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Spreading of kaolin and sand mixtures on a horizontal plane: physical experiments and SPH numerical modelling

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Abstract

The investigation of the collapse of a well-known soil volume is a simple experiment that permits to make several interesting considerations. This paper, at first, presents a brief overview of some physical experiments led to understand how the composition of a three-phase mixture influences the mass collapse. In particular, the run-out and the maximum height of the deposit are considered as two fundamental quantities for characterizing the behaviour of the mass in each test. In a second step, the experimental results obtained are used as case studies for the calibration of a mesh-less numerical model. Several simulations are carried out using the SPH-Geoflow code implementing a Bingham law to reproduce each bi-phases test. A comparison between the numerical results and the physical data permits to choose the most reliable value of the constitutive parameters for each tested case. The errors between the physical and the numerical run-out and maximum heights become the fundamental quantity to define the quality of the best simulation. Indeed, some final considerations about the relationship existing among the constitutive parameters and the kaolin content of the mixtures are reported.

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Keywords: cylinder collapse; rheology; calibration; SPH; Bingham.

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1. Introduction

The choice of a suitable rheological model and its parameters is one of the most significant ingredients for modelling the behavior of viscous frictional materials, which are involved in debris flow phenomena. The

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rheological model could be defined on the base of specific laboratory tests, such as the viscometer tests, or through back-analysis of real cases or laboratory tests.

Viscometer tests are commonly used to collect physical measurements of the rheological properties of viscous materials. The relative rotation of two coaxial cylinders, containing a thin material layer in the gap, allows to measure the shear stress as a function of the shear strain. Various rheological models may be used to fit the collected data and therefore to calculate the rheological parameters. Unfortunately, the viscometers are normally used for fine materials and cannot work correctly when the grain size exceeds a limit value. Therefore, when the material contains granular fractions, it is preferable to obtain a reliable estimate of the parameters using the back-analysis (e.g. rotating drum [4], ball measuring system [6], collapse tests [2,8]).

Moreover, the analysis of real cases requires the knowledge of many aspects. For instance, the boundary and initial conditions (e.g. the initial ground topography and the extension of the mobilized volume) are essential information for the evaluation of both the kinematic and the final deposit of the moving mass. Moreover, the intrinsic variability of soil properties, of water content and other hidden variables (i.e. the soil erosion, the fluidization given by local springs, etc.) makes the calibration phase a quite difficult task, with indirect effects on the further risk assessment and mitigation purposes.

The uncertainty of the calibration phase may be surely reduced using standardized and controlled conditions like in a laboratory test. Moreover, it allows performing several tests in different conditions, which can be used as benchmark for the numerical models.

In this work, we performed cylinder collapse tests and consequently utilized the experimental results for calibrating a numerical model devoted to the analysis of flow-like landslide propagation. The adopted model integrates the shallow water equations with an SPH-approximation and considers the flow of a single-phase material with averaged physical and rheological properties.

Among the laboratory tests generally used for reproducing flow-like landslide and studying the behavior of materials, the collapse of a material column is one of the most largely used [3,5] because the experimental conditions are quite simple, the axial-symmetry limits the measurements to acquire and the results are easily reproducible.

The strategy here chosen is using the geometrical features of final deposit to select the most reliable rheological characteristics of the material. The main goal is to understand the differences on the final shape of deposit and on rheological properties given by the inclusion of different percentages of granular material.

2. Experimental tests

A transparent tube of inner diameter *D* is positioned on a horizontal 40x40cm glass plate and is connected to a weight–pulley system in order to be vertically lifted releasing its content on the plane. The tube is partially filled with the material, a mixture of kaolin, carbonatic sand (D_{50}=0.42 mm; G_s= 2.710) and distilled water, in different percentage. All mixtures are assumed to be saturated and with a volumetric concentration $c_v = V_s/V_{tot}$ in the range 0.26÷0.33, being V_s and V_{tot} the solid (kaolin or sand) and total volumes of the mixture respectively. Two tubes, with the inner diameter equal to 9.3 and 5.8cm respectively, are used for these collapse experiments, while the height of material is maintained equal to 8cm. The total volume of material used is 0.465 and 0.211 liters for the big and the small cylinders respectively.

