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Numerical Modeling of Concrete Flow in Drilled Shaft

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Numerical Modeling of Concrete Flow in Drilled Shaft

by

Jesudoss Asirvatham Jeyaraj

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering
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DEDICATION

This dissertation is dedicated to my wife, Vimala Jesudoss, without her continuous support, encouragement, understanding and love, this accomplishment and everything it stands for would never be possible. This dedication is extended to my son Joel Asirvatham for providing me a firm moral support to fulfill this task. Also extending the dedication of this dissertation to my daughter Florie Stevenson and son-in-law, Stevenson Rajkumar James for having provided conditions to achieve the finish line of this journey.
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ABSTRACT

Drilled shafts are cylindrical, cast-in-place concrete deep foundation elements. Their construction involves drilled excavation of soil or rock using large diameter augers, and placement of the necessary reinforcing steel in the excavation followed by concreting. Where a high water table is encountered, drilling slurry is used to support the excavation walls and concreting is tremie-placed. Even though the history of drilled shaft construction goes back to the 1950s, the occurrence of anomalies persists in the form of soil inclusions, reduction in shaft cross-sectional area and exposure of reinforcement. One of the main reasons for the anomalies is attributed to the kinematics of concrete flowing radially from within the reinforcing cage to the surrounding annulus/concrete cover region. In view of this radial component of concrete flow and thus radially flowing interfaces between the concrete and slurry, the region outside the cage is more likely to contain veins of poorly cemented or high water-cement ratio material. These veins contain trapped slurry, which oftentimes consists of bentonite, jeopardizing the integrity of the shafts.

This research program focuses on the numerical evaluation of self-consolidating concrete (SCC) for drilled shaft application by taking into account realistic non-Newtonian concrete flow properties and the shaft structural blockages. For this objective, a 3-D computational fluid dynamics (CFD) model of the concrete flow in the shaft excavation is developed in ANSYS-Fluent. As a precursor to 3-D modeling, 2-D CFD modeling is carried out using COMSOL Multiphysics. In both 2-D and 3-D models, the Volume of Fluid method is used for computing the motion of the interface between the concrete and the drilling slurry. The models predict the flow
patterns and volume fraction of concrete and slurry. The results are encouraging as the flow pattern from the simulation shows both horizontal and vertical creases in the concrete cover region. Moreover the flow pattern shows the concrete head differential developed between the inside and the outside the reinforcement cage. Further, the 3-D model is evaluated by studying the influence of the size of drilled shaft and arrangement of the bars and the results obtained are realistic.

With this 3-D model developed as a tool, the simulation of SCC and the normal standard concrete (NC) flow in drilled shaft concreting are studied in terms of creases and concrete head differential encountered in the flow. From the simulation, it is observed that in the flow pattern of SCC, the creases are very few compared to the one obtained from the flow pattern of NC. Moreover, the concrete head differential in the flow pattern of SCC is much less, than the head differential obtained from the flow pattern of NC flow. In the case of SCC, the head differential encountered is about one inch. In the case of NC, the concrete head differential is 4-inch when the vertical rebars are spaced at 7-inch apart and 10-inch when the rebars are placed at 3.5-inch apart. Based on this numerical evaluation of SCC flow in the drilled shaft excavation, it is concluded that the performance of SCC is better than the performance of NC in filling the cover annular region of drilled shafts.
Drilled shafts are cylindrical, cast-in-place concrete, deep foundation elements that may be selected over driven piles because of cost effectiveness, the soil strata encountered, and/or controlling vibrations due to sensitive surroundings. The shaft sizes can range from 2 feet to 10 feet and can be of length up to 300 feet. In general, the process of constructing shafts involves the drilled excavation of soil or rock using large diameter augers to form a deep cylindrical void space. Within the excavation, placement of the necessary reinforcing steel is followed by concreting (Figure 1.1). Due to the presence of high water table in Florida, the excavation is carried out using slurry to stabilize the excavation walls and concreting is carried out using a tremie pipe. Sometimes permanent or temporary casing is used to maintain the stability of the excavation.

Figure 1.1 Shaft Construction: (Left) Excavation, (Center) Cage Placement and (Right) Concreting
Even though the history of drilled shaft construction goes back to 1950s, every step of the
shaft construction process is challenging and the occurrence of anomalies persists in the form of
soil inclusions, reduction in shaft cross-sectional area and exposure of shaft reinforcement. The
two most common complications that arise during shaft construction and in the order of operation
are: (1) excavation stability until the end of concreting and (2) concrete-related flow properties.
The latter of which is further complicated by the reinforcing cage congestion/spacing. In view of
this, there is a need for a comprehensive study on the concrete flow in the shaft excavation for
enhancing the flow performance.

1.1 Background

The stability of a drilled shaft excavation, during excavation and concreting is maintained
mechanically, hydrostatically, or with a combination of both means. When the stability is
maintained hydrostatically, the flow of concrete that is heavier than slurry is considered as a rising
fluid that displaces the slurry effortlessly. However, studies have shown that the rising concrete is
drastically affected by the presence of the reinforcing cage (Mullins and Ashmawy, 2005) and
encountered with a concrete head differential between inside and outside the reinforcement cage.
Figure 1.2 shows a conceptual comparison between the idealized and the actual concrete flow.
Based on field test results it was found that the cage rebar spacing and the concrete flow rate in
the shaft excavation were linked to a differential concrete level between the inside and outside of
the reinforcing cage mesh. Smaller diameter shafts where the tremie size occupies a large fraction
of the interior cage region, the differential may be even more drastic considering the substantial
increase in the upward concrete velocity from a standard concrete truck placement rate. The
differential concrete head increase was shown to be proportional to the square of the upward
concrete velocity within the cage (Figure 1.3).
From Figure 1.3, plot of head differential vs cage spacing to maximum aggregate diameter ratio (CSD) at concrete velocity of 1.5 ft/min is shown in Figure 1.4 and a practical cut off can be shown below which larger head differentials would occur. A cage spacing that produced a CSD smaller than 8 could result in more concrete build-up inside the cage which in turn has a higher potential for slurry inclusions (outside the cage) or that may prevent concrete from sufficiently bonding to the surrounding soil. In spite of state and federal specifications, the issues of concrete flow and the complete slurry displacement in the concrete cover region persist. There are instances where the hardened concrete of drilled shaft were exposed with anomalies when the shafts were exhumed. Figure 1.5 shows an example of a shaft with anomalies of exposure of reinforcement bars that exhibited concrete flow problems in the shaft excavation during concreting, either from fresh concrete or from slurry.
Figure 1.3 Head Differential vs. Upward Concrete Fill Velocity, (Deese and Mullins, 2005)

Figure 1.4 CSD vs Head Differential: Recommended CSD Ratio
From this perspective, Self Consolidating Concrete (SCC) which is a more flowable type of concrete than the normally used conventional concrete (NC) for drilled shaft, has been attempted as field tests and on a small scale as actual foundation element. However in all such cases the evaluation of SCC has been made by empirical methods and not specific to the shaft construction. Moreover, there is no mention in the literature about any study on the flow of concrete in the shaft excavation.

In the shaft excavation, as the concrete flows, there is a dominant radial component concrete flow and thus a radially flowing interface, with laitance of fine particles, between the concrete and drilling fluid. During the concrete flow around vertical rebars and horizontal stirrups, a separation occurs whereby two separately contaminated faces then recombine pressing these two faces together. This process continues up and repeats for all stirrup levels above. Figure 1.6 shows a conceptual view of the radial concrete flow and the vertical creases (consisting of trapped laitance) formed behind the vertical rebars. Figure 1.7 shows the same phenomenon that forms
horizontal creases. Further, the experimental studies have shown that the radial flow of concrete is drastically affected by the rebar cage and thus the rising concrete in the shaft.

Figure 1.6 Top View of Concrete Flowing Radially through Cage: (Left) Initial, (Right) Final

Figure 1.7 Profile View of Radial Concrete Flow through Stirrups

1.2 Objectives and Approach

In this research program, a 3-D numerical model is developed to simulate the concrete flow in the shaft excavation. The simulation is expected to give the concrete flow pattern that shows the concrete head differential and the creases behind the reinforcement cage in both vertical and
horizontal directions. The flow patterns are qualitatively validated with the available experimental data.

Using the simulation as a tool, the flow performance of SCC for drilled shaft application is evaluated.

1.3 Structure of the Dissertation

This dissertation is comprised of five chapters. The introduction (Chapter 1) of the dissertation is followed by literature review of SCC for drilled shaft application and simulation of concrete flow (Chapter 2). The drilled shaft construction method, rheological model for concrete, previous case studies on SCC for drilled shaft application, and rheological parameter case studies are presented and discussed in this chapter. The case studies are summarized and the chapter concludes with the need for a realistic evaluation of SCC using a numerical modeling and simulation of SCC flow in drilled shafts. In Chapter 3, a 3-D numerical modeling of drilled shaft using ANSYS-Fluent, covering the geometry, the meshing and the simulations performed are discussed. The 2-D modeling carried out using COMSOL Multiphysics® as a precursor to 3-D modeling is included in this chapter. Chapter 4 discusses the results from the simulations. The validation of the modeling, by comparing the results from the simulations performed with the results from the experimental study of Mullins, (2014) is discussed. The performance of SCC over normally used conventional concrete and the effect of shaft sizes as well as the rebar arrangement on the flow performance are presented in this chapter. The dissertation ends with Chapter 5, which covers the conclusions and prospects for future study.
CHAPTER 2: REVIEW ON SCC FOR DRILLED SHAFT APPLICATION AND SIMULATION OF CONCRETE FLOW

The function of a drilled shaft is to transfer the loads from the super structure to hard soil strata. Drilled shafts are applicable to most of the soil condition and hence have a very wide range of applications. Proper specification for the material and for the construction is essential to achieve the final drilled shaft product of required quality. This literature review covers the properties of drilled shaft material and mainly the application of SCC for drilled shaft concrete to enhance the flow performance of drilled shaft concreting.

2.1 Drilled Shaft Design

When a load from the structure acts on the drilled shaft, it is resisted by the forces as summarized below:

- Frictional resistance mobilized from the shaft peripheral surface in contact with soil
- Base resistance derived from the shaft base

The total shaft resistance is the combination of the above two components. The contribution of each component is based on the type of soil strata in which the drilled shaft is installed. The shaft frictional resistance and the base resistance are calculated from the soil properties, which are obtained from the field soil investigation and from the laboratory test results of the soil samples. There are established design guidelines by which the shaft resistance is calculated.
2.2 Drilled Shaft Construction

In general, the drilled shaft construction method can be classified into three broad categories, which are the dry method, the wet method and the casing method. In some instances, drilled shaft construction involves combination of the above methods depending on the subsurface soil conditions. These methods are based on the experience of practitioners, the Florida DOT specifications, QC and QA guidelines and the FHWA-NHI Drilled Shaft Manual (2010). The FHWA manual serves as a reference source for the drilled shaft installation practitioners.

2.2.1 Dry Method of Construction

Dry method of construction or dry hole construction is a relatively simple method. Since the shaft excavation sides should not cave in, the shaft bottom should be stable during the entire process of excavation and concreting. The ideal subsurface materials to implement this method are stiff clay and rock, which are above the water table. The dry method of shaft installation is relatively rare and only applicable where the ground water table is below the shaft depth.

2.2.2 Wet Method of Construction

In the wet method of construction, the stability of the drilled shaft excavation walls and base is maintained by slurry, which is a mixture of clays and water. Slurry properties (percentage of sand, viscosity, density and pH) are specified such that the shaft construction is achieved. In addition, the slurry density would be of lighter weight so that the concrete would displace the slurry mixture. During concreting of the shaft, the displaced slurry finally reaches the top of the shaft and flows out yielding clean concrete (FDOT specifications). The steps involved in the wet method are: setting a starter casing (if required), filling with slurry, excavation to the required depth, cleaning excavation bottom, placing reinforcement, concreting through a tremie pipe and extracting the tremie while adding concrete. These processes are shown in Figure 2.1. During
concreting, the tremie bottom is always maintained at least 10 ft. below the surface of the fresh concrete to prevent the mixing of concrete with the slurry (FDOT).

![Figure 2.1 Drilling Process with Slurry Stabilization. (a) Setting of Starter Casing, (b) Slurry Filling, (c) Cleaning of Excavation and Placing of Reinforcement, (d) Placing of Concrete through Tremie pipe, (e) Pulling of Tremie while Adding Concrete, (FHWA-NHI, 2010)](image)

2.2.3 Shaft Construction with Casing

The casing method is used where wet method by itself is not able to hold the excavation walls due to excessive caving. This method consists of using either temporary or permanent casing. Several types of drilling rigs are available to advance the casing into the rock, such as Oscillating Rig and Vibro-Hammer.

Temporary casing is used to prevent the caving of upper surficial soils that are loose and tend to cave. In this case, temporary casing is driven through the depth of these loose soils and the shaft excavation is done through the casing. Below the depth of loose soils, slurry could be used for stabilizing the excavation similar to the wet method. Permanent casing is used when the slurry method is not stabilizing the excavation and encountered with large body of loose soil and water intrusion. In this case, slurry is used initially and then casing is set and advanced into the bearing stratum and sealed. The hole is cleaned thoroughly, reinforcement is set and concrete is placed.
In most cases, the wet method of construction is applicable. However if the excavation walls are not able to hold by the wet method, then the casing method has to be adopted. The stability of the excavation wall and base and the concrete properties are the two important elements that need careful attention during the drilled shaft construction. These two are briefly covered in the following sub-sections.

2.3 Slurry Stabilization of Drilled Shaft Excavation

The slurry supports the shaft excavation by exerting hydrostatic pressure on the walls and it remains in the excavation without substantially flowing into the adjoining soil media. Also, the slurry should ensure clean displacement by concrete, with no significant interference with the bond between reinforcement and set concrete.

Slurry could be mineral slurry, natural slurry/water or polymer. Natural slurry is a mixture of natural clays and water. Mineral slurry consists of processed bentonite, which is one common type of drilling slurry. Bentonite is from powdered clay, predominately consisting of the mineral montmorillonite. When it is mixed with water, it forms a suspension of microscopic, plate-like solids and it contributes to borehole stability. All newly mixed bentonite should be allowed to hydrate fully for 24 hours before final mixing and introduction into a borehole. The slurry properties are essentially maintained so that in addition to achieving the stability of the excavation, the specifications for slurry ensure the shaft concrete is not contaminated. Table 2.1 summarizes the slurry properties as per the specifications mentioned in the table.
Table 2.1 Specified Property Ranges for Mineral Slurry

<table>
<thead>
<tr>
<th>Property</th>
<th>Required range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AASHTO (2016); FHWA (2010)</td>
</tr>
<tr>
<td></td>
<td>FDOT (2017b)</td>
</tr>
<tr>
<td>Density (lb/ft$^3$)</td>
<td>64.3 to 72</td>
</tr>
<tr>
<td></td>
<td>64 to 73 (fresh water)</td>
</tr>
<tr>
<td></td>
<td>66 to 75 (salt water)</td>
</tr>
<tr>
<td>Viscosity (s/qt)</td>
<td>28 to 50</td>
</tr>
<tr>
<td></td>
<td>28 to 40</td>
</tr>
<tr>
<td>pH</td>
<td>8 to 11</td>
</tr>
<tr>
<td></td>
<td>8 to 11</td>
</tr>
<tr>
<td>Sand Content (%)</td>
<td>$\leq 4.0$</td>
</tr>
<tr>
<td></td>
<td>$\leq 4.0$</td>
</tr>
</tbody>
</table>

2.4 Drilled Shaft Concrete Currently Used

In view of the unique construction techniques involved for drilled shafts compared to other concrete structural elements, it is essential that the concrete used must be designed for the specific requirements of drilled shaft concreting. The important requirements for the drilled shaft construction relate to the workability specifications for the fresh concrete mix during transport and placement operations. Oftentimes, the mix needs to be transported long distances to a remote site and to flow readily through a tremie and congested reinforcement under slurry to fill the excavated hole; the mix may be required to stay fluid for periods of 4 to 8 hours or more. Moreover, the mix must consolidate under its own self-weight without vibration, and free from segregation, excessive bleeding, or excessive heat of hydration. The specification of drilled shaft concrete is given below:

- Fresh concrete:
  - Maximum aggregate size - 3/4 inch.
  - Water-to-cementitious material ratio: 0.40 to 0.41
  - Slump - 7 to 9 inch during placement under slurry displacement method.
Hardened concrete:

- Concrete strength - 4000 to 5000 psi (28 days compressive cylinder strength); higher strengths are used if the designer requires them.

