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Recipe for Success with Drilled Shaft Concrete

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Introduction

The purpose of this article is to outline some essential properties of concrete that allow drilled shafts to be constructed with high quality and structural integrity. A good chef pays close attention to quality ingredients, carefully measured and mixed to the correct consistency, and prepared with attention to detail. With the great demands on constructors these day (larger shafts, greater depths, congested cages) and the more discriminating clientele (with intensive non-destructive testing technologies), today's drilled shaft chef is under more pressure than ever to deliver. And to complicate things even more, we often have several different "cooks" stirring the pot! Designers and contractors need to consider and emphasize constructability in designs, workability in construction materials, and individual responsibility toward quality on the jobsite.

Key Elements For Quality Concrete In Drilled Shafts

The writer's experiences suggest that the majority of construction problems which compromise the quality of drilled shafts come from a failure to adequately consider one or more of the following categories:

- Workability of concrete
- Maintaining workability for the duration of the pour
- Compatibility of congested rebar and concrete mix
- Cohesive paste to avoid segregation and bleeding
- Control the sand content of the slurry and the stability of the hole during excavation and concrete placement

To this list can be added a broader category, which is human attentiveness to any or all of the above. Inattentiveness can be the result not only of carelessness in workmanship, but also to contractual arrangements that do not encourage attentiveness and to inadequate resources devoted to inspection and quality control.

Workability

Workability can be defined as the ability of the concrete to readily flow through the tremie, the rebar cage, and to all places within the hole where it needs to go. With drilled shaft construction, this must be achieved without the need for external sources of energy such as a vibrator. Most commonly, slump is the measured property associated with concrete workability, and slump values in the range of 7 to 9 inches usually produce the workability needed for drilled shafts. The term "self compacting concrete (SCC)" is a hot topic at the moment, but the concrete we use in drilled shafts has ***always*** been self compacting, since we don't use external sources of energy to compact it!

Maintaining Workability

Not only must the concrete be workable when it arrives on the jobsite, this workability must be maintained for the duration of the pour. With the large shafts constructed nowadays, it is not uncommon to see pours of several hundred cubic yards taking several hours to complete. When concrete has inadequate workability, several problems can ensue:

- During tremie placement of concrete, there is a tendency for debris to become entrapped within the concrete and thus produce flaws in the structural integrity of the foundation. This can occur as the oldest concrete in the shaft is riding on top of the rising column of concrete, and as this old concrete becomes stiff then the fresh concrete can tend to "burp through" and trap the debris and/or contaminated concrete on top. Loss of workability can also lead to plugging in the tremie itself, which may cause the contractor to breach the tremie in order to get flow going again. The result of the breach would also be to trap debris and/or contaminated concrete as some concrete would tend to flow through water and lose cement.