A digital high-speed camera (Casio Exilim EX-F1) with 300 fps is used to capture the longitudinal profile during the collapse tests. The camera is remotely controlled with a computer, and the digitized images are processed in ImageJ and Matlab in order to extract the height profiles $h(r, t)$ of the granular mass throughout time t, being r the radial coordinate. Thanks to the axial symmetry of the phenomenon, the 2D profiles obtained by the images are assumed to fully characterize the true three-dimensional shape of the mass.

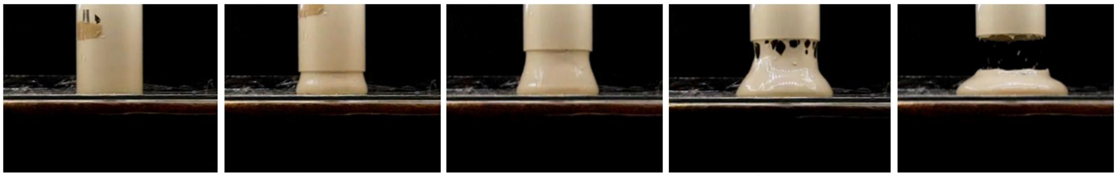
The composition of the mixtures used in the collapse tests is listed in table 1. Six tests consider water-kaolin mixtures (WK1-6) with a water content varying from 43.5% to 52.6%. Six other tests are performed with mixture of water, sand and kaolin (WSK2-7): in this case, the adopted strategy is to keep constant the kaolin/water ratio, equal to that of WK5 mixture, and to add different quantities of sand. The tests WK1-5 are performed using both the cylinders: consequently, we have a total of 17 experimental tests.

Figure 1 shows a sequence of photos captured during the collapse test WK1 performed with the big cylinder. Note that, even though the transparency of the cylinder, the profile evolution cannot be tracked in the central portion (*r*<*D/2*) in all the test instants, being this part hidden by the material adhering the inner surface of the cylinder. For this reason, only the final deposit profiles are used for analyses, while the initial photos are used to evaluate the runout kinematics.

Table 1. List of the mixtures used in the collapse tests and their gravimetric contents.

Water-kaolin mixtures			Water-sand-kaolin mixtures			
Name	Water (%)	Kaolin (%)	Name	Water (%)	Sand (%)	Kaolin (%)
WK1[a,b]	43.5	56.5	WSK2[a]	35.5	20	44.4
WK2[a,b]	45.5	54.5	WSK3[a]	31.2	30	38.8
WK3[a,b]	46.7	53.3	WSK4[a]	26.7	40	33.3
WK4[a,b]	48.1	51.9	WSK5[a]	22.3	50	27.7
WK5[a,b]	49.5	50.5	WSK6[a]	17.8	60	22.2
WK6[a]	52.6	47.4	WSK7[a]	13.4	70	16.6

[a] test performed with small cylinder, [b] test performed with large cylinder



(a) t=0.0s (b) t=0.2s (c) t=0.4s (d) t=0.6s (e) t=0.8s

Fig. 1. Sequence of images for the test WK1 with big cylinder.

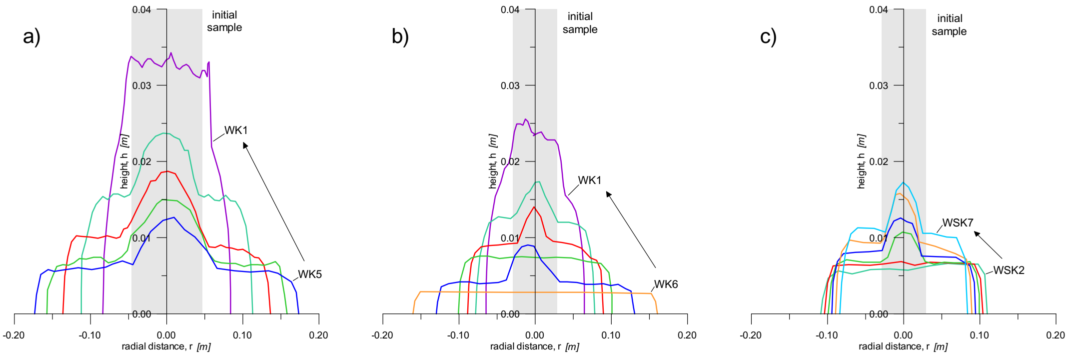


Fig. 2. Final profiles obtained for collapse tests with WK (a) big and (b) small cylinder and (c) WSK. Not equal x-y scale.

