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Advancements in Drilled Shaft Construction, Design, and Quality Assurance: The Value of Research

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Abstract: For the past 20 years, researchers at the University of South Florida have been striving to bridge the gap between research and practice and to speed the process by which academic findings are implemented by the foundations industry. Their aim is and has been to solve on-going construction problems, enhance usable capacity, and assure quality foundation elements. This article addresses the findings of several research projects and how they are in use today. The topics include: seal slab construction, rapid hydration of mineral slurry, tip-grouted drilled shafts, and quality assurance using Thermal Integrity Profiling.

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Introduction

Research is a broad field that spans from basic research, with the quest for knowledge of any kind, to applied research, which at its most rudimentary is trial and error. This spectrum has been qualitatively compared to the works of Niels Bohr whose work defined how electrons produce light to Thomas Edison who labored to find long-lasting light-producing filaments.[1] Basic research has been shown to have the most long-lasting effect although it may have no direct application, whereas applied research has a shorter life expectancy but with more immediate uses.[2] Civil engineers are applied scientists who must balance theory with practice and likely lean more towards Edison. Construction must take this further and perhaps unwittingly subscribes to the mantra “mater artium necessitas” [3] or “necessity is the mother of invention”; it only takes one on-site visit to recognize these innovations.

Civil engineering research faculty members are faced with identifying niches that both add to the body of knowledge and provide functional solutions. Often researchers identify an area of interest in anticipation of, or with the perception of, an impending concern. As a result, some research goes unnoticed and may not be implemented or even be implementable. In reality, a crystal ball is not needed; the problems are already there for the solving. It has been the goal of the author and his colleagues to conduct research with usable outcomes and long-lasting value.

This article presents the results of past research studies and the present impact on practice. These studies will be limited to those that apply directly to drilled shaft construction, capacity enhancement, and quality assurance. Each section begins with the problem statement followed by the research findings. References sorted by topic as well as downloadable software are provided.

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Rapid Hydration of Mineral Slurries

Over the past 30 years, drilled shafts have become more widely used, thus the quality of construction practices and inspection has heightened. Use of mineral slurry is a common wet construction technique to stabilize the excavation walls especially in the presence of a high water table. Two areas of mineral slurry will be discussed: preparation of slurry and the effects on bond in seal slab design.

Problem Statement

Dry powdered montmorillonite is used in the preparation of drill slurry, which may take several hours or even days to properly hydrate. In practice, many contractors will mix a sufficient volume one or two days in advance in agitating holding tanks to minimize delays at the time of drilling. When permeable soils or limestone cavities are encountered, some, if not all, of the slurry can be lost. This results in backfilling and construction delays. Therefore, a means to rapidly prepare and replace mineral slurries lost during construction is needed. Additionally, the cost of single shaft applications where only a small quantity of slurry is needed (1.2m diameter shaft, 8m long or 9m^3) can be drastically increased when specialized holding tanks must also be mobilized. Rapid slurry mixing could also aid these cases.

Solution

The efficiency of the slurry mixing/hydration process stems from the initial contact between the powder and water. Slowly applied amounts of powder to moving or agitated water mix more thoroughly and readily, whereas dumping bags of powder into large mixing vats only produces large clumps of dry powder encased in a skin of partially hydrated clay. If not mechanically broken apart, the clumps will never become slurry. In some states a minimum hydration time (e.g. 24 hrs) is specified to account for inefficient powder introduction methods [4]. Similarly, in other states, specifications are performance driven to assure the slurry will perform adequately [5].