In practice, the slump test (Figure 2.2) is the established test method that is widely used in the field to characterize the workability of fresh concrete. The test method uses a slump cone (Figure 2.2a) and standards ASTM C 143 in the United States and EN 12350 in Europe, part 2 (for ordinary concrete) and part 8 (for SCC).

![Slump Test](image)

(a) Slump Cone  
(b) Slump Test

Figure 2.2 Slump Test for Standard Concrete for Drilled Shaft

2.5 Anomalies in Drilled Shaft

Generally, for the case of foundations, a drilled shaft is constructed below the ground level and more than that with soil as the formwork. Hence, the actual shape and the quality of the shaft depends on various factors such as the method of construction, shaft concrete mix, drilling fluid/slurry, placement and arrangement of reinforcement cage and method of concreting. In some instances when the shafts have been exhumed or at least partially exposed, aberrant conditions
have been found in the form of soil or slurry inclusions, concrete segregation, reduction in cross sectional area and exposure of reinforcement. One of the main factors attributed to the anomalies is the flow of concrete in the shaft excavation during concreting. In order to enhance the flow behavior of concrete to prevent the anomalies, the use of Self Consolidating Concrete (SCC) is considered for drilled shaft concreting.

2.6 Self Consolidating Concrete (SCC)

Self-Consolidating Concrete (SCC) or Self-Compacting Concrete also called High-Workability Concrete, Self-Leveling Concrete, or Flowing Concrete is normally considered as a concrete mix of exceptional deformability during casting, which still meets resistance to segregation and bleeding. The first SCC prototype was demonstrated by Ozawa (1989). SCC has mostly been used in the precast industry. Recent overviews of SCC types, test methods, and properties are given by Khayat (1999), and Bonen and Shah (2004, 2005).

Some of the benefits of using SCC as noted in the literature are summarized as follows:

- Reduction in construction cost due to less labor
- Decrease in construction time
- Comparatively simple casting process as no vibration is needed
- Ability to cast congested and complex structural elements in various shapes and dimensions that are not achievable by any other conventional techniques
- Improving appearance and quality of the finished surfaces and reduction in the occurrence of bug holes, honeycombing, and other surface irregularities
- Higher durability of concrete structures
In view of the possibility of better pumping system with SCC, reduction in the requirement of cranes and other logistics for delivering concrete at the job site.

Despite the benefits of SCC, there are limitations that should be taken into consideration. The cost of raw material for SCC can be 13% to 30% higher than the cost of conventional mixtures with similar mechanical properties (Schlagbaum, 2002, Martin, 2002). SCC requires greater quality control and quality assurance measures at both plant and site to ensure proper workability, including high resistance to segregation and stability of entrained air voids. In addition, the increased fluidity of SCC can lead to near hydrostatic conditions. In spite of these few limitations, which can be addressed, SCC might be considered as a better option for drilled shaft concreting.

2.6.1 ACI Guidelines for SCC Mixture

The American Concrete Institute (ACI) published a code specifically addressing SCC concrete (ACI 237R-07) wherein it defines SCC in the following manner:

*Self-consolidating concrete (SCC) is highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. In general, SCC is concrete made with conventional concrete materials and, in some cases, with a viscosity-modifying admixture (VMA). SCC has also been described as self-compacting concrete, self-placing concrete, and self-leveling concrete, which all are subsets of SCC. The nomenclature of this technology has been previously discussed (Szecsé 2002).*

The definition is not specific and established but rather it is performance based. However, ACI does provide some guidance on mix designs with examples but does not limit users to those
examples (ACI 237R-07). Suggested values for key parameters of SCC and the values of the parameters for normal concrete specified in ACI 211 are given in Table 2.2.

Table 2.2 Suggested Value for Key Parameters in SCC Trial Mixture Proportioning

<table>
<thead>
<tr>
<th>Workability</th>
<th>SCC (based on ACI 237)</th>
<th>Normal Concrete (based on ACI 211)</th>
<th>ClassIV Drilled Shaft Concrete (based on FDOT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slump flow: based on reinforcement level, element size and shape intricacy, surface finish importance and coarse aggregate content, the target values are &lt;22in, 22 to 26in, and &gt;26in.</td>
<td>Concrete slump: varies from 3in to 5in depends on the types of construction</td>
<td>Concrete Slump: 8.5 inch</td>
<td></td>
</tr>
</tbody>
</table>
| Water-
Cementitious Material Ratio | 0.32 to 0.45 | 0.40 to 0.50 | 0.41 |
| Slump flow in (mm) | Cement/cementitious material content lb/yd³ (kg/m³) | Department Approved Design Mix. |
| < 22 (<550) | 600 to 650 (355 to 385) | a)Fly ash:33% to 37% |
| 22 to 26 (550 to 600) | 650 to 750 (385 to 445) | b)Slag:58% to 62% |
| >22 (>650) | 750 + (458+) | c)Fly ash and Slag: Fly ash-10% to 20%, Slag-50% to 60%, Cement-30% |

In addition to the above guidelines for SCC, the absolute volume of coarse aggregate, the paste fraction, and the mortar fraction suggested are 28 to 32%, 34 to 40%, and 68 to 72% respectively, in the ACI code.

2.6.2 Test for Fresh SCC

2.6.2.1 Slump Flow Test

There are several tests that are used to test the properties of fresh SCC. The slump flow test (Figure 2.3) is the main test, which is commonly used to determine the flowability of SCC mix. 

16
This test is similar to the slump cone test for standard concrete and is governed by ASTM C1611. It measures slump flow and flow time T50, which is the time taken for the SCC to reach a 20-inch diameter circle when the slump cone is lifted vertically, allowing the concrete to flow out freely. The slump flow indicates the free unrestricted deformability and the flow time indicates the rate of deformation within a defined flow distance.

![Slump Flow Test](image)

**Figure 2.3 Slump Flow Test**

### 2.6.2.2 J-Ring Test

The J-Ring simulates a reinforcing steel cage to test the passing ability of SCC. This test (Figure 2.4) is basically the slump flow test performed within a reinforcing steel ring. The passing ability of the mix is determined based on the slump flow difference with and without the ring. The test is governed by ASTM C1621. The standard J-Ring design includes sixteen 0.625-inch bars, four inch high and evenly placed in a 12-inch diameter circle. The ring simulates the reinforcement pattern by which the passing ability of SCC though the reinforcement can be tested. Hence, this test is an improvement over the slump flow test and a simple one that can be performed in laboratory and at project site.
2.6.3 Workability of SCC in Terms of Rheology

Since the drilled shaft concreting is done without the aid of vibration, concrete must possess the following three characteristics to meet the workability requirements for its flow performance:

- **Filling ability:** The ability of concrete to flow into and fill entire spaces within the formwork under its own weight without any vibrations.

- **Passing ability:** The ability of concrete to flow through sharp and tight openings such as between rebar cages without segregation or blocking.

- **Segregation resistance:** The ability of concrete to remain homogeneous during transportation and placing.

The above requirements are not a clear specification but a performance-based definition. In the case of shafts, the concrete must be placed in a submerged state in the presence of slurry and not in free flow state.

The workability of fresh normal concrete and SCC are measured by empirical tests, such as the slump test, slump flow test, etc., as explained in previous sections which have been used for many years. However, tests based on fundamental physical quantities and on established
rheological properties are the most appropriate to ensure the above flow performance characteristics.

### 2.6.4 Rheological Properties of SCC

Rheology of a liquid is the relation between shear stress and shear rate of its flow under the effect of an applied force. In rheology we move from static deformation of basic mechanics to dynamic deformation. One of the basic properties in rheology is viscosity, which is defined as the resistance to flow under shear stress and mathematically represented as the ratio of shear stress to shear rate. In the case of Newtonian fluids, the shear stress at each point is linearly proportional to its shear rate at that point.

The two most important rheological properties of SCC are yield stress and plastic viscosity:

- **Yield stress** is the energy required to make a fluid material to flow. Fluid materials that exhibit a yield stress start flowing when the shear stress exceeds the yield stress value $\tau_0$. When the yield stress is not yet reached, the material behaves like a solid. When the yield stress is exceeded the sample can display Newtonian (linear flow) behavior. To be considered SCC, concrete must flow easily under its own weight, so its yield stress must be very low.

- **Plastic viscosity** is the resistance of a material to flow due to internal friction, once the yield stress has been exceeded. SCC should have a plastic viscosity as low as possible, but must have an adequate viscosity in order to suspend aggregate particles in a homogenous manner within the concrete matrix without segregation, excessive bleeding, excessive air migration, or paste separation (Annika Gram et al 2009).
SCC, in its fresh state, is most often assumed to behave like a Bingham fluid in which the flow is defined by yield stress \( \tau_0 \) and plastic viscosity \( \mu \) as below,

\[
\tau = \tau_0 + \mu \dot{\gamma}
\]

where \( \dot{\gamma} \) is the shear rate.

The flow curves of Newtonian fluid and Bingham fluid are shown in Figure 2.5

![Figure 2.5 Shear stress Curves for Newtonian and Bingham Fluids](image)

In the case of non-Newtonian fluid, the viscosity is a function of shear stress and time. Fluids characterized by a viscosity decreasing with an increasing shear rate are examples of shear-thinning fluids. A material that has a viscosity that decreases under shear stress and then continues to decrease with time is said to be thixotropic. Fluids which thicken when worked or agitated are called shear-thickening fluids. In the case of shear thickening fluid, if the viscosity increases over time the material is said to be rheopectic (Barnes, H.A. et al, 1989).
Concrete rheology exhibits a complex behavior where the Bingham model parameters are affected by virtually all aspects of the mix (e.g. w/c which is water-cement ratio, cement content, admixtures, etc.). In concrete, particles of coarse aggregate are dispersed in mortar and within mortar, particles of fine aggregate are dispersed in cement paste and within cement paste, and cement particles are dispersed in water.

The flow properties of suspensions are governed by the interfaces between solid and water. When SCC or the conventional concrete for drilled shaft is sheared, the force that attracts two particles has to be broken; this mechanism of the shear-induced breakdown of the structure is termed as structural breakdown. Table 2.3 shows the range of values of yield stress and plastic viscosity for different material components in concrete. Table 2.3 also states whether the structural breakdown process for these components is significant.

Table 2.3 Range of Values for the Yield Stress and Plastic Viscosity of Cement Paste, Mortar, and Concrete (P.F.G Banfill, Rheology Review, 2006)

<table>
<thead>
<tr>
<th></th>
<th>Cement Paste Grout</th>
<th>Mortar</th>
<th>Flowing Concrete</th>
<th>SCC</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress (Pa)</td>
<td>10 - 100</td>
<td>80 - 400</td>
<td>400</td>
<td>50 – 200</td>
<td>500 - 2000</td>
</tr>
<tr>
<td>Plastic Viscosity (Pa-s)</td>
<td>0.01 – 1</td>
<td>1 - 3</td>
<td>20</td>
<td>20 – 100</td>
<td>50 - 100</td>
</tr>
<tr>
<td>Structural Breakdown</td>
<td>Very significant</td>
<td>Present</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

2.6.5 Rheological Models for SCC

The Bingham model is mostly satisfactory for describing the behavior of ordinary concrete. Even though Bingham model is considered for SCC, the behavior of SCC is different. SCC has thixotropic characteristics in which the viscosity decreases with time when flow begins for a
sample that has been previously at rest and the viscosity recovers in time when the flow is discontinued.

2.6.5.1 Herschel-Bulkley Model

Materials that have a yield value and show a shear thinning or shear thickening behavior when the yield stress is exceeded can be described by the Herschel-Bulkley model via the following equation:

\[ \tau = \tau_0 + K \dot{\gamma}^n \]

where K is the consistency index. For \( n > 1 \), the model describes shear thickening and for \( n < 1 \), shear thinning behavior is described. The Bingham model is a subset of the Herschel-Bulkley with \( n = 1 \).

Feys et al. (2007) studied the applicability of these rheological models for SCC. When the Bingham model was applied to the data obtained from experiments, negative yield stress values were generated in the region of low shear stress. Using the Herschel-Bulkley model, a better fit of the test data was achieved when compared with the Bingham model. Most notably, a more meaningful positive yield stress was obtained.

Even though the Herschel-Bulkley model described the behavior in a better manner, some disadvantages were encountered. In some particular cases like shear thickening, it overestimated the yield stress (Feys et al. 2007). Also, when the physical interpretation of the parameter K was analyzed, it was observed that its dimension was \([\text{Pa.s}^n]\), thus depending on n. As a result, the dimension of K was variable, having no easily identifiable physical meaning.

2.6.5.2 Modified-Bingham Model

Subsequently a modified-Bingham model was studied to describe the rheological behavior of SCC (Feys et al, 2007). This model is an extension of the Bingham model with a second order
term. The modified Bingham model was applied to investigate the yield stress of cement paste.

The equation of the modified Bingham model can be written as

\[ \tau = \tau_0 + \mu \dot{\gamma} + B \dot{\gamma}^2 \]

where, \( B \) is the constant.

This equation gives a more reliable results in the region of low shear rate also. Moreover shear thickening can be analyzed. Hence, the issues faced in the case of the Herschel-Bulkley model are addressed in this model. In view of this, the flow behavior of SCC can be modeled in a better approach than with the Herschel-Bulkley model.

2.6.5.3 Carreau Model

Carreau model has been used for turbulent flow in pipes (Andrade et al. 2007). This model describes the variation of viscosity with shear rate, and is given by the following equation:

\[ \mu_{\text{eff}}(\dot{\gamma}) = \mu_{\text{inf}} + (\mu_0 - \mu_{\text{inf}}) \left(1 + (\lambda \dot{\gamma})^2\right)^{(n-1)/2} \]

and \( \tau = \mu_{\text{eff}} \dot{\gamma} \)

where:

\( \mu_0 \) = viscosity at zero shear rate (Pa s)

\( \mu_{\text{inf}} \) = viscosity at infinite shear rate (Pa s)

\( \lambda \) = relaxation time (s)

\( n \) = power index

With this model, at low shear rate \( \dot{\gamma} < 1/\lambda \) the fluid exhibits Newtonian behavior and at higher shear rate \( \dot{\gamma} > 1/\lambda \) the fluid exhibits a non-Newtonian power behavior. Since this model defines the non-Newtonian behavior and considers the variation of shear rate, this might be a good option for SCC.
2.6.6 Thixotropic Characteristics of SCC

For Newtonian fluids, the viscosity of a fluid is constant irrespective of shear rate and hence viscosity vs shear rate is linear. However, in the case of non-Newtonian and time dependent fluids, the viscosity depends on both the applied shear rate and the time during which the shear rate is applied. The structure of this type of material changes with time at a given shear which affects the viscosity. These materials can be divided into two groups called thixotropic and rheopectic.

Thixotropic materials have an internal structure. When exposed to shear, this structure is broken down and when the material is at rest, the structure is built up again. The breakdown and build up depends on the time that the shear is applied and on the material properties. Thixotropic materials have a shear thinning and time dependent behavior. Rheopectic materials have precisely the opposite properties as thixotropic materials. Their structure builds up when exposed to shear over a period of time and breaks down when at rest. These materials have shear thickening and time dependent behavior. This type of behavior is much less common but can occur in a cornstarch / water solution.