In figure 2 are shown the final profiles recorded at the end of all the experiments, grouping in tests with WK mixtures, performed in big or small cylinder, and WSK mixtures. In all the tests, the mass tends to form a disk with quite vertical lateral borders, a rather uniform height and a central bulge, which is higher for higher kaolin content. The bulge is due to the confinement effect produced by the mud glued to the inner surface of the cylinder: this ring of material experiences a delayed collapse that produce a second shock wave pointing to the axis of the cylinder and slowing down the tendency to the radial spreading of the mass.

Regarding the WK mixtures, it can be noticed that a higher kaolin content increases the maximum height with an exponential, while the runout of the final deposit linearly decreases (figure 3).

For the WKS mixtures, even if the bulk density of the mixture increases with sand content, providing a higher initial potential energy, the final runout slightly decreases while the final maximum height increases. This fact is similar to what observed in the WK mixtures for increasing of kaolin content, even if here it is less evident. To explain this behavior one may consider the theory of mixtures. A three-phase mixture is a mix of a matrix (clay and water in our case) with a coarse material (sand). When the matrix content is high the coarse particles float in this phase and the material behavior is controlled by the rheology of the matrix (cohesive regime); at the contrary when the matrix fills the voids of the solid skeleton, the latter mainly controls its mechanical behavior (frictional regime). Considering the range of porosity of our sand, the tested sand contents are compatible with the first regime (cohesive) and an increment of granular portion produces a higher viscosity of the matrix.

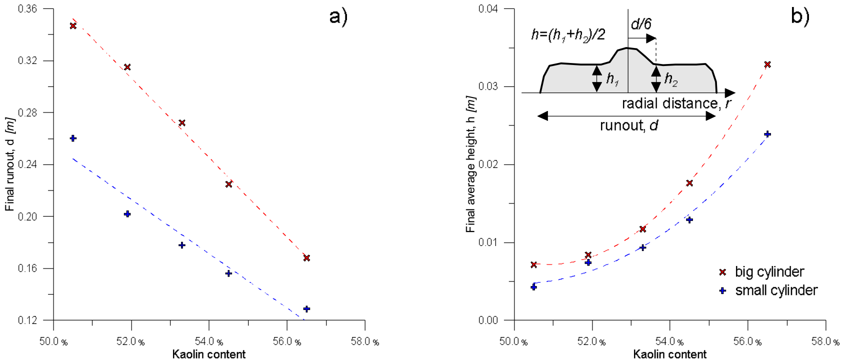


Fig. 3. Geometrical features of the deposit profile for WK mixtures.

3. Numerical simulations

The experimental tests are simulated with the SPH-GeoFlow code [7], using the Bingham's rheological law for the material [1]. The main goal of numerical simulations is the calibration of the rheological parameters (i.e. the yielding shear stress τ and the dynamic viscosity μ) and the analysis of their dependence from the mixture composition. In the cases of WK mixtures, the calibration procedure is performed both for tests carried out with the big and small cylinders in order to verify if the result are eventually influenced by the cylinder size. It has to be underlined that no boundary conditions are imposed in the numerical model, so the collapse cannot consider the effect of lifting of the cylinder.

To perform the calibration, first of all it is necessary to identify the overall performance indices for the optimization of the parameters. Three variables are used for this purpose: i.e. the relative error on the final runout distance (E_d) and on the heights at r=±1/6 of the runout distance (E_{h1} and E_{h2}). Noticeably, a single height value in the central axis is supposed to be less representative because of the emergence of the bulge in the middle of the sample.

