

THE USE OF SELF-CONSOLIDATING CONCRETE FOR DRILLED SHAFT CONSTRUCTION: PRELIMINARY OBSERVATIONS FROM THE LUMBER RIVER BRIDGE FIELD TRIALS

Dan Brown¹, Joe Bailey², Anton Schindler³

ABSTRACT: Several drilled shafts have been constructed using self-consolidating concrete (commonly referred to as “SCC”) as part of a field trial with this material. Identical shafts were constructed with a concrete mix typically used in coastal South Carolina. Although the project is ongoing at the time of this writing, the preliminary observations of the performance of the concrete during construction provides insight into the behavior of tremie-placed concrete. Both mixes were observed to have excellent workability characteristics. The observations of the hardened concrete from recovered drilled shafts provide indicate that generally good performance can be achieved in difficult construction conditions (congested cage, tremie placement, lengthy placement times) if highly workable concrete is utilized. Some imperfections in the concrete were observed even under these closely monitored conditions, and some degree of imperfection in this type of construction appears to be practically unavoidable. The imperfections observed in these field trials were detected by crosshole sonic logging, but do not appear to have significant adverse consequences to foundation performance.

Introduction

As a part of a Federal Highway Administration (FHWA) program for implementation of new technology, a bridge project in South Carolina was selected as an experimental project for the use of self-consolidating concrete (commonly referred to as “SCC”) in drilled shaft construction. SCC is a concrete mix with ultra-high workability characteristics, and is formulated for general use in cast-in-place concrete construction so as to flow through rebar and fill formwork without the need for vibration. In a sense, drilled shaft concrete has traditionally been depended upon to “self-consolidate”, since no

¹ Dept. of Civil Engineering, Auburn University, AL 36849

² Applied Foundation Testing, 4015 J. Louis St., Green Cove Springs, Florida 32043

³ Dept. of Civil Engineering, Auburn University, AL 36849

vibration is used as an aid to placement. However, the term SCC is generally used with concrete mixes designed to flow with much greater workability than is commonly specified for conventional drilled shaft concrete.

Drilled shafts have been constructed as experimental castings and as load test shafts using both SCC and using a more nearly conventional mix with very high workability. The experimental castings were 6 feet diameter and 30 feet deep and served as test installations of the two concrete mixes constructed under slurry. These shafts were exhumed and cut in several places with a wire saw in order to examine the concrete; color-dyed concrete was used in portions of the shafts to reveal flow patterns. The load test shafts were 6 feet diameter and 71 feet deep and were subject to axial loading to a maximum static load of 2500 kips using the Statnamic device.

This paper presents a summary of some preliminary observations from the construction, examination, and testing of the experimental castings and load test shafts. Additional testing of the as-built properties of the concrete from the castings is ongoing at the time of this writing. In addition, construction of six piers for one of the bridges at this project is ongoing using the SCC mix.

Mix Characteristics

The two mixes used for this project included the SCC mix and the “conventional” drilled shaft mix (the latter referred to herein as the SC coastal mix). The SC coastal mix was actually a mix with extremely high workability, utilizing a rounded gravel aggregate and slump ranging from 9 to 10 inches. This mix (or similar) has been used with success on numerous bridge projects in coastal South Carolina, where rounded gravel aggregates are available and the need for high workability is recognized. Most of the drilled shafts in this area are large and deep due to poor soil conditions, are designed with congested rebar cages due to seismic lateral loading, and the construction is typically performed using tremie placement under slurry. Some of the relevant characteristics of each mix are shown in Table 1 below. Also shown for comparison are properties of a typical drilled shaft mix recently utilized in Alabama.

Several noteworthy features are indicated in Table 1:

- 1) The coastal SC mix uses a blend of pea gravel (the #789 gravel) and larger size (#67 gravel has particle size up to $\frac{3}{4}$ inch) with a relatively high proportion of pea gravel. This blend gave very good workability and passing characteristics.
- 2) The coastal SC mix also utilized water reducers to achieve an unusually high slump compared to most drilled shaft mixes. Conventional drilled shaft concrete is typically specified to have slump ranging from 7 to 9 inches for tremie placement (O’Neill and Reese, 1999).
- 3) The SCC mix workability characteristics are based on a measurement of slump flow rather than slump. Slump flow is determined by placing the mix within a conventional slump cone (without rodding) on a plexiglass surface, then withdrawing the slump cone and measuring the diameter of the resulting concrete “pie” as shown on Figure 1. The target for this project was a slump flow of 21 inches, +/- 3 inches, but the actual slump flow as indicated on Table 1 was slightly higher than the target value.

