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ZEN AND THE ART OF DRILLED SHAFT CONSTRUCTION: THE PURSUIT OF QUALITY

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ABSTRACT: With apologies to author Robert Pirsig (Zen and the Art of Motorcycle Maintenance), this paper pursues the concept of quality with respect to construction of drilled shaft foundations. With the evolution of more sophisticated techniques for integrity testing and load testing, it is possible now to better observe the end result of our construction activities and make judgments about the effectiveness of techniques and materials at achieving quality. This paper describes some aspects of construction techniques and materials which can lead to defects or less than optimal performance for drilled shaft foundations. Examples are cited of some of the more common problems encountered in drilled shaft construction in order that lessons can be learned from these problems. The case is made for designers and contractors to emphasize constructability in designs, workability in construction materials, and individual responsibility toward quality on the jobsite.

INTRODUCTION

In the book "Zen and the Art of Motorcycle Maintenance", author Robert Pirsig describes a personal spiritual journey (and a motorcycle trip) in a quest for "quality". In the construction of drilled shaft foundations, developments in integrity testing and load testing have afforded the industry an improved opportunity to assess the "quality" of the end product of our labors in terms of the integrity and load carrying capacity of the foundation. While this improved "vision" has often lead to disputes over the definition of "quality" that was specified in the contract documents and that is generally provided by current practice, most engineers and constructors can recognize those attributes of quality that are desirable in a drilled foundation:

- The foundation should consist of a relatively uniform mass of sound concrete,
- The concrete should have good bond and load transfer to the bearing formation,
- The reinforcement should be in the intended position and should be bonded to the concrete.

This paper will address some aspects of design and construction which influence the tendency to achieve quality in drilled foundations. A brief description of some selected case histories is included in order that lessons may be learned from these experiences. The general theme which emerges from these case histories is that 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 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 for the duration of the pour
- Compatibility of congested rebar and concrete
- Control the stability of the hole during excavation and concrete placement, especially with the use of casing
- Drilling fluid which avoids contamination of the bond between the concrete and bearing material or excessive suspended sediment

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 OF CONCRETE

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. When concrete has inadequate workability, several problems can ensue:

1. 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.
2. 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 200 mm (8 inches) should be used for tremie placed concrete. Many state DOT’s use specifications which routinely call for a slump of at least 100 mm (4 inches) to be maintained for a period of 4 hours after batching. It is the opinion of the writer that a 100 mm (4 inch) slump is probably not adequate for most conditions. If concrete with 200 mm slump is being placed into concrete which now has 100 mm 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 50 mm, or 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.

Example 1 Surface Flaws in Concrete

Observation

Single drilled shafts were used to support individual columns for a bridge over a lake in the southwest. The shafts utilized casing extending through the lake and the relatively thin alluvial soil overlying rock. The upper portion of the shafts were formed using a removable casing so that no permanent steel casing would be visible within the zone of water fluctuation. The shafts were drilled using water only as a drilling fluid and the contractor appeared to do an excellent job of cleaning the hole. The rebar cage was not particularly restrictive to concrete flow, with relatively wide openings of at least 200 mm between longitudinal and transverse rebars.

The project was a 45 minute drive from the concrete plant. Upon arrival at the jobsite, the concrete trucks were placed on a barge and ferried to the foundation location. Concrete was placed using a tremie, with concrete delivered from the truck to the tremie by using a bucket. The tremie was maintained at least 2 m below the surface of the concrete in the hole at all times. Each shaft required 5 to 6 concrete trucks to complete the pour and the concrete placement took approximately 4 to 6 hours from start to finish.

Upon removal of the forms, the inspectors noted the presence of pockets of weak concrete which could be chipped away quite easily with a hammer. These pockets appeared to be a weak, cemented grout-like material that had no aggregates within it. Photographs of this material, along with a typical pattern after the weak material had been chipped away, are provided on Figure 1.

Figure 1 Surface flaws in concrete (left), after removal for repair (right)

Explanation

At first it was suspected that either bleed water was contributing to this problem, or the contractor's removal forms were somehow not sealing and water was mixing with concrete during placement. However, further investigation revealed that the concrete mix did not maintain sufficient workability for the duration of the pour during the hot summer months. As tremie placement of concrete continued, the tremie would be lifted from the bottom of the shaft but always maintaining the base of the tremie at least 2 m below the surface of the concrete. As the initial charge of concrete (now riding on top, above the tremie) started to lose workability, the freshly place concrete entering the shaft through the tremie below the surface of this now-stiff concrete tended to erupt through this old, stiff concrete like a volcano rather than lifting the entire surface upwards. As this fresh, fluid concrete vents through the surface of older, less fluid concrete, the latent cement/water mixture on the surface of the rising concrete plug flowed to the lower surface outside the cage and became trapped below the fresh concrete. This flow pattern was visibly revealed in one of the shafts when the contractor pumped off the water above the concrete after the concrete was well up into the casing, and the placement continued using the tremie. The inspector reported the "volcano" of fresh concrete with the lateral displacement and subsequent trapping of latent water/concrete mixture that was present on top of the old concrete.

