Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0604

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Investigations on fresh concrete flow mechanisms in bored piles based on CFD simulations

Investigations sur les méchanismes de l'écoulement du béton frais dans les pieux forés basées sur des simulations de CFD

C. Fierenkothen
University of Wuppertal, Wuppertal,Germany

M. Pulsfort
University of Wuppertal, Wuppertal,Germany

ABSTRACT: Cured and subsequently excavated bored piles often uncover defects and damages such as insufficient concrete cover, insufficient bonding with the reinforcement, and entrapment of debris. The mentioned damages are assumed to be caused by an insufficient fresh concrete flow. To investigate the physical flow process during concrete placement using a tremie pipe numerical simulations based upon CFD are used. By means of laboratory scale tests and their numerical simulations it can been shown, that the numerical code OpenFOAM is capable of simulating the spreading and form-filling behaviour of fresh tremie concrete. In order to prove the capability of this method to predict the flow pattern under real-scale conditions, results of a full-scale and fluid-supported test pile poured with coloured concrete are used. The result of the numerical simulation and the experimental full-scale test are in satisfactory agreement with regard to the concrete flow pattern. It can be shown that the fresh concrete spreads in a shell-shaped structure around the tremie pipe and that incoming batches displace the previous batch in vertical direction only inside the reinforcement cage. In contrast, the concrete cover zone outside the reinforcement cage is mainly filled from the top of the rising fresh concrete column in a horizontal direction. Hence a better understanding is gained about the fresh concrete flow in bored piles and the observed defects may be explained.

RÉSUMÉ: L'excavation de pieux forés mûris souvent revèle des défaits et des dégâts, par exemple une couverture de béton insuffisante, une adhérence insuffissante avec les bars de renforcement et des débris piégés. Les dégâts mentionnés suggèrent un comportement d'écoulement du béton frais insuffisant. Des simulations numériques à base de CFD sont utilisées pour investiguer le processus du comportement d'écoulement physique pendant la mise en place du béton à la trémie. Des essais en laboratoire à l'échelle et leur simulation numérique peuvent montrer que le code numérique OpenFOAM est capable de simuler la propagation et le comportement de remplissage en forme. Pour vérifier la capabilité de la méthode à estimer la forme de l'écoulement à l'échelle réelle, les résultats d'un pieu foré à la boue de bentonite à grande échelle avec du béton coloré sont utilisés. Les résultats des simulations numériques et les tests en laboratoire à grande échelle sont en bonne concordance concernant la configuration de l'écoulement. On peut montrer que le béton frais s'étale en forme de coque autour de la trémie pendant la mise en place en déplaçant les livraisons précédentes plus ou moins verticalement à l'intérieur de la cage d'armature. Par contre, la couverture du béton à l'exterieur de la cage de renforcement est rempli principalement horizontalement d'en haut de la colonne augmentant du béton frais. Ainsi, une compréhension approfondie a été acquise sur le comportement d'écoulement du béton frais dans les pieux forés qui permet une explication des défaits obervés.

Keywords: bored piles; fresh concrete flow; numerical simulations; OpenFOAM

1 NUMERICAL SIMULATION OF THE SPREADING BEHAVIOUR OF FRESH CONCRETE

Several methods can be used for the simulation of fresh concrete flow. The methods can be classified according to two main types: single fluid models (continuous models) and particle models (discontinuous models). In this research project, fresh concrete flow is calculated based on the Computational Fluid Dynamics (CFD) method, which belongs to the single fluid approach. Limits of this method are that the model is not able to simulate fresh concrete behaviour like blocking, bleeding or segregation. However, the CFD-method consumes far less computing time than particle-based methods. This advantage is decisive especially with regard to the simulation of the casting processes of deep foundation elements with large calculation meshes. The used CFD-software is the open-source software OpenFOAM (Open Source Field Operation And Manipulation). OpenFOAM is a C++ library containing numerous numerical solvers and pre-/post-processing utilities to solve several kinds of flow problems.

1.1 Rheological model for fresh concrete

Regarding the numerical method based on the continuous body approach, fresh concrete is described as a homogeneous fluid. OpenFOAM offers different transport models for incompressible fluids. To calculate the flow the transport model Herschel-Bulkley is selected, which is transformed into the Bingham-model by setting the exponent to n = 1, as can be seen in equation (1):

$$\tau = \tau_0 + \eta \cdot \dot{\gamma}^n \tag{1}$$

where τ is total shear strength, τ_0 is yield stress, η is viscosity; $\dot{\gamma}$ is shear strain rate and n is a factor describing a shear thinning ($n < 1$), shear thickening ($n > 1$) or Bingham ($n = 1$) behaviour.