SCC has thixotropic characteristics in which the viscosity decreases with time when flow starts from rest and the viscosity recovers in time when the flow is discontinued. This is due to the fact that SCC is a colloidal suspension, which is built around very fine particles like cement that has a very large combined surface area (high surfaces area to volume ratio). The particles are electrically charged and attract each other. When the SCC is sheared, the force that attracts the two particles has to be overcome and this force is the yield stress in the Bingham model. As the shearing stops, the particles start to attract each other and the yield stress is built up again. In view of the thixotropic characteristics of SCC, a non-Newtonian fluid behavior is required to be considered.
2.7 Previous Case Studies

This section reviews case studies that have explored SCC concrete for drilled shaft application, physical case studies of drilled shafts, and rheological parameter case studies.

2.7.1 Case Studies of Drilled Shafts with SCC

In this section, some case studies of drilled shaft constructed with SCC are covered with respect to SCC mixtures and, with normal concrete mixtures used simultaneously.

2.7.1.1 Hodgson et al, (2005), The National Geotechnical Experiment at Opelika, Alabama

It is interesting to note that the National Geotechnical Experimental Site in Opelika, Alabama, is the first documented place where SCC was used for drilled shaft application (Mullins and Ashmawy, 2005; Hodgson, et al, 2005). The main objectives of the research (among others) were to evaluate the use of SCC in drilled shaft construction and to identify any potential challenges or issues. The evaluation was done by comparing the performance of a SCC to conventional drilled shaft concrete in a full-scale field application.

In this study program, five drilled shafts, each approximately 965 mm (38 inch) in diameter and 7.30 m (24 ft.) deep were constructed. Table 2.4 presents the important parameters adopted for these five test shafts (TS). The shafts were cast with four different concrete mix designs: a conventional drilled shaft concrete mix with #57 limestone but at two different slumps, another mix with #7 river gravel in place of #57, and two with an experimental SCC mix. TS-1, TS-2, and TS-3 were made with conventional concrete mixtures with the Alabama DOT drilled shaft specifications whereas TS-4 and TS-5 were cast with SCC mix. The shafts were constructed with tremie placement. The first four shafts were cast in dry conditions with tremie placed and the last was tremie placed through water. Dry construction method was adopted to video tape the flow of concrete.
The reinforcement within the drilled shafts was designed to be congested but still representative of the current practices. Certain reinforcing cages were outfitted with filled sandbags in order to simulate “debris” near the wall of the shaft to evaluate each mixtures ability to self-consolidate. The clear cover to reinforcement and CSD, which is cage spacing to maximum aggregate diameter ratio for the shafts, are given in the Table 2.4.

During the concrete placement, a head difference from inside the cage to outside was recorded for all the shafts. It was as much as 16-inch with conventional drilled shaft concrete and 10-inch with the SCC mixture. This indicated that the SCC mixture was easily able to move through the reinforcement cage, while the conventional drilled shaft concrete resisted movement through the cage. Figure 2.6 shows the head differential between the inside and the outside of the cage observed in standard shaft mix (TS-1). From the conclusions drawn from the research, the following recommendations were made:

- Use the slump flow, T50, and L-box as the field quality control test for SCC.
- Correctly batch the chemical admixtures at the origin of mixing and avoid adjustments to chemical admixtures in the field.
- Adopt No. 7 river gravel to prevent blocking around reinforcement, to have better flow around obstacles, and to derive a more consistent distribution of the mixture.
- A quantitative approach for determining coarse aggregate distribution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shaft Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Concrete/Aggregate size</td>
<td>TS-1</td>
</tr>
<tr>
<td>NC, #57</td>
<td>NC, #7</td>
</tr>
<tr>
<td>Slump/Slump Flow (in)</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Table 2.4 (continued)

<table>
<thead>
<tr>
<th></th>
<th>560</th>
<th>560</th>
<th>560</th>
<th>420</th>
<th>420</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type 1 Cement Content (lb/yd³)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly Ash Class F (lb/yd³)</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fly Ash Class C (lb/yd³)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>227</td>
<td>227</td>
</tr>
<tr>
<td>*GGBF Slag (lb/yd³)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td><strong>w/c ratio</strong></td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Reinforcement Clear Cover (in)</strong></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>CSD</strong></td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Excavation Method</strong></td>
<td>DRY</td>
<td>DRY</td>
<td>DRY</td>
<td>WET</td>
<td>DRY</td>
</tr>
<tr>
<td><strong>Head Differential (in)</strong></td>
<td>8–10</td>
<td>3–5</td>
<td>12–16</td>
<td>8 – 10</td>
<td>0 – 2</td>
</tr>
</tbody>
</table>

*Ground Granulated Blast Furnace Slag  
NC - Conventional Concrete Mix; SCC - Self-Consolidating Concrete

Figure 2.6 Standard Shaft Mix (TS-1) Head Differential between Inside and Outside Cage
2.7.1.2 Brown et al, (2005), Evaluation of SCC for Drilled Shaft at Lumber River Project, South Carolina

Brown et al., (2005) performed a field study on the evaluation of SCC for drilled shafts. The drilled shaft size was 1.8 m (6 ft) in diameter and 9.1 m (30 ft) deep. Drilled shafts were constructed using self-consolidating concrete and a high slump gravel aggregate concrete mixture, which was typically used in coastal South Carolina and was referred to as SC Coastal mixture. The SC Coastal mixture was actually a mixture with workability higher than the South Carolina DOT specifications. In their test program, the shafts constructed were: (a) two experimental shafts 6 ft in diameter by 30 ft deep to be cast and exhumed; (b) two load test shafts 6 ft. in diameter by 72 ft deep; and (c) the foundations of two bridges. One each of the experimental and load test shafts were constructed using SCC and the SC Coastal mixture, respectively. The smaller of the two bridges had six shafts to be constructed using SCC, and the larger of the two bridges had 20 shafts to be constructed using the SC Coastal drilled shaft mixture. Table 2.5 gives the slump, the cement content, and the water-cement ratio used in the different mixtures. The shafts were constructed using bentonite slurry and within the upper 15 ft temporary casing was introduced.

Based on the quality assessment it was concluded that both the SCC mixture and the SC Coastal gravel mixture appeared to perform very well under construction conditions that present challenges for concrete placement without defects.

The more fluid SCC mixture resulted in flow closer to the tremie. The upward flow of concrete from the discharge point on the tremie was confined to a central portion of the shaft. Some mixing of new fresh concrete with older and previously placed concrete may have occurred. Additionally small pockets of trapped laitance or silt were observed. These pockets tended to concentrate between the inner and outer cages, where obstructions caused concrete flow to be
disrupted. The inclusions observed in this shaft were small and not sufficient enough to produce any measurable reduction in the structural capacity of this shaft.

Table 2.5 Mixture Proportions Used for Test Shafts

<table>
<thead>
<tr>
<th>Items</th>
<th>South Carolina Coastal (SC Coastal)</th>
<th>Conventional South Carolina DOT</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump/Slump Flow (in)</td>
<td>9 to 10.5</td>
<td>7 to 9</td>
<td>18 to 24 (flow)</td>
</tr>
<tr>
<td>Type 1, Cement Content (lb/yd$^3$)</td>
<td>540</td>
<td>560</td>
<td>500</td>
</tr>
<tr>
<td>Fly ash Class F (lb/yd$^3$)</td>
<td>162</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>w/c Ratio</td>
<td>0.40</td>
<td>0.41</td>
<td>0.41</td>
</tr>
</tbody>
</table>

It was observed that despite the use of two congested rebar cages, both of these highly workable mixtures passed through the cages to fill the surrounding space with sound concrete. Although the segregation is a logical issue associated with the highly fluid concrete mixtures, no indication of any significant segregation was observed in either of the exhumed shafts.

Based on performance of the SCC used in this project, it was concluded that it is a feasible choice for use in drilled shaft construction. Greater slump, slump flow, and subsequent improved workability, could prove useful especially where seismic detailing requirements result in congested reinforcement. As a result of observations from the experimental shafts and load tests, the drilled shafts for the smaller of the two bridges at this site were successfully constructed by using entirely the SCC mixture.
2.7.1.3 Ozyldirim and Sharp, (2013), Evaluation of Drilled Shafts with SCC at Route 28 Bridges, Virginia

Ozyldirim and Sharp (2013) attempted an evaluation of drilled shafts with SCC. The evaluation was implemented at two adjacent bridges on Route 28 over Broad Run in Bristow in Prince William County, Virginia. For this study, the bridge carrying the northbound traffic had 24 drilled shafts with conventional concrete with high slump values. The bridge carrying the southbound traffic also had 24 shafts, in which 12 shafts were built with conventional concrete and the other 12 shafts with SCC. Important concrete mix parameters are given in the Table 2.6. The shafts had varying lengths from 18 to 32 ft. The shaft excavations were stabilized by metal casings, which were removed after the placement of the concrete. Reinforcement cages were placed and the specified cover was maintained using spacers. Four metal access tubes, with an interior diameter of 2 in, were attached to the inside of the reinforcement cages for the Cross-hole Sonic Logging (CSL) testing.

Since CSL was time-consuming and CSL tubes were to be inserted in the shaft prior to concrete placement, in addition to CSL, sonic echo/impulse response (SE/IR) was used to nondestructively measure the length of shaft and determine the location of the voids.

Table 2.6 Mixture Proportions of Conventional Concrete and SCC

<table>
<thead>
<tr>
<th>Items</th>
<th>Mixture Proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional Concrete</td>
</tr>
<tr>
<td>Slump/Slump Flow (in)</td>
<td>5.8 – 8.0</td>
</tr>
<tr>
<td>Type II Cement Content (lb/yd³)</td>
<td>388</td>
</tr>
<tr>
<td>Slag Cement (lb/yd³)</td>
<td>388</td>
</tr>
<tr>
<td>Water-cementitious material Ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>
At the site, the drilled shaft with SCC had high workability, better flowability, and was easy to place. In addition, it was observed that the removal of casings was comparatively easier than seen in the conventional mixtures.

It was reported that the hardened properties of SCC drilled shaft, such as strength properties and elastic properties were higher than the properties of the conventional concrete. The permeability values of SCC were lower than that of the conventional concrete. Also, an interesting observation during the study was the presence of large clumps (balls filled with cement and sand) in the SCC mixtures. Mixing was unable to break these large clumps; such clumps were rare in the conventional mixtures.

2.7.1.4 Madrio et al, (2014), Influence of Placement Method to In-Place Hardened Properties of Deep Foundation Using SCC

Madrio et al., (2014), from Roads and Maritime Services (RMS) Australia, carried out a study on the use of SCC for cast-in-place applications in 2008. As part of the project verification, three trial full-scale bored piles were cast-in-place with SCC using three common placement scenarios, namely: tremie placement on dry hole, tremie placement on wet hole, and free fall placement on dry hole.

Three trial bored cast-in-place piles with SCC were cast and then exhumed for testing. The objective was to assess the influence of placement methods on the in-place hardened properties of the piles using SCC. The pile depth was 6.0 m (19.7 ft.) and 900 mm (2.95 ft.) diameter. The reinforcing cage used 12 - No. 28 mm (11/8 inch) main bars with 12 mm (1/2 inch) diameter stirrups at 150 mm (6 inch) center to center spacing. Some of the mix design parameters and the corresponding characteristic properties, as measured from the laboratory prepared mold specimen, are shown in Table 2.7. Destructive testing was performed on the samples prepared from molds
and on core samples, which were cored from the trial piles. The core samples were extracted from top section located within top 40 inch (1000 mm) from top of the shaft, from middle section located at mid-height, 120-inch (3000 mm) from top of the shaft and from bottom section located at the toe, 4 - 8 inches from toe of the pile.

Also, non-destructive testing (NDT) on the trial piles was performed. The trial piles were tested after five days for integrity by the pulse echo method. The piles were exhumed from the ground after 28 days and tested for hardened properties. The visual inspection of all the three piles showed that they were generally in good condition.

The Ultrasonic Pulse Velocity (UPV) test values indicated that the concrete was relatively consistent along the shaft depth and having similar characteristics for the three piles. However, interestingly one typical observation was that the SCC placed on dry hole by free fall method appears to have an average value of 15 MPa higher at every section of the pile as compared to the tremie placed SCC. The authors mentioned that there was no explanation for such results and suggested further studies to address this.

Table 2.7 Mix Design and Characteristic Properties

<table>
<thead>
<tr>
<th>Material Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength Grade</td>
<td>40 MPa</td>
</tr>
<tr>
<td>Filling Ability, target/range</td>
<td>650 ± 50 mm</td>
</tr>
<tr>
<td></td>
<td>(25 inch ± 2 inch)</td>
</tr>
<tr>
<td>Cementitious Material</td>
<td>440 kg/m³</td>
</tr>
<tr>
<td></td>
<td>(741 lb./yd³)</td>
</tr>
<tr>
<td>Water-Cementitious material Ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The mass per unit volume of the core appears to be within the range of normal concrete. In addition, durability tests were carried out from the cores taken from the three piles. The core samples taken were within 1000 mm from the top of the pile, which is believed to be subjected to
the worst case scenario. Sorptivity tests conforming to ASTM C 1585 as well as tests for water absorption and apparent volume of permeable voids as per Australian specification AS 1012.21 were performed. From the test, it was found that the SCC placed by free fall indicated higher sorptivity level and appeared to have more permeable voids than compared to SCC placed by the tremie method. However, the results also indicated that all SCC regardless of the placement method, performed within the minimum criteria for each test method.

The authors concluded the following:

- The durability, the strength properties, and the shaft integrity with SCC are up to the specification requirements.
- SCC could be used for deep foundations as a more reliable alternative than conventional high slump concrete.
- SCC could be placed by free fall without adverse effects to its hardened property. However, in that study the free fall was limited to only 6.0 m.

2.7.1.5 Sweet et al, (2012), Implementation of SCC in Caisson Construction for Stalnaker Run Bridge

Sweet et al., (2012) presented a study on implementation of self-consolidating concrete in caisson construction for the Stalnaker Run Bridge, located on Old Route, 219 in Elkins, West Virginia. This was part of the Innovative Bridge Research and Deployment (IBRD) initiative with the objective of introducing the use of SCC in the state of West Virginia.

For this project, SCC was used to cast elements of both the substructure and the superstructure of the single span bridge. For the sake of comparison, traditional vibrated concrete (TVC) also was used to cast identical elements. In this initiative, SCC was used for three caissons underlying Abutment 1 and TVC was used for three caissons underlying Abutment 2. The caissons...
were designed to consist of 3.5 ft diameter, 6 ft deep drilled shafts overlying an integral 3 ft diameter, 12 ft deep rock socketed. Table 2.8 shows cement content and the water to cementitious material ratio of the mix designs of traditional caisson mix and SCC caisson mix used for the construction of the caissons. To ensure adequate filling of the caissons at site, trial casting in the laboratory of a member with cross-sectional dimensions similar to those of the actual construction was conducted. Also, the trial casting was done in a manner that would closely simulate the actual field condition.

Table 2.8 Mixture Proportions of Traditional Caisson Mix and SCC Caisson Mix

<table>
<thead>
<tr>
<th>Items</th>
<th>Traditional Caisson Mix</th>
<th>SCC Caisson Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Cement Content (lb/yd^3)</td>
<td>564</td>
<td>638</td>
</tr>
<tr>
<td>Fly Ash Class F (lb/yd^3)</td>
<td>70</td>
<td>112</td>
</tr>
<tr>
<td>Water-cementitious material ratio</td>
<td>0.394</td>
<td>0.381</td>
</tr>
</tbody>
</table>

The SCC mix developed in this project was ultimately used to construct the three caissons for Abutment 1 of the bridge. The caissons for the other abutment were made using a traditional WVDOT “B Modified” mix design and was designed to have a 7½ in slump and a target of 7% entrained air. Both types of concrete were placed into “wet hole” conditions using a tremie pipe, which was fed using a pump system. No slurry was used for concrete placement, but a removable steel casing was used for the drilled shaft portion of the construction. The fresh properties measured for all concrete as delivered by each truck are given in Table 2.9.

From the test results of the fresh and hardened concrete property testing, it was seen that SCC would be acceptable for use in the field. The Rapid Chloride Permeability test (RCPT) results (ASTM C1202) indicated that the SCC mix design used for the caissons exhibited a low
permeability. CSL testing did not reveal any significant flaws for the caissons cast using the SCC or those cast using the traditional caisson concrete. The hardened property tests revealed that the SCC had compressive strengths and modulus of elasticity values in the same range as the traditional caisson concrete. It was concluded that SCC was cast successfully in the caissons.

