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Understanding concrete flow mechanisms in deep foundation construction using numerical modelling

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ABSTRACT: Computational Fluid Dynamics (CFD) is utilised in this research to simulate the concrete-pour phase of deep foundation construction via the tremie method, providing insight into the occurring flow mechanisms. Such numerical techniques provide a cost-effective alternative and offer data not readily available from physical experimentation. The open-source CFD software OpenFOAM is used to model tremie concrete as a non-Newtonian Bingham fluid. The general flow mechanism observed within bored piles is highly dependent on the level of reinforcement. Unreinforced piles exhibit "plug" flow, where the concrete at the interface layer remains constant throughout the pour. Reinforced piles demonstrate a "consumption" flow mechanism, in which concrete within the reinforcement cage is consumed into the cover zone, leading to the concrete in contact with the support fluid continually changing. Concrete deeper than approximately 0.6 m from the tremie exit remained undisturbed by the subsequent pour. The type of dominant flow mechanism observed within deep foundation elements can affect concrete consistence retention time requirements.

KEYWORDS: Tremie concrete, computational fluid dynamics, deep foundations, concrete flow mechanisms, concrete retention time.

1 INTRODUCTION

The flow mechanisms of fresh concrete during the construction of deep foundation elements using the tremie method have not been well understood until recently, as the process occurs unseen below ground. In the past, such mechanisms were inferred indirectly from observations made during construction and from the pile's final quality upon exposure. Thus, there has been much conjecture regarding this process, with little evidence to support specific theories.

It has become common practice to specify concrete consistence retention time (referred to as 'retention time' throughout this paper) based on the total duration of the pour to minimise concrete-flow-related defects. However, the overuse or incorrect application of chemical admixtures that provide such long retention times increases the likelihood of bleed and segregation (Larish, 2019) and contributes to resource shortages and environmental pollution (Lai et al., 2023). Improving the understanding of how concrete flows within bored piles during pouring will provide insight into the necessity of this methodology.

This research employs Computational Fluid Dynamics (CFD) based numerical modelling to further understand the bulk-flow behaviour of fresh concrete in deep foundation elements. The pouring process of two separate concrete charges is simulated in both reinforced and unreinforced elements. The final charge distribution and flow mechanisms are compared by analysing the velocity vectors throughout the domain. The results are then used to comment on the influence of the dominating flow mechanisms on retention time requirements.

2 CONSTRUCTION PROCESS

2.1 *The tremie method*

The tremie method is a standard construction technique for placing concrete in submerged conditions, typically used in the excavation of deep foundation elements, where support fluids are often employed to stabilise sidewalls and prevent collapse. Concrete is placed by gravity feed via a hopper and a tremie pipe, filling the excavation from the bottom up and displacing the support fluid upward within the bore. This minimises the direct contact between fresh concrete and support fluid, as the tremie exit remains embedded in the concrete after the initial batch is poured. Increased direct contact between fresh concrete and the support fluid can enhance mixing between the two, compromising concrete quality (EFFC/DFI, 2024). An overview of the tremie method construction process is shown in Figure 1.

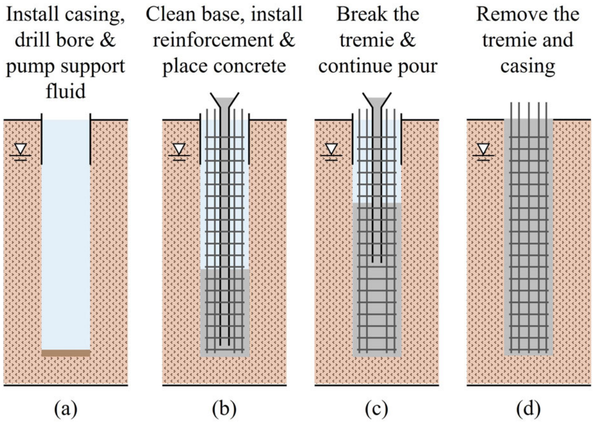

Figure 1. The construction process of a cast-in-place bored pile using the tremie method.

2.2 *Tremie concrete*

The specific concrete used in this method is known as 'tremie concrete'. It is favoured due to its high workability (Wilkes et al., 2023), which allows for effective form-filling under gravity, while maintaining stability to resist segregation and bleed under high hydrostatic pressure. The term 'workability' has been replaced with 'consistence' in European standards, but is still widely used in the United States (Mitchell et al., 2025). Both words are frequently used interchangeably and refer to fresh concrete's ability to flow and the ease with which it can be mixed and poured (EFFC/DFI, 2024). The term consistence is used throughout this paper to maintain continuity.