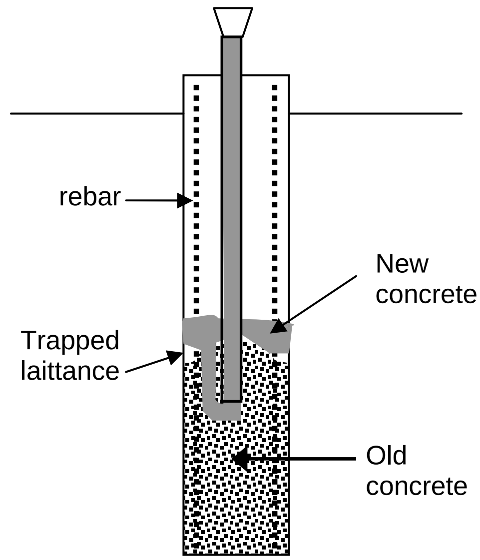

Figure 1 Loss of Workability in Tremie Placed Concrete

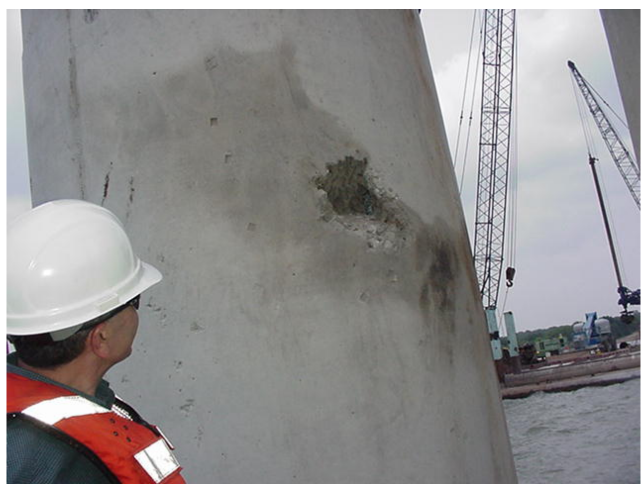

Figure 2 Trapped Laittance in a Shaft Observed after Casing Removed

- Even with placement of concrete into a cased hole without the use of a tremie, there is a need for concrete workability to be maintained from start to finish. When the casing is removed, the concrete must have adequate workability to flow through the rebar cage, displace the water that may be present outside the casing, and produce lateral stress against the soil or rock so as to provide a good bond within the bearing stratum. If the concrete workability has been lost by the time the casing is pulled, it may be very difficult to remove the casing. The concrete could tend to arch within the casing and be lifted with the casing, thus forming a neck. Even if the casing is recovered without necking the concrete, a column of stiff concrete that has been "slip-formed" into an oversized hole is not likely to provide good bond to the bearing formation. The presence of a heavy rebar cage can complicate the problem, as the lateral concrete flow after removal of the casing will be restricted by the cage.

The FHWA guidelines (O'Neill and Reese, 1999) for drilled shaft concrete suggest that a slump of around 8 inches should be used for tremie placed concrete. Many state DOT's use specifications which routinely call for a slump of at least 4 inches to be maintained for a period of 4 hours after batching. It is the opinion of the writer that a 4 inch slump is probably not adequate for most conditions. If concrete with 8 inch slump is being placed into concrete which now has 4 inch slump, there will be two dissimilar fluids interacting within the hole with potentially undesirable consequences.

Rather, it is suggested that the concrete mix be designed to have a very high workability (slump loss of no more than 2 inches) for the duration of the period required for placement, whatever that period may be. These days, it is quite possible to use admixtures to retard concrete for many hours. The concrete mix design should have workability and the time required for the construction sequence as a primary component of the mix design process.

Compatibility of congested rebar and concrete

In recent years, it seems that contractors have become more well equipped to construct very large diameter drilled shafts and so engineers have become more prone to design and specify very large diameter drilled shafts. Large shafts have some compelling advantages for structures such as highway bridges, where large lateral and overturning forces are produced by design conditions for seismic, vessel impact, wind, etc. And a single large diameter shaft can have a smaller footprint than a pile footing, an advantage when working on congested sites or nearby existing structures. However, with the use of large diameter shafts designed for large bending moments, the rebar cages can become quite dense. Added to the rebar is the frequent addition into the cage a number of access tubes for integrity testing.

Figure 3 Defect in Shaft with Double Rebar Cages and 1 inch Maximum Aggregate

Problems can arise from restrictive rebar cages in the following ways:

- If the lateral flow of concrete is significantly impeded, then there is an increased likelihood that debris will become trapped in the annular space outside the cage. This trapping of debris can result from the fact that the rising column of concrete inside the cage tends to be at a higher elevation than the concrete outside the cage, so there would be a natural tendency for any accumulated sediment on top of the concrete to slough off toward the side. Even a small accumulation outside the cage can be detrimental to the bond in the bearing formation.

- Even with a clean slurry, the concrete can be impeded to such a degree that voids form outside the cage or the lateral stress at the concrete/rock/soil interface is diminished.

The FHWA guidelines (O'Neill and Reese, 1999) recommend that the clear space between bars be at least 5 times the size of the maximum aggregate. The writer has seen this guideline routinely violated in practice. In particular where seismic loads are important, there is a tendency for designers to use spiral confinement with a 90 mm pitch (3.5 inches), leaving only about 75 mm (3 inches) or less clear between spirals. The FHWA guidelines would suggest a mix design using a pea-gravel size aggregate for this case. Some state DOT's are using such a mix with success. Workability of the concrete is enhanced in such severe cases if the aggregate is specified to be a rounded gravel rather than a crushed stone. It would also be prudent for designers to consider the implications of the use of such tight spiral reinforcement, and consider if the needed confinement of the interior concrete can be provided in a way which is more easily constructed.

It should also be noted that it is not sufficient for an agency to ALLOW the use of a pea gravel mix, and then place the burden entirely upon the contractor. Because a pea gravel concrete mix is more expensive on a materials basis, the result of such practice is that the winning bid on the job goes to the contractor who uses the least expensive mix allowed by the project specifications rather than the one which is needed. Subsequent problems can lead to poor quality, disputes about who is responsible, and claims.

Cohesive Paste to Avoid Segregation and Bleeding

With the greater demands on concrete workability and the natural tendency to use very high slump mix, there is an ever increasing potential for segregation and bleeding. If there is water in the mix in excess of the amount of water required to hydrate the cement, then that water has to go somewhere. The most common problems with bleeding occur with shafts having deep permanent (or removable) casing, since the casing prevents the excess water from escaping into the surrounding soil.