Implications for Performance

The concrete outside the rebar cage serves primarily to transfer load to the soil and as cover to protect the rebar from corrosion. In this case, the concern is for the long term durability of this cover. Discussions with a bridge inspection diver with the Texas DOT indicates that at least one bridge (Lake Houston) built in 1988 using similar construction techniques is now suffering spalling of concrete from the surface of the shafts.

Lessons Learned

It is critical that the concrete mix have sufficient retarder that the concrete maintain its workability for the duration of the pour. In this case, that was at least 6 hours from the time of batching because of the slow delivery of concrete to the foundation location.

Also, the slump life of the concrete mix varies with the temperature, and increased retarder dosage is required during hot weather.

Example 2 Poor Bond in Rock Socket

Observation

A drilled shaft was installed through about 12 m of soil and socketed approximately 3 m into an underlying rock formation. In order to allow downhole visual inspection of the bottom of the shaft, the contractor was required to case the hole for the full length. Once satisfied with the inspection, a load test shaft was constructed using an Osterberg cell placed at the base of the socket. After placement of the O-cell and rebar, concrete was placed within the rock socket and the casing subsequently removed. The O-cell was found to mobilize only less than 0.5 MN of side shear resistance, a small fraction of the amount which had been expected.

Another test shaft was constructed, only this time a wet hole method was used with tremie placement of concrete and without casing into the rock. In this case the O-cell test indicated over 10 MN of side resistance in the socket.

Explanation

The amount of time required after concrete placement to extract the casing allowed the concrete workability to diminish to the point that the shaft was almost like a “slip-formed column” within the rock socket. Because of the lack of lateral pressure between the concrete and the rock, the side shearing resistance of the socket was very low. There may have been some additional detrimental effects of using the casing, such as trapping of debris behind the casing which contaminated the bond between concrete and rock.

Lessons Learned

Even though the casing provides a “dry hole” the need for concrete workability for the entire duration of the construction process remains. And although a shaft is constructed without any observable structural defects in the concrete, it may not be a “quality” shaft.

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.

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

1. 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.

2. 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.

Example 3 Observations on the Flow of Tremie-Placed Concrete

Observations

During the winter of 2002-2003, several drilled shafts were cast at the Auburn University National Geotechnical Experimentation Site (NGES) at Spring Villa, Alabama for the purpose of closely observing concrete flow during tremie placement. Concrete consistent with the Alabama DOT standard mix was used, with a #57 crushed aggregate (19 mm (¾ inch) maximum size) and approximately 200 mm (8 inch) slump was placed using a tremie within a 1.1 m diameter hole and the process filmed using a downhole camera. The hole was dry so that the concrete could be observed, but the placement was conducted as if in a wet hole environment. Rebar included longitudinal bars with about 200 mm (8 inches) clear between bars and hoops with approximately 125 mm (5 inches) clear between hoops.

The concrete was observed to flow up alongside the tremie pipe and produce a rolling action of the top of the rising concrete column, with the concrete surface rolling from the center of the vent near the tremie radially towards the perimeter of the shaft. There was typically about ½ m difference in head between the concrete within the rebar cage and the concrete in the annular space outside the cage. The concrete could be seen to "cascade" over the hoop steel to fill the annular space outside the cage.

Another shaft was constructed similarly and using a similar slump, but with a gravel aggregate of 12 mm (½ inch) maximum size. There was less noticeable "rolling" of the

Figure 2 Surface of the Shaft with #57 Stone

concrete from the center of the shaft towards the perimeter and the difference in head between the interior and the annular space was significantly less.

Subsequently, the shafts were exhumed and the surface of the concrete examined (see Figure 2). The surface texture of the shaft with the pea gravel aggregate appeared less permeable. There was no trapped debris, since both shafts were constructed using tremie placement in the dry.

Lesson Learned

Concrete does not flow upward above the tremie as a nice homogeneous mass. Rather, the surface is a rolling, boiling three dimensional thing which could easily entrap any debris which resides on top and which can build up a head differential between the interior and the exterior of the rebar cage.