1.2 Calibration of the Bingham parameters for fresh concrete

The measurement of the fresh concrete material parameters yield stress and viscosity is still challenging, especially with regard to time-dependent properties like stiffing behaviour or thixotropy. Currently, there are no reliable methods to determine directly the absolute values of these parameters for fresh concrete. For this reason, the required parameters to simulate fresh concrete as a homogenous fluid are calibrated based on laboratory tests for each concrete mixture and age. The calibration process includes a modified experimental slump test in accordance with DIN EN 12350-8 and ASTM C1611 and its numerical modelling in OpenFAOM.

1.2.1 Experimental Setup

For the laboratory tests the further advanced slump test apparatus described in Fierenkothen et al. (2017) is used. The purpose of this apparatus is to record the time-dependent fresh concrete shape after pulling the cone. A laser distance sensor with a recording rate of 50 Hz is selected in order to reach a complete recording of the slump. Additionally, a digital camera records the spreading with a recording rate of 10 Hz. An average time-dependent diameter of the fresh concrete shape can be calculated thereof by means of digital image analysis. With this experimental setup, usual fresh tremie concrete mixtures with different consistency and concrete ages are examined to obtain further information about fresh concrete behaviour in terms of time.

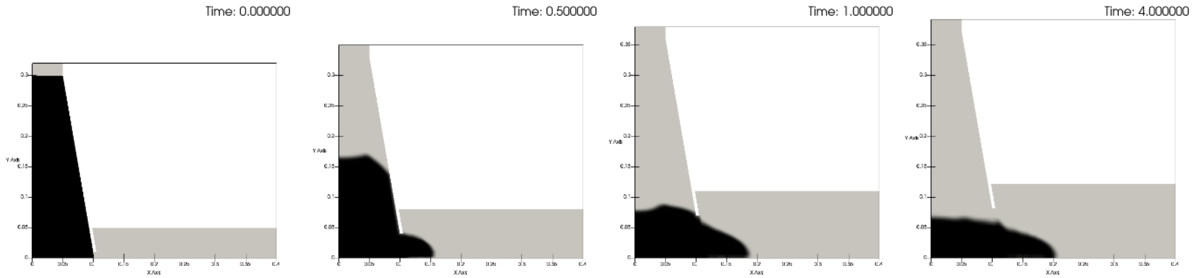

Figure 1. Numerical simulation of the slump test for different times (0, 0.5, 1, 4s) and with a homogenous non-Newtonian fluid

1.2.2 Numerical model

The simulation of the modified slump test is conducted with OpenFOAM. The mesh is modelled considering the rotational symmetry of the shape. Thus, a cross section wedge with symmetric boundary conditions corresponding to the physical dimensions of the slump cone represents the full model. In order to represent the real physical boundary conditions as close as possible, the vertical pulling process of the cone is modelled with the same velocity as in the experimental setup (Figure 1). A certain Bingham fluid was created with a spreading behaviour similar to fresh tremie concrete for the validation of this numerical model.

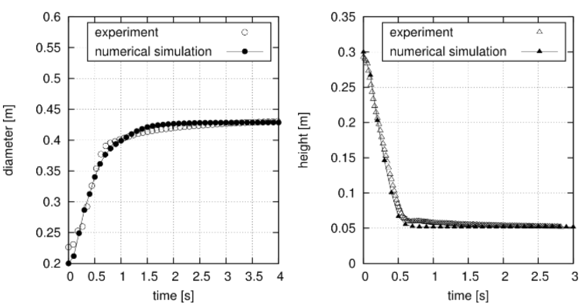

Figure 2. Comparison of the experimental with the numerical results for the modified slump test with a non-Newtonian test fluid for the time-dependent increasing diameter (left) and the time-dependent decreasing height (right; measured in the middle of the shape)

The required material parameters plastic viscosity and shear stress of this test fluid were reliably determined with a rotational rheometer (HAAKE RS 600), which belongs to rheological absolute measuring systems.

The comparison of the experimentally and numerically obtained results of the modified slump test shows good accordance for the test fluid (Figure 2). Thus, the used numerical model for the slump test is valid to calculate the time-dependent spreading behaviour of non-Newtonian fluids, which behaves like fresh concrete.