	SCC	SC Coastal Mix	AL Limestone Mix
Cement, lbs/cu yd	500	540	560
Fly Ash, lbs/cu yd	250	162	140
Coarse Aggregate	73% #67 Gravel; 27% #789 Gravel	57% #67 Gravel; 43% #789 Gravel	#57 Crushed Limestone
Fine Aggregate to Coarse Agg. ratio	0.98	0.66	0.59
Water Reducer	4 oz/cwt Polyheed 1025; 10 oz/cwt Glenium 3030	8 oz/cwt Glenium	-
Retarder/Stabilizer	9 oz/cwt Delvo	15.5 oz/cwt Delvo	-
Other	2 oz/cwt VMA	-	-
Water/cement ratio	0.40	0.40	0.38
Workability	24 to 26 inch slump flow	9.5 to 10.5 inch slump	6 to 7 inch slump

Table 1 Concrete Mix Characteristics



Figure 1 Slump Flow Test on SCC (Concrete is Colored Black)

- 4) The SCC mix utilizes a high ratio of fine to coarse aggregate and a relatively higher fly ash content than other drilled shaft mixes. These higher fines contents aid in achieving the extremely high workability without segregation of the coarse aggregate fraction. The use of water reducing admixtures and also viscosity modifying admixture (VMA) also assist in this regard.

Shaft Construction

The shafts constructed for this study include: 1) two experimental shafts 6 foot diameter by 30 feet deep to be cast and exhumed, 2) two load test shafts 6 foot diameter by 71 feet deep, and 3) two bridges. The smaller of the two bridges includes 6 shafts to be constructed using SCC, and the larger of the two bridges includes 20 shafts to be constructed using the SC coastal drilled shaft mix. One each of the experimental and load test shafts were constructed using SCC and the SC coastal mix, respectively.

Rebar

All of the shafts for the project include a full length rebar cage with longitudinal #14 bars at approximately 6 inch center to center spacing and 6 inches cover. The cage is confined using #5 hoops at 6 inch center to center over most of the length of the shaft and at 3 inch center to center spacing within the upper 12 feet. In addition to the longitudinal bars there were 6 metal tubes (approximately 1.5 inch diameter) for crosshole sonic logging tied into the cage.

Within the upper 13 feet of the shaft is a second cage of column reinforcing inside the shaft reinforcing, with the column steel composed of #11 bars at 5 inch center to center spacing and #5 hoops at 6 inches on center. The upper 12 feet of the shaft thus represents a very difficult requirement for concrete flow, with the concrete required to flow through two dense cages and one of these cages containing hoops with only 2.37 inch clear space between bars. This space is 3.2 times the maximum coarse aggregate size (3/4 inch), although a large portion of the aggregate is of pea gravel size.

Drilling and Concrete Placement

The 30 foot long experimental shafts were constructed using bentonite slurry and temporary casing within the upper 15 feet. The shafts extended through interbedded layers of clay and silty sand alluvium. The casing was installed using a vibratory hammer, and then the shaft was excavated using a combination of augers and drilling buckets. Final cleaning of the base was performed first with a flat bottom bucket and then using an air-lift pipe. Inspection of the base was made by sounding with a short section of #14 bar attached to a wire, and the shaft accepted if the bottom felt sound and free of soft debris according to the judgment of the SCDOT inspector.

After drilling and cleaning the shaft excavation, the concrete was placed via a 12 inch diameter segmental tremie pipe. The tremie was placed into the hole as an open tube and concrete flow initiated through the tube using a traveling plug. The traveling plug was a foam ball which had been saturated with water prior to use. The tremie was maintained at least 10 feet into the concrete at all times; concrete was placed with the tremie held stationary until the concrete was 20 feet above the tremie discharge end, then the tremie was lifted and a 10 foot section removed. After completion of the shaft, the temporary casing was removed using a vibratory hammer.

The load test shafts were constructed in much the same manner, except that the shafts were 71 feet long and a 22 foot long permanent casing (74 inch inside diameter) was used.

