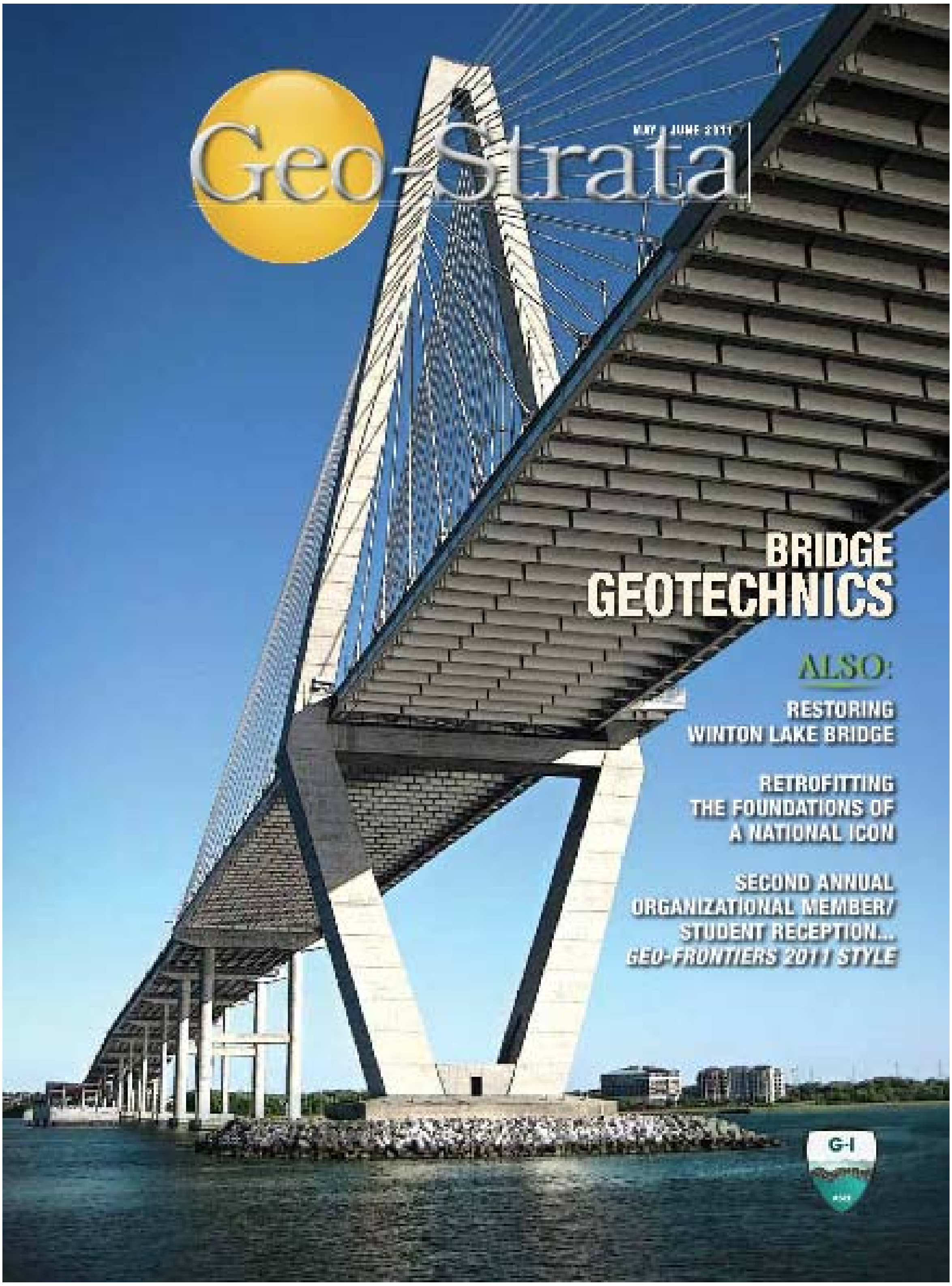
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Constructability Considerations When Designing Drilled Shaft Foundations for Bridges

By Dan Brown, Ph.D., P.E., D.GE, M.ASCE

Compared to other structures, drilled shaft foundations for bridges are often subject to significant lateral load demands, including live loads, wind, vessel collision, and seismic loadings. The flexural strength requirements may be compounded by scour, liquefaction, and liquefaction-induced lateral spreading. Because they are drilled rather than impact-driven, drilled shafts can be installed into scour-resistant rock or other hard strata, and can be constructed in congested urban sites in close proximity to existing structures. Drilled shafts provide foundations with great strength and ductility in a small footprint to meet large axial and flexural demands and a single non-redundant drilled shaft often comprises the foundation for a single column supporting the bridge structure (Figure 1).

Figure 1. Drilled shafts provide small footprint at congested locations.