Example 4 Extreme Rebar Cage

Observations

A bridge on the west coast was designed to utilize a single 4 m diameter shaft to support an oval shaped column. In order to mate the rebar cage in the shaft to the shape of the column, a double rebar cage was utilize in which two cages overlap in a sort of "fat figure 8" configuration. As a result, concrete was forced to flow through not one, but two rebar cages, both of which were had extremely congested cages due primarily to the closely spaced transverse steel. The shafts were socketed through an overlying sandy alluvial soil into sandstone. The concrete mix had an aggregate which used crushed stone with a 25 mm (1 inch) maximum size. The contractor attempted to case through the overlying sand with a temporary casing; due to aesthetic reasons, permanent casing to the ground surface was not permitted.

Integrity testing indicated the presence of voids around the perimeter of several shafts. Access shafts were constructed to examine the problem and pockets of sand were discovered within the zone where the two cages overlap, as illustrated on Figure 3.

Figure 3 Defect in Shaft with Double Rebar Cages

Coring was performed from the top of the shaft and showed good concrete of consistent compressive strength within the center of the shaft but very erratic compressive strengths around the perimeter.

Lesson Learned

A simple cage with considerations of constructability is needed in order to make drilled shafts less vulnerable to defects and to promote quality construction. A permanent casing socketed into the underlying rock could also have reduced the likelihood of defects in this case because the hole could have been kept dry, although the difficulty with the rebar and concrete would still be present. The concrete mix in the case of severely congested rebar should incorporate good flow characteristics with small rounded gravel aggregates.

Example 5 Concrete Placement in a Large Shaft with Tight Spiral Reinforcement

Observation

During construction of the test shafts for a new bridge in South Carolina, careful observations were made of the concrete behavior during tremie placement (Camp et al, 2002). The shafts were 2.4 m diameter (8 feet) and up to 50 m deep (160 feet), with a rebar cage which included a heavy longitudinal reinforcement tied with a spiral transverse rebar at a 90 mm (3.5 inch) pitch. The concrete used a small crushed stone maximum aggregate less than 12 mm size (½ inch) and 200 mm slump (8 inch). In spite of the small aggregate and high slump, measurements indicated as much as a 1.4 m difference in head between the concrete levels on the interior and exterior of the cage.

Lesson Learned

If any adverse performance of the test shafts resulted from the tight spiral reinforcement in the cage, it was masked by other factors. Nevertheless, the observations indicate that the potential exists for debris to be trapped on the outside of the cage under these circumstances, and designers and contractors were alerted to the need to take extra precaution to maintain a clean slurry during construction of the production shafts.

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. However, seepage from the bearing formation below the casing can result in softening of the bearing materials and the accumulation of debris on the base of the hole. In shales or fractured rock materials, there may not be a large quantity of seepage observed, but the unbalanced fluid pressures and the stress relief provided by the hole may be sufficient to produce softening. If seepage is observed, it is often preferable to complete the excavation in the wet to avoid uncontrolled seepage into the hole.

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 4, a large loss of concrete volume into a hole around the casing 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.

Example 6 Cavity Around Casing

Observation

A drilled shaft was installed at a site in Florida by vibro-driving a casing through the overlying water-bearing sand into the top of limerock. The shaft excavation was completed within the limerock and concrete placed to near the top of the casing. The casing was pulled upwards approximately 0.6 m (2 feet) and the concrete level within the casing dropped to near the bottom of the casing. Although the contractor attempted to

