1981 m) where granite and other crystalline rocks of the basement complex exist. A conceptual diagram of the three basic units of Central Florida geology can be found in Figure 2.

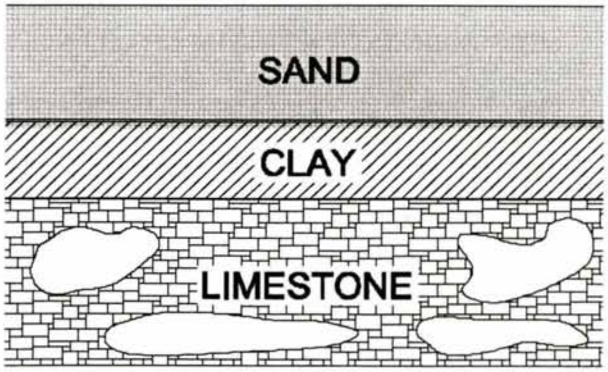

Figure 2

Central Florida Geology

The hydrogeologic situation in Central Florida basically consists of a surficial water table aquifer separated from the Floridan limestone aquifer by the Hawthorn Group. When present, the confining Hawthorn Formation impedes the flow of groundwater between the upper and lower aquifers. In areas where the confining unit is absent, breached or has low clay content and the hydraulic head of the surficial aquifer is higher than the limestone aquifer, groundwater moves downward, recharging the Floridan. The relationship between the water table aquifer and the Floridan aquifer in recharge areas is illustrated in Figure 3. This downward groundwater movement enhances the development of sinkholes by causing raveling of the overlying soils into limestone solution channels and interconnected caverns as shown in Figure 4.

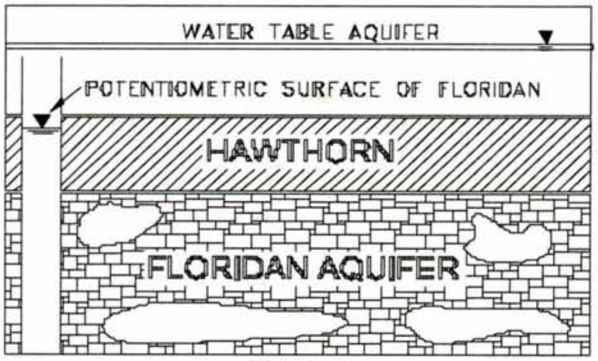

Figure 3
Central Florida Hydrogeology

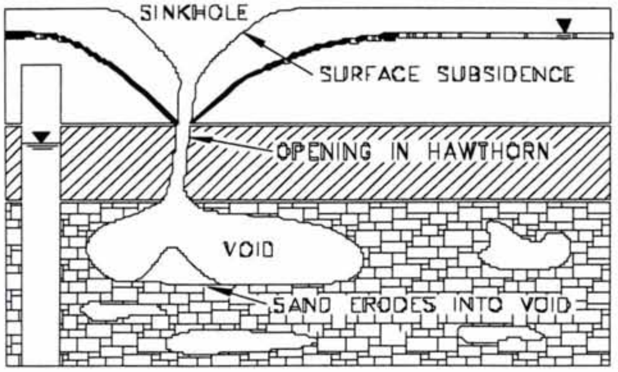

Figure 4

Sinkhole Formation Mechanism

The vast recharge areas of Central Florida are characterized by sinkhole formation and karst topography. When viewed from high above, the Central Florida landscape is dominated by literally thousands of ponds and lakes of various sizes that were formed by sinkhole activity over thousands of years. In some instances sinkholes formed in areas where wetland vegetation flourished and caused the sinkholes to become filled with soft, compressible organic soils, sometimes to depths of over 100 feet (30.5 m). Addressing the challenges of past, present and future sinkhole activity is a major concern in civil engineering design and construction in Central Florida.

Artesian conditions are present in discharge areas where the confining layer is ineffective and the potentiometric level of the Floridan Aquifer is higher than the surficial groundwater table. The natural springs present in Seminole, Volusia and Marion Counties are examples of Floridan aquifer discharge. The Atlantic Coast of Central Florida is characterized by Floridan aquifer potentiometric levels well above ground surface, but the thickness of the Hawthorn Group and overlying sediments preclude discharge or springs. Severe artesian conditions in this area however can pose a challenge to deep foundation construction that breaches the confining layer.