Working closely with the manufacturer [6], off-the-shelf eductors

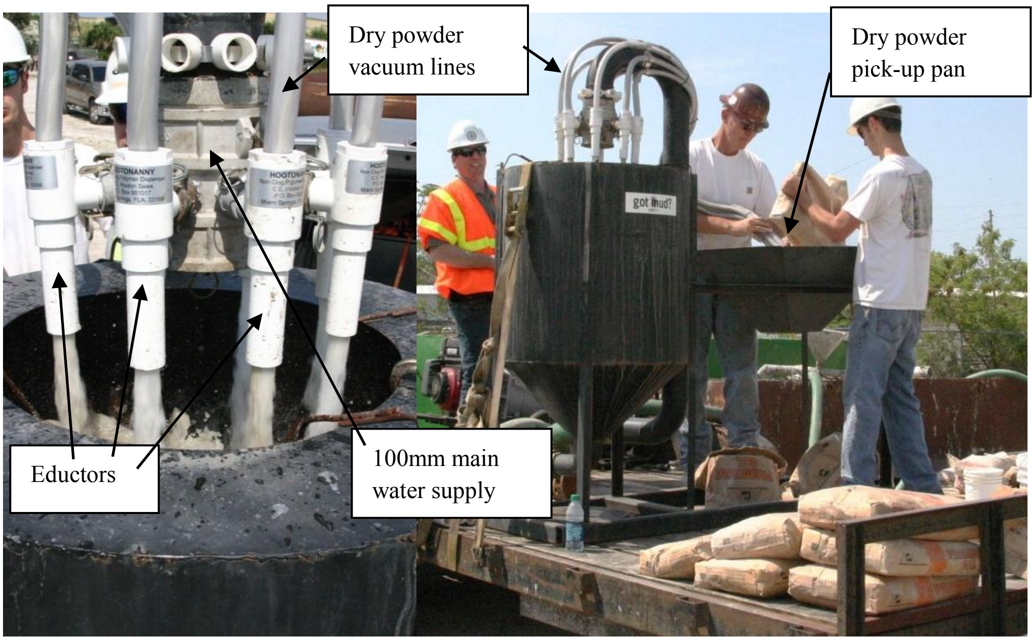

Fig. 1. Mixing System with Multiple Eductors to Increase Contact Area Efficiency.

Fig. 2. Precast Coffer Cell Sealed to Drilled Shaft with Tremie Placed Seal Concrete.

normally used to mix powder polymers were substituted for the traditional mud gun. When combined into a system using a funnel bottom tank and a transfer pump, the target 9 m^3 (2500 gal) volume of slurry could be mixed in less than 15 minutes. Although an intermediate slurry tank was used, the slurry viscosity and density met local state standards immediately upon exiting the system. The system uses 8 parallel eductors to mix at rates up to 1 m^3/min (260 gpm) with ratios of 60 g/L (50 lbs/100 gal).

Each eductor produces a vacuum (0.8atm below atmospheric) which draws the dry powder into to mixing chamber at a rate proportional to the water flow. Interestingly, where the supplier-recommended mix ratio for bentonite powder was 66 g/L (55 lbs/100 gal) to achieve a 42 s/L (40 s/qt) viscosity, only 43 g/L (36 lbs/100 gal) were required due to efficient mixing of all material (no unmixed clumps). Full details can be found elsewhere [7, 8].

Bond of Seal Slabs to Concrete Foundation Elements

Problem Statement

Seal slabs are unreinforced concrete slabs cast inside cofferdams to prevent the intrusion of water and provide a dry working surface at the base of cofferdams for subsequent construction of the footing (Fig. 2). The design of seal slabs prior to this study did not fully recognize the contribution of bond to the piles or shafts in resisting uplifting buoyancy pressures. Despite numerous related studies, there was no rational design for the seal slab bond capacity, making seal slabs much thicker than necessary.

Solution

Full scale pullout tests of steel and concrete piles cast into seal slabs were used to quantify the effects of varied casting conditions which were placed through with a tremie: bentonite slurry, salt water, fresh water, and in the dry.

The old design approach simply balanced an equivalent weight of concrete with the buoyancy caused by that depth of water, and little to no allowance was given for the bond between the piles or shafts and the seal slab; hence, 3 m of water would require a 1.2 m thick seal slab by balancing the products of density and thickness. Standards allowed for 69 kPa (10 psi) between the seal and all pile surface but did not address environmental conditions (e.g. slurry, salt or fresh water) [9, 10].