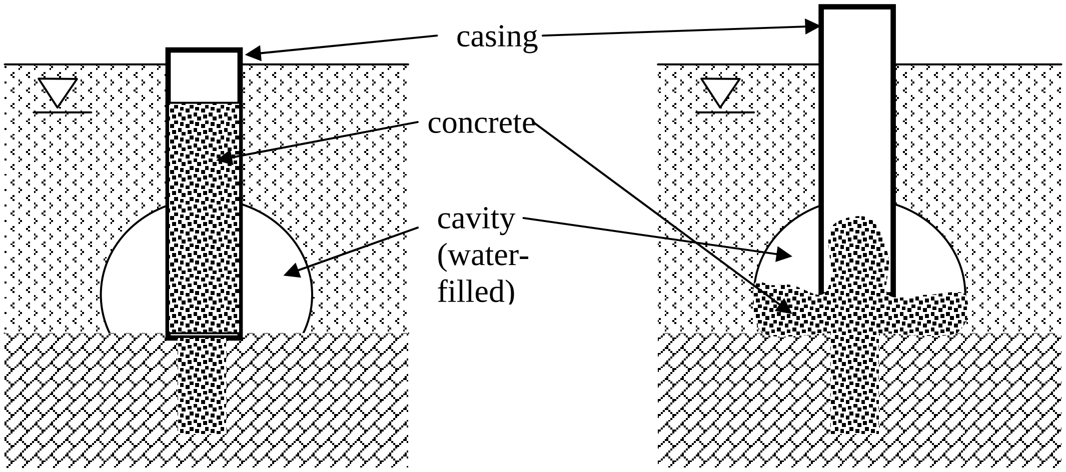

Figure 4 Loss of concrete into cavity during casing extraction

place additional concrete with a pump, the hole eventually was abandoned. No significant inflow of sand had been noted during the excavation into the limerock.

Explanation

Although the contractor had used care to avoid causing a cavity around the casing during excavation, the limerock in this area had natural cavities formed by solution activity. These cavities tend to be found most often near the top of the formation. The contractor used good practice when withdrawing the casing only by a small amount so that additional concrete could be added to maintain the head, but the volume lost was so large that the head of concrete dropped below that of the surrounding groundwater and the structural integrity of the shaft was compromised.

Lesson Learned

Because this cavity was a natural occurrence, the design of the shaft needs to accommodate the possibility of large cavities as a construction consideration. This condition would be more effectively handled with the use of a permanent casing.

A CLEAN SLURRY HELPS AVOID CONTAMINATION

The use of drilling slurry can be a very effective means to maintain control over the stability of the hole. However, it is important that the slurry properties be controlled in order to avoid potential contamination of the bond between the shaft and surrounding soil or rock, or within the concrete due to excessive suspended sediment.

Several recent comparative tests have demonstrated that polymer slurries can significantly outperform bentonite in terms of side shearing resistance, as illustrated by the data on Figure 5 (Brown et al, 2002). This trend appears most notably in granular soils where there is some fluid loss into the surrounding formation and a bentonite filter cake is likely to form (Brown, 2002; Majano et al, 1994; Meyers, 1996). Where slurry is used in a relatively cohesive formation and there is little opportunity for fluid loss, differences in unit side shear have been insignificant (Camp et al, 2002). Although current design procedures do not generally delineate values used for design on the basis of construction technique, it is clear that the construction procedure used can have a major effect on performance. Where bentonite slurry is used within the bearing formation, the quality of the bond is enhanced by minimizing the exposure time.

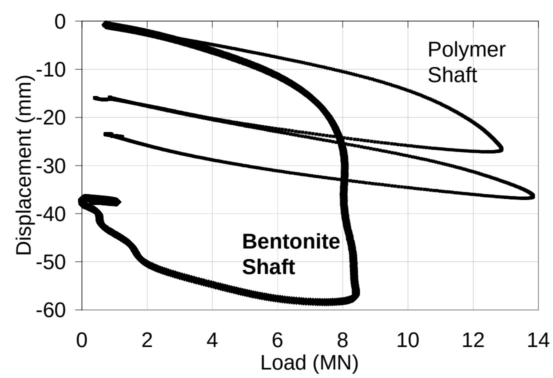

Figure 5 Comparison of Two Identical Shafts in Cemented Fine Sand with Different Slurry, Brown et al (2002)

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.

With polymer slurries, there is a tendency for a false sense of security about suspended sediment, since sand particles tend to settle out quickly. However, silt sized particles (smaller than the #200 sieve) and fine sands have been observed to remain in suspension for extended periods and result in contamination atop the concrete column. There have been numerous cases of projects with polymer slurry where removal of silts and fine sands from the slurry has been very difficult. On one recent project near the Atlantic coast, a contractor constructing shafts using a polymer slurry was forced to overpour the shafts by over 2 m (6 feet) in order to remove concrete contaminated with silt. On another project at a site in Florida with very fine silty sands, the base of several shafts were inspected using a downhole camera to evaluate the condition of the base of the shaft excavation prior to concrete placement. The camera revealed the bottom 0.6 m (2 feet) of the slurry to be heavily laden with silt in an appearance which resembled that of a gel. These and many other anecdotal experiences with polymer slurries in silty fine sands suggest that engineers and contractors should exercise caution in the use of these materials.

Example 7 You Broke My Shaft!

