Numerical Modeling of Concrete Flow in Drilled Shaft

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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. A research program is presently underway to perform 3-D modeling of drilled shaft concreting using COMSOL Multiphysics® software. This can take into account the fluid flow with rheological properties and the effects of structural blockages. Hence, the influence of the size of drilled shaft, size of reinforcement and arrangement of the bars can be analyzed. Non-Newtonian fluid behavior is considered and the level set method is used for computing the motion of the interface between the concrete and the drilling slurry. As a precursor to 3-D modeling, this paper discusses the 2-D modeling carried out for 4-minute simulation times and the flow patterns and volume fraction of concrete and slurry were determined. Results are encouraging as the flow patterns obtained are consistent with those observed at project sites.

Key words: Drilled shaft, concrete flow, modeling of drilled shaft, COMSOL Multiphysics®

1.0 Introduction

Drilled shafts are cylindrical, cast-in-place concrete, deep foundation elements used for heavy structures such as highway bridges and tall buildings. This foundation is often the best option from the aspects of cost effectiveness, applicability to the variety of soil strata encountered and minimum disturbance in terms of noise and vibrations to surroundings.

Even though the history of drilled shaft construction goes back to the 1950s, the occurrence of anomalies still persist 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 flowing concrete inside the excavation containing the reinforcing steel. There are several studies on the concrete flow in structural elements like slabs for floors and roofs, but the study of concrete flow in drilled shafts is lacking.

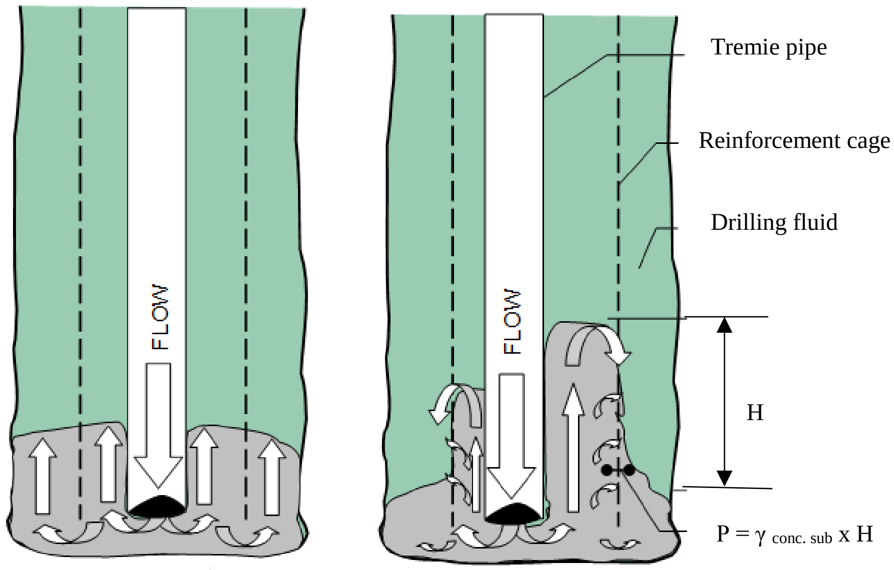
A research program is being carried out to develop 3-D models of drilled shaft concreting using COMSOL Multiphysics® software. The model should take into account the concrete and slurry fluid flows with corresponding rheological properties and effects of the size of drilled shaft, size of reinforcement and arrangement of the bars on the fluid flow. For the motion of fluid flow, non-Newtonian behavior is considered and the level set method is used for computing the motion of the interface between the concrete and the drilling slurry. Preliminary 2-D models are presented herein.