For each laboratory test, 100 simulations are performed varying the Bingham rheological parameters in a reasonable range ($\mu = 0.01 \div 50$ Pa·s; $\tau = 1 \div 200$ Pa). Finally, for all tests, we are able to obtain the combination of μ and τ (see table 2) that minimizes the total error E_{total} defined as:

$$E_{total} = 0.50 E_d + 0.25 E_{h1} + 0.25 E_{h2} \qquad (1)$$

In figure 4, the final profiles obtained in some tests are compared with the profiles predicted with the numerical model using the optimum values of Bingham parameters selected for the same test. We can observe the good correspondence obtained between the experimental and the numerical data, also quantified by the low total errors reported in table 2.

In figure 5 the trend of the calibrated parameters with different mixtures and cylinder size are depicted for comparison. It should be noted that both μ and τ present an exponential trend in relation with the volumetric concentration of the WK mixture, like what observed in similar works [4]. Considering that the cohesive behavior of the material increases with both parameters, for higher (μ, τ) values we expect shorter runout distances and higher final heights as observed in the previous experimental data.

From figure 5, a good agreement is noticeable for each mixture between the calibrated Bingham's parameters of the two cylinder sizes, especially for lower volumetric solid content. A greater difference is recognizable for WK1 (the most cohesive mixture), particularly for the viscosity value. The reason of this discrepancy can be attributed to the boundary conditions, which are unavoidable in the laboratory tests and instead were necessary simplified in the simulations. In the experimental setup, when the cylinder is lifted, it drags a thin layer of material in touch with the inner surface of the tube, as it is clearly evident in Figure 1*d*. Supposing the thickness of this layer dependent on the viscosity of the material, we can assume that the boundary effect of the cylinder is strong for small cylinders and high value of μ. On the other hand, SPH simulations are obtained with a z-depth-integrated equation system with boundary conditions which are partially unable to represents the initial lifting phase.

Table 2. List of the optimized parameters obtained for tests with WK mixtures in small and large cylinders.

			Small cylinder (D = 5.8 cm)			Big cylinder (D = 9.3 cm)		
Mixture	Kaolin [%]	c_v	τ [Pa]	μ [Pa s]	E_{total} [%]	τ [Pa]	μ [Pa s]	E_{total} [%]
WK1	56.5	0.33	71.88	10.77	3.7	79.37	23.21	1.8
WK2	54.5	0.32	40.90	2.32	1.2	40.90	2.39	4.7
WK3	53.3	0.31	27.42	1.08	1.1	25.61	0.70	7.7
WK4	51.9	0.29	21.89	0.58	1.8	21.60	0.24	7.8
WK5	50.5	0.28	7.45	0.17	3.6	16.51	0.14	9.3
WK6	47.4	0.26	2.71	0.05	7.6			

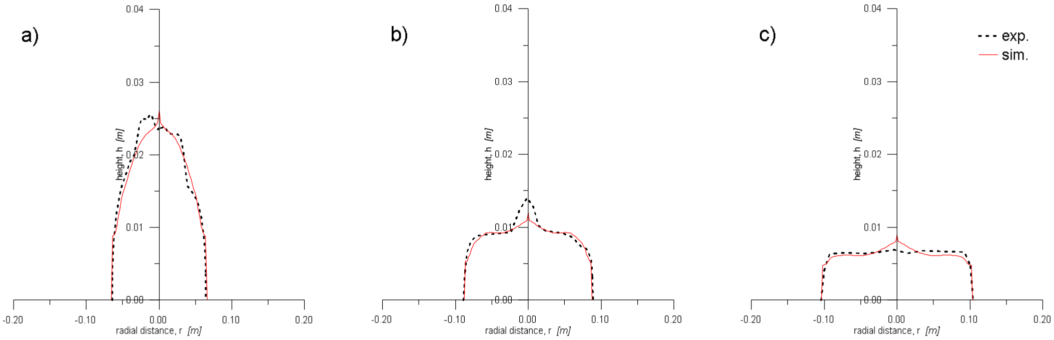


Fig. 4. Examples of experimental and numerical profiles of small cylinder with (a) WK1 (b) WK3 and (c) WSK3. Not equal x-y scale.

