Evaluation of uncertainties in settling velocities of particles in urban stormwater runoff

A. Torres and J.-L. Bertrand-Krajewski

ABSTRACT

Field experiments were carried out to contribute to the assessment of the VICAS protocol aiming to measure settling velocities of particles. Samples of deposited sediments have been taken in the Django Reinhardt stormwater detention and settling tank in Chassieu, France, using sediment traps located on the tank bottom. The first set of experiments was designed to assess the VICAS protocol in terms of mass balance and repeatability. A bias in the measurement of settling velocities distributions of deposited sediments (i.e. particles with high settling velocities) was suspected and confirmed by specific tests. Uncertainties in the final distribution curves have been evaluated by using Monte Carlo simulations and the law of propagation of uncertainties. All uncertainty calculations were implemented in a MatLab code named UVICAS used for each experiment. This code allows analysing the main sources of uncertainties and their evolution during experiments. Uncertainties in the final distribution curves decrease with increasing values of settling velocities and are lower than 1%.

Key words | measurement, sediment, settling velocity, stormwater, uncertainties

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INTRODUCTION

Many pollutants in urban stormwater are present in the particulate phase, attached to particles transported in suspension, with diameters ranging from a few micrometres to 1–2 mm, and a median diameter $d_{50} = 30–40\ \mu m$ (see e.g. Chebbo 1992; Bertrand-Krajewski *et al.* 1993; Ashley *et al.* 2004). According to numerous case studies and research experiments, these particles have median settling velocities v_{50} ranging from 0.2 to 11 m/h, depending on storm events, land use, urbanization and soil characteristics. This is why settling is an efficient technique to remove particles and particulate pollutants from stormwater to protect receiving water bodies (see e.g. Chebbo 1992; Marsalek *et al.* 1992; Strecker *et al.* 2004). In order to better design and operate settling facilities, the knowledge of stormwater particles settling velocities is necessary. Various protocols have been developed and compared with measure stormwater particle settling velocities in the 1990s (Aiguier *et al.* 1996; Lucas-Aiguier *et al.* 1998; Chebbo *et al.* 2003*b*). In France, after some tests and new developments, a protocol named VICAS (VItesse de Chute en ASsainissement – Settling Velocities in Sewer Systems) has been developed by Chebbo *et al.* (2003*a*). This paper is a contribution to the evaluation and the validation of the VICAS protocol when used for deposited sediments, based on both laboratory tests and field measurements carried out in the Django Reinhardt stormwater settling tank located in Chassieu, France. It provides successively: (i) a brief description of the VICAS protocol, (ii) tests of mass balance, (iii) tests of bias detection, (iv) tests of repeatability and (v) a detailed analysis of the uncertainty in measured settling velocities.

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MATERIALS AND METHODS

The VICAS protocol (Gromaire & Chebbo 2003), developed for suspended solids in stormwater, is based on the principle of homogeneous suspension, assuming that all particles settle independently of one another, with neither aggregation nor dispersion. The measurement is made in the laboratory in a Perspex settling column (height = 645 mm, diameter = 70 mm): the sample to be analysed (water + particles) is initially poured in the sample vessel and then pumped upwards very fast into the settling column by means of a vacuum pump (Figure 1). The solids settled during pre-determined times t are collected in aluminium plates at the bottom of the column, dried and then weighed. Thus, the evolution of the cumulated mass of solids settled according to time, noted $M(t)$, can be calculated. From this distribution, the settling velocity curve $F(V_s)$ can be derived, indicating the cumulative fraction F of the total mass of particles having a settling velocity lower than or equal to V_s, using Equation 1:

$$F(V_s) = 100\left(1 - \frac{S(t)}{M_{dec} + M_{fin}}\right) \tag{1}$$

with $S(t)$ the cumulated mass of particles having settled at the bottom of the column after the duration t with a settling velocity greater than H/t with H the water depth in the column (Chebbo 1992; Chancelier *et al.* 1998), $S(t) = M(t) - t(\mathrm{d}M(t)/\mathrm{d}t)$, $V_s = H/t$, M_{dec} the total mass settled in the column and M_{fin} the mass of solids remaining in the column at the end of the experiment. Bertrand-Krajewski (2001) proposed that the curve $M(t)$ could be represented by means of a simple function with three calibration parameters (b, c and d), according to Equation 2:

$$M(t) = \frac{b}{1 + \left(\frac{c}{t}\right)^d} \tag{2}$$

The parameter b represents the theoretical maximum mass which would have settled in the column when $t \to \infty$.