While drilled shafts can provide a very robust and reliable foundation system, these large reinforced concrete structural elements must be cast-in-place in the ground, often under water or drilling fluid, and the quality control/assurance can be challenging. As such, constructability must be considered during design and specification probably more than other deep foundation types. A few of the most common constructability challenges include inappropriate concrete specifications, congested reinforcement, splices, and construction of the column/shaft connection.

Performance Requirements for Fresh Concrete

The most important aspects of concrete mix design for drilled shafts are the properties of the fresh concrete. Drilled shaft concrete must have the ability to flow readily through the tremie and reinforcing cage to fill the shaft excavation and restore the lateral stress against the sides of the excavation. Vibration of concrete in a drilled shaft excavation is not possible, so the fresh concrete must fill and consolidate under self weight.

Because the fresh concrete must have high workability, it is especially important that the paste within the concrete mix have a high degree of cohesion so that the coarse aggregate particles are evenly distributed through the mix without any tendency to segregate. Likewise, the water within the mix should remain distributed without a tendency to bleed and result in non-uniform properties or bleed water channels. With underwater placement or when casing must be withdrawn after completion of concrete placement, the drilled-shaft concrete must often retain its workability for several hours. If concrete loses workability during tremie placement of concrete, pockets of laitance or contamination may become entrapped within the shaft.

The most successful concrete mixes for drilled shafts have different features than normal structural concrete:

- smaller coarse aggregates, typically no larger than ¾-inch and often of pea-gravel size,
- an increased proportion of sand as a proportion of total aggregate,
- a target slump of 8 inches or more,

- extensive use of supplementary cementing materials (SCM) such as fly ash or slag cement, and
- water-reducing and hydration control admixtures.

Fly ash or slag (ground-granulated blast-furnace slag) substitutes for a portion of the Portland cement and aids workability, delays setting time, and reduces the heat of hydration. Water-reducing admixtures help to achieve workability with a water/cementitious materials (w/cm) ratio of around 0.4 or less, which helps reduce the tendency for segregation and bleeding of highly workable mixtures. Hydration control admixtures are used to maintain workability for the duration of the anticipated placement time, plus some contingency for unanticipated delays.

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Self-consolidating concrete (SCC) provides greater workability and passing ability than conventional concrete. Besides the extensive use of SCM and chemical admixtures, these mix designs have a greater ratio of sand content in proportion to the total aggregate than the 40 percent or less typical of conventional mixes. Viscosity modifying admixtures (VMA) are often included to help reduce the tendency for segregation and bleeding. Engineers are starting to gain experience with the use of SCC-type mixes in drilled shafts, and a summary of mix design characteristics from several successful applications are described in the 2010 FHWA Drilled Shaft Manual *http://content.geoinstitute.org/files/pdf/nhi10016.pdf.*

Figure 2. Slump flow of SCC-type drilled shaft mix.

The fluid properties of these mixtures are characterized using "slump flow" (sometimes referred to as "spread") rather than conventional slump. Slump flow (Figure 2) is a measure of the diameter of the fresh mix after discharge from an inverted slump cone. Slump flow values for drilled shaft concrete of 18-24 in. provide the desired workability with less risk of segregation than for higher slump flow values. The evolution of SCC-type mixes into drilled shaft construction practice underscores the importance of concrete workability in this application.

Design of Drilled Shaft Reinforcement

Deep scour, seismic loads with liquefaction of shallow strata, and design for vessel impact loads are some of the issues for which drilled shaft foundations are often utilized. Because drilled shafts can now be constructed in large diameter to provide great strength in flexure, the tendency for congestion in the reinforcement has increased. Thus, the connection between the drilled shaft and column is another location where congestion of reinforcement can be an issue, particularly where single drilled shaft foundations are used for an individual column.

Drilled Shaft Reinforcement. Close spacing between longitudinal bars, lap splices, and tight pitch on spiral transverse reinforcement present constructability problems for drilled shafts. Some effective ways to avoid constructability problems from congestion in the drilled shaft reinforcement include:

- Minimum dimensions of five inches clear between bars in both the longitudinal and transverse reinforcement are recommended to allow concrete passage. Bundled longitudinal and transverse reinforcement can increase the clear openings for the concrete.
- Adjusted spacing between longitudinal bar bundles at the locations of the access tubes for non-destructive testing to verify concrete integrity.
- Staggered bar couplers, rather than lapped bars, are preferred to avoid excessive congestion at splices. The use of couplers is preferred for large-diameter bars.

The large-diameter cage in Figure 3 includes bundled longitudinal and transverse bars in a large-diameter drilled shaft. This cage was fabricated with extra internal stiffening hoops and bracing to minimize the risk of distortion as the cage is lifted and placed into the shaft.