Table 2.9 Measured Fresh Properties of SCC and B Modified Mixes as Delivered to Site

<table>
<thead>
<tr>
<th>Fresh Property</th>
<th>SCC</th>
<th>B Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Truck 1</td>
<td>Truck 2</td>
</tr>
<tr>
<td>Spread (in)</td>
<td>19.5</td>
<td>19</td>
</tr>
<tr>
<td>Slump (in)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$T_{50}$ (s)</td>
<td>2.2</td>
<td>4.55</td>
</tr>
<tr>
<td>J-Ring Value (in)</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>Unit weight ASTM C136 (lb/ft$^3$)</td>
<td>141.0</td>
<td>140.9</td>
</tr>
</tbody>
</table>

2.7.1.6 Rausche et al, (2005), Quality Assurance for Drilled Shafts Using SCC

Rausche et al (2005) demonstrated the suitability of Non Destructive Test methods (NDT) for SCC used for drilled shafts. The test program was conducted with 12 concrete mixtures and 24 concrete specimens, size 205 mm wide, 760 mm long and 660 mm in height. Both conventional and SCC specimens were used. Provisions with tubes were introduced in the specimen to carry out Cross Hole Sonic Logging (CSL) testing. Table 2.10 gives the summary of mixes.

The first six mixes represented high strength concrete of the same compressive strength. The second set of six mixes, with different compressive strengths, were more typical of drilled shaft construction. While casting the specimen, the concrete was continuously poured into the
center of the form and 70 mm distance was kept between each side of the form and the CSL test tube. This was done to simulate a typical rebar spacing and realistic conditions in drilled shaft construction.

Table 2.10 Summary of Mixes

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Concrete Type</th>
<th>Slump* or Slump Flow (mm)</th>
<th>Design Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conventional</td>
<td>25 - 50*</td>
<td>55.2</td>
</tr>
<tr>
<td>2</td>
<td>Conventional</td>
<td>102 - 107*</td>
<td>55.2</td>
</tr>
<tr>
<td>3</td>
<td>Conventional</td>
<td>178 - 203*</td>
<td>55.2</td>
</tr>
<tr>
<td>4</td>
<td>SCC</td>
<td>457</td>
<td>55.2</td>
</tr>
<tr>
<td>5</td>
<td>SCC</td>
<td>559</td>
<td>55.2</td>
</tr>
<tr>
<td>6</td>
<td>SCC</td>
<td>660</td>
<td>55.2</td>
</tr>
<tr>
<td>7</td>
<td>Conventional</td>
<td>178*</td>
<td>20.7</td>
</tr>
<tr>
<td>8</td>
<td>Conventional</td>
<td>178*</td>
<td>34.5</td>
</tr>
<tr>
<td>9</td>
<td>SCC</td>
<td>559</td>
<td>34.5</td>
</tr>
<tr>
<td>10</td>
<td>SCC</td>
<td>559</td>
<td>34.5</td>
</tr>
<tr>
<td>11</td>
<td>SCC</td>
<td>559</td>
<td>34.5</td>
</tr>
<tr>
<td>12</td>
<td>SCC</td>
<td>559</td>
<td>55.2</td>
</tr>
</tbody>
</table>

For the assessment of the compressive strength and static elastic modulus for each mix, cylindrical specimens were cast for each mix and were tested. NDT by Pulse Echo Method (PEM) and CSL were carried out. For PEM, Pile Integrity Tester and for CSL, Cross Hole Analyzer both manufactured by Pile Dynamics, Inc. were used.

The conclusions from this study were as follows:

- SCC has superior flow characteristics that would help to improve drilled shaft quality and acceptance, especially in heavily reinforced shafts.
- The NDT tests performed showed that standard NDT methods are suitable for SCC as they are for conventional concrete.
• Actual field comparison between conventional concrete and SCC mixtures to drilled shaft needs to be performed as a next step in the implementation of SCC to drilled shafts.

2.7.1.7 Robertson, (2012), Use of SCC for Drilled Shaft Construction at Kahana Bridge

This research project was conducted by Robertson (2012), in an attempt to utilize SCC for drilled shaft construction in Hawaii. First, the trial placement of SCC provided by Ameron for the North Kahana Bridge SCC drilled shafts was performed. SCC mix trials were conducted using locally available aggregates from both of Honolulu’s main quarries, Halawa and Kapa’a. Hence, the effect of angularity and high aspect ratio of the local aggregates, which may increase the aggregate interlocking thereby affecting the concrete flow, were taken into account in the mix trials. A sample mix was also batched at a local ready mix plant to observe any differences caused by producing a large volume in a plant setting.

A total of 30 mix trials were conducted for this project. After a reasonable mix was found, it was used as the basis for mixes from both quarries. The evaluation was performed using slump flow, J-ring, T-50 and segregation tests at 30-minute intervals after concrete batching. Even though the slump flow matched the lower limit of 25 inches, the concrete showed excellent flow and filling potential.

Three test drilled shafts were constructed to evaluate the suggested concrete mixture designed from the mix trials. The test shafts were approximately 59 in in diameter and 160 ft deep. Two test shafts were made of SCC and one was made using conventional concrete. For each test shaft, the concrete was poured in multiple batches, and standard sized test cylinders were made from each batch. Cores were later obtained throughout the depth of the shafts for testing.
A series of tests were performed on several molded test cylinders and cores obtained from the shafts, to determine the dynamic and static moduli of elasticity and the compressive strength of the concrete. It was found that the SCC shafts have higher and more desirable properties over the load test shaft using conventional concrete (LTC). This suggested better homogeneity along the depth of the SCC shafts, meaning no significant segregation occurred, and possible concrete placement problems for the LTC shaft. Based on the results of this research, it was concluded that the SCC mixture design had better hardened concrete material properties than the conventional concrete mixture.

In the report, it was mentioned that a visual inspection of the cores revealed poor concrete quality at a number of locations in the SCC shafts. Most notably, near the top of the SCC Load Test shaft (top 19 ft), there was significant washout and loss of core in one of the two core samples. It was of the opinion that this might have been caused due to the result of premature removal of the top casing unit while the contractor waited for delivery of the final concrete truck. However, small cavities and possible bleed channels were observed at various depths in the SCC cores. No such defects were noted in the conventional concrete cores. The author suggested a detailed study to identify the cause of the anomalies.

2.7.2 Physical Case Studies

2.7.2.1 University of South Florida, Previous Research on Upper Viscosity Limits

At USF, a study was carried out to investigate the upper viscosity limit on shaft performance for bentonite and polymer slurry. For this purpose, 18 fabricated shafts of size 42 in diameter 2 ft tall using varying viscosities for bentonite and polymer slurries were cast. The physical appearance of these shafts were inspected and the flow pattern was noted. The physical appearance of these shafts is demonstrated below in Figures 2.7. It should be noted that the shafts
cast under mineral slurry (bentonite) seem to leave deep creases that reflected the location of the rebar cage. Because of the deep creases and the poor quality of concrete observed on the side of the shafts, many of these shafts were highly questionable, thus leaving durability of these shafts in question. Even the SCC cast shafts under mineral slurry, which is expected to show better performance, encountered these creases. The SCC mix details were not available for further mix evaluation. Apart from the observation of creases on the cast shafts, the radial flow of concrete that fills the annular cover region during the concrete placement was also reported (Figure 2.8).

![Concrete shaft cast under polymer slurry](image1.png) ![Concrete shaft under mineral slurry](image2.png) ![SCC shaft cast under water](image3.png) ![SCC shaft cast under mineral slurry](image4.png)

Figure 2.7 Experimental Shafts Cast with Concrete / SCC under Mineral Slurry, Polymer Fluid and Water, (Mullins, 2015): Physical Observation of Shafts
From the cast shafts, the following observations were made:

- In both the shafts cast with conventional concrete and SCC under mineral slurry, creases had occurred.
- Creases in the concrete coincided with the pattern of reinforcement arrangement.
- Coring revealed trapped bentonite slurry in the creases.
- Even shafts cast with SCC under mineral slurry encountered creases
- Radial component of concrete flow that occurred during the concrete placement was reported.
- In the shafts cast under polymer and water, no creases were seen.
- While the vertical component of flow fills the interior cage, the radial component flow fills the annular cover region.
2.7.3 Rheological Parameter Case Studies

Even though rheological parameters are more well-known than the conventional workability parameters, such as slump, the rheological test methods are not simple for use at a working site and are generally time consuming. Therefore, it is very useful to have suitable workability test methods for continuous use at the site and proper calibration to achieve the required rheological parameters. There are some studies which were carried out to establish the correlations between rheological parameters and the workability parameters of SCC like slump flow. However, these correlations are mainly for yield stress and there are difficulties to arrive at analogous correlations for plastic viscosity.

2.7.3.1 Hocevar et al., (2013), Rheological Parameters of Fresh Concrete-Comparison of Rheometers

In this study, the rheological parameters (yield stress, plastic viscosity) for 26 different types of fresh normal concrete were measured with two co-axial cylinder rheometers: ConTec Viscometer 5 and ICAR Rheometer.

A comparison was made between the results from both the rheometers, and more importantly, a correlation between the rheological parameters and workability (slump, slump flow) was established. The Bingham model, the simplest form of non-Newtonian model was used to obtain the values of rheological parameters. From the comparison, it was found that the ICAR Rheometer gave on average 42 % higher values for yield stress and on average 43 % lower values for plastic viscosity when compared to the ConTec Viscometer 5.

The correlation obtained for the yield stress-slump was 0.82 for the ConTec and 0.77 for the ICAR rheometer, and the yield stress-flow value correlation was 0.73 for both rheometers. Figure 2.9 shows these correlations. The correlation obtained for the plastic viscosity was not ideal.
The plastic viscosity-slump correlation was 0.61 and 0.43, and the plastic viscosity-flow value correlation was 0.54 and 0.28, for the ConTec and ICAR rheometer, respectively. Figure 2.10 shows these correlations.

2.7.3.2 Utsi et al., (2003), Relation between Workability and Rheological Parameters

Another study looking for any correlation between workability test parameters and rheological properties was carried out by Utsi, et al. (2003). It was shown that the scatter was rather high and some correlation was derived between the workability and rheology. Figure 2.11 shows the results of viscosity vs. slump flow obtained for two mixtures.
2.7.4 Summary from the Case Studies

From the review of above case histories, the following useful information has been identified. From a mix design perspective, several recommendations can be made:

In terms of aggregates rounded/river gravel are preferred over crushed stone/aggregate for the concrete mix. It is also recommended to use a sand to total aggregate ratio in the 0.44 to 0.5 range. Fly ash and/or slag should be included to increase the cementitious materials content while reducing the Portland cement content. In terms of post construction evaluation, Non Destructive Testing (NDT) methods were shown to work equally well for shafts constructed with SCC.

In the study conducted by Brown et al, 2005, it was reported that, in the SCC mixtures, large clumps of cement and sand were observed. Such type of clumps were rare in the conventional mixtures. In addition, in the research conducted by Robertson 2012, it was reported that small cavities and possible bleed channels were observed in the cores taken at various depths of SCC shafts indicating poor concrete quality and recommended further study.

In general, most of the case studies have established that SCC can be introduced for drilled shafts. However, there is no study on the evaluation of the concrete to rebar bond, and the concrete strength in the cover region. Specifically, no study is reported on the behavior of concrete flow in
the shaft excavation, considering the rheological properties of SCC and the effect of reinforcement
cage. Hence, there is a need to scrutinize the variables that may affect SCC performance, with
particular focus on tremie placed conditions.

2.8 Simulation of Concrete Flow

Numerical simulation of concrete flow could be used to study the total form filling and the
detailed flow pattern. Numerical simulation can be a potential tool for understanding the
rheological behavior of concrete and for mix proportioning. Thus, this simulation of the casting
process could allow engineers to specify a minimum workability of the fresh concrete that could
ensure the proper filling of a given formwork. Also, with the simulation, a correlation between
mix proportioning and rheological parameters can be developed and the entire approach of mix
proportioning be more scientific.

The concrete casting can be considered as a free surface flow of a non-Newtonian liquid. The
fresh concrete is generally considered to behave as a yield stress fluid. The Bingham or Herschell
Bulkley models are the most common models, but to choose this type of modeling, it is necessary
to assume that concrete is considered a homogeneous single fluid.

2.9 Approaches of Computational Modeling of Concrete Flow

The computational modeling of concrete flow can be divided into three different approaches
(Gram and Silfwerbrand, 2011):

- Particles: individual particles are simulated.
- Fluid: the concrete flow is modeled as a continuous matter of single fluid.
- Particles in fluid: individual physical particles are studied in a fluid with given
  rheological properties.
2.9.1 Discrete Element Method (DEM) and Simulation of Discrete Particles

In the case of SCC, the amount of coarse particles in the mixture is low, and hence the SCC concrete is expected to behave as a fluid suspension, whereas, in the case of ordinary concrete with a greater amount of coarse particles, behavior is dominated by its granular nature (Roussel, et al, 2007). The discrete element method takes into account the movement and interaction of particles.

Particle flow code PFC\textsuperscript{3D} developed by Cundall (1996), which is a DEM based application, was used to simulate and predict physical particle blocking in the JRing test. The numerical results obtained showed good agreement between laboratory tests and the numerical simulation. The particle simulation was successfully used for the construction design of mixers. It was also used to simulate the transport and the form-filling process of the fresh concrete (Shyshko, 2002). It is to be noted that the particle models require extensive levels of computer power and memory.

2.9.2 Continuous Body Approach and Single Fluid Simulation

There are examples of computational modeling of full-scale castings assuming single fluid behavior (Roussel et al. 2007). As with many continuum methods, single fluid simulation requires a clear definition of boundary conditions. Fresh concrete displaying a moving free boundary is thus particularly difficult to simulate. The code Flow 3D was used to perform 3D simulations. Roussel (2007) also performed a numerical simulation of casting of a pre-cambered composite beam to determine the optimal values of the rheological parameters required for successfully accomplishing the casting process.

Mori and Tanigawa (1992) used the Viscoelastic Finite Element Method (VFEM) and the Viscoelastic Divided Element Method (VDEM) to simulate the flow of fresh concrete. Both VFEM and VDEM assume that concrete can be described as a homogeneous single fluid with given rheological properties. In VFEM, the fresh concrete is divided into elements in which the
deformation is calculated, and the flow is described by displacement of nodal points. In VDEM, space in which the concrete is cast is divided into elements and cells, which are either empty or full. The movement of an imaginary ball cock, called a marker, depicts the flow of fresh concrete during casting.

Both VFEM and VDEM are applicable to three dimensional problems. However, they have not been used in three-dimensional analysis until recently, because of the high computer capacity demand of the model. These methods more easily clarifies the outline of the filling of fresh concrete into a mold. However, the flow in small scale spaces such as the mold’s corners, and the finishing state of fresh concrete are difficult to simulate.

2.9.3 Simulation of Particle in Fluid - Suspension Flow

In the suspension flow approach, concrete is considered as particles suspended in a fluid matrix, and finite element simulation is employed. The most familiar methods for simulation of suspension flow are Visco-plastic Suspension Element Method (VSEM) and Finite Element Method with Lagrangian Integration Point, FEMLIP (Shyshko 2002).