Several factors can affect the tendency for a mix to bleed. The most important of these is the water/cement ratio; in the writer's experience, when this ratio gets very much above 0.4 it is common to see excessive bleed water and more likely to see segregation. Increased fines, use of fly ash in the mix, increasing cement content, and increased sand/aggregate ratio are some things that can be used to reduce the tendency to segregation and bleeding. For a given workability (slump) requirement, things other than adding water that can be done to increase workability can allow the water/cement ratio to be reduced and therefore reduce the tendency for segregation and bleeding. There are much improved admixtures available these days to increase workability. Some contractors remember bad experiences with the older naphthalene-based superplasticizers, in which it was common to see dramatic and sudden slump loss in the mix. The current polycarboxylate agents are much more effective at extending workability time and can be used with additional retarding agents such as Delvo (Masterbuilders) or Recover (W.R. Grace) to both increase and extend workability.

Viscosity-modifying admixtures (VMA) area also available to provide cohesion to the paste and avoid the tendency for segregation.

It should also be noted that these mixes with the extremely high workability are inherently more sensitive to water content. This requires attention at the plant to details relating to mix water, including the water contents in the aggregate stockpiles, consistency from batch to batch, and even washout water in the trucks which can add unaccounted water into the mix. Details, details!

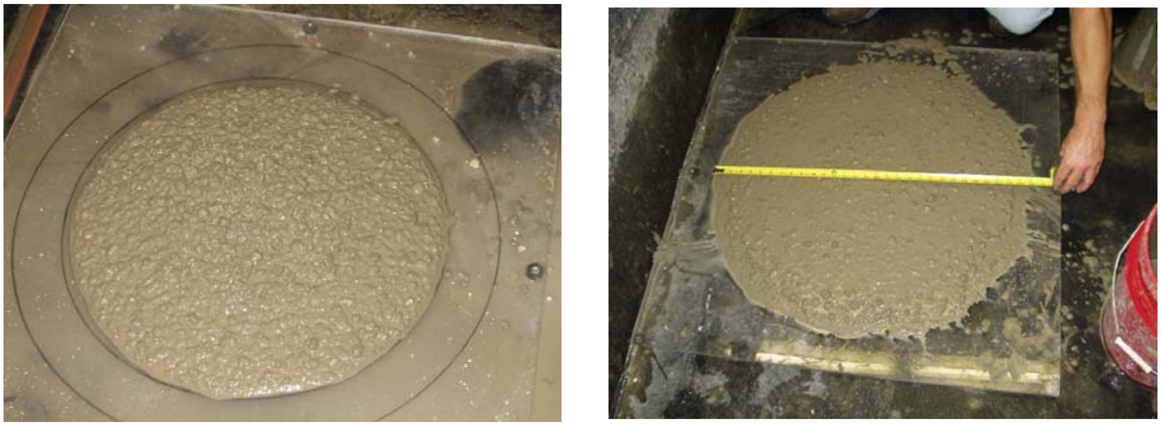

Figure 4 SCC Mixes, with cohesive paste (left) and segregation (right)

Control the stability of the hole

The successful installation of a drilled shaft is predicated on the ability of the contractor to maintain a stable hole in order that the foundation can be cast-in-place with quality materials and workmanship. However, it is not sufficient to only gain stability of the hole prior to concrete placement. Quality foundation construction requires that the stability of the hole be maintained at all times in order to preserve the integrity of the bearing formation and to avoid defects resulting from voids and irregularities in the overlying strata.

In wet hole construction, it is essential that a positive pressure be maintained against the sides of the hole at all times. Groundwater should not be allowed to seep from surrounding soil into the hole, as cave-ins and sidewall sloughing can occur. Even if sloughing does not occur, the surrounding soil can become loosened and lateral stresses can be reduced around the shaft and around nearby structures. Problems with ground subsidence are an all too common occurrence with augered cast-in-place piles (although not the subject of this paper) in water-bearing sands. An unstable and loosened sidewall could result in sloughing during concrete placement which would result in defects within the concrete.