GEOTECHNICAL CONDITIONS

As described in the preceding section, the geology of Central Florida can be described in terms of three basic layers: the surficial sand layer, the Hawthorn Group and the Floridan aquifer limestone. Foundation design over most of the region is concerned with the upper sands and the Hawthorn Group, and both layers vary widely in composition, density, strength and compressibility. The most common methods of subsurface exploration to evaluate geotechnical properties are Standard Penetration Test (SPT) borings and Cone Penetration Test (CPT) soundings. The upper sands are generally comprised of very loose to very dense fine quartz sands with varying amounts of silt and clay. Within the upper sand profile there are often sublayers of sand in a cemented condition that greatly increases the sand's shear strength, and are identified by high penetration resistances. Layers of cemented sand and shell are often present within this upper zone, which also can be characterized by high penetration resistances. In areas where the upper sand layer is deeper than 100 feet (30.5 m), driven piles typically bear within this layer with the pile toe embedded in a dense or cemented sand zone. Friction resistance along the pile sides also provides a significant contribution to pile capacity.

The Hawthorn Group is even more variable than the upper sand layer in terms of its composition and engineering properties. It generally has an increased clay and silt content compared to the surficial sands. A key focus of the subsurface exploration for deep foundations is to evaluate the nature of the upper zone of the Hawthorn Group. In aquifer recharge areas, the upper surface of the Hawthorn has often been disrupted by the downward raveling associated with sinkhole-type activity, sometimes creating a mixture of sand, silt, clay and phosphate with a very loose, slurry-like consistency. Standard penetration resistances within raveled soils are often less than 1 and cone resistances of 5 tons/foot^2 (5 kg/cm^2) and lower are not uncommon. In some instances, loss of drilling fluid circulation is noted in SPT borings within this zone, indicating that the Hawthorn confining layer has been at least partially breached. CPT soundings with piezocone measurements can measure pore water pressures below hydrostatic within this loose zone, also indicating penetration of the confining layer. These findings indicate that the confining layer is at least partially comprised of the loose, raveled soils and the risk of future sinkhole formation is elevated.

Even in areas where the upper zone of the Hawthorn has been degraded by raveling, more competent dense sand or weathered limestone layers are typically encountered within the Hawthorn at greater depths. Borings and soundings are extended at least 15 ft (4.6 m) to 20 ft (6.1 m)into very dense sand or limestone to confirm adequate bearing for pile foundations. In this case pile capacity is derived from end bearing within the dense layer and side friction in the upper sand zone, with little strength derived from the intermediate zone of very loose soils.

In the northwest portion of Central Florida, the Floridan limestone aquifer is at relatively shallow depths and provides significant pile capacity in shaft friction and end bearing. However, the extensive system of voids and caverns throughout the limestone often leads to highly variable pile lengths and challenging installation.

DEEP FOUNDATIONS PRACTICE

Deep foundations work involved in bridge construction is generally governed by the Florida Department of Transportation's three main documents:

- Soils and Foundations Handbook,
- Structures Design Guidelines for Load and Resistance Factor Design, and
- Standard Specifications for Road and Bridge Construction.

In addition, project-specific plan notes and special provisions are developed to address items such as minimum pile tip elevation, predrilling depth, jetting, capacity testing, and soil setup.

Foundation construction in the private sector also follows the FDOT practice to a large extent. The foundation design, construction, and quality assurance/control process is somewhat standardized by the local industry's practice.

As previously mentioned, during the exploratory phase geotechnical conditions are typically evaluated by use of SPT borings and CPT soundings. Generally, one boring or sounding is performed in each bent or pier location and is typically extended to depths on the order of 100 ft (30.5 m) to 150 ft (45.7 m). If pier spacing is not known at the time of the field exploration, borings are performed at a minimum horizontal interval of 100 ft (30.5 m) along the bridge length. To ensure that a competent bearing layer has been penetrated, borings are extended to achieve a minimum termination criterion of 15 ft (4.6 m) with SPT blow counts in excess of 50.

Soil classification tests are performed on split-spoon samples obtained from the SPT borings. These tests typically include percent fines, Atterberg Limits, organic content and natural moisture content tests. Shelby tube samples are obtained of soft, compressible clays or organic material for consolidation and shear strength testing. A double-barreled core sampler is used to obtain 2.4-inch (6.1 cm) diameter samples of competent rock for unconfined compression and splitting tensile strength tests.