In the VSEM method, the two-phase model is used and this method is based on the extreme simplification that fresh concrete is a three-dimensional truss structure with node points of spherical coarse aggregates. Mori and Tanigawa (1992) used VSEM to simulate the concrete flow in various tests. Moresi (2003) developed the FEMLIP method, which makes use of a combination of Lagrangian and Eulerian approaches. This is based on an Eulerian finite element mesh with Lagrangian particles carrying material properties and time variables. However, for simulating the larger samples of suspension, extensive amounts of computer power and memory are required. With the constant development of high-speed computers, larger samples of suspensions may be simulated.
2.10 Numerical Modeling and Simulation of SCC Flow in Drilled Shaft

SCC is a highly fluid type of concrete, and hence the hardened properties of the cast-drilled shaft are influenced by the flow pattern of SCC in the shaft. While considering SCC for drilled shaft application, in order to achieve the required quality shaft in addition to mix design, the concrete flow behavior in the shaft should also be taken into consideration. Hence, the simulation of SCC flow in a drilled shaft can act as a tool to model and predict the shaft concrete workability. From the modeling and simulation of drilled shaft concreting, a suitable workability for the shaft concrete could be achieved, and hence, the issue of anomalies in drilled shaft concrete can be addressed.

2.11 Computational Fluid Dynamics (CFD) for Fluid (SCC) Flow

2.11.1 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) consists of solving numerically the governing equation for fluid flow. High speed computers are required to perform the computations. In CFD, the concrete is represented as a fluid whose flow behavior is governed by a system of equations, namely the Navier-Stokes equations. The governing equations are partial differential equations (PDEs) which represent the conservation laws for mass, momentum and energy of a moving fluid. The equations describe how the velocity, pressure, temperature, and density of a moving fluid are related. In CFD, the PDEs are approximated numerically by a method such as the finite element, finite volume and finite difference methods yielding a set of algebraic equations which are solved using computers.

2.11.2 Simulation of SCC Flow in Formwork Filling Using COMSOL Multiphysics

COMSOL Multiphysics® from Comsol Inc. is a finite element software package designed to address a wide range of physical phenomena. Different modules, for example kinematics, heat
transfer, chemical reactions, CFD, and structural mechanics can be combined; hence, it is possible to simulate complex multi physics phenomena such as fluid structure interaction.

The flow of SCC in formwork filling was simulated using COMSOL Multiphysics by Alfi (2013). The flow was considered as a single-phase yield stress fluid between two infinite plates. The flow of SCC in formworks with varied rheological properties (yield stress and plastic viscosity) was verified with different configurations of reinforcement (rebars), such as spacing between the rebars and the distance between the rebars and the wall. The yield-stress fluid was modeled as a Bingham fluid. A triangular mesh was used for the whole domain. The focus was put on avoiding dead zones where the concrete is at rest and entrapped air bubbles are less likely to evacuate, reducing the mechanical properties of the concrete. The influence of reinforcement on the flow of SCC in the formwork was studied. Four different rebar configurations were chosen in terms of concrete cover and the distance between the rebars. For different rebar arrangements, the flow patterns from the simulations were obtained considering different set of rheological properties to get the optimum values.

<table>
<thead>
<tr>
<th>Cases</th>
<th>( d_w ) m (in)</th>
<th>( d_p ) m (in)</th>
<th>( \mu_p ) Pa.s</th>
<th>( \tau_y ) Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases A-1</td>
<td>0.025 (1.0)</td>
<td>0.10 (4.0)</td>
<td>70</td>
<td>14</td>
</tr>
<tr>
<td>Cases A-2</td>
<td>0.05 (2.0)</td>
<td>0.10 (4.0)</td>
<td>60</td>
<td>21</td>
</tr>
<tr>
<td>Cases B-1</td>
<td>0.0375 (1.5)</td>
<td>0.05 (2.0)</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>Cases B-2</td>
<td>0.0375 (1.5)</td>
<td>0.25 (10.0)</td>
<td>50</td>
<td>76</td>
</tr>
</tbody>
</table>

The paper presents results of the optimum rheological properties of plastic viscosity and yield stress obtained for different configurations of reinforcement arrangement. The simulation
results show that the occurrence of the dead zones is less likely in the configurations with a larger distance between the rebars or with a larger distance between rebar and the wall. The optimized values of plastic viscosity and yield stress for different cases of rebar configuration, obtained from the simulation are given in Table 2.11.

2.11.3 Simulation of Fresh Concrete through Reinforced Elements Using ANSYS-Fluent

Considerable studies have been performed on simulation of concrete flow using CFD simulation software in ANSYS-Fluent, which is a finite volume based solver. Vasilic et al, (2016) performed a simulation of concrete casting with SCC, which was modeled as a single-phase Bingham fluid flow model. The flow of concrete was considered through a reinforcement zone, and as a free surface flow. In this study, a new modeling approach was introduced with the main objective of decreasing the simulation time. In this approach, the reinforcement bar arrays were modeled as porous media zones. Since the rebars were modeled as porous media, the simulation was defined by geometrical properties such as porosity and permeability, and by a shift factor which relates the rate of flow of liquid propagating to the shear rate in the porous media.

The Bingham model was considered for the concrete viscosity. In the paper it is mentioned that for very low shear rates, higher range viscosity values between 30,000 Pa-s and 160,000 Pa-s were considered, representative of the fluid behaving as a solid material once it stops flowing. From the comparison of experimentally and numerically obtained results of the flow pattern, it is reported that there was good agreement between both of them. The paper also presents the details of the mesh elements and the computation time for both the cases of simulation with discrete steel bars and with porous media zones for steel bars. Based on the details presented, it was inferred that considerable reduction in the number of mesh elements and the computation time could be achieved for this new approach.
It was concluded that using Bingham model and porous media zones, the SCC flow through reinforcement networks could be simulated.

There are considerable studies on the simulation of concrete flow and even some research has been done on the field form filling of concrete. However, a study based on 3-D simulation of concrete flow in drilled shaft with tremie placed concrete, requiring two fluids flowing through reinforcement, is lacking.
CHAPTER 3: NUMERICAL MODELING AND EVALUATION OF
SCC FOR DRILLED SHAFT

3.1 Flow Mechanism in Drilled Shaft Casting

There is some difference between SCC filling for drilled shaft and for other structural members like roof slab, beam and column. The drilled shaft is generally cast below ground level, and the casting is done in the shaft that is formed by the drilled excavation of soil to the specified size and depth from the ground level. In most of the cases, the in situ soils act as the formwork and the excavation establishes the shape of the shaft concrete. In Florida, due to the presence of a high water table, drilling fluid is used to stabilize the excavation walls and concreting is always tremie placed.

Considering the above factors, in the simulation of SCC flow in the drilled shaft, the following mechanism are to be taken into account:

- Flow of SCC through the tremie pipe placed at the center of the shaft. The tremie extends from the top of the shaft to the bottom of the shaft leaving a gap of 6 to 10 inches from the excavation bottom.
- SCC flowing out from the tremie pipe spreads out radially throughout the entire cross section of the shaft, passing through the reinforcement steel and displacing the drilling fluid.
- Filling of SCC in the shaft from bottom to top and displacing the drilling fluid.
Figure 3.1 shows the above flow mechanisms in the drilled shaft in an idealized and actual flow pattern.

Even though the objective is to create a 3-D model simulation, 2-D modeling was initially performed as a precursor, given the challenges of the flow involving (1) resolution of the concrete-slurry interface, (2) the rheology of the fluids, and (3) the complex flows expected potentially characterized by pockets of slurry trapped within the concrete.

![Flow Mechanism in Drilled Shaft: Idealized and Actual Flow Pattern.](image)

The numerical modeling and simulation of SCC flow in a drilled shaft can also be applied to normal standard concrete flow in a drilled shaft. Hence, in the following sections, the flow mechanism is referred as concrete flow that is applicable to both normal drilled shaft concrete (NC) and SCC. Analysis is performed for both SCC and NC flows.
3.2 Modeling and Simulation in 2-D

2-D modeling and simulation has been performed with a finite element CFD model built using COMSOL Multiphysics® software (Introduction to Comsol MultiPhysics 5.2a). The COMSOL CFD Module with incompressible laminar fluid flow has been considered for the modeling. The simulation of concrete flow in drilled shaft involves two fluids consisting of the concrete flowing from the tremie pipe and the outgoing slurry from the excavation, displaced by the concrete. Tracking the moving interface between the two fluids is of prime importance to study the flow pattern of SCC and NC that is required for the evaluation of SCC for drilled shaft. Considering the axis symmetry of the shaft, an axisymmetric model was developed so that the problem size and computational expense could be greatly reduced. The modeling and simulation process can be divided into two parts:

- Pre-processing, in which the model geometry is made, the mesh is generated, boundary conditions are set, and the fluid properties are assigned.
- Computation, in which the fluid mechanics equations are numerically solved on the mesh.

3.2.1 Model Geometry

Geometry is formed as a combination of solid objects mainly rectangular shapes using boolean operations like union, intersection and difference. For this study as shown in Figure 3.2, a shaft excavation of four feet diameter and five feet depth is modeled as a rectangular element. The steel rebars are modeled as vertical elements with gaps that match the spacing in a full-scale shaft. In the geometry, the tremie pipe of size 10 inches in diameter is modeled as a rectangular element. The tremie pipe element is provided at the center of the drilled shaft from top of the shaft to 6 inches above the bottom of excavation.
3.2.2 Material Properties

The material properties, used in the modeling, for SCC, NC, and the slurry are given in Table 3.1.

![Diagram of 2-D Model in COMSOL: Shaft Model Geometry]

**Figure 3.2 2-D Model in COMSOL: Shaft Model Geometry**

**Table 3.1 Properties of Concrete, SCC and Slurry**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Properties</th>
<th>Density in lb./cft.</th>
<th>Viscosity Pa-s</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td></td>
<td>156 (2400)</td>
<td>50 - 100</td>
</tr>
<tr>
<td>SCC</td>
<td></td>
<td>150 (2300)</td>
<td>20 - 100</td>
</tr>
<tr>
<td>Slurry</td>
<td></td>
<td>75 (1150)</td>
<td>0.10 – 0.5</td>
</tr>
</tbody>
</table>
3.2.3 Boundary Conditions

Boundary conditions have been set at the inlet and outlet of the axisymmetric model (see Figure 3.2). The inlet for the concrete flow is at the bottom of tremie pipe where the concrete flows out into the shaft excavation. The outlet is at the top of excavation where the slurry flows out of the excavation. Velocity at the inlet and pressure at the outlet have been given as the boundary conditions. The inlet velocity value given is equivalent to the velocity of concrete flow in the tremie pipe, which is calculated from the concrete supply rate from the truck at the field. Considering a 10 cubic yard capacity truck discharging concrete in the shaft excavation in 20 min, the inlet velocity is calculated to the tremie size. The no-slip condition is enforced at the vertical side wall of the shaft excavation and at the bottom of the excavation. At the rebar surface free slip is considered.

3.2.4 Rheological Model

Apart from initial computation that took Newtonian fluid behavior for both the concrete and the slurry, the axisymmetric model also considered non-Newtonian behavior for concrete and Newtonian behavior for slurry. With the CFD module, a predefined Carreau model has been used to input the viscosity values for concrete and the model describes the variation of viscosity with shear rate. For slurry, Newtonian behavior has been followed as the flow behavior is expected to be more close to that of water.

3.2.5 Governing Equations

The fluid motion is governed by the Navier-Stokes equation, which is Newton’s second law of motion for fluids:

\[ \frac{\partial \mathbf{u}}{\partial t} = \rho \mathbf{g} - \nabla p + \nabla \cdot (\mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)) \]

\[ \text{------------------------- (3.1)} \]
The Navier-Stokes equation is a vector equation with components in x, y and z directions. In these equations $\nabla = \left( \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \right)$ and $\nabla^2 = \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right)$. Also, $\mathbf{u}$ is velocity vector, $\mathbf{g}$ is gravity, $\rho$ is density and $\mu$ is viscosity. The left side of the equation represents acceleration. The three terms on the right side are the gravitational force, the pressure gradient, and the viscous term.

For an incompressible flow, the conservation of mass or continuity equation is

$$\nabla \cdot \mathbf{u} = 0 \quad \text{--------------------------------------------} \quad (3.2)$$

which is solved in conjunction with the Navier-Stokes equation.

### 3.2.6 Level Set Method

In the case of two phase or multi fluid flow, the objective is to characterize the moving interfaces. The two important methods to characterize the moving interfaces are, interface tracking and interface capturing techniques. In COMSOL, the interface is captured by using the Level Set method, which is an interface tracking technique. This method is widely adopted and is well suited to applications where topological changes and/or sharp corners are present (Ismail 2006). In the Level Set method, a smooth function denoted as $\alpha$ called the level set function is used to represent the interface between the two fluids: the concrete (conventional shaft concrete or SCC) and drilling fluid (slurry or water). The interface is represented by the 0.50 contour of the function $\alpha$ which divides the fluid region into zones each corresponding to the two fluids. The zones where $\alpha$ is less than 0.5 correspond to concrete and the zones where $\alpha$ is greater than 0.5 correspond to slurry. For incompressible multi-fluid flows, the level set equation that is solved in the CFD module of COMSOL is as follows:

$$\frac{\partial \alpha}{\partial t} + \mathbf{u} \cdot \nabla \alpha = \gamma \nabla \cdot \left\{ \epsilon \nabla \alpha - \alpha (1-\alpha) \frac{\nabla \alpha}{|\nabla \alpha|} \right\} \quad \text{--------------------------------------------} \quad (3.3)$$
The left side of the equation defines the motion of the interface while the right side provides stabilization or reinitialization. The parameter $\varepsilon$ defines the interface thickness and parameter $\gamma$ introduces the intensity of reinitialization or stabilization. For example, if $\gamma$ is too small the thickness of the interface may not remain constant and parasitic oscillations may appear in the level set function $\alpha$. If $\gamma$ is too large, the interface may move incorrectly. As noted in the COMSOL manual, a recommended value of $\gamma$ is the maximum absolute value of the flow velocity.

For incompressible two-phase flow, the above level set equation is coupled with the Navier-Stokes equation as shown below:

$$
\rho \frac{Du}{Dt} = \rho g - \nabla p + \nabla \cdot (\mu (\nabla u + (\nabla u)^T)) + \sigma K \delta n \quad \text{--- (3.4)}
$$

where $\sigma$ is the surface tension, $K$ is curvature of the interface, $n$ is the unit normal to the interface and $\delta$ is the delta function. The expression $\sigma K \delta n$ denotes the surface tension force at the interface. Furthermore, the density and viscosity are defined as,

$$
\rho = \rho_1 + (\rho_2-\rho_1) \alpha \quad \text{--- (3.5)}
$$

$$
\mu = \mu_1 + (\mu_2-\mu_1) \alpha
$$

where, $\rho_1$ and $\rho_2$ are the densities of concrete and slurry, respectively, and $\mu_1$ and $\mu_2$ are the dynamic viscosities of concrete and slurry, respectively.

### 3.2.7 Meshing

The model geometry has been partitioned with a triangular element mesh consisting of 48,972 elements shown on Figure 3.3.

### 3.2.8 Computations

Computations are performed using the BDF (Backward Differentiation Formulas) time-dependent solver for four-minute simulation times. The motion of the interface is captured and thus the concrete flow patterns are obtained. The flow patterns, in terms of the volume fraction of
concrete are saved at 15-second time intervals and the plots are extracted at the required time time intervals. A typical volume fraction plot with the concrete flow pattern from the COMSOL output is shown in Figure 3.4. The flow pattern clearly shows a concrete head differential between inside and outside the reinforcement. This phenomena has been observed in the experiments carried out by Mullins and Ashmawy, (2005), as described earlier.

Figure 3.3 2-D Model in COMSOL: Shaft Model Meshing

The computations are performed to study the concrete flow pattern for different concrete viscosities, different rebar spacing, and different concrete flow velocities. In the computations shown in Figure 3.5, concrete viscosity of 100 Pa-s at infinity shear rate and 1000 Pa-s at zero shear rate, 7 rebars spaced at 9 in vertical spacing, and the concrete flow velocity of 1.14 ft. /min (0.0058 m/sec) are considered. Figure 3.5 shows the concrete flow pattern at various flow time intervals. For example, the head differential is 10 in (250 mm) at 210 s flow time. Figure 3.6 shows variation of concrete head differential with respect to the concrete inflow velocity when the other
parameters like viscosity values of concrete and drilling fluid, shaft size, and rebar arrangement are kept the same.