In order to evaluate the concrete flow patterns in the experimental shafts, color-dyed concrete was used in portions of the concrete. The 30 foot long shafts required approximately 36 cubic yards of concrete for filling, slightly more than 1 cu. yd. per foot of shaft. The first 4 cu. yds. were dyed black, followed by 16 cu. yds. of normal gray concrete, followed by 4 cu. yds of red concrete, followed by the remainder of the concrete as gray. Because of the requirement of 10 feet minimum tremie embedment and the segmental tremie composed of 10 foot long sections, the tremie discharge point remained near the bottom of the shaft (within about 1 foot of the bottom) until the 4 cu. yds. of red concrete were placed. After this load had been discharged (a total of 24 cu. yds. now in the shaft) the tremie was lifted 10 feet and a section removed so that the subsequent gray concrete started with the tremie 10 feet above the bottom. In order to simulate a potential delay in concrete delivery, an intentional delay of 30 minutes was imposed after the first 24 cu. yds. had been placed and prior to continuation of concrete placement.



Figure 2 Tremie Placement of Concrete

The construction of the shafts occurred without significant incident. The concrete from both mixes appeared to flow very well through the tremie, and at no point was there any difficulty achieving flow from the tremie (even after the 30 minute delay). The jobsite was quite far from the batch plant, and approximately 45 minutes elapsed during travel time for each truck. Other than the two 4 cu. yd. colored batches and the 30 minute delay, each truck delivered 8 cu. yds at approximately 15 minute intervals. Both mixes had slump (or slump flow) slightly higher than the target value, with slump for the SC

coastal gravel mix of around 10 to 10.5 inches and slump flow for the SCC of around 24 to 27 inches.

After completion of the pour and removal of the temporary casing, both mixes were observed to discharge significant quantities of bleed water from the surface. The bleed water appeared to be concentrated within the center of the shaft around the location from which the tremie was removed. It was not possible to measure the quantity of bleed water with any degree of precision, but rough visual estimates suggest that a volume of water equal to around 6 to 10 inches of shaft height may have occurred (around $\frac{1}{2}$ to $\frac{3}{4}$ cu. yds.). The next day after construction, the center of the shaft was depressed from the reduction in volume.

Integrity Testing

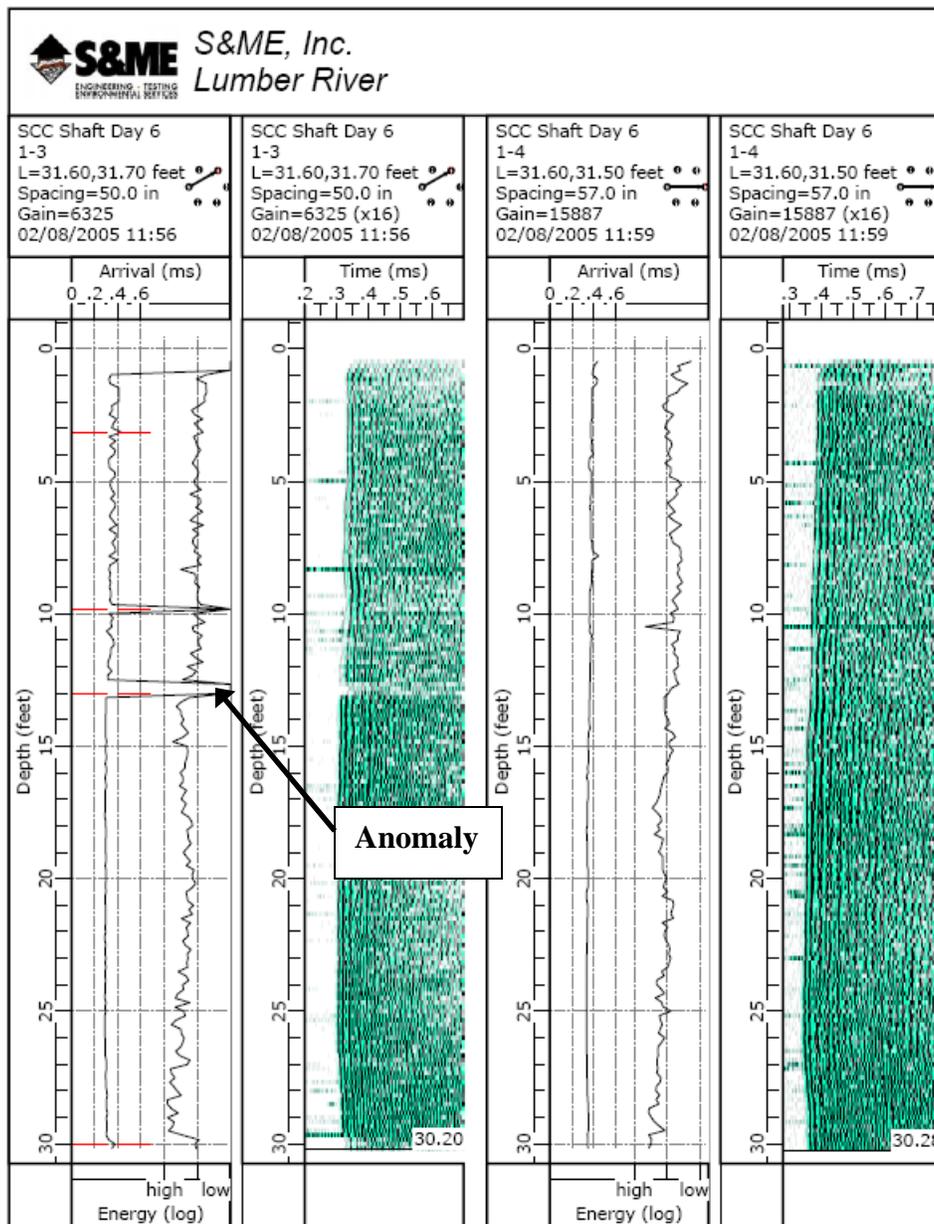
All of the shafts were subject to integrity testing using crosshole sonic logging (CSL) via the 6 metal tubes. CSL tests were typically performed 6 to 8 days after casting, at which time concrete compressive strengths from cylinders were in excess of 3300 psi. The experimental shaft cast with the SCC mix had an indication of a significant anomaly at the 13 foot depth as indicated on Figure 3. This measurement indicated 100% loss of signal between tube 3 and several other tubes. Smaller loss of signal in the range of 25% to 64% was indicated in the 9.5 to 10 foot depth range at some locations in this shaft.