2.0 Drilled Shaft Construction

The main activities involved in drilled shaft construction are the excavation of cylindrical voids using large diameter augers and subsequent concreting after placing the necessary reinforcement. A drilling fluid is generally used to maintain the stability of the excavated portion prior to concreting. When the excavation is advancing, the drilling fluid or slurry is pumped into the excavation in volumes that equal the removed soil. After it is completed to the required drilled shaft depth, a cylindrical steel reinforcing cage is placed and subsequently concrete is placed using a long pump truck hose or tremie that prevents the concrete from mixing with the slurry as it is pumped to the bottom of the excavation. Concrete displaces the drilling fluid and fills the excavation. While the concreting is taking place the tremie pipe can be withdrawn in stages or might be left near the bottom for the entire concrete pour. Whether or not the tremie is incrementally removed provides another variable in the flow of concrete within the reinforcing cage that the modeling could ultimately address.

In view of the above process, the flow of concrete in a shaft has been visualized as a rising fluid that displaces the lighter slurry effortlessly (e.g. oil on water). However, studies have shown that the rising concrete is drastically affected by the presence of the reinforcing cage (Mullins and Ashmawy, 2005; Deese, 2004; Deese and Mullins, 2005) whereby a head differential between the concrete inside and outside the cage develops. These findings are different from the years of preconception that in a tremie-placed drilled shaft, the concrete uniformly rises from the bottom of the tremie pipe to the top of excavation. Figure 1 shows the comparison of idealized concrete flow and the actual concrete flow.

The proper flow of concrete from the tremie pipe to the excavation is requisite in achieving the desired quality of drilled shaft concrete over the entire cross section and to full depth. The important requirement of concrete flowability is related to its workability in its fresh state, which is measured through a slump test using a slump cone. For self-consolidating concrete (SCC), which is a high workability concrete, the workability is measured from slump flow test. The concrete used for a drilled shaft is highly flowable compared to the normal concrete used for structural elements such as columns, beams and slabs. In view of this, the rheology of the concrete for drilled shafts needs to be considered and the rheological properties are more appropriate than the conventional empirical parameters used for the above ground applications.



(a) Idealized concrete flow **(b) Actual concrete flow**

Figure 1. Comparison of idealized concrete flow with observed flow

3.0 Rheology of Concrete

One of the basic properties in rheology is viscosity, which is defined as the resistance to flow under shear stress and expressed as the ratio of shear stress to shear rate ($\dot{\gamma}$). In the case of Newtonian fluids, the stress at each point is linearly proportional to its strain rate at that point.

The two most important rheological properties of concrete, especially drilled shaft concrete and SCC, are yield stress and plastic viscosity.

The yield stress, τ_o, is the energy required to make the concrete flow. Fluid materials that exhibit a yield stress, start flowing when the shear stress exceeds the yield stress value. For concrete to flow easily under its own weight the yield stress must be low.

Plastic viscosity, μ, is the resistance of the concrete to flow due to internal friction. Concrete must have a high viscosity in order to suspend aggregate particles in a homogenous manner within the concrete matrix.

Drilled shaft concrete, in its fresh state, can be assumed in a simple model to behave like a Bingham fluid in which the fluid stress is defined as $\tau = \tau_o + \mu \dot{\gamma}$ (Hocever, 2013). A Bingham fluid has a yield stress and when the fluid stress exceeds the yield stress, the fluid displays Newtonian behavior. A non-Newtonian fluid is one in which 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. Fluids that thicken when worked or agitated are called shear-thickening fluids. Drilled shaft concrete in its fresh state is similar to a shear thinning fluid and exhibits thixotropic behavior that is described as a flow condition in which the viscosity reduces with time. Moreover, it is a complex suspension of particles. It consists of particles of coarse aggregate that are dispersed in mortar and within mortar, particles of fine aggregate are dispersed within cement paste, cement particles are dispersed in water. So the Bingham model is not fully realistic to consider for the concrete flow in drilled shaft.