The consistence of fresh concrete can be quantified using a variety of on-site tests. Kränkel and Gehlen (2018) demonstrated correlations between the measured slump-flow value and the dynamic yield stress, as well as between the slump-flow velocity and the viscosity of the concrete. The ability to correlate such information, alongside the ease of use of this test, makes it the preferred consistence test to ensure suitable fresh properties before pouring (Barker & Nicholson, 2025). This test involves filling a standard slump concrete cone placed on a base plate with concrete, before lifting smoothly over 1-3 seconds. The concrete spreads, and the final diameter is measured as the slump-flow value. BS EN 12350 (2019) provides details on the test methodology and required equipment.

3 MODELLING METHODOLOGY

The open-source CFD software OpenFOAM is used for the numerical modelling presented in this paper. Notably, the multiphaseInterFoam solver, which is capable of modelling n-phase incompressible, immiscible, isothermal flow. This solver has been validated for the application of fresh concrete flow by comparing numerical results with consistence tests (Fierenkothen & Pulsfort, 2017), novel laboratory-scale tests (Wilkes, 2021) and partial full-scale tests (Fierenkothen and Pulsfort 2019; Böhle 2013). Three fluid phases are considered in the model: two concrete charges and a support fluid. The volume of fluid (VOF) method is implemented within this solver to capture the interface between the phases.

3.1 *Modelling concrete rheology*

Fresh concrete exhibits non-Newtonian rheological behaviour which can be captured numerically with the Bingham fluid constitutive model, first applied by Tattersal (1991). This model defines two key characteristics that govern concrete's consistence: yield stress, which represents the stress application required to initiate flow, and plastic viscosity, which is a measure of the fluid's resistance to flow (Mitchell et al., 2025). Equation (1) describes the relationship between stress and strain according to the Bingham model.

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

Where τ is the shear stress, τ_0 is the yield stress, μ is the plastic viscosity, and $\dot{\gamma}$ is the strain rate. If the applied shear stress is smaller than the fluid's yield stress, the fluid will act as a rigid body. Applied shear stresses greater than the yield stress will cause the fluid to behave as a viscous fluid with constant viscosity.

3.2 *Study parameters*

Two distinct cases are simulated within this study: concrete flow within a reinforced pile and an unreinforced pile. All parameters, apart from the reinforcement, remain constant across both cases. The reinforcement is designed with 40 mm diameter vertical bars with 100 mm clear spacing, and 16 mm diameter horizontal bars with 200 mm clear spacing. The cover zone is 100 mm. The pile geometry has a depth of 8 m and a diameter of 1.5 m. The tremie pipe is 6 m long and 0.25 m in diameter. The simulation is initialised with one charge of concrete already in the pile, with a volume of 6.2 m^3, yielding an initial concrete level of 3.5 m above the pile base. These values are typical as defined in SPERWall (ICE 2016). This provides an initial tremie embedment of 1.5 m, measured from the concrete surface to the tremie exit. BS EN 1536 (2010) specifies a minimum embedment of 1.5 m to 3 m. The lower limit was selected for these simulations to allow for the visualisation of the total consumption process of the initial concrete charge within the model, which is discussed further in Section 4.

Both concrete charges have identical rheological properties and were calibrated to a fresh concrete mix with a slump-flow of 500 mm by Wilkes (2021). The Bingham properties used throughout this research for this mix design are τ_0 = 130 Pa, μ = 30.2 Pa·s, and ρ = 2400 kg/m³. These concrete parameters have been chosen as they are within the EFFC/DFI (2024) recommended slump-flow target range of 400 mm to 550 mm. The support fluid's Bingham properties are consistent with those of a clean bentonite slurry, with $\tau0$ = 7 Pa, μ = 0.03 Pa·s, and ρ = 1075 kg/m³ (Wilkes, 2021).

3.3 *Boundary conditions*

The boundary conditions applied to the model are shown in Figure 2, where a shortened pile is visualised for clarity in labelling. To reduce the computational cost, a wedge encompassing a single vertical reinforcement bar is modelled. This assumption is valid due to the pile's rotational symmetry about the y-axis, and is the typical approach taken when modelling such problems (Fierenkothen and Pulsfort, 2016; Wilkes, 2021). Concrete is pumped into the pile via the concrete inlet at a fixed rate of 0.35 m/s, corresponding to a total charge pour time of 6 minutes. The atmospheric boundary condition allows the support fluid within the pile to leave the system as the concrete displaces it. All walls are modelled with no-slip boundary conditions.