Observations of Exhumed Experimental Shafts

After completion of the CSL testing, the two experimental shafts were exhumed for further examination. The exhumed shafts were pressure washed and cut at select locations using a wire saw. Cuts were made across the diameter of the shafts at depths of 6 feet from the base and 13 feet from the top (corresponding to the location of the most significant anomaly). Both the bottom 6 foot long segment and the top 13 foot long segment were then cut longitudinally through the center, with the cut centered across the shaft through tube numbers 3 and 6. Photographs of the entire operation are shown on Figures 4 through 12.

Exterior

The exterior surface of both shafts looked excellent, with no appearance of surface irregularities even at the location of anomalies from the CSL data. The bottoms of the shafts showed the pattern left by the clean-out bucket as shown on Figure 5. There were some irregularities around the perimeter of the base of the shafts. According to the inspector on the job, the bottom hole sounding appeared somewhat cleaner on the excavation corresponding to the SC coastal mix shaft although his judgment was that both shafts were within acceptable tolerance for cleanliness according to typical construction in South Carolina.



 Pile Dynamics, Inc. S&ME, Inc. Project No. 1131-04-1095 4 / 8
Cross-Hole Analyzer

Figure 3 CSL Test Data from SCC Experimental Shaft



Figure 4 Exhuming Shaft



Figure 5 Shaft Base (Bottom 6 feet)



Figure 6 Wire Saw Operation



Figure 7 SCC Shaft after First Cut



Figure 8 Section of SC Coastal Mix, 6 ft from Base



Figure 9 Section of SCC Mix, 6 ft from Base



Figure 10 SC Coastal Mix, View Through Bottom 6 ft. (top of photo is bottom of shaft)



Figure 11 SCC Mix, View of Mixing in Upper 13 ft.