Different non-Newtonian models also have been used for concrete. D Feys et al. (2007) in their study on rheological models for SCC, found that instead of the Bingham model, the Herschel-Bulkley model was more appropriate to describe the rheological properties. However since it overestimated the yield stress in the region of low shear rates, a modified Bingham model was used in their study. The Herschel-Bulkley model and modified Bingham models are expressed as $\tau = \tau_o + K \dot{\gamma}^n$ and $\tau = \tau_o + \mu \dot{\gamma} + c \dot{\gamma}^2$ respectively where K is the consistency index and both n and c are flow indices. Another approach, the Carreau –Yasuda (CY) model has been used for turbulent flow in pipes (Andrade et al. 2007). This is a generalization of the Newtonian model, describes with more accuracy the variation of viscosity with shear rate. The equation of CY model is as below:

$$\mu_{eff}(\dot{\gamma}) = \mu_{inf} + (\mu_0 - \mu_{inf})\,(1+ \lambda\dot{\gamma})^{a})^{(n-1)/a} \qquad (1)$$

and $\tau = \mu_{eff}\ \dot{\gamma}$

where:

μ_0 = viscosity at zero shear rate (Pa s)

μ_{inf} = viscosity at infinite shear rate (Pa s)

λ = relaxation time (s)

n = power index

a = shape 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. When considering a = 2 in the equation 1, it becomes the four parameter Carreau model. This model was found to fit the response very well at both high and low shear rates. The CY model is a general one applicable for both Newtonian and non-Newtonian fluid flow and this facilitates its application for both slurry and concrete flow.

4.0 Experimental Study of Concrete Flow in Drilled Shafts

In a recent laboratory study carried out at University of South Florida (Mullins, 2015) with 24 cast shafts, 42in diameter and 2 feet height, the concrete flow in the shaft was observed. In the cast concrete, creases were seen which coincided with the pattern of reinforcement arrangement (Figure 2). Further, it was observed that a dominant radial component of concrete flow fills the annular cover region (Figure 3) while the vertical component fills the interior cage and supplies the volume that subsequently exits radially. In view of the radially moving interfaces, the region outside the cage is highly likely to contain veins of poorly cemented or high water/cement ratio material. In the cases where bentonite mineral was used as the drilling fluid or slurry, these veins contained trapped bentonite. This process affects the density and the durability of concrete in that region, resulting in corrosion of the reinforcing steel. Hence, the hardened properties of the cast structural element drilled shaft are largely influenced by the flow pattern of concrete in the excavation.

Figure 2. Shaft - 50 sec/quart mineral slurry

Considering this, a numerical simulation of concrete flow in a drilled shaft will help to achieve an optimum workability of the fresh concrete that could ensure the proper filling of the given drilled shaft of size and rebar cage.

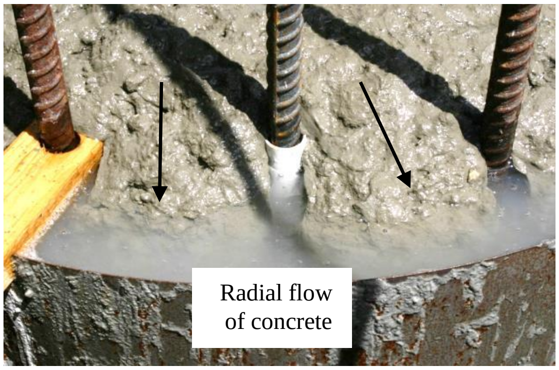


Figure 3. Radial concrete flow responsible for filling cover region

Studies that have attempted to model the rheological effects on SCC flow through rebar cages (Mehrdad, 2013) consist of mostly 2-D steady state single-phase channel flows, which are significantly different from concrete flow for drilled shaft application. A modeling and simulation of concrete flow in drilled shafts could be a useful tool to optimize the rheological properties of the fresh concrete and the reinforcing cage configuration. The designer could visualize the flow patterns of concrete flowing in the drilled shaft excavation under different circumstances to assess potential trapping of slurry within the concrete.

5.0 Numerical Simulation of Concrete Flow

This research program will undertake comprehensive 3-D modeling using COMSOL Multiphysics software, which can take into account the fluid flow with rheological properties and effects of structural blockages. Even though the objective is to create a 3-D model simulation, 2D modeling has been performed first as a precursor given the challenges of the flow involving resolution of the concrete-slurry interface, the rheology of the fluids, and the complex flows expected potentially characterized by pockets of slurry trapped within the concrete.