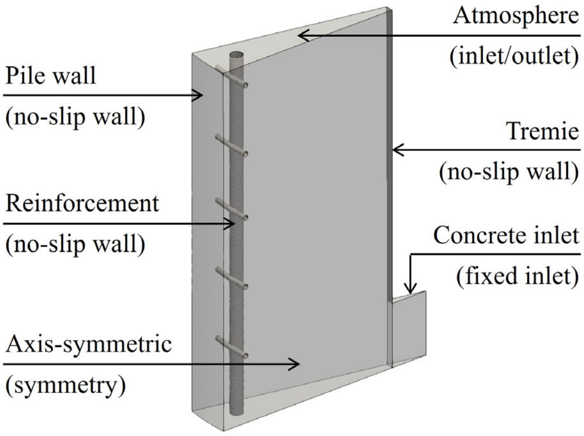

Figure 2. Model boundary conditions.

4 RESULTS AND DISCUSSION

4.1 *Charge distribution*

The final charge distributions for the unreinforced and reinforced piles are shown in Figure 3, where the light grey represents Charge 1, and the dark grey represents Charge 2. The images visualise the pile's centre cross-section upon completion of the pour.

In the unreinforced case, upon exiting the tremie, Charge 2 spreads radially to the pile surface. The "plug" of Charge 1, initially located above the tremie exit, is carried upward at the support fluid interface. Upon completion of the pour, Charge 1 remains at this interface region.

In the reinforced case, Charge 2 spreads radially up to the reinforcement cage but does not initially enter the cover zone. The flow of Charge 2 is contained within the reinforcement cage until it reaches the support fluid interface, at which point it begins to fill the cover zone. Upon completion of the pour, Charge 2 is at the interface region, with a small amount of Charge 1 trapped in the centre. Charge 1 has been consumed in the cover zone.

4.2 *Flow mechanisms*

Analysing the velocity vectors during the pour explains the significant discrepancy in the charge distribution between the two cases. Figure 4 and Figure 5 visualise the velocity magnitude and velocity vectors within the concrete in the reinforced and unreinforced cases, respectively. Red colouring denotes relatively fast-moving concrete, while dark blue denotes stationary concrete. The velocity vectors are represented by black arrows and are scaled to the magnitude of the velocity.

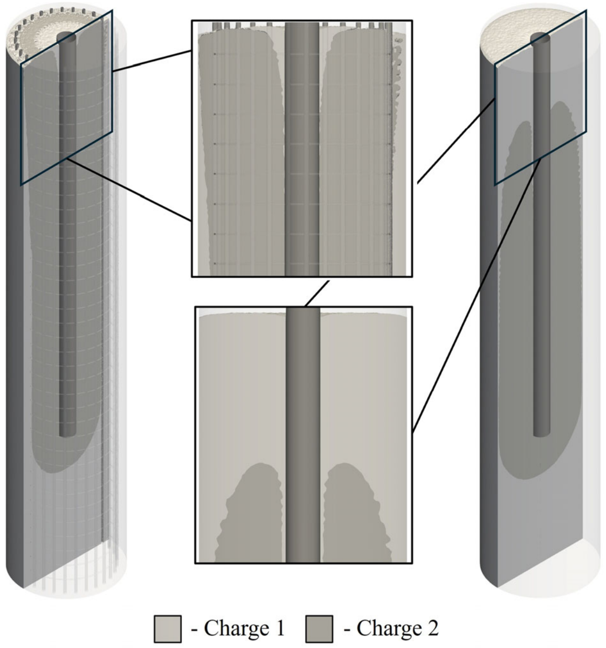

Figure 3. Charge distribution in reinforced (left) and unreinforced (right) piles after completion of pour.

Figure 4 shows how, in a reinforced pile, the concrete flow is restricted to the region inside the reinforcement cage for most of the pile's depth. Within this region, the flow is purely vertical, and there is no flow within the cover zone until it approaches the interface with the support fluid. Upon reaching approximately 0.5 m from the support fluid interface, the radial component of flow increases, and concrete begins to fill the cover zone. Upon entering the cover zone, the concrete flow rapidly stops, effectively becoming locked in place.