In order to identify the fresh concrete parameters in the following research step, several calculations were performed with different sets of material parameters for yield stress and plastic viscosity.The result is a database with numerous sets of parameters.

1.2.3 Calibration procedure for determination of rheological parameters for fresh concrete mixtures

For each concrete mixture being analysed in the modified slump test (as given in section 1.2.1), the rheological parameters (yield stress and plastic viscosity) were calibrated according to the following procedure: The rheological parameters were determined by comparing the recorded time-dependent experimental results (diameter and height of the fresh concrete cone) with all numerically calculated results.

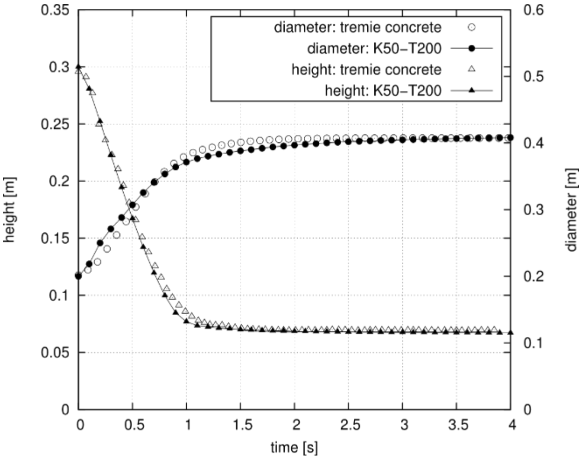

Figure 3. Comparison of the experimental time-dependent shape (diameter and height of the fresh concrete cone) for an usual tremie concrete with the most correlating numerical simulation with OpenFOAM (η = 50 Pa·s; τ_0 = 200 Pa)

The numerical simulation correlating as close as possible with the recorded function provided the best suited parameter set for the respective concrete mixture. The results of the calibration process for an usual tremie concrete mixture are exemplary shown in Figure 3. The final values as well as the time-dependent function of diameter and height of the slump cone show good agreement with the numerical results. The good match between the experimental and numerical results proves that the used model is able to calculate the spreading behaviour of fresh tremie concrete.

2 VALIDATION OF THE NUMERICAL CODE FOR FRESH CONCRETE FLOW INSIDE CASING

In the previous research step, it was demonstrated that the numerical model is valid to predict the time-dependent spreading behaviour of fresh concrete using fresh concrete test methods. However, before using the OpenFOAM code to calculate the pouring process in deep foundation elements, a comparison with experimental results should prove that the code is able to calculate numerically the flow process of non-Newtonian fluids in casing. Therefore, a laboratory test box was developed, which simplifies the flow problem as most as possible. The experimental setup was designed considering the same boundary conditions for the numerical and the physical model. Furthermore, a concrete mixture with a maximum aggregate size of 8.0 mm was designed to take into account scale effects. The following factors were varied in the scope of this laboratory test: filling velocity, concrete age, vertical and horizontal clear distance of bars. Additionally, laboratory tests with piles were performed using coloured concrete. They are described in Fierenkothen et al. (2016).

The physical model of the performed box experiments was modelled in OpenFOAM in 1:1 scale. The required material parameters yield stress and plastic viscosity were previously determined according to the procedure described in section 1.2.3. The results and the analysis of this validation procedure are not part of this paper which should only give a coarse overview on this research step. However, it shall be mentioned that the experimental and numerical results show good agreement. Thus, the used OpenFOAM code is capable of predicting the form-filling process of non-Newtonian fluids

3 COMPARISON WITH FULL-SCALE TESTS

3.1 Experimental setup

The experimental investigation concerning full-scale tests with cased and fluid-supported bored piles is part of a doctoral research project. Results are partly published in Böhle et al. (2013) and in Böhle et al. (2014). The experimental setup and results are taken from Böhle et al. (2013).

Full-scale tests were executed on cased and fluid supported test piles in order to investigate concrete flow behaviour under real-scale conditions. The test piles had a diameter of 1.20 m (47.2 in.) and an average length of 8.0 m

(315 in.). In order to reveal the spreading pattern of fresh concrete, these piles were poured using dyed concrete excavated and subsequently cut open longitudinally. The fresh concrete properties were controlled by means of the standard test methods according to DIN EN 12350-5.