A static analysis of pile capacity is performed based on the in situ test data. The predominant method of analysis on FDOT projects is the SPT97 computer program. The SPT97 program provides estimates of pile capacity versus pile embedment depth, generally based on correlation with the results of static load tests performed after pile driving was completed. Therefore, SPT97 was not designed to estimate pile capacity during pile driving, which may be significantly different (lower) than the long-term pile capacity (which a static loading test would evaluate/produce). However, since SPT97 truncates blow counts higher than 60, it may underestimate capacity for piles driven into hard bearing material. Drilled shaft capacity evaluations are performed using the SHAFTUF computer program that is based on the methodology included in the FHWA Drilled Shafts: Construction Procedures and Design Manual.

Prior to the start of construction, the contractor, a specialty contractor or the project general contractor experienced in pile driving installation, submits to the project geotechnical engineer (directly or through the project construction manager) a Pile Installation Plan (PIP) for evaluation and preliminary approval of the contractor's equipment, means and methods. The PIP typically includes: list and size of all proposed equipment (e.g., cranes, barges, auger-drills); manufacturer's specification data of the proposed pile driving hammer system (i.e., properties of hammer, pile cushions and helmet); detailed drawings of piles, cofferdams, pile template, and follower; details of load testing equipment and method; sequence of pile driving within each pile group configuration; proposed schedule for test pile and production pile driving; and other information (e.g., methods and equipment proposed to protect existing structures, placement of fill, and noise and vibration abatement). The engineer evaluates the PIP for conformance with the project contract documents and engineering considerations.

Preliminary wave equation analyses are performed to evaluate the suitability of the proposed equipment to drive the piles to the required depth and capacity within project specifications. For example, the FDOT Standard Specifications for Road and Bridge Construction contain requirements regarding maximum allowable pile driving (compression and tension) stresses, and also minimum and maximum blow counts allowed at the required driving resistance (36 to 120 blows per ft/30.5 cm). Approval of the contractor's pile driving equipment and procedures will be given after demonstration of satisfactory field performance during the test pile driving program.

Typically, and especially for an FDOT bridge project, a test pile driving program is undertaken prior to the start of production pile driving. Depending on the size of the project, the test pile driving program can be a separate contract involving extensive pile driving (with several pile types to various depths) and testing (static and dynamic during initial driving and restrikes), or it can be a part of the project contract done at the beginning of the production work. The purpose of the test pile driving program is to evaluate/finalize the foundation design and construction procedure. Even though they are typically driven in permanent foundation pile locations, test piles are exploratory in nature. They are driven deeper and harder than what would be needed from a production pile. Aspects of the geotechnical design (e.g., driving resistance, and potential for pile/soil-setup), construction equipment, and installation procedures are tested and evaluated during the test pile driving program.

Dynamic pile testing, utilizing the Pile Driving Analyzer® (PDA) and CAPWAP® data analysis computer program, is typically performed during the test pile driving program. Dynamic pile testing is performed to evaluate hammer driving system performance, dynamic pile driving stresses and structural integrity, pile static load bearing capacity, and soil resistance variables including their distribution in skin friction and end bearing and quake and damping values (Hussein and Likins, 1995). Results from the test pile driving program are used to finalize acceptance of the PIP and to determine production pile lengths and driving blow count criteria by performing refined GRLWEAP® wave equation analyses.

Production pile installations are inspected by certified pile driving inspectors who follow standard quality assurance and control procedures. A pile installation log that includes driving blow counts (and for open-ended diesel hammers, corresponding ram stroke heights by utilizing a Saximeter® unit) and other information related to each production pile (e.g., pile location, number, date, hammer model, pile length, cushions, reference elevation, final pile tip elevation, and other information and notes). The pile driving logs and related information are forwarded to the project geotechnical engineer in a timely manner, so that potential problems can be detected and solved without undue delay to the construction schedule, and adverse effect on the project's budget.