With temporary casing used to provide stability of the hole, it is often attempted to complete the shaft excavation and place concrete in the dry. Where temporary casing is sealed into the top of a relatively impervious formation, it is important that the seal be successful so as to avoid seepage into the hole around the base of the casing. Such seepage could result in a large cavity forming around the outside of the casing, and large cavities can result in large concrete overruns and lead to potential defects in the concrete. As illustrated in Figure 5, a large loss of concrete volume into a hole around the casing

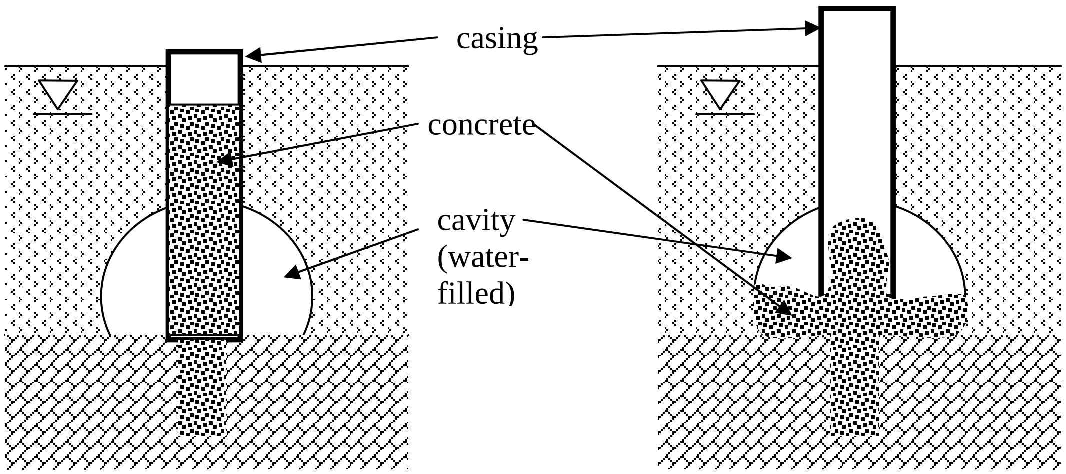

Figure 5 Loss of concrete into cavity during casing extraction

could result in the head of concrete within the casing becoming less than the head of water on the outside of the casing. If this condition occurs, there will be flow of water into the casing, potentially displacing or mixing with the concrete.

The quality of the shaft also depends on the control of the amount of suspended sediment in the slurry. Years ago, contractors were routinely permitted to have as much as 10% sand within bentonite slurries. In recent years, most state DOT's have adopted a 4% criterion for suspended sand within the slurry. However, the key concern is not so much the amount of sand in suspension, but the amount of sediment which can settle out during concrete placement. As drilled shafts have become larger diameter and deeper, the time required to place concrete has increased and thus the time opportunity for sediment to settle out of suspension has increased. Because of considerations described previously of the rolling surface and the potential for differential head across the top of the rising concrete column, and sediment which occurs during concrete placement may be subject to become included within the concrete. As shafts become larger and deeper, the allowable sand content within bentonite slurry will likely need to be reduced.

Contractual and organizational factors

In order to achieve quality construction, the work must be organized so that all parties involved have incentive to achieve quality. This aspect of quality is perhaps the most difficult to achieve. If only the structural integrity of the concrete between the crosshole sonic logging tubes is tested and observed, the contractor's workers often have little concern for other aspects of quality, such as preservation of the integrity of the bearing stratum. Engineers may sometimes focus so much on the optimal arrangement of reinforcement for bending forces that constructability issues are overlooked.

Quality construction of drilled shafts requires that:

- The design engineer should be knowledgeable regarding constructability issues and would produce a design for which ease of construction is a key element,
- The general contractor should appreciate the need for a qualified sub and provide the resources and support needed to ensure that this critical part of the work is performed without interruptions. The general contractor should allow the drilled shaft subcontractor to complete the shaft, and not separate the responsibility for placing concrete from that of drilling the hole, even when the

hole is cased and/or apparently dry. In the writer's experience, this practice is a recipe for disaster.

- The drilling subcontractor should be conscientious and genuinely interested in producing a quality product, and would have well trained workers who are properly equipped for the job,
- The inspector should be well trained and knowledgeable regarding drilled shaft construction, the critical aspects of the design, and the geologic conditions at the site,
- The project should include provisions for measuring quality using the latest techniques for inspection, non-destructive testing, load testing, and test installations where necessary. Measurements provide the feedback necessary to correct small problems early in the project before they can become large problems.

The entire project team must work together to achieve quality, with each party accepting individual responsibility for their own role in the process. Responsible team members expect and demand quality from other members of the team while at the same time working cooperatively to resolve difficulties. It is too often the case that the various parties adopt and adversarial position early in the project in order to position themselves for the anticipated battles (claims, damages, disputes over problems) with other team members. These expectations for disputes seem to be self-fulfilling.

But although project demands are more difficult than ever, the resources available are also better than ever. With a good recipe and quality ingredients, carefully prepared by well-trained people working together and attentive to details, the opportunities exist to ensure that drilled shafts remain a delicious, er, high quality deep foundation choice for designers and owners.