3.2 Experimental results

This paper shows and compares only the results of the fluid-supported test piles. By infiltration and forming a filter cake, the bentonite mud used as supporting fluid effectuates a sealing of the surrounding soil. Thus, the fresh concrete does not have the ability to discharge free batch water into the soil pores. This effect is comparable to the impermeable boundary conditions in the numerical model as described in the following section.

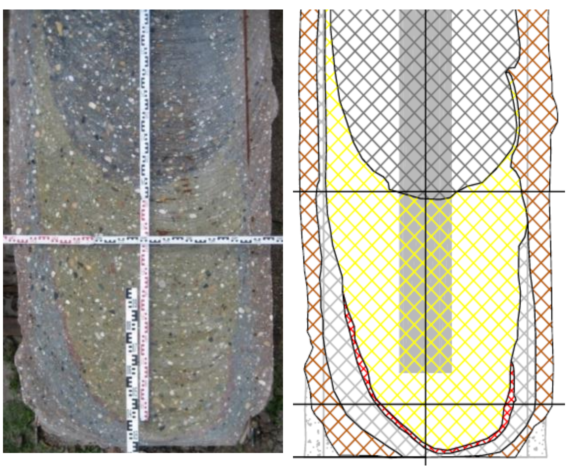

Figure 4. Longitudinal cut through the bottom of the fluid-supported and reinforced bored pile poured with dyed concrete (Böhle et al. 2013)

The longitudinal cut of the fluid-supported bored pile with reinforcement cage is shown in Figure 4. It presents the final position of each coloured batch and thus reveals the final flow pattern. The differently coloured zones represent the five different concrete batches which were poured in the following order: brown, grey, red, yellow and black. After pouring the yellow batch, the tremie pipe was partly pulled. One of the main characteristics of the visible concrete flow pattern is a mainly shell-shaped structure around the tremie pipe. Additionally, it can be seen that the first concrete batch (brown) is solely distributed in the concrete cover zone. Thus, it is concluded that the first batch is displaced by the following batch and is horizontally pressed through the reinforcement into the zone outside of the cage. This leads the authors to the assumption that the concrete cover zone is mainly filled horizontally at the top of the rising fresh concrete column. Furthermore, the red batch is almost completely replaced by the incoming yellow batch in vertical direction inside the reinforcement cage.

3.3 Numerical model

The size of the numerical model and the boundary conditions correspond as close as possible to the physical experiment of the reinforced fluid-supported bored pile. In order to decrease the number of cells and thus to decrease the required calculation time, rotational symmetry was applied. A wedge (Figure 5) with symmetric boundary conditions represents the numerical model of the full-scale test pile described in section 3.1.

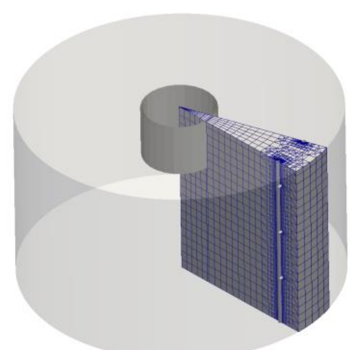

Figure 5. Mesh detail of the reinforced full-scale test pile

An average filling speed was calculated for each batch by its volume and its pouring time measured on-site. In this paper, the pulling process of the tremie pipe is neglected and the flow pattern is only analysed up to the end of the pouring time of the yellow batch. The corresponding slump flow values were deduced according to DIN EN 12350-5 from the measured on-site fresh concrete values for each concrete batch and age. The required material parameters for the numerical simulation were determined by means of the mentioned procedure (section 1.2.3) in terms of time.

3.4 Results of the numerical simulation

The following pictures of Figure 8 present the result of the numerical simulation of the pouring process of the reinforced fluid-supported test pile in comparison with the final state of the experimental result from Böhle et al. (2013). It shows the results of selected times from the beginning up to the end of the pouring time of the black batch.

The results of the simulation and the experimental full-scale test are in satisfactory agreement with regard to the concrete flow pattern. The numerical simulation shows the main characteristics of the concrete flow mechanism as well as the experimental test:

- At the bottom of the pile the flow pattern shows a mainly shell-shaped structure.
- The first concrete batch (brown) is solely distributed in the concrete cover zone.
- The incoming concrete batches displace the previous batches in vertical direction inside the reinforcement cage.