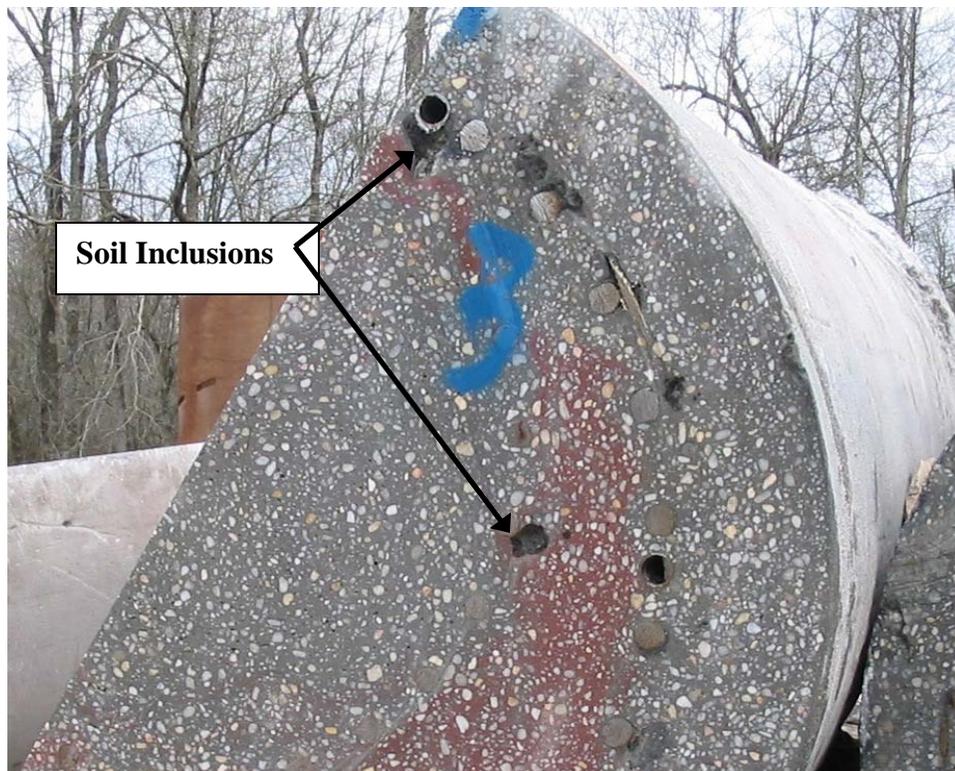


Figure 12 Cross Section at Location of Anomaly with 100% Velocity Reduction in CSL Measurements

Several observations are noted from the exhumed shafts as follows:

- 1) The base cleaning process appeared to provide an adequate cleaning of the shaft excavation at this site, even with inspection only performed by sounding in lieu of bottom hole camera inspection.
- 2) The more fluid SCC mix resulted in flow very much closer to the tremie as indicated by the differences in diameter of the red concrete in Figures 8, 9, and 10. The upward flow of concrete from the discharge point on the tremie is apparently confined to a central portion of the shaft. Some mixing of new fresh concrete with older and previously placed concrete appears to occur, as evidenced by the patterns in Figure 11 and the concentric rings of colored concrete present in both shafts.
- 3) Small pockets of trapped laitance or silt occurred as evident in Figure 12. These pockets tended to concentrate between the inner and outer cages, where obstructions cause concrete flow to be disrupted. Note also that the inner cage was displaced at the bottom and the small pocket adjacent to tube 3 occurred within the space between the tube and the inner cage where the two cages were very close. The large velocity reduction appears to be associated with the near proximity of the inclusion pocket to tube number 3. The size of the inclusions observed in this shaft are not sufficient to produce any measurable reduction in the structural capacity of this shaft; the inclusions reduce the cross sectional area of the shaft by less than the reduction produced by the CSL tubes.