DEEP FOUNDATION TYPES

Many types of conventional deep foundations are used in Central Florida. Square prestressed concrete piles (mostly 18-inch (457 mm) or 24-inch (610 mm)) are commonly used for bridge foundations. They usually range in length from 50 ft (15.2 m) to 150 ft (45.7 m); the maximum one-piece pile length deliverable to job sites is typically 130 feet (39.6 m). Epoxy-dowel and mechanical type concrete pile splices are sometimes used, but are avoided when possible during design to limit possible driving problems and delays. Prestressed concrete piles are also used to support many other types of structures, e.g., the extensive addition to the Orange County Convention Center complex, Port Canaveral ship terminal facilities, high-rise towers in downtown Orlando, Orlando International Airport structures, the massive multi-level parking structure (possibly the largest in the world at the time of its construction) at Universal Studios, and countless others. Spun, post-tensioned and prestressed cylindrical concrete piles are also occasionally used (e.g., 26,000 lineal ft (7925 m) of 36-inch (914-mm) diameter piles were used for the construction of the 1700-ft (518.2-m) long East-West Expressway Bridge over Lake Underhill in Orange County, one of the piles was driven to the record length of 355 ft (108.2 m) (Cook, 1974)). Prestressed concrete pile service load capacities are usually in the 60 ton (534 kN) to 150 ton (1335 kN) range.

Steel piles, pipes and H-piles, are also used as deep foundations in Central Florida. H-piles (typically HP 12x53 and 14x89, with lengths of 100 ft (30.5 m) to 150 ft (45.7 m) are almost exclusively used in the bridge widening work associated with the extensive effort to improve the transportation system, especially along the I-4 corridor; pile tip reinforcements are sometimes used. Typical H-pile service load capacities range from about 40 tons (356 kN) to 80 tons (712 kN). Steel pipe piles (typically 12-inch (305 mm) to 24-inch (610 mm) in diameter), open and closed-ended, partially or completely concrete filled, are also used to support bridges, buildings, water storage towers, and many other types of structures. Their ease of length adaptability to the varied subsurface conditions of Central Florida makes steel piles a preferred choice in many cases; one of the case histories discussed below demonstrates this advantage. Steel pipe pile capacities range from about 60 tons (534 kN) to 120 tons (1068 kN).

The use of timber piles is generally limited to small structures (e.g., houses and pedestrian bridges) and marina facilities along the Atlantic Coast and inland waterways. Cast-in-place deep foundations, auger-cast piles and drilled shafts, are also used in Central Florida, but to a lesser extent than driven piles. Auger-cast piles (typically 12-inch (305 mm) to 24-inch (610 mm) in diameter, 50 ft (15.2 m) to 75 ft (22.9 m) in length), conventional and displacement types, are used to support many types of buildings, e.g., high-rise office buildings, hotels, hospitals, and other structures, but not bridges due to its lack of acceptance by the Federal Highway Administration (FHWA) for bridge foundation support. The use of drilled shafts in Central Florida is somewhat limited due to the absence of a shallow hard clay or rock bearing layer that can provide significant capacity.

Other types of deep foundations that provide particular benefits in the special Central Florida geotechnical conditions are also used, such as prestressed concrete piles with steel H-pile extensions employed in seaport construction, and an innovative pile consisting of a tapered square concrete pile with an upper-body smaller-size steel pile designed to minimize settlement due to downdrag (McGillivray and Hussein, 1994).

Local contractors use a variety of pile driving systems for pile installation. Open-ended, i.e., single-acting, diesel hammers with rated energies typically between 50 kip-ft (67.8 kN-m) and 100 kip-ft (135.6 kN-m) are most commonly used to install concrete and steel piles on both public and private sector projects. External combustion, e.g., air/steam and hydraulic hammers are also occasionally encountered on job sites in Central Florida.

Lake Bosse Bridge- A Case History Demonstrating Subsurface Variability

Construction of the S.R. 414 (Maitland Boulevard) Bridge over Lake Bosse in Seminole County encompassed unique and challenging geologic and geotechnical conditions for deep foundations. Lake Bosse was formed by ancient sinkhole activity and subsurface conditions below the lake bottom are comprised of relic sinkholes filled with deep organic soil deposits; extensive soft and raveled soil zones and limestone voids. Eight exploratory SPT borings were performed for assessment of subsurface conditions and foundation design. Some of the soil borings were extended to depths of 300 ft (91.4 m) due to the highly variable and extremely soft soil conditions that were encountered.