Observation

A small diameter drilled shaft was constructed for a load test at a site with sand and clay overlying limerock. Temporary casing was seated into the rock, and the shaft drilled into the stable limerock formation in the wet. The limerock was stable, but dewatering the excavation was not attempted due to the potential for seepage. Since the rock was stable and the overburden was cased, the slurry was not given much attention; water was used, although some mixing with the native materials occurred. The shaft was completed and the casing was pulled. No integrity testing was performed.

When the load testing was performed, the shaft failed suddenly at approximately 150% of the design load. Strain gauges within the shaft suggested that very little load was reaching the lower portions of the limestone socket. Upon excavating the upper 2 m of the shaft (6 feet), the shaft was observed to have suffered structural failure at a load corresponding to less than 14 Mpa (2000 psi) over the theoretical cross sectional area of the shaft (see Figure 5). The shaft was cut off cleanly at about 2 m below grade, a new top formed, and the load test was successfully carried out to over 2 times the design load without achieving failure (either geotechnical or structural).

Figure 6 Broken Top of Shaft after Load Test

Lesson Learned

The shaft was constructed with a false sense of security regarding concrete placement because of the casing and the stable limerock formation. Even though only water was used during drilling, the properties of the resulting slurry are important because of the potential effect on the concrete during placement. It appears that the concrete integrity was compromised within the upper 2 m of the shaft, resulting in structural failure when loaded to high stresses. The lesson learned from this is example is that any wet pour has the potential to impact concrete integrity and the drilling fluid must be clean and the concrete must have good workability.

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 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.

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.

There is no magic solution to resolve problems in these areas. Quality construction requires preparation and persistent attention to details. Just as an army succeeds because of extensive training for its mission, designers, inspectors, and constructors can succeed by preparing themselves with extensive training. And a final key ingredient is that quality be measured in a timely fashion so that adjustments to construction techniques can be adopted before small problems become major ones.

Example 8 I Didn't Do It, Nobody Saw Me Do It, You Can't Prove a Thing

Observation

A bridge project in the Midwest was constructed using a group of drilled shafts installed into a rock formation through water and overlying soil using permanent casing. The general contractor hired a drilled shaft subcontractor to provide services only consisting of drilling the holes. In order to plan their work efficiently, the general contractor had the sub drill the entire bent (with up to 12 shafts), after which the concrete would be placed and the bent completed. Although the bridge was over water, the holes were expected to be dry due to the permanent casing.

Fortunately for the owner, there was at least post-construction integrity testing performed using crosshole sonic logging. These logs indicated that several shafts had zones of very poor quality concrete. Coring indicated that there was weak concrete in some areas and some zones had washed aggregate in places where sound concrete should be present. The shafts required extensive grouting and underpinning with micropiles.

Explanation and Lessons Learned

Because the holes had been expected to be dry, the concrete was placed using free-fall into the hole. Some of the holes were open for weeks between drilling and completion. In fact, the rock had some small fractures that resulted in seepage into the holes. In some holes, concrete was dropped through water resulting in defective zones of concrete within these shafts.

The divided responsibility for completion of the drilled shaft foundations is a very undesirable arrangement. The work of constructing a drilled shaft cannot be easily subdivided into drilling the hole and placing the concrete as if they were two independent operations; once the hole is drilled to the required depth, it is important that the shaft be completed in a timely fashion with a single point of responsibility for making this happen.

Although the inspection failed to prevent concrete placement through water, it was fortunate that the designers had included crosshole testing, which allowed the defects to be discovered. Many state DOT's require integrity testing only where tremie placement of concrete is used. The effects on the axial capacity from the seepage and extended period of open holes is not determined, but the conditions at this site are not conducive to quality in this respect.

CONCLUSIONS

Like a motorcycle trip across America, the pursuit of quality in drilled shaft construction is a long and arduous journey. More powerful drilling equipment and better techniques have lead designers to utilize drilled shaft foundations in larger diameters and to greater depths than ever before. The challenges for quality in construction have increased. However, improvements in technology with respect to integrity testing and load testing have made it possible to measure quality in ways that were never before possible. Improvements in construction materials, including better concrete and more sophisticated slurry products, have made it possible to construct quality drilled shafts in more difficult conditions. Improved quality in drilled shafts is being realized.

But perhaps the most influential component in the process and the most difficult to control is the human element. All of the examples cited in this paper in which quality was compromised could have been avoided or corrected by engineers, constructors, and inspectors who were knowledgeable of their craft and attentive in their work. The challenge remains to put into place systems of training (for all members of the team) and jobsite control to encourage and emphasize quality in construction.

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