5.1 Two Phase Flow and Tracking of Interface by Level Set Method

Modeling and simulation of drilled shafts involves two phases consisting of the concrete flowing from the tremie pipe and the slurry flowing from the excavation displaced by the concrete. The level set method is a well-known interface-capturing technique and it is used here for computing and analyzing the motion of the interface between the concrete and the drilling fluid (the slurry).

In the 2-D model used for this study (Figure 4), a 4 feet diameter excavation 7 feet deep was considered as a rectangular element. The rebars are modeled as vertical elements with gaps, which match the spacing in a full-scale shaft. A tremie pipe of size 10 inches in diameter is considered at the center of the drilled shaft.

Drilled shaft concreting was simulated by considering the concrete inside the tremie pipe and bentonite drilling fluid in the excavation outside the tremie as the initial condition. For normal concrete, the viscosities are in the range of 50 Pa-s and 100 Pa-s and for SCC the range of viscosity is between 10 Pa-s and 25 Pa-s. The densities are 2400 kg/m^3 (150 lb. /ft^3) for normal concrete and 2200kg/m^3 (137 lb. /ft^3) for SCC. The density of the drilling fluid is in the range between 1025 kg/m^3 and 1150 kg/m^3 (64 and 72 lb/ft^3) and the viscosity is in the range between 28 s to 50 s (per quart) Marsh funnel time which is the viscosity indicator normally used in the construction site.

No slip boundary condition was considered at the excavation side face. A triangular mesh with finer size was selected for the analysis to ensure convergence of the solution. For the preliminary computations, Newtonian behavior was used for the flow of fluids and subsequently, the non-Newtonian behavior of the fluids using the Carreau model described earlier was considered.

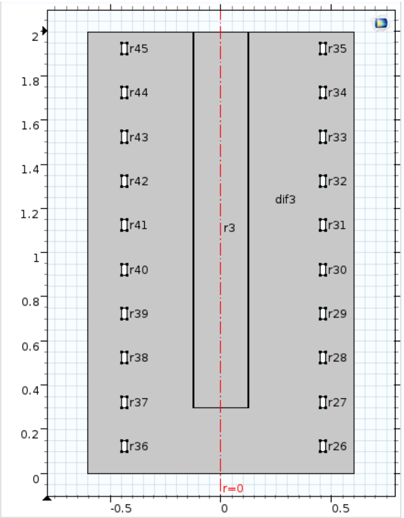


Figure 4 2 D Model - Geometry

Computations were carried out for 4-minute simulation time and the flow patterns in terms of the volume fraction of concrete are extracted for 15s, 60s, 120s, and 210s time intervals (Figure 5). From the figures, it can be noted that the concrete initially flows vertically up within the rebar cage and then after the required head is developed, the concrete flows radially out of the rebar cage into the annular space. The simulation captures the concrete head differential