The 700-ft (213.4-m) long, 4 lane-wide, low-level FDOT bridge included seven pile supported bents. Each of the two End Bents contained 12 piles, Intermediate Bents 2, 5, and 6 contained 22 piles each, and each of Intermediate Bents 3 and 4 contained 26 piles; for a total of 142 piles. Pile design service loads were 120 tons (1068 kN), with downdrag loads of 50 tons (445 kN) for the end bent piles and 25 tons (222.4 kN) for the other piles, and no scour consideration for any of the piles.

During foundation design it was recognized that the required pile lengths at some bent locations would be very large (greater than 250 ft (76.2 m)) and that the pile lengths would vary widely from bent to bent. Therefore, steel pipe piles were selected for ease of splicing and were considered preferable to H piles since they provided better toe resistance due to their greater end area. The pipe piles were 20-inch (508 mm) diameter, ½ -inch (12.7-mm) thick wall, open-ended, spiral-welded, pipes conforming to ASTM A 252, Grade 3 steel.

The preconstruction test pile program, utilizing the Pile Driving Analyzer® (PDA), included the driving of seven test piles, one in each bent. The following table indicates: (**A**) the original design test pile lengths based on standard geotechnical considerations and foundation analyses, (**B**) actual driven test pile lengths, and (**C**) production pile length ranges in each bent.

Table 1
Predicted and Actual Test Pile and Production Pile Lengths
Lake Bosse Bridge

Bent	1	2	3	4
A	90 ft (27.4m)	240 ft (73.2 m)	260 ft (79.2 m)	270 ft (82.3 m)
B	81 ft (24.7 m)	344 ft (104.9 m)	387 ft (118.0 m)	262 ft (79.9 m)
C	51-81 ft (15.5-24.7 m)	194-387 ft (59.1-118.0 m)	160-387 ft (48.8-118.0 m)	249-400 ft (75.9-121.9 m)

Bent	5	6	7
A	180 ft (54.9 m)	180 ft (54.9 m)	90 ft (27.4 m)
B	228 ft (69.5 m)	307 ft (93.6 m)	81 ft (24.7 m)
C	110-358 ft (33.5-109.1 m)	110-358 ft (33.5-109.1 m)	56-216 ft (17.1-65.8 m)

Some of the piles driven on this project are the longest land piles on record in Florida, and possibly the United States. The longest pile (more than 600 ft (182.3 m) and not included in Table 1) exceeds the record established 30 years ago on another Central Florida project (Foundation Facts, 1971). A total of 37,908 lineal ft (11,554 m) of piles were driven to form the bridge foundations, a 54% increase over the originally assumed design quantity. This case history illustrates the geotechnically and contractually challenging aspects of deep foundation design in highly variable subsurface conditions unique to Central Florida.

SR 527 Over Boggy Creek Bridge – A Case Demonstrating Soil Setup

This case history presents testing results from a project where a significant amount of pile/soil setup (advantageous time-dependent effect) was incorporated into an economical foundation solution. Deep foundations for the mid-size road bridge carrying SR 527 over Boggy Creek in Orange County consisted of 18-inch (457-mm) square prestressed concrete piles with lengths of about 118 ft (36.0 m). The bridge substructure was comprised of two end bents and four intermediate bents. The subsurface conditions can generally be described as layers of loose to medium dense silty and clayey sand with standard penetration resistances generally ranging between 3 and 30. Pile driving and PDA dynamic testing were performed with an open-ended (single-acting) diesel hammer with a ram weight of 6,744 pounds (30 kN).

Figure 5 presents the end of driving and 6-week restrike testing results showing plots of PDA-obtained pile-top force and velocity records along with CAPWAP analysis simulated pile load-movement relationships. Initial pile driving can generally be described as easy to medium driving (with blow counts of less than 4 blows per 0.82 ft (250 mm) and ram strokes of 6 feet (1.8 m) to a depth of 76 ft (23.2 m). The driving resistance increased to an average of 28 blows per 0.82 (250 mm) with strokes of 7.5 ft (2.3 m) at the end of driving penetration of 112 ft (34.1 m). For most of the driving, the pile experienced elastic rebound of 1 inch (25 mm) to 2 inches (50 mm). Pile rebound was much less at the end of driving.