As expected from experiments, the head differential, $H_{\text{diff}}$, increases with increasing concrete inflow velocity (Mullins and Ashmawy, 2005). Figure 3.7 shows $H_{\text{diff}}$ plots for different rebar spacing. The values are taken at 210 s. When studying the effect of rebars, there is an increase in the concrete head as the rebar spacing reduces or as the number of bar increases. Similar scenario
Figure 3.5 2-D Model in COMSOL: Concrete Flow Patterns at Different Flow Time Intervals
is observed during the actual shaft construction in the field; the concrete flow is affected due to the rebar blockage (Donald Hodgson et al, 2005).

![Graph: 2-D Model in COMSOL: Concrete Flow Velocity (v) vs Head Differential (H_{diff})](image)

**Figure 3.6 2-D Model in COMSOL: Concrete Flow Velocity (v) vs Head Differential (H_{diff})**

### 3.3 Limitations of 2-D Simulations

Considerable approximations had to be made in 2-D modeling. The concrete flow from the central tremie pipe to the excavation and the vertical rebar arrangement are not fully representative of conditions in the field. For example, horizontal ties were not considered in the model geometry. In spite of these limitations and approximations, the flow pattern from the simulation shows the expected phenomena. However, performing the simulation using a 3-D shaft model was anticipated to provide a closer agreement with experimental data.

### 3.4 Modeling and Simulation in 3-D

#### 3.4.1 3-D Simulation in COMSOL

In the case of 3-D modeling, the number of nodes and number of elements are expected to be large compared to the corresponding 2-D model developed. Hence, selecting the suitable shaft size for the 3-D model is important in order to perform the analysis in a reasonable amount of time.
and obtain reliable results. Thus, a 3-D shaft model with a size of 18-inch diameter and 20-inch depth was considered to perform the analysis. For the simulation performed, the mesh size was in the range of 0.08 to 1.10 in.

![2-D Model in COMSOL: Concrete Flow Velocity (v) vs Head Differential (H_{diff})](image)

**Figure 3.7 2-D Model in COMSOL: Concrete Flow Velocity (v) vs Head Differential (H_{diff}) for Different Rebar Spacing**

The tremie pipe size was four-inch diameter and centrally placed from the top of the shaft to six inch above the shaft bottom. Reinforcement cages were placed at four-inch cover. The vertical rebars were of six number, one-inch diameter size placed at five-inch spacing. The horizontal ties were in the form of a helix with half an inch diameter size bar placed at six-inch pitch. The shaft geometry was developed with cylindrical solid type objects and the meshing was generated. The number of elements generated were 95,189. The shaft model geometry and the mesh generated are shown in Figure 3.8. The material properties were same as considered in the 2-D analysis and given in Table 3.1. Similar to the 2-D analysis, simulations were performed with the finite element formulation in COMSOL Multiphysics® software with non-Newtonian behavior.
for the concrete and Newtonian behavior for slurry. The viscosity of concrete was set according to the non-Newtonian Carreau model.

### 3.4.1.1 Computations

Computations were performed in the same approach as in 2-D analysis using the BDF time dependent solver method. The Level Set method was used to track the interface between concrete and the drilling fluid. The analyses were performed for 80-second flow time, the results were stored at desired time intervals, and the volume fraction plots were extracted to study the concrete flow pattern. Parametric studies were carried out for re-initialization intensity parameter $\gamma$, surface tension $\sigma$, and interface thickness $\varepsilon$. The flow pattern obtained from the parametric study performed for $\gamma$, with values 0.5, 0.1, 0.05, and 0.01, are given in Appendix A. Based on the study, a $\gamma$ value of 0.05 m/sec (9.84 ft./min) was selected. Other values of $\gamma$ led to generation of unphysical pockets of slurry within the concrete. For $\sigma$, flow patterns were studied for the values 0.05, 0.1 and 0.50 N/m and a value of 0.1 N/m was selected which showed a realistic flow pattern of the concrete in the excavation compared to other values. For $\varepsilon$, a value of 0.007 m (0.28-inch) was selected after studying the flow patterns for the values of 0.005, 0.007, 0.010 and 0.015m. The flow patterns obtained from the parametric studies for $\sigma$, and $\varepsilon$, are also given in Appendix A.

![Figure 3.8 3-D Model in COMSOL: Shaft Geometry and Meshing](image)
Figure 3.9 3-D Model in COMSOL: Flow Pattern on Vertical Planes at Different Time Intervals.

Figure 3.10 3-D Model in COMSOL: Flow Pattern on Hor. Planes at Different Time Intervals.

Figure 3.11 3-D Model in COMSOL: Concrete Flow Pattern at Rebar Locations
Figure 3.9 shows the concrete flow patterns simulated from the 3-D model, at different time intervals. For the shaft model of 18-inch diameter and 20-inch height, the wall-clock solution time was 13 hrs. running on a desktop Dell computer. Even though the concrete filling was progressing in the excavation, the realistic concrete flow pattern with concrete head differential inside and outside the rebar cage is not apparent as had been observed in the 2D simulation presented earlier. Figure 3.10 shows the flow pattern at different horizontal planes at each time intervals.

When observing the concrete flow at the rebar locations and at the concrete cover region in Figure 3.11, the simulation shows that the concrete does not flow around the vertical rebars but flows across the vertical rebars, which is not realistic and is attributed to poor resolution To get a simulation with better resolution, it is essential to generate a finer mesh system than the one adopted. This mesh system with 95,189 elements needed to be further refined. Considering the various components such as, tremie pipe, vertical rebars, and the horizontal ties involved in the geometry and for generating adequate number of elements around the rebars and in the shaft cover region an estimate of at least four to five million elements would be required to accurately resolve the flow around the rebars. Moreover, these computations necessitate parallel computing in order to be carried out in a reasonable amount of time. In order to run the model on parallel computers available through CIRCE (Central Instructional Research Computing Environment) at University of South Florida, the model was transferred to Fluent, which is a finite volume CFD code. Fluent implements the same incompressible Navier-Stokes equations presented earlier, while tracking the interface between the concrete and slurry using the Volume of Fluid method, which is based on the marker-and-cell method discussed earlier making use of a volume fraction function tracked via an advection equation similar to the Level Set function in Eqn. 3.3. The non-Newtonian Carreau
model is also available in Fluent. Please see the Fluent user manual for more information (ANSYS Fluent Tutorial Guide, ANSYS Help Viewer: ANSYS Fluent 18.1).

3.4.2 2-D Simulation with Simple Model

Before performing the shaft analysis in ANSYS-Fluent (ANSYS Fluent Tutorial Guide, ANSYS Help Viewer: ANSYS Fluent 18.1), a preliminary analysis was carried out with a simple 2-D model. The objective was to verify the flow pattern and to estimate the mesh size required to be adopted in the 3-D model. A small size 2-D rectangular model, 12 inch width and 18 inch depth with only one rebar with 1.0 inch diameter was considered. The distance between the rebar center and the outlet edge was kept at six inch to simulate the normal dimension used for the shaft cover region. Since the geometry was small and had only one rebar, extremely fine meshing having a mesh size ranging from 0.05 inch near the rebar to 0.11 inch away from the rebar was generated. The concrete flow patterns obtained are shown in Figure 3.12. The concrete flow patterns obtained from the simulation show better flow behavior behind the rebar that is similar to the one observed in the laboratory investigation carried out by Mullins (2015), as shown in Figure 3.13. This is in contrast to the behavior in the earlier 3-D simulations in which the concrete did now flow around the rebar, but rather crossed through it. Thus in order to properly resolve the flow around the rebars, the mesh size (0.05 inch around the rebars) has to be finer than the size of the rebars (1.0 inch).

![2-D Model in ANSYS-Fluent: Flow Pattern from a Simple Model Analysis](image)

Figure 3.12 2-D Model in ANSYS-Fluent: Flow Pattern from a Simple Model Analysis
3.4.3 3-D Simulation in ANSYS-Fluent

Four foot and three foot diameter shafts were considered for the simulation. These size shafts predominantly represent the foundations for various structures. The tremie pipes of sizes twelve inch and ten inch were considered for the four foot and three foot diameter shafts, respectively. The tremie was placed from the top of the shaft to six inch above the shaft bottom. Reinforcement cages were placed with a six-inch cover. The vertical rebars were one-inch diameter in size and the horizontal ties were 1/2-inch diameter in size. Two types of rebar and tie arrangements were considered to study the pattern of concrete flow under these conditions. The details of the different model geometries considered for the analysis are given in Table 3.2.

Table 3.2 Shaft and Tremie Sizes and Reinforcement Cage Details

<table>
<thead>
<tr>
<th>Shaft Size (in)</th>
<th>Tremie Size (in)</th>
<th>Vertical Rebar Spacing (in)</th>
<th>Horizontal Tie Spacing (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>12</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>48</td>
<td>12</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>36</td>
<td>10</td>
<td>6.3</td>
<td>6</td>
</tr>
<tr>
<td>36</td>
<td>10</td>
<td>3.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>
3.4.3.1 Model Geometry

3-D Model geometry was developed in SolidWorks (SolidWorks 2015 Tutorial), and shaft sizes of 48 inch and 36 inch diameter, were considered by creating a ninety degree segmented model (Figure 3.14). The centrally placed tremie pipe, the vertical rebars and the horizontal ties were incorporated in the geometry. The model developed was imported in ANSYS-Workbench (ANSYS Workbench 15.0 Tutorial) to generate mesh. The geometries of 48-inch dia. and 36 inch diameter shaft models with the rebar details are shown in Figure 3.14.

3.4.3.2 Meshing

Based on the mesh sizes adopted in the simple model that is discussed in the previous section, meshing was generated in the size range 0.033 to 0.13 inch. Since the model geometry consisted of shaft excavation, tremie pipe, vertical rebars and horizontal ties, a mesh size within the range of 0.033 to 0.13 inch required on the order of 1.1 million nodes and 6.3 million elements (see Table 3.3). With this mesh system, the simulation could capture the flow pattern that exhibited the realistic flow behavior around the rebars as well as in the concrete cover region. Figures 3.15 and 3.16 show the meshes generated for 48-inch and 36-inch diameter shafts, respectively.

Figure 3.14 3-D Model in ANSYS-Fluent: Geometry of 48-inch, 36-inch Dia. and 20-inch Depth Shafts

(a) 48-inch dia shaft model: 4 vertical rebars and 4 ties
(b) 48-inch dia shaft model: 8 vertical rebars and 6 ties
(c) 36-inch dia shaft model: 3 vertical rebars and 4 ties
(d) 36-inch dia shaft model: 5 vertical rebars and 6 ties

Figure 3.14 (Continued)

Figure 3.15 3-D Model in ANSYS-Fluent: Meshing for 48-inch Dia. Shaft
Table 3.3 gives the details on the mesh sizes, the number of nodes and number of elements.

**Table 3.3 Details of Mesh Sizes, Number of Nodes and Number of Elements**

<table>
<thead>
<tr>
<th>No</th>
<th>Shaft Size</th>
<th>Reinforcement Details</th>
<th>Mesh size</th>
<th>Number of Nodes</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min. (in)</td>
<td>Max. (in)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>48 inch dia. 20 inch depth</td>
<td>4 Rebars and 4 Ties</td>
<td>0.033</td>
<td>0.12</td>
<td>1,188,233</td>
</tr>
<tr>
<td>2</td>
<td>48 inch dia. 20-inch depth</td>
<td>8 Rebars and 6 Ties</td>
<td>0.035</td>
<td>0.13</td>
<td>1,176,169</td>
</tr>
<tr>
<td>3</td>
<td>36 inch dia. 20-inch depth</td>
<td>3 Rebars and 4 Ties</td>
<td>0.03</td>
<td>0.11</td>
<td>99,4014</td>
</tr>
<tr>
<td>4</td>
<td>36 inch dia. 20-inch depth</td>
<td>5 Rebars and 6 Ties</td>
<td>0.03</td>
<td>0.11</td>
<td>1,069,758</td>
</tr>
</tbody>
</table>
3.4.3.3 Boundary Conditions

As described for the earlier 2-D simulations, boundary conditions were set at the inlet and outlet. The inlet for the concrete flow was at the bottom of tremie pipe and the outlet was at the top of excavation. In the earlier COMSOL simulation, the inlet was at the top of the tremie pipe whereas in the current cases with Fluent the inlet was set at the bottom of the tremie pipe in order to reduce the size of the domain and thus the number of grid points (see Figure 3.17). Velocity at the inlet and the pressure at the outlet were given as the boundary conditions. The inlet velocity value given was equivalent to the velocity of concrete flow in the tremie pipe, which was again calculated from the concrete delivery rate in the field, from a typical 10 cu. yard capacity truck in 20 minutes. Table 3.4 gives the inlet velocity for both 48 inch and 36-inch shafts. No slip conditions were considered at the shaft excavation side vertical face to simulate the zero velocity for the flow of concrete and the slurry along the excavation face. At the outlet, the flow is out of the excavation and the pressure was equal to the atmospheric pressure. Symmetry boundary conditions were assigned at the azimuthal ends of the 90-degree segmented domains in Fluent.

Figure 3.17 3-D Model Boundary Conditions at Inlet:
(a) CFD Model Built in COMSOL (b) CFD Model in ANSYS-Fluent
Table 3.4 Inlet Velocity of Concrete at Tremie Bottom

<table>
<thead>
<tr>
<th>Shaft size - in</th>
<th>Tremie size - in</th>
<th>Inlet velocity - ft/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>12</td>
<td>17.7</td>
</tr>
<tr>
<td>36</td>
<td>10</td>
<td>25.6</td>
</tr>
</tbody>
</table>

3.4.3.4 Material Properties

In the Navier-Stokes equations, the viscosity of the concrete was given by the non-Newtonian Carreau model. For both SCC and concrete, the viscosity value at zero shear rate ($\mu_0$) and at infinity shear rate ($\mu_\infty$) are given in Table 3.5. For density, constant values were assigned for SCC and normal concrete. For slurry, Newtonian behavior was followed and constant value of density and viscosity were considered. Analysis was also performed with water as drilling fluid. The properties of SCC, normal shaft concrete, slurry and water used in the computations are given in Table 3.5. High viscosity value of 2500 Pa-s was considered for $\mu_0$ for concrete so that, at very low shear rates the material was nearly rigid. Very high values of initial viscosity in the range between 30,000 Pa-s to 160,000 Pa-s were chosen to input into the bi-viscosity model for a numerical simulation of concrete casting (Vasilic et al 2016).

Table 3.5 Properties of SCC, Concrete, Slurry, and Water Used in the Computations

<table>
<thead>
<tr>
<th></th>
<th>Density Kg/m3 (lb./ft3)</th>
<th>Viscosity ($\mu$) Pa-s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\mu_0$</td>
</tr>
<tr>
<td>SCC</td>
<td>2300 (143.58)</td>
<td>250</td>
</tr>
<tr>
<td>NC</td>
<td>2400 (149.83)</td>
<td>2500</td>
</tr>
<tr>
<td>Slurry</td>
<td>1150 (71.79)</td>
<td>0.5</td>
</tr>
<tr>
<td>Water</td>
<td>1000 (62.43)</td>
<td>0.01</td>
</tr>
</tbody>
</table>
3.4.3.5 Computations

The numerical model prepared with the shaft geometry and the mesh generated with the ANSYS-Workbench was used to perform the simulations in ANSYS-Fluent. For both sizes of shafts of 48-inch and 36-inch diameters, two types of reinforcement arrangements were considered to study the effect of rebar arrangement on the flow. Simulations were performed for both SCC and concrete, using slurry as the drilling fluid, to study and evaluate the flow performance for both the materials in the shaft excavation. Additional simulations were performed with water as a drilling fluid. The summary of the cases simulated and studied are given in Table 3.6 and Table 3.7 for 48-inch and 36-inch diameter shafts, respectively. To perform the computations, the number of time steps selected achieved the filling of the majority of the shaft.