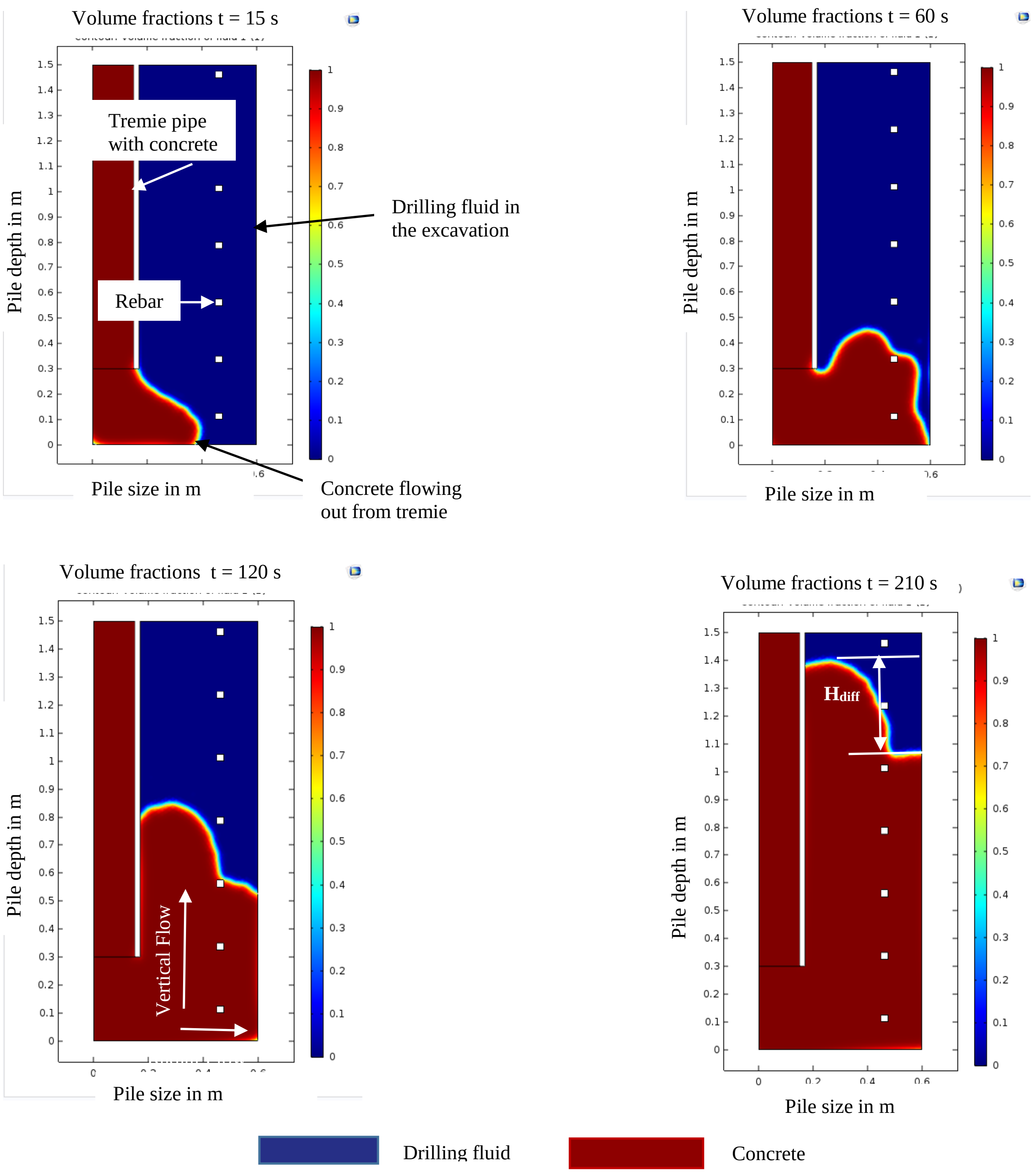


Figure 5. Volume fraction of fluid -1 concrete at, 15 sec, 60 sec, 120 sec, and 210 sec. Non-Newtonian analysis

($H_{diff,}$ shown in Figure 5 bottom right, t =210 s) between the inside and outside of the rebar cage, consistent with the laboratory work of Mullins (2015). A head differential of 0.350 m (14inch) was obtained from the computation using the non-Newtonian fluid behavior and this is close to the values obtained from experiments that range between 0.20 m to 0.40 m (8 inch to 16 inch). In the case of Newtonian analysis, $H_{diff,}$ obtained was 0.90 m (36 inch) which is on the higher side. The flow patterns of volume fraction of concrete are extracted for different time intervals (Figure 6). Further analysis needs to be carried out to study the influence of the size of drilled shaft, size of reinforcement and arrangement of the bars.