Restrike testing (performed 41 days after end of driving) consisted of driving the pile an additional 2 inches (50 mm), with blow counts of 27 and 25 blows per 1 inch (25 mm) and stroke heights of 9.8 ft (3 m). Testing results indicated an end of initial driving capacity of 124 tons (1100 kN) (94 tons (832 kN) in side resistance and 30 tons (268 kN) in end bearing) and a beginning of restrike capacity of 464 tons (4128 kN) (438 tons (3893 kN) in side resistance and 26 tons (235 kN) in mobilized end bearing).

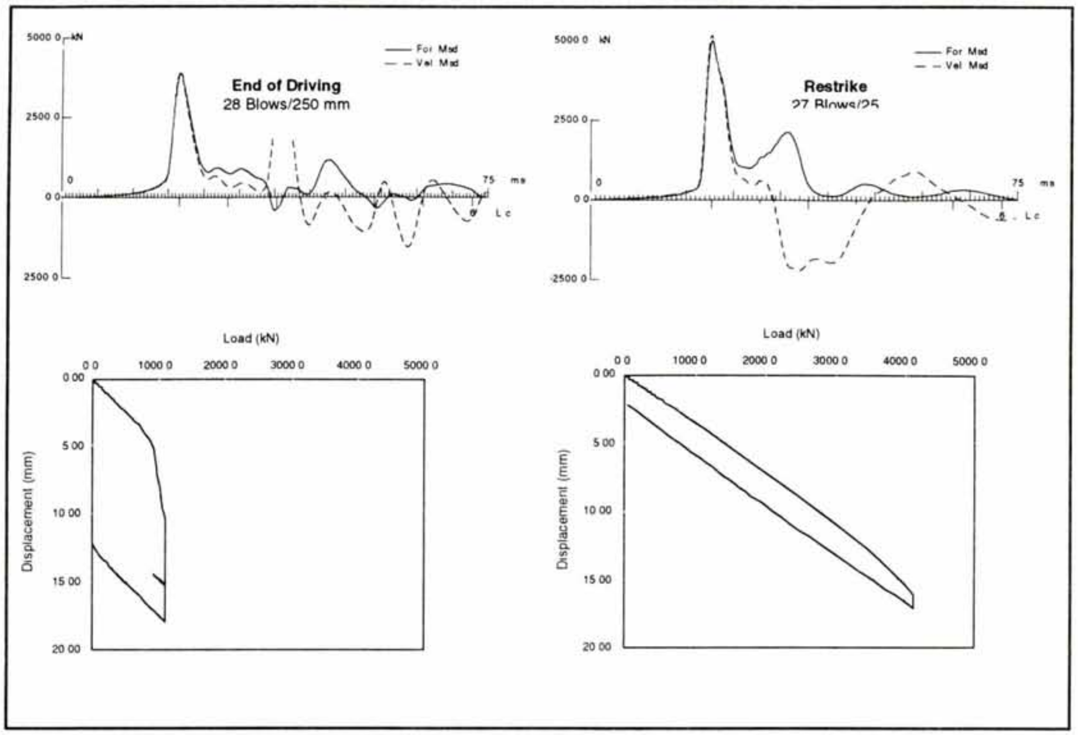

Figure 5

End of Driving and Restrike Dynamic Test Results for SR 527 Over Boggy Creek Bridge

Testing and data analysis results presented in Figure 5 show the beneficial time effects on the pile ultimate capacity and load-movement relationship. This case history demonstrates how under the favorable geotechnical conditions at this site, the piles may be used with a design load of at least 185 tons (1650 kN). The finished bridge is shown in Figure 6.

Figure 6
Photograph of SR 427 Over Boggy Creek Bridge

The Broadway Bridge – A Drilled Shaft Case History

Drilled shafts are seldom used in Central Florida for support of major structures since the significant depth to a hard clay or rock bearing layer requires a large, deep shaft to achieve sufficient shaft capacity, thereby limiting their cost-effectiveness. However, geologic conditions along the Atlantic Coast make shafts practical for some large bridges, particularly when lateral loads (e.g. ship impact loads) are critical in the design.