A test setup was devised that used an inverted version of field conditions, where, instead of pulling the seal slab upwards off of the piles, a pullout frame was placed on top of the slab, and piles were pulled upward out of the slab one a time (Fig. 3). Test results showed that a critical bond length was developed beyond which additional embedment depth had progressively less effect. To account for the decreased effective bond strength as a function of embedment depth, local state specifications chose an extrapolated capacity of 517 kPa (75psi) to account for any slab thickness (Fig. 4) [11].

Fig. 3. Bentonite Slurry in Coffercell (Left); Pullout Testing of Concrete Pile (Right).

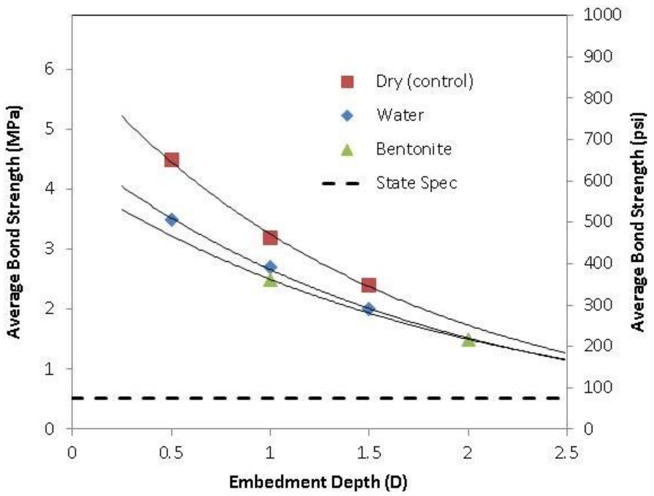

Fig. 4. State Specified Bond Strength Increased to 517 kPa (75 psi) [11].

As a result, the minimum slab thickness (t) required to balance uplift buoyancy using both bond and slab weight can be calculated with the following equation:

$$s^2(9.8d_{water} - 23.6t) = 517\pi d_{shaft}t \tag{1}$$

Solving for t:

$$t = \frac{9.8d_{water}s^2}{517\pi d_{shaft} + 23.6s^2} \tag{2}$$

where the depth of the water (d_{water}), diameter of the shaft (d_{shaft}), and shaft spacing (s) are all input values. However, the unreinforced slab capacity often controls where the modulus of rupture (f'_t) is dictated by the tensile strength of the seal concrete.

$$\frac{9.8d_{water}(s - d_{shaft})^2}{8} = \frac{f'_t(t^2)}{6} \tag{3}$$

Full details of the research findings can be found elsewhere [12-16].

Post Grouting to Enhance End Bearing

Problem Statement

The unit end bearing of drilled shafts tipped in cohesionless soil can be on the order of twenty times the unit side shear. But, it requires 10 to 30 times more displacement than side shear in order to mobilize the same percentage of its ultimate value. As a result, engineers typically discount or significantly reduce the end bearing contribution to the overall capacity of drilled shafts to accommodate service/displacement limits. Any means that could improve the strain compatibility between end bearing and side shear would greatly increase the usable end bearing. In the early 1960s, efforts to improve the end bearing of drilled shafts began in other countries using high pressure neat cement grout injected beneath the shaft tip. This both densifies the soil and decreases the displacement needed to develop usable end bearing. However, in the absence of rational design procedures, only one instance of its use in the United States had been documented [17-19].

Solution

A four-year study involving full scale load testing of drilled shafts with grouted and ungrouted tips was undertaken to isolate the variables affecting performance/improvement and incorporate them into a design methodology. The findings encompassed both geotechnical design considerations and field implementation.

With regards to end bearing strength gain many of the results are intuitive: (1) higher grout pressure imparted to the tip provides more improvement, (2) longer shafts or shafts with higher side shear resistance can withstand higher pressure, (3) higher length to diameter ratios provide more resistance, and (4) both stiffness and ultimate capacity are increased.

From an implementation standpoint the study found: (1) grouting provides a "proof" test of the shaft capacity, (2) free draining soils compress more readily within the short lifespan of the liquid grout and result in higher improvement ratios, yet (3) all soils can be improved, and (4) field monitoring of grout pressure, shaft uplift, and grout volume provides the fundamental quality assurance mechanism to assure proper end bearing enhancement.