Table 3.6 48-inch Diameter and 20-inch Depth Segmental Shaft: Summary of Simulations

<table>
<thead>
<tr>
<th>Case No</th>
<th>Material</th>
<th>Drilling Fluid</th>
<th>Types of Reinforcement</th>
<th>Model No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SCC</td>
<td>Slurry</td>
<td>4 Rebars and 4 Ties</td>
<td>5101</td>
</tr>
<tr>
<td>2</td>
<td>SCC</td>
<td>Slurry</td>
<td>8 Rebars and 6 Ties</td>
<td>5102</td>
</tr>
<tr>
<td>3</td>
<td>SCC</td>
<td>Water</td>
<td>4 Rebars and 4 Ties</td>
<td>5103</td>
</tr>
<tr>
<td>4</td>
<td>SCC</td>
<td>Water</td>
<td>8 Rebars and 6 Ties</td>
<td>5104</td>
</tr>
<tr>
<td>5</td>
<td>NC</td>
<td>Slurry</td>
<td>4 Rebars and 4 Ties</td>
<td>5105</td>
</tr>
<tr>
<td>6</td>
<td>NC</td>
<td>Slurry</td>
<td>8 Rebars and 6 Ties</td>
<td>5106</td>
</tr>
<tr>
<td>7</td>
<td>NC</td>
<td>Water</td>
<td>4 Rebars and 4 Ties</td>
<td>5107</td>
</tr>
<tr>
<td>8</td>
<td>NC</td>
<td>Water</td>
<td>8 Rebars and 6 Ties</td>
<td>5108</td>
</tr>
</tbody>
</table>
Table 3.7 36-inch Diameter and 20-inch Depth Segmental Shaft: Summary of Simulations

<table>
<thead>
<tr>
<th>Case No</th>
<th>Material</th>
<th>Drilling Fluid</th>
<th>Types of Reinforcement</th>
<th>Model No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SCC</td>
<td>Slurry</td>
<td>3 Rebars and 4 Ties</td>
<td>6001</td>
</tr>
<tr>
<td>2</td>
<td>SCC</td>
<td>Slurry</td>
<td>5 Rebars and 6 Ties</td>
<td>6002</td>
</tr>
<tr>
<td>3</td>
<td>SCC</td>
<td>Water</td>
<td>3 Rebars and 4 Ties</td>
<td>6003</td>
</tr>
<tr>
<td>4</td>
<td>SCC</td>
<td>Water</td>
<td>5 Rebars and 6 Ties</td>
<td>6004</td>
</tr>
<tr>
<td>5</td>
<td>NC</td>
<td>Slurry</td>
<td>3 Rebars and 4 Ties</td>
<td>6005</td>
</tr>
<tr>
<td>6</td>
<td>NC</td>
<td>Slurry</td>
<td>5 Rebars and 6 Ties</td>
<td>6006</td>
</tr>
<tr>
<td>7</td>
<td>NC</td>
<td>Water</td>
<td>3 Rebars and 4 Ties</td>
<td>6007</td>
</tr>
<tr>
<td>8</td>
<td>NC</td>
<td>Water</td>
<td>5 Rebars and 6 Ties</td>
<td>6008</td>
</tr>
</tbody>
</table>

The time step size was chosen to ensure that the Courant-Friedrichs-Lewy (CFL) condition was satisfied. The number of iterations of about 250 to 500 were considered in order that convergence was achieved at each time step to residual levels recommended in the Fluent user manual. The analysis was performed availing the high performance computing resources through the CIRCE cluster computer.
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Concrete Flow Pattern from the Simulation

Simulations were performed for eight cases each for 48 inch and 36-inch diameter shafts and are summarized in Table 3.6 and Table 3.7, respectively. The results were processed using ANSYS-CFD Post, which is the post processing tool within ANSYS, and the concrete flow patterns were obtained on horizontal planes at different depths and on vertical planes. A typical flow pattern obtained on horizontal planes at different depths in the shaft excavation is shown in

![3-D Model in ANSYS-Fluent: Typical Flow Pattern on Horizontal Planes](image)

Figure 4.1 3-D Model in ANSYS-Fluent: Typical Flow Pattern on Horizontal Planes
Figure 4.1. This flow pattern was obtained from the simulation of NC flow when casting under slurry and at flow time of 35 sec. In the flow pattern, the creases that developed behind the rebars in the concrete cover region can be seen through the interface between the concrete and the slurry. A similar flow behavior was observed during the study carried out at University of South Florida (Mullins, 2015) with 24 cast shafts, 42-inch diameter and 2 feet height (Figure 4.2).

Figure 4.2 Experimental Study with Cast Shafts at USF: Creases Behind Rebars, (Mullins, 2015)

In addition, the flow patterns from the simulation were extracted on the surface elevations at concrete cover region and are shown in Fig 4.3. Both vertical and horizontal creases are clearly seen. Similar patterns of vertical and the horizontal creases were observed during the experimental study with cast shafts and are shown in Figure 4.4

Figure 4.3 3-D Model in ANSYS-Fluent: Typical Flow Pattern on the Surface Elevation - (a) Elevation at the Concrete Cover Region (b) Elevation Close to the Excavation Edge
Moreover, the flow pattern extracted on the vertical plane shows the concrete head differential between inside and outside the rebar cage in Figure 4.5. This similar pattern of concrete flow was obtained from the research study carried out at USF with the Lateral Pressure Cell (LCP) developed by Mullins and Ashmawy, (2005). The objective of Mullins and Ashmawy, (2005) was to study the rheology of concrete flow as it flows from the tremie bottom and rises inside the excavation.
Head differential of rising mortar between inside and outside the reinforcement cage were measured by the LCP tests. Figure 4.6 shows the pattern of rising mortar observed in the LCP test. Field testing programs were also carried out and the concrete head differential was measured at Port of Tampa, Essex Cement Company Project, Crosstown Expressway Reversible Lanes Bridge site, and Alagon Condominium project.

From the above comparison made between the concrete flow patterns obtained from the simulation and from the experimental study, it can be concluded that the 3-D model developed provides qualitatively reliable results. It is not possible to make a stronger comparison between the model and experiments because the flow time was not measured in the experiments. Furthermore, the viscosity of concrete given by the non-Newtonian Carreau model is for a homogeneous fluid, thus it does not consider the suspended solids present in concrete.

4.2 Evaluation of Flow Performance of SCC and NC

4.2.1 Evaluation Based on Creases in the Concrete from Simulation

The flow patterns obtained from the simulations performed with SCC and NC for 48-inch diameter and 20-inch depth shaft models are shown in Figures 4.7 and 4.8, respectively. The flow
patterns are visualized on horizontal and vertical planes. The flow patterns on the horizontal planes are shown in Figures 4.7(a) and 4.8(a) and on the vertical planes in Figures 4.7(b) and 4.8(b).

In the flow pattern of NC extracted on the horizontal planes, creases formed behind the vertical rebars in the concrete cover regions, are observed. Similar flow patterns on the horizontal planes. Meanwhile in the case of SCC these creases are not observed. Hence, the shafts cast with SCC can ensure a high degree of concrete integrity free of anomalies.

Figure 4.7 3-D Model in ANSYS-Fluent: Evaluation of Flow Performance of SCC- Shaft Size 48-inch Dia. and 20-inch Depth, t =100 sec, (a) on Horizontal Planes (b) on Vertical Plane

Figure 4.8 3-D Model in ANSYS-Fluent: Evaluation of Flow Performance of NC- Shaft Size 48-inch Dia. and 20-inch Depth, t = 83 sec, (a) on Horizontal Planes (b) on Vertical Plane
4.2.2 Evaluation Based on Concrete Head Differential from Simulation

The concrete head differential between inside and outside the rebar cage was obtained from the simulation of both SCC and NC. For the evaluation of flow performance, the flow pattern of SCC and the NC were compared by keeping the other parameters like shaft size, tremie pipe size, vertical rebars, and horizontal tie arrangements the same. The shaft details are 48-inch, diameter, with 12-inch diameter tremie pipe, four one-inch diameter size vertical rebars and four 1/2 inch diameter horizontal ties in the 90 degree segmented shaft. For both the shaft models with SCC and NC, slurry was considered for the drilling fluid. The flow patterns obtained from the simulations extracted on the vertical plane are shown in Figure 4.7 (b) and Figure 4.8 (b) for SCC and NC, respectively. It can be seen that in the case of NC the head differential was about four inches, whereas in SCC, the head differential was negligible and less than an inch.

A similar evaluation was performed from the simulation obtained for 36-inch diameter shaft with SCC and NC. The flow pattern of SCC and NC extracted on the horizontal planes and vertical plane are shown in Figures 4.9 and 4.10. As observed in the simulation of 48-inch diameter shaft model, the flow pattern of SCC shows no creases and the concrete head differential is less than an inch in height. But the flow pattern of NC extracted on the horizontal plane shows creases.

![Figure 4.9 3-D Model in ANSYS-Fluent: Evaluation of Flow Performance of SCC- Shaft Size 36-inch Dia. and 20-inch Depth, t = 50 sec, (a) on Horizontal Planes (b) on Vertical Plane](image-url)
in the concrete cover region and the flow pattern on the vertical plane exhibits the concrete head differential of about 4.5 inch.

Hence, from the simulations performed on both 48-inch dia. and on 36-inch dia. shaft models, it can be seen that, the flow behavior of SCC was free of creases or creases if formed were negligible and with significantly less concrete head differential. In contrast, the flow behavior of NC showed clear patterns of creases in the concrete cover region and with concrete head differentials on the order of 4 inches at the times the instantaneous solutions were plotted.

4.3 Effect of Shaft Sizes on the Flow Performance

The effect of shaft sizes on the flow performance were studied by comparing the results of the simulation with 48 inch and 36-inch dia. shaft models. The shaft depths were kept same, as 20 inch for both the shafts. The head differential from the simulation, obtained for the shaft with SCC was negligible whereas for the shaft with NC, the head differential obtained was considerable about four inches. Hence, to determine the effect of shaft sizes, only the simulations with NC were considered. The flow patterns extracted on horizontal planes and a vertical plane for both models are given in Figure 4.11 and in Figure 4.12. Creases are observed in the flow patterns of both the
models, and no considerable differences in the crease patterns between the two models can be seen. However, differences are observed between the concrete head differential encountered in both models. The concrete flow velocities in the 48-inch and 36-inch models were 1.15 ft/min and 2.07 ft/min, respectively. The head differentials obtained for both the models are shown in Figure 4.11 and 4.12. The concrete head differential obtained were four inches and four and half inches for the 48 inch and 36-inch shaft models, respectively, at t = 83 sec and 50 sec.

Figure 4.11 3-D Model in ANSYS-Fluent: Effect of Shaft Sizes on Flow Performance of NC-Shaft Size 48-inch Dia. and 20-inch Depth, t = 83 sec, (a) on Horizontal Planes (b) on Vertical Plane

Figure 4.12 3-D Model in ANSYS-Fluent: Effect of Shaft Sizes on Flow Performance of NC-Shaft Size 36-inch Dia. and 20-inch Depth, t = 50 sec, (a) on Horizontal Planes (b) on Vertical Plane
Hence, it is observed that there is increase in head differential as the shaft size reduces or the concrete flow velocity increases. Similar observations were made from the results of the experiments carried out at USF.

4.4 Effect of Rebar Arrangement on the Flow Performance

The effect of rebar arrangement or the spacing of vertical rebars on the flow performance was also studied. The flow patterns extracted on horizontal planes and vertical plane for both models of 48-inch dia. with four rebars at seven inch spacing and with eight rebars at 3.5-inch spacing, (model No 5105 and model No 5106 as referred in Table 4.4) are given in Figure 4.13 and in Figure 4.14, respectively. Creases are observed in the flow patterns obtained from both of the reinforcement arrangements and there was some increase in the intensity of crease pattern obtained in the flow pattern of model 5106, shown in Figure 4.14, where the reinforcements were kept at a closer spacing of 3.5-inch. Moreover, the concrete head differential obtained from the simulation performed in these two models were 4-inch and 10.75-inch, respectively. This shows that the head differential increases as the reinforcement spacing decreases, which is a realistic flow behavior. The concrete head differentials from these models are shown in Figure 4.13(b) and 4.14(b).

The effect of the rebar arrangement on the flow performance was observed from the flow patterns viewed on the surface elevation planes. The planes were extracted in the concrete cover region close to the reinforcement as well as close to the shaft edge. These flow patterns are shown in Figure 4.15 and Figure 4.16. Creases are observed in the flow patterns obtained from both of the reinforcement arrangements. However, considerable increase in the intensity of crease pattern is observed when the reinforcements were kept at closer spacing of 3.5-inch.
Figure 4.13 3-D Model in ANSYS-Fluent: Effect of Rebar Arrangement on Flow Performance of NC- Shaft Size 48-inch Dia. with 4 Rebars and 4 Ties, t = 83 sec, (a) on Horizontal Planes (b) on Vertical Plane

Figure 4.14 3-D Model in ANSYS-Fluent: Effect of Rebar Arrangement on Flow Performance of NC- Shaft Size 48-inch Dia. with 8 Rebars and 6 Ties, t = 70 sec, (a) on Horizontal Planes (b) on Vertical Plane
4.5 Concrete Head Differential and the Concrete Flow Velocity

- The concrete head differential encountered in the concrete flow for both SCC and NC were compared with the flow velocity in the shaft excavation. The plots of head differential vs the flow velocity, for 48-inch dia. and 36-inch dia. shafts, are shown in Figure 4.17. The concrete flow velocities in the 48-inch dia. shaft with 12-inch dia. tremie pipe and in the 36-inch dia. shaft with 10 inch. dia. tremie pipe were 1.15 ft/min and 2.07 ft/min, respectively. In these plots, the vertical rebar spacings...
are 7 inch in the case of 48-inch dia. shaft and 6.3 inch in the case of the 36-inch dia. shaft. Even though only two results are available for this plot, the results show that as the flow rate increases and thus the concrete flow velocity increases, there is increase in the concrete head differential. This trend is similar to the trend obtained in the experimental tests with the cast shafts of Mullins and Ashmawy (2005) shown in Figure 4.19. Similar plots of head differential vs flow velocity, made for 48-inch dia. and 36-inch dia. shafts with rebars placed at 3.5-inch and at 3.8-inch spacings, respectively, were obtained for both SCC and NC are shown in Figure 4.18. The differential head values obtained from the models are given in Table 4.1.

- The plots of the head differential vs concrete flow velocity obtained for SCC and NC from the simulations are compared with the actual field values of head differential vs concrete flow velocity, and shown in Figure 4.19. Note that the field data is for different CSD (cage spacing to maximum aggregate diameter ratio) values and the results from the simulations are for different viscosities and rebar spacing, thereby making a direct comparison difficult. Also note that the simulations do not take into account the effect of the aggregates.