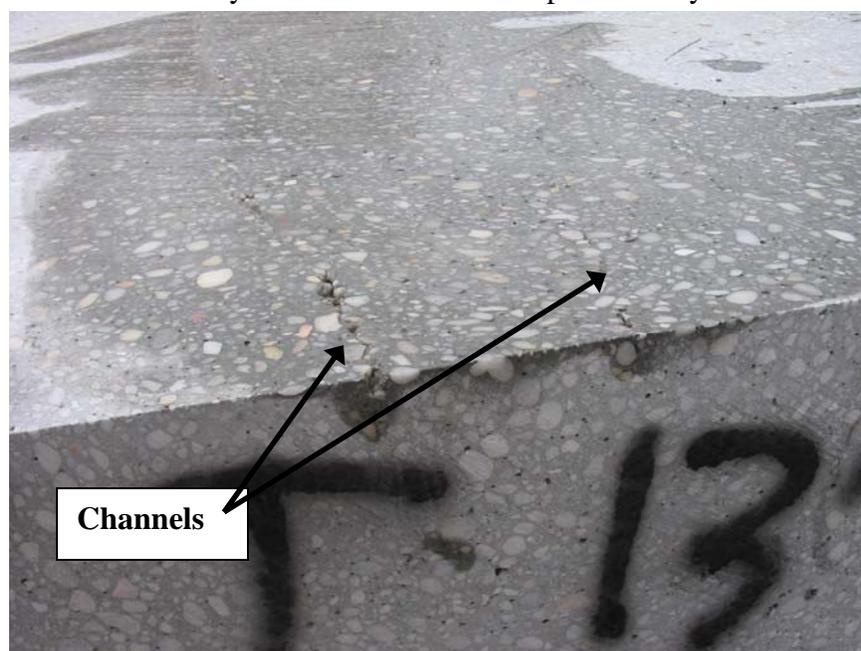


Figure 13 Segregated Channels Thought to be Associated with Bleed Water

- 4) Bleed water produced small but detectable channels of segregated aggregate about $\frac{1}{4}$ to $\frac{1}{2}$ inch wide within the interior of both shafts in the upper 13 feet. An example of these channels is shown in Figure 13. None of these were

detected in the CSL data, probably because the average modulus of the mass of concrete was not affected in a significant degree. However, the first author is aware of several instances of drilled shaft projects at bridge sites in coastal areas of the Carolinas where unexplained reductions in CSL velocity has occurred within the upper 20 feet of the shaft and only within the center of the shaft; in these cases there was no reduction in velocity between tubes around the perimeter. The small bleed channels may be a possible explanation of these conditions. Attention to mix properties in order to avoid excessive bleeding could be of benefit in such instances.

- 5) Although segregation is a logical concern with such highly fluid concrete mixes, there was no indication of any significant segregation in either of the exhumed shafts. There was also no indication of any significant poor concrete at the base of the shaft which could be attributed with mixing in the tremie associated with a poorly performing plug.
- 6) In spite of the use of two very congested rebar cages, both of these highly workable mixes passed through the cages to fill the surrounding space with sound concrete. There was some trapping of small pockets of laitance or debris, but one would generally conclude that a sound protective cover is provided over the rebar cages by the construction practice used and either of these two mix designs. Note that the cages were designed with a 6 inch cover thickness, which may be helpful in this regard.

Load Test Shafts

Two additional shafts were constructed similarly to the exhumed shafts, except with the addition of a short section of permanent casing and with shaft length of approximately 71 feet. Each of these shafts were loaded using the Statnamic device to an equivalent axial load of around 2500 kips. Both shafts supported these loads with relatively small vertical deflections on the order of ½ inch, and it was concluded that the full capacity of the shafts was not mobilized.

Other

A number of core samples were obtained from the exhumed shafts for testing of strength and chloride permeability. These tests are ongoing as of this writing, although there appears to be no indication that any of the concrete is likely to fall below generally accepted performance criteria. An extensive laboratory investigation of SCC for drilled shaft applications was also performed as a part of this study, but a full description of the results of the lab study is beyond the scope of this paper. As a result of the initial observations from the exhumed shafts and load tests, the drilled shafts for the smaller of the two bridges at this site will be constructed entirely using the SCC mix.

Summary

The Lumber River Bridge project in coastal South Carolina has provided an opportunity to evaluate the use of super-high workability concrete mixes with drilled shaft construction. Both the SCC mix and the somewhat unconventional SC coastal gravel mix appeared to perform very well under construction conditions that present challenges for concrete placement without defects. Some small trapped inclusions were observed and correlated with major loss of signal from CSL test results; these observations suggest that conventional interpretation of CSL data may greatly exaggerate the magnitude of potential defects within the concrete. The appearance of the base of the shaft with fairly conventional slurry construction techniques suggests that good performance can be obtained with relatively modest attention to quality control and inspection.

Acknowledgements

The authors wish to gratefully acknowledge the contributions to this project of Jeff Sizemore, Benar Amado, and Robert Powers of SCDOT as well as Chris Dumas and Gerald Schroeder of FHWA for promoting the concept. In addition, the project benefited from the excellent workmanship and cooperation of the general contractor, United Construction, the drilled shaft subcontractor, Trevi-Icos South, project designers Kimley-Horn and Associates, and the concrete supplier, Ready Mix Concrete.

References

O'Neill, M.W. and Reese, L.C. 1999. "Drilled Shafts: Construction Procedures and Design Methods," Publication No. FHWA-IF-99-025, U.S. Dept. of Transportation, 537p.