The design procedure that ensued was based on the load test results from over 100 shafts from 5 different sites and was summarized with the follow expression to predict grouted end bearing capacity in cohesionless soil [20]:

$$q_{grouted} = TCM(q_{ungrouted}) \tag{4}$$

where

$$TCM = 0.713(GPI)(\%D^{0.364}) + \frac{\%D}{0.4(\%D)+3} \tag{5}$$

and

TCM = tip capacity multiplier

$q_{grouted}$ = grouted unit end bearing capacity

$q_{ungrouted}$ = ungrouted unit end bearing capacity (normal shaft capacity)

GPI = grout pressure index (grout pressure / $q_{ungrouted}$)

$\%D$ = permissible displacement / shaft diameter x 100%

The maximum grout pressure (P_{max}) to determine the GPI is then dependent on the side shear resistance and the tip area of the shaft such that:

$$P_{max} = (average\ unit\ side\ shear)\pi DL \tag{6}$$

When grout pressure is zero, the first term (Eq. 5) drops out and the *TCM* reverts to Reese and O'Neill's relationship for end bearing capacity as a function of displacement [21]. The *TCM* forms a surface dependent on displacement and grout pressure as shown in Fig. 5.

Today hundreds, if not thousands, of post grouted shafts have been constructed throughout the country, and the design procedure has been used worldwide. Complete details of the testing programs and development of the design method can be found in the references [22-27] .

Thermal Integrity Profiling

Problem Statement

The durability as well as structural and geotechnical capacity of drilled shafts relies on the thickness and quality of the concrete cover around the steel reinforcement cage. Although geotechnical resistance factors for shaft capacity are based on the level or type of testing, structural resistance factors are the same for both above- and below-ground structures. As the shaft shape cannot be visually verified, there is need for quality assurance measures to remove this uncertainty.

Solution

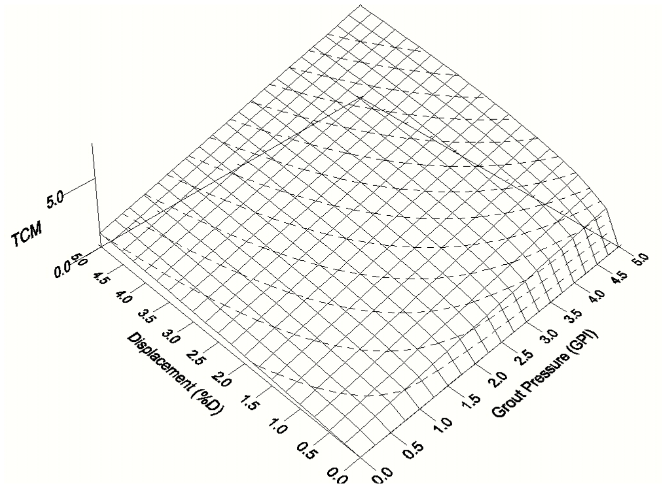

Fig. 5. TCM linearly Related to GPI and Exponentially Related to %D.

Fig. 6. Field Testing Using Thermal Probe (Left); Thermal Wire (Right).

Thermal Integrity Profiling (TIP) is a newly developed method capable of detecting the presence (or absence) of intact concrete both inside and outside the reinforcing cage where other testing methods are less sensitive.

The test method uses temperature measurements taken at the location of the cage by way of a probe lowered into standard access tubes or by full length embedded thermal wires tied to the cage in a similar configuration (Fig. 6). Small shafts or augercast piles can use a single wire system like shown in Fig. 6 (right).

The presence of hydrating cementitious materials (e.g. cement, flyash, or slag) produces an increased temperature proportional to the amount of binder and the volume of the concrete mass. For any given shaft mix, variations in the shaft diameter will produce higher temperatures for larger diameters and vice versa (Fig. 7).

At the radial location of the cage (dashed lines in Figs. 7 and 8), the slope of the temperature versus position curve is steepest. This makes temperature measurements at the cage highly sensitive to cage eccentricities. Hence, both cage alignment and shaft diameter affect the measured temperature. Effects of cage alignment are noted by lateral movements up or down the Fig. 7 curves while effects of the local shaft radius are represented by vertical movement between curves on Fig. 7 to a different curve.

