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Numerical simulations of concrete flow: A benchmark comparison

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ABSTRACT

First, we define in this paper two benchmark flows readily usable by anyone calibrating a numerical tool for concrete flow prediction. Such benchmark flows shall allow anyone to check the validity of their computational tools no matter the numerical methods and parameters they choose. Second, we compare numerical predictions of the concrete sample final shape for these two benchmark flows obtained by various research teams around the world using various numerical techniques. Our results show that all numerical techniques compared here give very similar results suggesting that numerical simulations of concrete filling ability when neglecting any potential components segregation have reached a technology readiness level bringing them closer to industrial practice.

1. Introduction

The first use of numerical simulations of concrete flow by Mori and Tanigawa traces back to 1992 [1]. Since then, the increasing use of Self Compacting Concrete (SCC) and the growing interest for rheology and processing has led to a very strong increase in the academic activity in this field along with an increasing number of publications dealing with concrete flow simulations using various numerical techniques. This topic is of a complex nature as it involves the non-steady free surface flow of a non-Newtonian fluid. Therefore, it requires the knowledge of modern computational techniques, of non-Newtonian fluid mechanics and of the specific concrete casting processes used in civil engineering. A lot of progresses have however been made in recent years. They are gathered in a recent RILEM State of the Art report [2].

Despite this academic activity, the use of concrete flow simulations in industrial practice is still sporadic. It can of course be expected that no one should consider simulating the casting of a residential concrete slab. It is however surprising that the optimization of pre-cast factory processes or the possibility to numerically forecast a critical phase of a concrete construction process in the case of advanced super-structures has not drawn much attention from the industry yet. We can note however that the use of these tools seem to have been steadily increasing in the field of litigation as they allow, in many case, to distinguish between the responsibility of the contractor and the responsibility of the concrete supplier.

It is our belief that the use of these advanced engineering tools is hampered by their diversities and the fact that, as for all computational tools, one always get a result but, without experience, one has no clue about the meaningfulness of the obtained prediction. This paper focuses therefore on demonstrating that numerical simulations of concrete flow are now fully able to predict accurately concrete filling ability (when components segregation is not an issue) and that these scientific and engineering tools are now ready to be used for a wide range of either academic or industrial purposes.

Our objectives here are two-fold. First, we define two benchmark flows readily usable by anyone calibrating a numerical tool for concrete flow prediction. Such benchmark flows shall allow anyone to check the validity of their computational tools no matter which numerical methods and parameters are chosen. Second, we compare numerical predictions for these two benchmark flows obtained by various research teams around the world using various numerical techniques.

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These simulations focus on the final shape of the sample only and the actual flow needed to reach this final shape is not studied in this paper. We therefore focus on the effect of yield stress on the final shape and on the numerical prediction of the filling ability of the simulated concrete. Our results suggest that numerical simulations of concrete filling ability have reached a technology readiness level bringing them closer to industrial practice.

2. The studied benchmark flows

We choose in this work to study and compare numerical predictions for two benchmark flows, namely the **slump flow** and the **channel flow**. These tests were chosen because approximate analytical solutions for the final shape of the concrete sample do exist. It can moreover be kept in mind that two benchmark flows are necessary, as all numerical methods compared here are not using the same input parameters. For instance, whereas Computational Fluid Dynamics methods (CFD) are using standard rheological parameters such as yield stress and plastic viscosity as input, Distinct Element Methods (DEM) are using interaction parameters between constitutive particles chosen to mimic the behavior of a given concrete (Cf. Section 3). We use therefore in this paper the slump flow as a calibrating benchmark flow for all methods while we compare the numerical predictions in the case of the channel flow.

2.1. The virtual concrete

The virtual concrete, which is studied here and implemented in the codes of the various CFD tools that are compared, can be described by a Bingham model. It has a yield stress of 50 Pa, a plastic viscosity of 50 Pa.s and a density of 2300 kg/m^3. This concrete is virtually mimicked by the DEMs by tuning the particle interaction laws until the behavior of the resulting virtual material is similar to the one of a 50 Pa yield stress material with a plastic viscosity of 50 Pa.s. It can first be noted that, as we focus here only on the final shape of the virtual concrete sample (*i.e.* concrete filling ability), the only parameter of interest is the yield stress. The value of plastic viscosity shall not play a role on the final shape as long as it is high enough for flow inertia to stay neglectable [2]. It can moreover be noted that, although, in this paper, only one yield stress value is studied, it was shown in [2] that both the analytical solution and the finite elements methods were able to predict accurately the final shape over a large range of yield stress values.

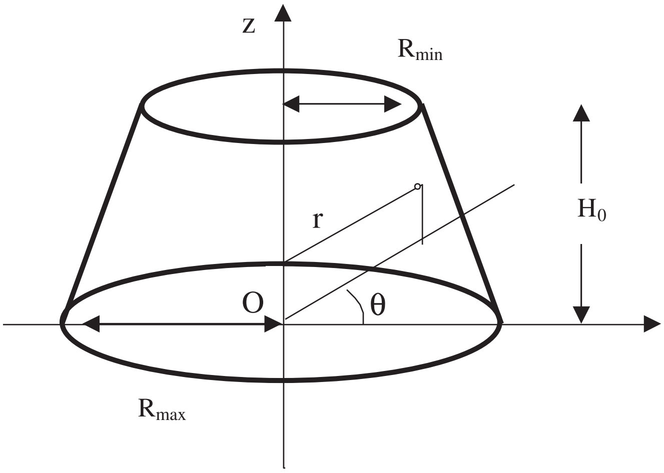

Fig. 1. Initial cone shape and cylindrical coordinates.

2.2. The slump flow

We are considering here the standard Abrams cone geometry, which corresponds to $H_0 = 300$ mm, $R_{min} = 50$ mm and $R_{max} = 100$ mm using the notations in Fig. 1.

Roussel and Coussot [3] described the various relations existing between slump/slump flow and yield stress from an analytical point of view for two asymptotic situations, namely H > > R and H < < R (H and R being the height and radius of the sample, respectively). In these two situations, the governing flow equations can be significantly simplified in order to obtain approximate analytical solutions. We focus here on the case $H << R$, which corresponds to the slump flow regime of interest in this paper. The three-dimensional flow problem simplifies then to a one-dimensional equation. The yielding criterion becomes mono-dimensional and flow simply stops when shear stress in the sample becomes equal or lower than the yield stress τ_c. It was shown in [3] that the final shape can then be computed from:

$$h(r) = \left(\frac{2\tau_c(R-r)}{\rho g}\right)^{\frac{1}{2}} \tag{1}$$

where h is the height, r the radial coordinate, ρ the density and g the gravity. Knowing the sample volume Ω and neglecting inertia and surface tension [4], the following equation relates the yield stress to the final radius of the sample:

$$\tau_c = \frac{225\rho g\Omega^2}{128\pi^2 R^5} \tag{2}$$

2.3. The channel flow

The geometry we consider here is the one suggested in [5] and shown in Fig. 2. The channel width is 200 mm. Its length is higher than 900 mm and the height of the lateral walls is higher than 150 mm. This geometry allows for a quick and easy measurement of the yield stress of SCC as there exists an analytical relation between yield stress and final channel flow length L when concrete is not reaching the end of the channel [5,6]. This relation writes:

$$L = \frac{h_0}{A} + \frac{l_0}{2A} LN\left(\frac{l_0}{l_0 + 2h_0}\right) \tag{3}$$

Where h_0 is the thickness of the deposit at $x = 0$, l_0 is the width of the channel and $A = 2\tau_c/\rho g l_0$.

Fig. 2. The channel flow and its geometry.