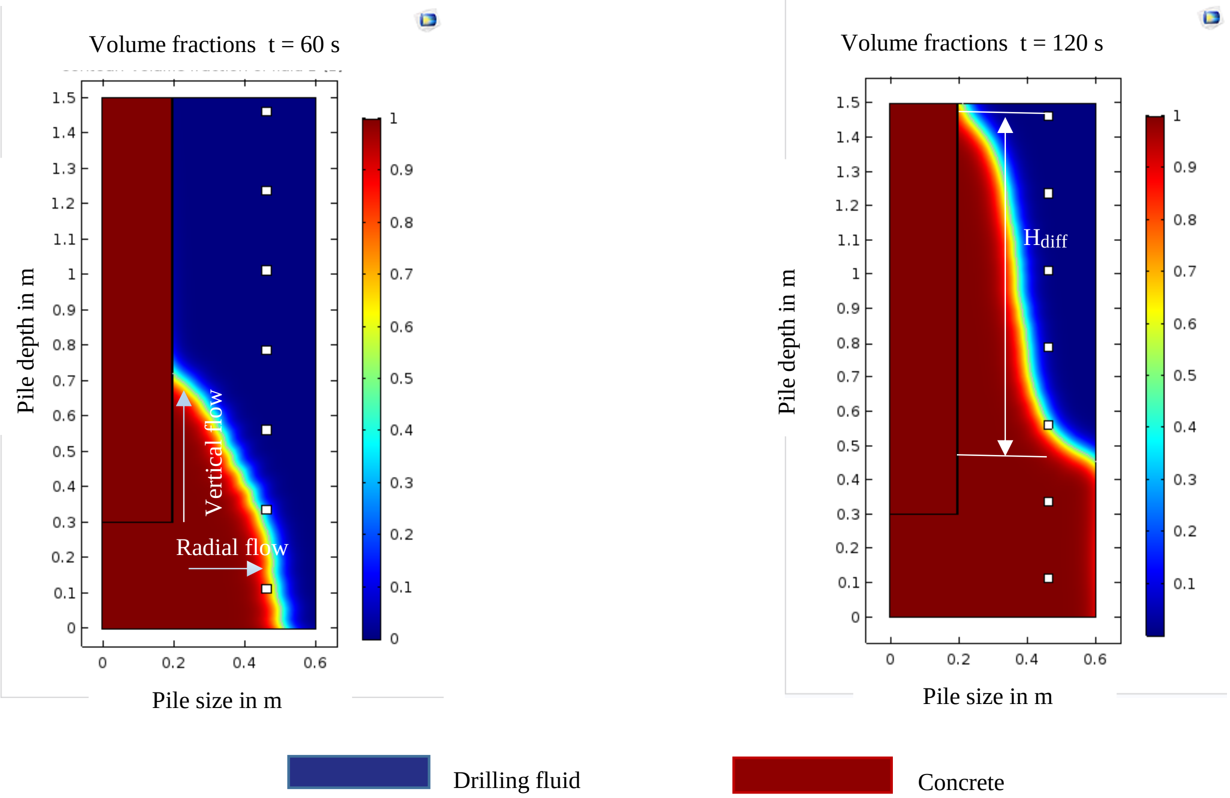


Figure 6. Volume fraction of fluid -1 concrete at, 60 sec, and 120 sec. Newtonian Analysis

6.0 Conclusion

Since drilled shaft concrete is a flowing type of concrete, rheological properties are to be taken into account in concrete specification to ensure the proper concrete flow and filling of the drilled shaft excavation. A numerical model and simulation of drilled shaft concreting could allow engineers to specify the optimum workability of the fresh concrete for a given drilled shaft of size and rebar cage. A 2-D model and simulation of drilled shaft concreting using COMSOL Multiphysics® software has been presented. The results show the pattern of concrete flow in drilled shaft including the head differential H_{diff} between the inside and outside of the rebar cage, observed in laboratory experiments. It is observed that for the concrete flow computations, the non-Newtonain fluid flow model is more appropriate than the Newtnian fluid flow model.

Further analysis are required to study the influence of the size of drilled shaft and the pattern of reinforcement cage. The model will be extended to 3-D in order to directly compare model simulations to drilled shaft flows in the lab and in the field.

7.0 References

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