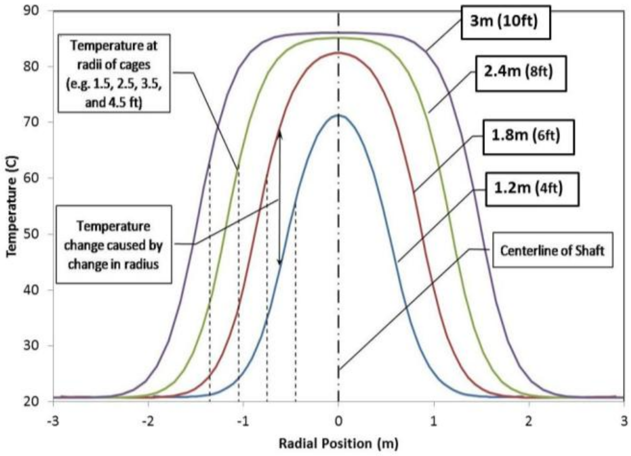

Fig. 7. Temperature Distribution Across Various Shaft Sizes, all with Same Concrete, f'$_c$ = 28 MPa (4 ksi).

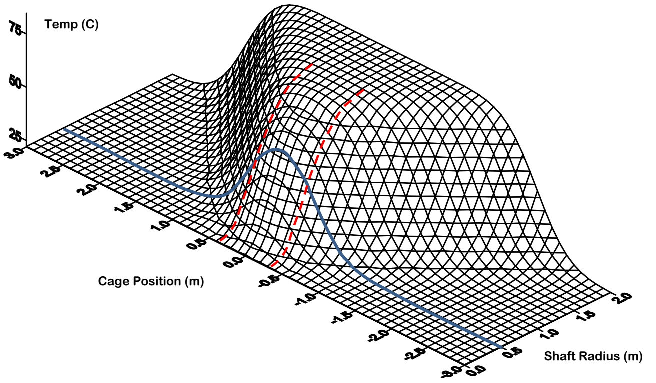

Fig. 8. Two Factors Equally Affecting Temperature: Cage Alignment and Shaft Radius.

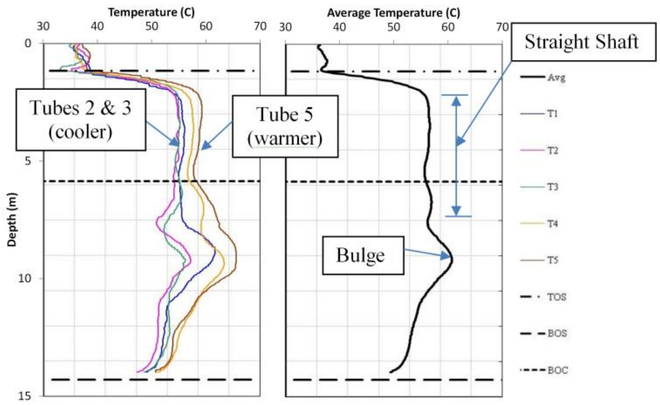

Fig. 9. Thermal Profiles from Individual Tubes (Left); Average of All Tubes (Right).

These effects can also be shown as a 3-D surface where cage movement and local shaft radius have equal effect on the measured temperature (Fig. 8). The position of the cage for a 1m shaft is noted as an example. Note that for large diameter shafts there is no increase in core temperature (cage position = 0).