The Broadway Bridge is a high-level, post-tensioned, segmental concrete structure which spans the Halifax River Intracoastal Waterway in downtown Daytona Beach, Florida. A narrow barrier island separates the Halifax River from the Atlantic Ocean. The bridge provides access from the mainland to the barrier island beaches via State Road 600 (US 92). Ground surface elevations in the area are relatively flat varying between about +10 ft (3.1 m) to +15 ft (4.6 m) NGVD. The river bottom in the bridge vicinity is about elevation –3 ft (-0.9 m) to –6 ft (-1.8 m) NGVD.

The structure has a total length of approximately 3,010 ft (917.5 m) and a vertical clearance of just over 65 ft (19.8 m). The 320-ft (97.5-m) long flat slab sections, which make up the western and eastern ends of the bridge, are supported on 4-ft (1.2-m) diameter drilled shafts with design capacities of 675 tons (6005 kN). The rest of the bridge is supported by 5-ft (1.5-m) diameter drilled shafts with design capacities of 844 tons (7509 kN).

The upper 50 ft (15.2 m) of the subsoil profile consists of loose to medium dense fine sands containing variable amounts of shell, silt and clay. From 50 ft (15.2 m) to 80 ft (24.4 m), the sandy soils become more clayey and are frequently interbedded with substantial layers of soft to stiff silts and clays with variable amounts of sand and shell. Below 80 ft (24.4 m), the borings encountered hard limestone to depths of approximately 130 ft (39.6 m). In some places, a thin layer (i.e., ≈ 1-ft (305 mm) thick) of cherty caprock was encountered at the limestone surface. Rock cores (2.4-inch (61 mm) diameter) of the sub-caprock limestone exhibited recoveries ranging from 12 to 100% (average 48%) and Rock Quality Designations (RQD) values between 0 and 72% (average 26%). Unconfined compression tests (ASTM D2938) and splitting tensile tests (ASTM D3967) on 168 samples of non-caprock limestone yielded values ranging from 37 psi (255 kPa) to 11,233 psi (77,448 kPa) (average 936 psi (6454 kPa) and 13 psi (90 kPa) to 499 psi (3,441 kPa) (average 203 psi (1400 kPa)), respectively. Four samples of the cherty caprock had unconfined compression and splitting tensile strengths of 11,233 psi (77,448 kPa) to 16,846 psi (116149 kPa) and 946 psi (6,522 kPa) to 2,144 psi (14782 kPa), respectively.

Load tests were performed on several drilled shafts *prior* to production shaft construction. The load test program consisted of one, 2-level Osterberg Cell axial test, three 3,372-ton (30-MN) Statnamic axial tests and one 4,496-ton (4-MN) Statnamic lateral test. The Osterberg Cell test yielded average rock shear and shaft bearing values of 6.9 tsf (661 kPa) and 60.9 tsf (5,832 kPa). An axial Statnamic test run on the same shaft resulted in an average Rock Shear value of 6.5 tsf (622 kPa). The other two axial Statnamic tests yielded average Rock Shear values of 5.2 tsf (498 kPa) and 7.1 tsf (680 kPa). None of the Statnamic tests achieved ultimate end bearing (toe resistance). The 4,496-ton (4-MN) Statnamic lateral test was run at loads of approximately 30 tons (267 kN), 59 tons (525 kN), 74 tons (658 kN) and 118 tons (1050 kN). The maximum deflections at these loads were 0.9 inches (23 mm), 2.0 inches (51 mm), 3.1 inches (79 mm) and 4.7 inches (119 mm), respectively.

Shaft construction equipment is shown in Figures 7 and 8. The shafts were constructed with permanent casing to the limestone surface. Soil excavation was accomplished with a digging bucket. A core barrel was then used a short distance (i.e. ≈ 1.5 ft (0.46 m) to extend the rock socket through the cherty caprock. The remainder of the socket was excavated with a rock auger. An over-reamer (i.e., tool with short protruding lengths of wire cable) was used to prepare the socket sidewalls. Rock cuttings were removed with a digging bucket and a cleaning bucket. Final cleaning of sediments and drilling fluid from the shaft bottom was done with an airlift. The average rock socket length was about 20 feet (6.1 m).