Connection between Drilled Shaft and Column. There are several possible approaches for designing the connection between the drilled shaft reinforcement and the column, each of which affects constructability. This detail is more easily fabricated if

Figure 3. Bundled bars in a drilled shaft cage.

the design allows a splice near the top of the drilled shaft or base of the column, but splices at this location may be unacceptable if there is a concern for ductility in a high moment area for seismic loading.

If the design allows a lap splice at the base of the column to connect to the drilled shaft reinforcement, then simple accommodations for construction tolerance in the shaft can improve constructability. For example, if the drilled shaft reinforcement is sized to provide six inches of cover, then the shaft reinforcement can be adjusted by three inches in any direction (the typical tolerance on location of the drilled shaft) and still line up with the column cage with at least three inches of cover. Another approach is to use a short "splice cage" to provide a non-contact splice into the top of the drilled shaft and a lap splice into the column. This type of connection is advantageous where the column reinforcement is square or rectangular.

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A continuous longitudinal cage extending from the shaft into the column with no splices near the ground line (sometimes referred to as a "Type I" connection) can result in a very long cage that requires special handling. This approach will increase costs because the contractor may be forced to work over and around a cage which extends many feet above the top of the shaft. In addition, concrete placement is more complicated and expensive due to the projecting cage, which may need to be externally supported until the concrete is placed and hardened.

A "Type II" connection (Figure 4) avoids the splice at the base of the column by extending the column reinforcement into the top of the shaft to form a "non-contact" lap splice for a sufficient distance to develop the strength of both the column and the shaft reinforcement. This approach provides ductility because the drilled shaft is designed to have greater moment resistance and any damage from a seismic overstress condition is confined to the base of the column above grade.

Where the drilled shaft must be constructed in a wet hole, it is necessary to provide a construction joint at the base of the splice for constructability. Attempts to place concrete through two cages in a wet hole environment is likely to result in flaws in the constructed shaft. Even though appropriate openings are maintained in each cage, the openings will never line up from one cage to the next, and the opportunities for entrapping drilling fluids or poor quality concrete are significant. The preferred solution for construction of a Type II connection in a wet hole is to provide a short piece of permanent casing extending below the column reinforcement to allow a construction joint at the base of this splice. When working over water, a short permanent casing combined with a larger diameter temporary casing or cofferdam can be used. Also, the shoring must be of sufficient diameter to provide space for workers around the column formwork.

The use of a Type II connection at a great depth below grade is undesirable. If the drilled shaft must be constructed using a

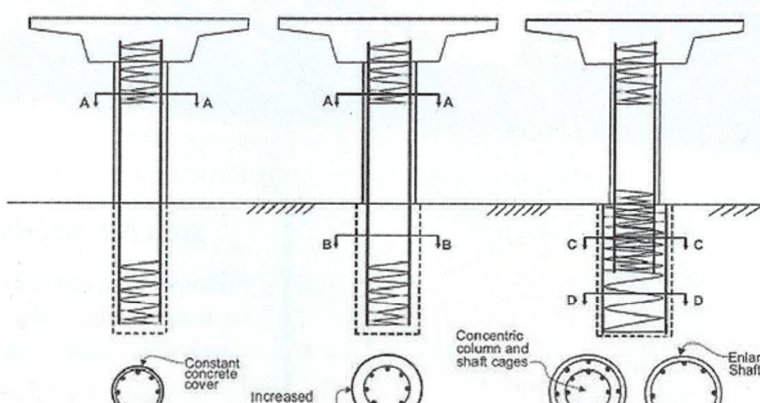

Figure 4. Type I and II connections, from Caltrans Seismic Design Criteria.

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fluid, then it will be very difficult to fabricate this connection in the dry as would be the preferred practice. Even if the excavation can be dewatered, the expense and difficulty of sending workers into a confined space at great depth is best avoided. In such a case, a Type I connection would be preferred, with the splices in the reinforcing strategically located in non-critical moment locations.

Take Aways

Drilled shafts provide robust and effective foundation solutions for bridges in many circumstances, but designers must have a basic understanding of construction techniques so that constructability is an essential aspect in the design of drilled shaft foundations. Many common construction problems with drilled shafts are related to congested reinforcement and connection details, and the selection of concrete mixtures with appropriate characteristics to meet the challenges associated with their use. Designers must:

- design the concrete mix with appropriate consideration of the workability characteristics of the fresh concrete,
- design the drilled shaft reinforcing cage to avoid congestion and maximize the passing ability of the concrete, and
- design the connection details between the drilled shaft and column reinforcement to allow construction of the splice in a dry environment.

With the proper considerations of constructability, drilled shaft foundations provide a robust and reliable foundation alternative for meeting the challenges of rebuilding America's bridge infrastructure.

AUTHOR

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