This flow process remains consistent throughout the pour once the flow has developed. It can be described as a ‘reinforced’ or ‘consumption’ flow mechanism, as the concrete close to the support fluid interface is continually consumed into the cover zone. Thus, the concrete at the support fluid interface is constantly changing. This consumption process is what leads to the final charge distribution visualised in Figure 3. As Charge 2 is poured into the pile, Charge 1 is consumed into the cover zone. Once Charge 1 has been fully consumed, Charge 2 takes its place at the support fluid interface.

Given that industry-scale piles are significantly longer than those simulated in this research (and thus provide an extended timeframe for consumption), it is unlikely that, within a reinforced pile, the initial charge of concrete will still be flowing by the end of the pour. Instead, it would be locked in place within the cover zone. The rate at which concrete is consumed in the cover zone is suspected by the Authors to correlate with the volume of the cover zone and is an area of ongoing research. The research presented here is not exhaustive enough to determine the specific retention times required within reinforced piles, but it does suggest that requiring concrete retention that lasts the entire pour is likely conservative.

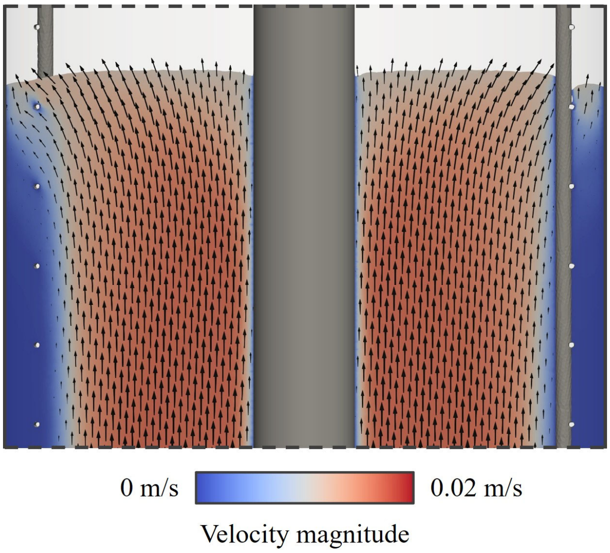

Figure 4. Concrete flow mechanisms in a reinforced pile

Figure 5 demonstrates a much simpler flow pattern in the unreinforced pile case. Purely vertical flow is observed throughout the entire radius of the pile. As such, the concrete at the support fluid interface is carried upwards as a “plug”, with no opportunity for consumption to occur. This explains why, in Figure 3, Charge 1 is still at the support fluid interface at the end of the pour. With this flow mechanism, any concrete above the tremie exit at the beginning of the pour will be carried upward. Thus, if sufficient embedment is maintained with each tremie break stage, Charge 1 would remain at the support fluid interface for the duration of the pour, regardless of the pile's depth. As such, if constructing an unreinforced pile, concrete retention would be required to last the duration of the pour. If this concrete “plug” were to reduce in consistence, it could lead to a reduction in the flow rate, or in more extreme cases, undesirable flow features such as volcano flow (EFFC/DFI 2024).

In both cases, unreinforced and reinforced piles, the concrete exits the tremie pipe in the negative y direction, penetrates approximately 0.6 m into the existing concrete charge, and is then redirected 180° to begin flowing upwards. Any concrete deeper than 0.6 m below the tremie exit was left undisturbed by the pouring process. This flow redirection is demonstrated in Figure 6.

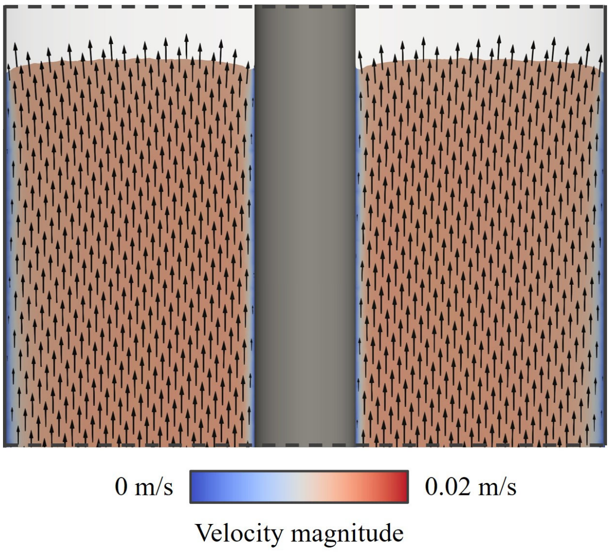

Figure 5. Concrete flow mechanisms in an unreinforced pile.