- In Figure 4.19 it can be seen that for the field data, the steeper slope plots correspond to lesser CSD values, which indicates closer rebar spacing and thus less flowability. Meanwhile, in the case of the simulations, less flowability is given by NC relative to SCC, as can be seen by the steeper slopes in the plots of the former (Figures 4.17-4.19).
Figure 4.17 3-D Model in ANSYS-Fluent: Concrete Head Differential ($H_{\text{diff}}$) vs Flow Velocity ($v$) - 48-inch Dia. Shaft with 4 Rebars and 36-inch Dia. Shaft with 3 Rebars

Figure 4.18 3-D Model in ANSYS-Fluent: Concrete Head Differential ($H_{\text{diff}}$) vs Flow Velocity ($v$) - 48-inch Dia. Shaft with 8 Rebars and 36-inch Dia. Shaft with 5 Rebars
Table 4.1 3-D Model in ANSYS-Fluent: Head Differential ($H_{\text{diff}}$) Obtained from Simulations

<table>
<thead>
<tr>
<th>Model No</th>
<th>Shaft Excavation size: dia. in inch</th>
<th>SCC/NC - Slurry</th>
<th>Conc./SCC flow velocity in shaft excavation - ft./min.</th>
<th>$H_{\text{diff}}$ inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>5101</td>
<td>48</td>
<td>SCC-Slurry</td>
<td>1.15</td>
<td>0.75</td>
</tr>
<tr>
<td>5102</td>
<td>48</td>
<td>SCC-Slurry</td>
<td>1.15</td>
<td>1.00</td>
</tr>
<tr>
<td>5105</td>
<td>48</td>
<td>NC-Slurry</td>
<td>1.15</td>
<td>4.00</td>
</tr>
<tr>
<td>5106</td>
<td>48</td>
<td>NC-Slurry</td>
<td>1.15</td>
<td>10.75</td>
</tr>
<tr>
<td>6001</td>
<td>36</td>
<td>SCC-Slurry</td>
<td>2.07</td>
<td>0.75</td>
</tr>
<tr>
<td>6002</td>
<td>36</td>
<td>SCC-Slurry</td>
<td>2.07</td>
<td>1.25</td>
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<td>6005</td>
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<td>NC-Slurry</td>
<td>2.07</td>
<td>4.50</td>
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<td>6006</td>
<td>36</td>
<td>NC-Slurry</td>
<td>2.07</td>
<td>12.50</td>
</tr>
</tbody>
</table>

4.6 Flow Performance of Shafts Cast under Water as Drilling Fluid

Simulations were performed for the shaft cast with SCC under water as a drilling fluid. The flow patterns are obtained on horizontal planes and on a vertical plane for 36 inch dia shaft model with three vertical rebars and for the same shaft with five vertical rebars and are shown in Figures 4.20 and 4.21, respectively. The flow patterns obtained from the simulations show that the creases in the concrete cover region were insignificant and the concrete head differential encountered were only 0.5 inch and 1.25 inch for the shaft models with three and five vertical rebars respectively. These simulations indicated that the flow performance of SCC in the shaft excavation with water as the drilling fluid was on par with the performance of SCC with slurry as
the drilling fluid. Similar flow performances of SCC were observed in the experimental shafts cast with water as the drilling fluid by Mullins (2015). The cast shafts in these experiments exhibited no creases as shown in Figure 4.22.

Figure 4.19 Concrete Head Differential vs Flow Velocity: Comparison between Field Data, and Results from Simulation. Note: Field Data is from Mullins and Ashmawy (2005).

Figure 4.20 3-D Model in ANSYS-Fluent: Flow Performance of SCC Shaft Cast under Water-Shaft Size 36-inch Dia. with 3 Rebars and 4 Ties, t = 40 sec,
(a) on Horizontal Planes (b) on Vertical Plane
Figure 4.21 3-D Model in ANSYS-Fluent: Flow Performance of SCC Shaft Cast under Water-
Shaft Size 36-inch Dia. with 5 Rebars and 6 Ties, $t = 35$ sec,
(a) on Horizontal Planes (b) on Vertical Plane

Figure 4.22 Experimental Study with Cast Shafts at USF, (Mullins 2015):
Flow Performance of SCC Shaft Cast under Water- Shaft Size 48-inch Dia.

4.7 Summary

This chapter discussed the flow patterns simulated from the 3-D model developed. In
addition, it covered the qualitative validation of the 3-D model and the simulation. The validation
was carried out by comparing the results from the model simulation with the experimental test
data. The pattern of vertical and horizontal creases obtained from the simulations in the shaft
concrete cover region were qualitatively compared with the creases developed in the experimental
cast shafts. In addition, the concrete head differentials between inside and outside the
reinforcement cage, observed in the flow pattern from the simulation were comparable to the results obtained at USF in laboratory experiments with LCP test apparatus (Mullins and Ashmawy, 2005).

Using this model as a tool, the performance of SCC for drilled shaft application was evaluated. It was observed that the flow pattern of SCC in drilled shaft excavation produced negligible creases and the concrete head differentials between inside and outside the rebar cage were minimal. In the case of NC, there were creases of considerable depth in the shaft concrete cover region and the concrete head differential was four inches to twelve inches depending on the shaft size and the reinforcement cage arrangement.
To address the issue of anomalies in drilled shaft concrete, which is attributed to the flow of concrete in the shaft excavation, SCC a highly flowable concrete, was considered in place of NC. A 3-D CFD model in ANSYS-Fluent was ultimately developed to simulate the concrete flow in a tremie placed drilled shaft excavation under the wet construction method. The model was developed taking into account the flow of both concrete and drilling fluid and their respective rheological properties leading to qualitative prediction of flow patterns around rebars and ties as heavily influenced by these structural blockages. In the 3-D model, the Volume of Fluid method was employed to track the interface between the concrete and drilling fluid and the non-Newtonian Carreau model was used to describe the rheological behavior of the concrete. The drilling fluid was taken as a Newtonian fluid.

The concrete flow pattern from the simulation showed both horizontal and vertical creases behind the rebars in the concrete cover region. In addition, the concrete head differential encountered between the inside and outside of the reinforcement cage was observed. These observations from the simulations were shown to be similar to those observed from earlier physical experiments carried out on the cast shafts at USF (Mullins 2014). Various simulations were performed to study the effect of shaft sizes and the reinforcement arrangements on the flow performance.

Simulations of SCC and NC flows in drilled shaft concreting were studied in terms of creases and concrete head differential. In the flow pattern of SCC, very few creases were observed,
compared to NC. In addition, in the flow pattern of SCC, the concrete head differential encountered was only about one inch whereas, in the case of NC, the concrete head differential observed in the 48-inch model simulation was 4-inch when the vertical rebars were spaced at 7-inch apart and 10-inch when the rebars were placed at 3.5-inch apart. Based on this numerical evaluation of flow performance, it is concluded that the flow performance of SCC is better than the NC as the latter serves to minimize anomalies in the concrete cover.

The development of the present numerical model to simulate concrete flow in drilled shaft and subsequent evaluation of the concrete flow performance as carried out in this research study are unique while making use of state-of-the-art numerical techniques and physical modeling. For example, the model developed takes into account the non-Newtonian nature of concrete flow. However, it does not take into account the effect of suspended aggregates in the concrete flow. As a next step, the model should be extended to particles in fluid-suspension to simulate more realistic concrete flow pattern facilitating a more direct comparison with physical experiments.

The same approach of modeling and simulation, with a change in the shape of the model geometry, can be applied to flow in a barrette a rectangular shaped drilled shaft and to diaphragm walls an underground earth retaining structure with rectangular panel walls. Barrettes are extensively used in the transportation industry. Therefore, this model has the potential for further research in various applications of underground structures.
REFERENCES


Dan A. Brown, Joe Bailey, Anton Schindler, “The use of Self-Consolidating Concrete for drilled shaft construction: Preliminary observations from the Lumber River Bridge Field Trials” Proceedings of the ADSC GEC3 Conference, Dallas, TX, 2005.


Fredrick van Waarde, “Formwork pressures when casting Self Compacting Concrete”. Master’s Thesis, 2007, Concrete Structures, Faculty of Civil Engineering, Technical University of Delft.


31 Ian N. Robertson, University of Hawaii at Manoa, “Use of Self-Consolidating Concrete For Bridge Drilled Shaft Construction”, Research Report UHM/CEE/12-09, December 2012.


33 Kamal H. Khayat (PI), Universite de Sherbrooke, David Bonen (co-PI), Purdue University, Surendra Shah, Northwestern University, Peter Taylor, CTL Group. “SCC Formwork Pressure, Task 1: Capturing Existing Knowledge on Formwork Pressure Exerted by SCC” Submitted to The National RMC Research Foundation and The Strategic Development Council, ACI. February 13, 2007.


42 Mullins G., “Development of Self Consolidating Mix Designs for Drilled Shafts” – Project, Scope of services, August 2015.


48 Pedley T. J., “Introduction to Fluid Dynamics”, Department of Applied Mathematics and Theoretical Physics, Scientia Marina, 61 (Supl. 1): 7-24, 1997 University of Cambridge, U.K.


Wallevik J.E., “Rheology of Particle suspensions, Fresh Concrete, Mortar, and cement paste with various Lignosulfonates”. The Norwegian University of Science and Technology, Trondheim, 2003.


https://www.google.com time vs. apparent viscosity curve for thixotropic and rheopctic fluid.


http://www.selfconsolidatingconcrete.org
APPENDIX A: PARAMETRIC STUDY OF RE-INITIALIZATION INTENSITY

PARAMETER $\gamma$, SURFACE TENSION $\sigma$, AND INTERFACE THICKNESS $\varepsilon$

The flow patterns were obtained from the parametric study performed for $\gamma$, with values 0.5, 0.1, 0.05, and 0.01 m/sec. From this study a $\gamma$ value of 0.05 m/sec was selected. For this $\gamma$ value of 0.05 m/sec, the flow pattern was better than the other $\gamma$ values. Other values of $\gamma$ led to generation of unphysical pockets of slurry within the concrete.

For $\sigma$, flow patterns were studied for the values 0.05, 0.1 and 0.50 N/m and a value of 0.1 N/m was selected which showed a realistic flow behavior of the concrete in the excavation compared to other values. For other values, the flow patterns along the excavation wall and tremie surface were showing some inclination from the anticipated vertical direction.

For $\varepsilon$, flow patterns were studied for the values of 0.005, 0.007, 0.010 and 0.015m. There was not much appreciable difference in the flow patterns obtained from these values and based on close observation, a value of 0.007m was considered.

The flow patterns obtained from the parametric studies for $\gamma$, $\sigma$, and $\varepsilon$, are given in Appendix-A.
Figure A.1 3-D Model in COMSOL: Parametric Study of Re-initialization Intensity Parameter $\gamma$— Flow Pattern of Concrete in 18-inch Dia. 20-inch Depth Shaft Model
Figure A.2 2-D Model in COMSOL: Parametric Study on $\sigma$, Surface Tension-Flow Pattern of Concrete in 2-feet Radius and 4-feet Depth Shaft Model.
Figure A.3a 2-D Model in COMSOL: Parametric Study on $\varepsilon$, Interface Thickness Parameter-Flow Pattern of Concrete in 2-feet Radius and 4-feet Depth Shaft Model,

$\varepsilon = 0.005 \text{ m}$  $\varepsilon = 0.007 \text{ m}$
Figure A.3b 2-D Model in COMSOL: Parametric Study on \( \varepsilon \), Interface Thickness Parameter-Flow Pattern of Concrete in 2-feet Radius and 4-feet Depth Shaft Model, \\
\( \varepsilon = 0.015 \, \text{m} \quad \varepsilon = 0.010 \, \text{m} \)
APPENDIX B: COPYRIGHT PERMISSIONS

The permission below is for the use of materials in Section 2.7.3.1 and the Figures 2.9 and 2.10 in Chapter-2

Jesudoss Asivatham Jeyaraj <jeyaraj@mail.usf.edu>  
Oct 26, 2018, 3:43 PM (10 days ago)  
Mr. Andraz Hocevar,

I have gone through your paper published in GRADEVINAR 65(2013) 2.99-100, on “Rheological Parameters of Fresh Concrete - Comparison of Rheometers”. It is quite interesting while going through many useful informations in the paper especially the plots showing the correlation between the slump and the yield stress and also between the slump and the plastic viscosity obtained from Cortec and ICAR rheometers.

I am PhD student, in University of South Florida, Tampa, FL and my research study is on numerical modeling of concrete flow in drilled shaft and evaluation of SCC for drilled shaft concrete.

Can I have your permission to use these correlations in my dissertation chapter on literature review and also few points from your paper and the conclusions in my Dissertation? Your early reply is appreciated.

Thanks and Regards,
Jesudoss Asivatham, Jeyaraj  
PhD Student, Civil and Environmental Engineering  
University of South Florida, Tampa, FL, 33613, US.

Andraz Hocevar  
Oct 29, 2018, 3:59 AM (7 days ago)  
Dear Jesudoss,

thank you for your email.

Nothing is wrong with using my data if you cite them correctly. You do not need our permission to do this so you are free to do it. But please do not use them as yours.

Although I would be glad to see you work when you are finished with it.

Best Regards,
Andraz Hocevar
The permission below is for the use of materials in Section 2.7.1.1 in Chapter 2.

Jesudoss Asirvatham Jeyaraj <jeyaraj@mail.usf.edu>  
Thu, Oct 25, 9:50 AM (11 days ago)  
Mr. Donald Hodgson,

I have gone through your paper published in ASCE - Journal of Materials, 2005, on "SCC for Use in Drilled shaft Applications". It is quite interesting while going through useful information in the paper. I am PhD student, in University of South Florida, Tampa, FL and my research study is on numerical modeling of concrete flow in drilled shaft and evaluation of SCC for drilled shaft concrete. Can I have your permission to use some information regarding the mixture parameters and properties from Table 1, Table 2 and Table 3; few points from your conclusions and recommendations, from your paper in my Dissertation? Your early reply is appreciated.

Thanks and Regards,
Jesudoss Asirvatham, Jeyaraj
PhD Student, Civil and Environmental Engineering
University of South Florida, Tampa, FL, 33613, US.

Trey Hodgson  
Oct 25, 2018, 8:16 PM (11 days ago)  
Jesudoss,

I have no objection to you referencing my work on SCC from that publication or my thesis from my graduate work at Auburn (reference below). I've CC'ed Dr. Anton Schindler who helped oversee my work on this subject - he's continued to pioneer research on concrete at Auburn, and I respect him and his opinion a great amount.


Best of luck with your own research!
The permission below is for the use of materials in Table 2.4 in Chapter 2

Jesudoss Asirvatham Jeyaraj <jeyaraj@mail.usf.edu>  Oct 25, 2018, 10:05 AM (11 days ago)  ⭐  ⬤  ...

to antons

Mr. A. K. Schindler,

I have gone through your paper published in Journal of the Transportation Research Board, No. 2020, on "Evaluation of SCC for Drilled shaft Applications at Lumber River Bridge Project at South Carolina" It is quite interesting while going through useful information in the paper. I am PhD student, in University of South Florida, Tampa, FL and my research study is on numerical modeling of concrete flow in drilled shaft and evaluation of SCC for drilled shaft concrete. Can I have your permission to use some information regarding the Mixture Proportions used for Test shafts, Table 1 and few points from your summary and conclusions, from you paper in my Dissertation? Your early reply is appreciated.

Thanks and Regards,
Jesudoss Asirvatham, Jeyaraj
PhD Student, Civil and Environmental Engineering
University of South Florida, Tampa, FL, 33613, US.

Anton Schindler <schinak@auburn.edu>  Oct 25, 2018, 11:27 AM (11 days ago)  ⭐  ⬤  ...

to me

Jesudoss,

Yes, you have my permission for the items you list in your email below. Once finalized, can you please send me a pdf of your dissertation?

Best regards,
Anton Schindler
The permission below is for the use of materials in Sections 2.6.5.3 in Chapter 2 and Section 3.2 in Chapter 3.
The permission below is for the use of material in Section 2.11.2 and Table 2.11 in Chapter 2.

Jesudoss Asirvatham Jeyaraj
<jeyaraj@mail.usf.edu>  Nov 4, 2018, 1:21 AM (1 day ago)

Mr. Joontaek Park,

I have gone through your paper on "Simulation of Formwork Filling by Cement Fluid: Effect of Formwork Structure on Yield Stress Fluid" presented in Comsol Conference 2013, Boston. It is quite interesting while going through many useful informations in the paper especially the optimization of Rheological Properties to avoid the presence of dead zone.

I am PhD student, in University of South Florida, Tampa, FL and my research study is on numerical modeling of concrete flow in drilled shaft.

Can I have your permission to use the information of your study, the information of the rebar configuration and the summary of optimized rheological properties in Tables 1 and 3, respectively in my dissertation chapter on literature review with the citation of your name along the Title of the table? Your early reply is appreciated.

Thanks and Regards,
Jesudoss Asirvatham, Jeyaraj
PhD Student, Civil and Environmental Engineering
University of South Florida, Tampa, FL, 3613, US.

Park, Joontaek  Sun, Nov 4, 11:20 AM (1 day ago)

to me.

Jeyaraj,

As long as the citation is properly made, I approve your using that information.

Just let you know that the optimized conditions presented in that paper may be different depending on the definition of the optimized condition.

Just be careful in using that. If you think that data does not support what you wish to verify, you may ignore that.

thanks for interest in my work.

regards,

Joontaek Park
Assistant Professor
Missouri University of Science & Technology