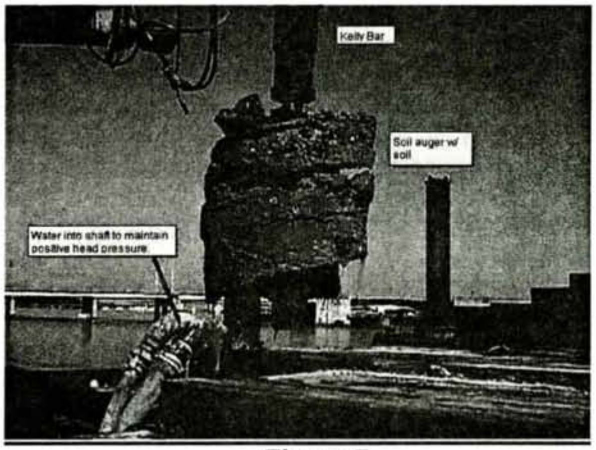

Figure 7
Soil Anger Excavation of Shaft

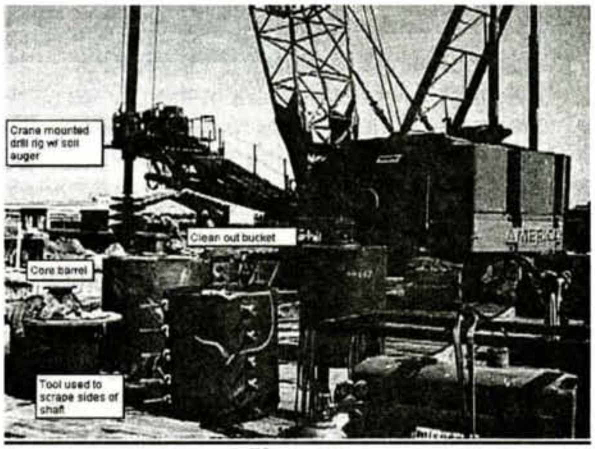

Figure 8
Shaft Excavation Equipment

SUMMARY

The geology of Central Florida is quite variable in terms of the thickness and elevations of the primary geologic units, and can generally be described in terms of three basic layers: the surficial sand layer, the Hawthorn Group and the Floridan aquifer limestone. The distinctive karst topography is prevalent throughout much of the region. The hydrogeologic situation enhances the development of sinkholes by causing raveling of the overlying soils into limestone solution channels and interconnected caverns.

Foundation design over most of the region is concerned with the upper sands (generally comprised of very loose to very dense fine quartz sands with varying amounts of silt and clay, often with sublayers of cemented sand and shell) and the Hawthorn Group, and both layers vary widely in their geotechnical properties. Where the upper sand layer is deeper than 100 ft (30.5 m), driven piles typically bear within this layer with the pile toe embedded in a dense or cemented sand zone. Friction resistance along the pile sides also provides a significant contribution to pile capacity. The Hawthorn Group is even more variable than the upper sand layer in terms of its composition and engineering properties, with generally an increased clay and silt content. A key focus of the subsurface exploration for deep foundations is to evaluate the nature of the upper zone of the Hawthorn Group. The most common subsurface exploration methods are the Standard Penetration Test (SPT) borings and Cone Penetration Test (CPT) soundings.

Deep foundation work involved in bridge construction is governed by the Florida Department of Transportation's design guidelines and specifications. Foundation work in the private sector also follows the same practice to a large extent. The foundation design, construction, and quality assurance/control process is somewhat standardized by the local industry's practice.

Many types of conventional deep foundations are used in Central Florida. Square prestressed concrete piles (mostly 18-inch (457 mm) or 24-inch (610 mm)) are commonly used for bridge foundations. Steel piles, pipes and H-piles, are also used; H-piles are almost exclusively utilized in the bridge widening work associated with the extensive effort to improve the transportation system. Cast-in-place piles and drilled shafts have also been used to support a variety of structures. Other types of deep foundations that provide particular benefits in the unique Central Florida geological conditions are also used.

The case histories presented in this paper illustrate the unique challenges and opportunities associated with deep foundation design and construction in Central Florida. Geotechnical engineers are challenged to deal with highly variable subsurface conditions, sinkhole activity, deep organic soil deposits and hydrogeologic considerations. There are also opportunities to take advantage of the time-dependent strength characteristics of Central Florida soils in driven pile design. Although Central Florida geology is often not conducive to drilled shafts, a case was presented that demonstrates that drilled shafts can be used effectively in the appropriate geologic setting.

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