Furthermore, the numerical simulation confirms the assumption of Böhle et al. (2014) that the concrete cover zone is mainly filled at the top of the rising fresh concrete column in a horizontal direction. The velocity components of the fresh concrete flow reveal the reason for this occurring effect. Figure 6 shows the velocity components in vertical and horizontal direction at the MIDDLE (see Figure 8) of the rising fresh concrete column for the time of 43 min.

It can be shown that the reinforced cage represents an obstacle and divides the cross-section of the pile in two areas. Inside the cage, the concrete rises vertically with a certain velocity. However, in the concrete cover zone, the flow stops and the concrete stays in its position. The increasing consistency of fresh concrete in terms of time and the loss of workability respectively provokes this effect additionally.

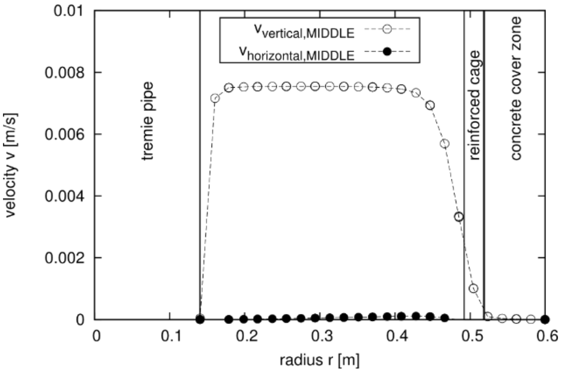

Figure 6. Velocity components of fresh concrete flow at the MIDDLE (see Figure 8) of the rising fresh concrete column for the time 43 min

Only at the top of the rising fresh concrete column the velocity vectors show a horizontal component and a flow through the reinforcement occurs (Figure 7).

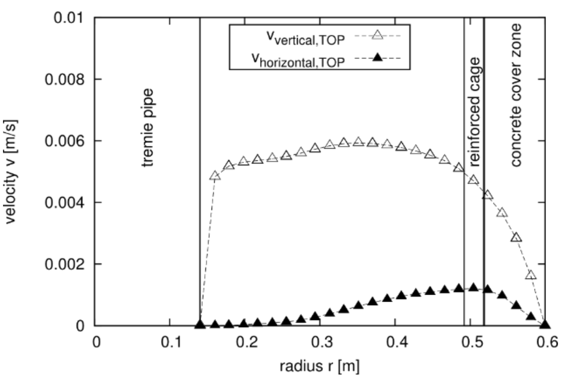

Figure 7. Velocity components of fresh concrete flow at the TOP (see Figure 8) of the rising fresh concrete column for the time 43 min