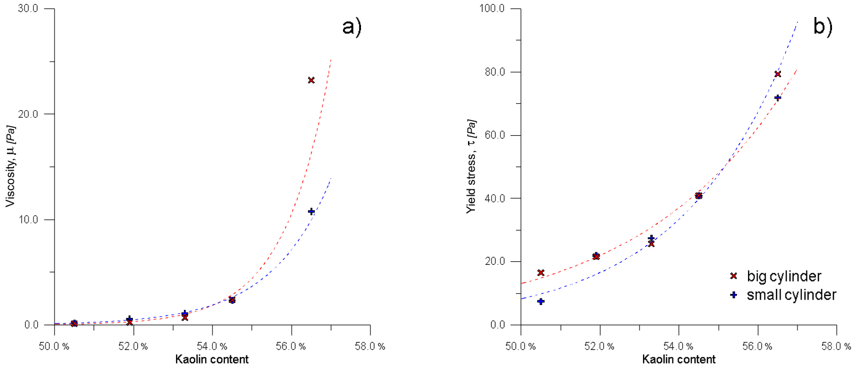


Fig. 5. Bingham's parameters of WK mixtures obtained after calibration with different kaolin contents and cylinder sizes.

From the analysis of the video sequences of the WK1 mixtures with the two cylinders, we observe that in the test with the small cylinder the radial spreading of the material starts with a certain delay respect the test in the large cylinder and this delay is clearly due to the stronger dragging effect exerted on the inner mass. As consequence, the small cylinder drags the mass upward for a larger path, permitting to the mass to accumulate a higher potential energy, which leads to a subsequent higher radial velocity of the flow and to a larger final runout distance. In the calibration phase, this effect produces an underestimation of the viscosity value, which results smaller in the test with the small cylinder.

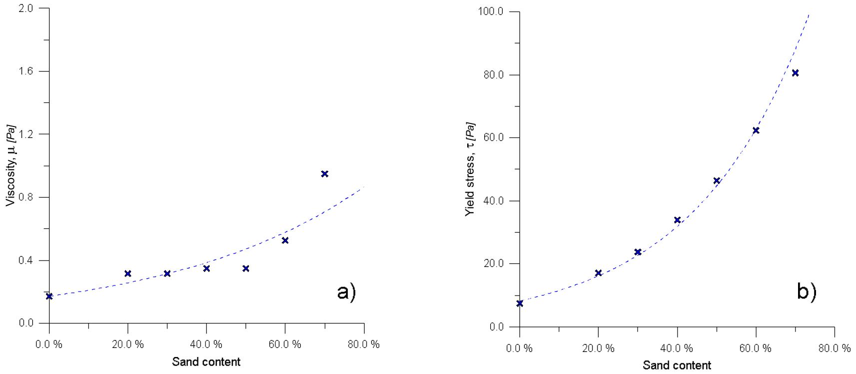


Fig. 6. Bingham's parameters of WKS mixtures obtained after calibration with different sand contents.

In figure 6, the calibrated values of μ and τ in tests with WSK mixtures are reported in relation with the sand content. It is evident that increasing the sand fraction for a constant water-kaolin ratio gives rise to an increase of the calibrated μ and τ to fit a more sticky and cohesive behaviour of the WKS mixtures. The variation due to the adding of sand is larger for the yield stress, which presents values varying from 10 to 80 Pa (an increase of 800% respect the value obtained for WK5 mixture). The variation of viscosity is only 500% that is not very large if compared with the viscosity variation observed in relation to the solid concentration in the WK mixtures (as reported in table 2, the viscosity in WK tests increases quite 2 orders of magnitude).

4. Final remarks

The laboratory tests reproducing the collapse of a cylindrical volume of water-kaolin and water-sand-kaolin mixtures are used for calibrating the rheological parameters of a Bingham law implemented inside a numerical model for the analysis of run-out. Even if the experimental system is very simple, the boundary conditions seem to have a not negligible effect on the calibrated parameters, especially with the most viscous materials.

Even if the runout numerical model adopted for the simulation of the experimental tests is based on a simplified representation of the real phenomena, it seems sufficiently reliable for the analysis of this simply test. Moreover, the Bingham law seems to well describe the behavior of WSK mixtures even when the sand fraction is very large (around 80% of the total weight).

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