As opposite sides of an eccentric cage are warmer and cooler dependent on the relative distance from the center or edge, the

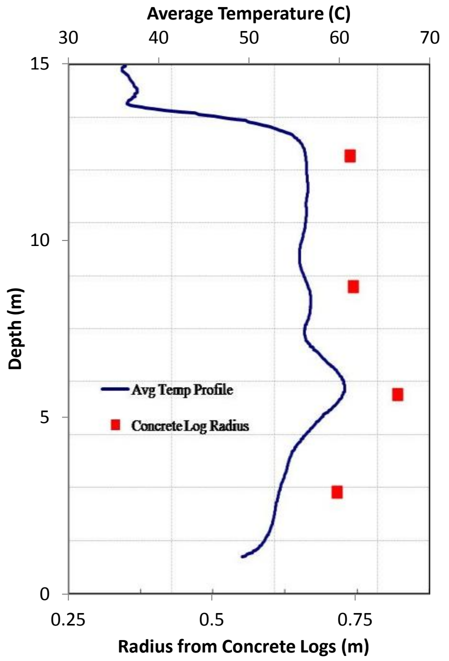

Fig. 10. Strong Correlations between Average Temperature and Shaft Radius.

overall shaft shape (average radius) can be approximated from the average of all tube or wire measurements. This removes the effects of cage alignment. The thermal profiles shown in Fig. 9 from all tubes indicate a straight but off-center cage for the upper 6 meters of a 1.3 m diameter shaft (5 tubes). The average is relatively constant indicating a uniform shaft radius within the cased region.

The strong correlation between temperature and radius can also be used to convert the measured temperature to local shaft radius at each tube. Therein, the volume of placed concrete is used as a boundary condition to establish a linear relationship. The profiles shown in Fig. 9 indicate a large bulge in the shaft below the casing, which is also confirmed by the concrete placement logs (Fig. 10).

When analyzing thermal profiling data, it is normal for the top and bottom of the shaft to show a reduction in temperature as it approaches the ends due to temperature dissipation both radially and axially. The inability of the shaft to dissipate heat axially in the rest of the shaft provides the means to develop the direct correlation between temperature and radius. Thermal diffusion theory is then used to correct end measurements to produce the shape at the ends.

It is interesting to note that thermal integrity profiling does not equate the measured temperature to strength of concrete, which has been problematic for maturation gauges (or similar); rather, it compares local temperatures to the rest of the shaft. When coupled with construction and concreting records from the field, additional insight into the as-built shaft can be provided. In depth details can be gathered from the cited references [28-39].

Conclusions

Several advances in the areas of drilled shaft construction, design, and quality assurance were presented which included: the preparation of mineral slurry used to stabilize drilled shaft excavations, quantifying the effect of casting conditions on the interface bond with seal slabs, end bearing enhancement using post grouting, and thermal methods of assessing the as-built presence and quality of the shaft concrete.

Contractor experiences were verified where mineral slurry could be prepared in less than an hour by taking special measures. However, by using off-the-shelf eductors from a different application, reliable slurry was prepared without the need for specialized hold tanks. In essence, the slurry is made as fast as the water source can supply up to 1 m^3/min (260 gal/min). This system is now in circulation with different contractors throughout the state.

The bond of seal slabs used to form water tight coffer cells was quantified and incorporated into local state standards. The allowable bond strength was raised from 69 kPa (10 psi) to 517 kPa (75 psi). As an example of these results, where 3 meters of hydrostatic water pressure was previously balanced by a 1.2 m-thick slab, the defined values allowed the thickness to be reduced to 0.15 m based on the bond limit (Eq. (2)) or 0.25 m based on the modulus of rupture (Eq. (3)) of the unreinforced slab.

A rational design approach for predicting the end bearing of post grouted shafts was developed for sandy soils. Other soil types which also benefit from grouting were not addressed but can be found in the references listed. Hundreds of shafts have been grouted using the prescribed techniques throughout the United States and abroad. The original database of shafts has grown dramatically as a result. Free software called *SHAFT-123* has been developed and can also be downloaded from http://geotech.eng.usf.edu/Shaft123.html to estimate both grouted and ungrouted shaft capacities [27].

Thermal integrity profiling was introduced and the basics of testing and analysis discussed. The measurements provide information to establish the cage alignment, concrete cover, and overall shaft shape. The method is now in use in states from the east to west coast; an ASTM standard is presently in the ratification process.

The motivation of the article was to show how active involvement of researchers with practitioners can help focus research institution on areas needing investigation. Likewise, interactions instigated by industry, from both consultants and contractors, can be established to call on the vast resources of universities that might otherwise go untapped.

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