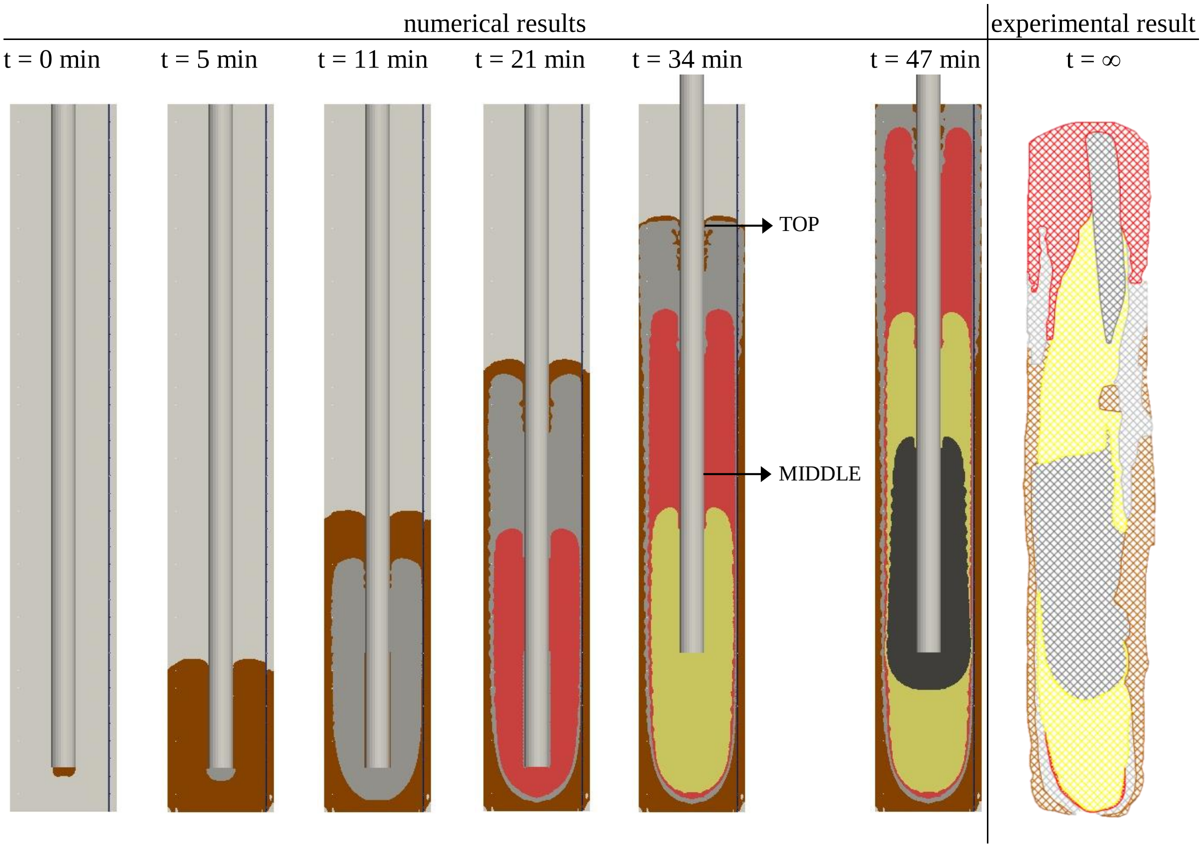

Figure 8. Results of the numerical simulation for different times (0, 5, 11, 21, 34 and 47 min) of the pouring process of the reinforced fluid supported test pile in comparison with the final state of the experimental result from (Böhle et al. 2013)

4 CONCLUSION AND FUTURE PERSPECTIVES

Numerical simulations based upon CFD are a useful tool to calculate flow problems of fresh concrete. This method provides a cost-effective opportunity for investigations of fresh concrete flow in bored piles and other deep foundation elements such as diaphragm walls or jet grouting columns. The used numerical code was validated through a comparison of laboratory experiments with numerical simulations. Additionally, the capability of predicting the flow process for bored piles was proved by a good match between the simulated and experimental results of full-scale tests. The results obtained from this investigation program allow for a new insight into the spreading of fresh concrete in bored piles. The next step of this research project is to perform a parameter study with numerical models at full scale to identify significant factors influencing the concrete flow patterns in bored piles.

5 REFERENCES

ASTM C1611-14:2014 Standard Test Method for Slump Flow of Self-Consolidating Concrete. ASTM Standard.

Böhle, B.; Pulsfort, M.; Linder, W.-R. et al. 2013: Untersuchungen zum Fließ- und Ansteif-verhalten von Beton bei der Herstellung von

Bohrpfählen (in German). *Vorträge zum 9. Hans-Lorenz-Symposium. Veröffentlichungen des Grundbauinstitutes der Technischen Universität Berlin (*Eds. Savidis, S. A.) Nr. 63: 81–92. Shaker Verlag, Aachen.

Böhle, B.; Pulsfort, M. 2014. Suspensions-gestützte und verrohrte Herstellung von Bohrpfählen und deren Auswirkungen auf das Betonfließverhalten (in German). *Vorträge zur 33. Baugrundtagung* (Eds: DGGT*)*, 203–209. DGGT, Essen.

DIN EN 12350-5:2009. Testing fresh concrete – Part 5: Flow table test. German version EN 12350-5:2009. European Committee for Standardization. Beuth Verlag. Berlin

DIN EN 12350-8:2010. Testing fresh concrete – Part 8: Self-compacting concrete – Slump-flow test; German version EN 12350-8:2010. European Committee for Standardization. Beuth Verlag. Berlin

Fierenkothen, C.; Pulsfort, M. 2016. New findings concerning the spreading of fresh concrete in bored piles. *Insights and Innovations in Structural Engineering, Mechanics and Computation. Proceedings of the Sixth International Conference on Structural Engineering, Mechanics and Computation*, (Eds. Zingoni, A.), 2116–2121. CRC Press, Taylor & Francis Group, South Africa, Cape Town.

Fierenkothen, C.; Pulsfort, M. 2017: The spreading of fresh concrete in bored piles – results of large and small scale model tests and numerical simulations. *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering*, 919–923. Seoul.