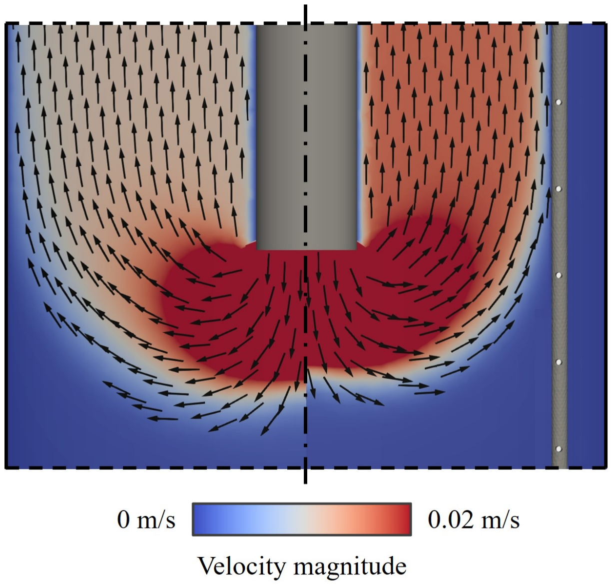

Figure 6. Concrete flow at the tremie exit in an unreinforced pile (left) and a reinforced pile (right).

5 CONCLUSIONS

The objective of this paper was to use CFD-based numerical modelling to improve the understanding of the flow mechanisms of fresh concrete within bored piles. The bulk flow mechanisms observed during the pouring of fresh concrete in bored piles are dependent on the level of reinforcement, with the general flow patterns observed presented in Figure 7.

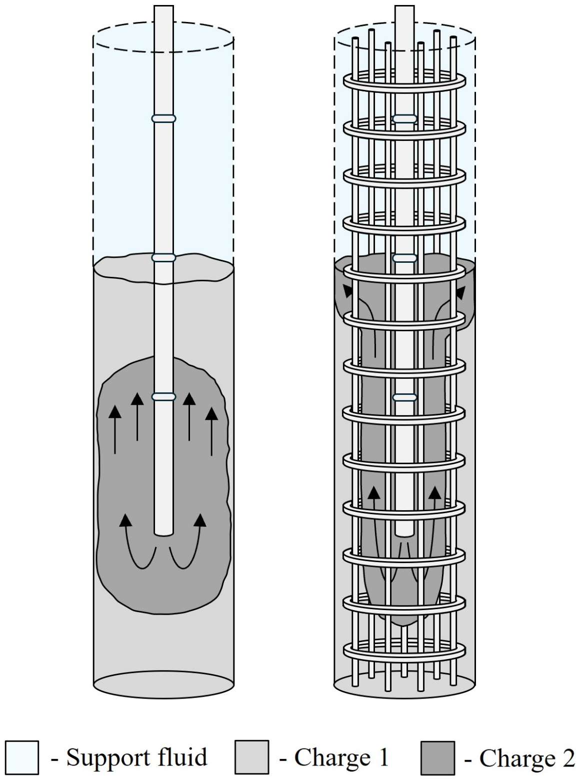

Figure 7. Schematic of charge distribution in an unreinforced pile (left) and a reinforced pile (right).

In unreinforced piles, vertical "plug" flow is observed over the total pile radius. Provided sufficient tremie embedment is maintained, the initial charge of concrete will be carried upwards at the support fluid interface for the total duration of the pour, and thus, a total pour retention time would be required.

In reinforced piles, "consumption" flow is observed. Concrete within the reinforcement cage near the support fluid interface is consumed into the cover zone as the concrete level within the pile rises. Upon entering the cover zone, the concrete quickly becomes stationary and is effectively locked in place. This process leads to the concrete near the support fluid interface being continuously replaced by fresher concrete. Given sufficient pile depth, the first charge of concrete will end up within the cover zone. Therefore, a shorter retention time is required for a fully reinforced pile. Further investigation is necessary before retention times can be specified.

6 FURTHER WORK

Further research is required to investigate the underlying factors that influence the rate of concrete consumption in the cover zone. Understanding this will enable more accurate predictions of charge locations and provide information regarding the concrete retention time required for different pile geometries.

7 ACKNOWLEDGEMENTS

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