$F(V_s)$ is calculated from the six variables t, b, c, d, M_{dec} and M_{fin} by means of the following equation derived from Equations 1 and 2:

$$F(V_s) = f_F(t, b, c, d, M_{dec}, M_{fin}) = 1 - \frac{b\left(1 + (1-d)\left(\frac{c}{t}\right)^d\right)}{\left(1 + \left(\frac{c}{t}\right)^d\right)^2 (M_{dec} + M_{fin})} \tag{3}$$

According to international metrology standards (see e.g. NF ENV 13005 1999), the uncertainty $u(y)$ of a value y depending on other values through a function like $y = f(x_1, x_2, \ldots, x_N)$ is called composed standard uncertainty. Its value is calculated by the law of propagation of uncertainties:

$$u^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j) \tag{4}$$

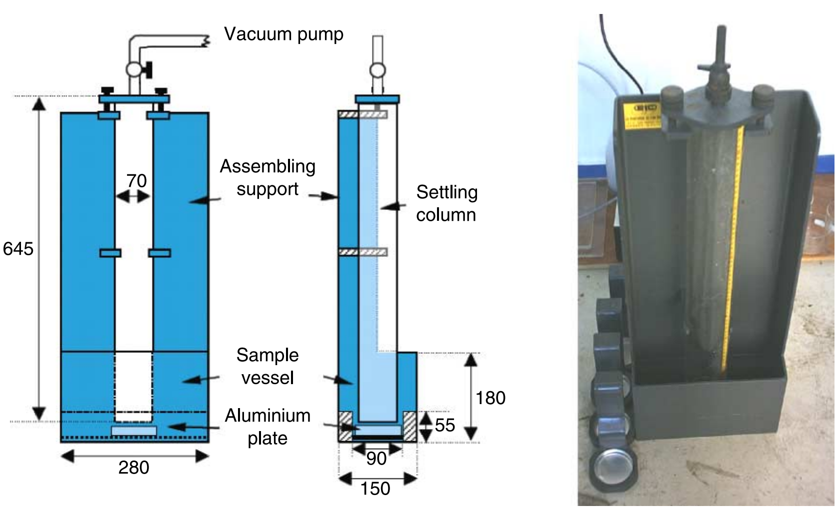


Figure 1 | Scheme (left, adapted from Chebbo *et al.* 2003a) and photo (right, A. Torres) of the VICAS settling column and apparatus.

with $u(x_i)$: standard uncertainty associated to x_i. It can be assessed from repeated observations, by the calculation of its standard deviation. If x_i is not obtained from repeated observations, its uncertainty can be estimated from: (i) results of past measurements; (ii) experience or general knowledge of the behaviour of the materials and instruments used; (iii) specifications from the manufacturers of the instruments used; (iv) data from calibration certificates or other certificates; (v) reference uncertainty values from books or handbooks.

$u(x_i,x_j)$: estimated covariance between x_i and x_j, related to the correlation coefficient $r(x_i,x_j)$ by $u(x_i,x_j) = r(x_i,x_j)$-$(x_i,x_j) = r(x_i,x_j)u(x_i)u(x_j)$.

The deposited sediment samples used for the experiments presented in this paper were collected at the Django Reinhardt stormwater detention-infiltration facility at Chassieu, France, by means of sediment traps laid on the bottom. Details about the facility and the sampling procedures are given in Torres & Bertrand-Krajewski (2007).

RESULTS AND DISCUSSION

Gromaire & Chebbo (2003) proposed to calculate a mass balance to evaluate the quality of the VICAS measurement results, in order to detect any loss of particles which would generate bias and errors in the final result. This mass balance rests on the comparison of the initial mass introduced in the column with the sum of M_{dec} (total mass of particles having settled in the column at the end of the experiment) and M_{fin} (mass of particles remaining in the column at the end of the experiment). As this mass balance is difficult to calculate (the initial mass in the column can not be directly measured) and not complete, the approach has been extended to calculate the mass balance by accounting for ALL particles used in the experiment. In addition to M_{dec} and M_{fin} defined as above, the following masses are defined:

M_{ini} initial total mass of particles in the bucket containing the sample to be poured in the sample vessel

M_{br} total mass of particles remaining in the sample vessel at the end of the experiment

M_{hom} total mass of particles lost by deposition on the mixer used to homogenize the sample in the bucket before to pour it into the sample vessel

M_s total mass of solids remaining in the bucket after the sample has been poured into the sample vessel.

M_{hom} and M_s are determined after a very meticulous washing of all equipments with distilled water. The mass balance is then written:

$$M_{ini} = M_{dec} + M_{fin} + M_{br} + M_{hom} + M_s + \Delta \quad (5)$$

with Δ the error in the mass balance.

Mass balance tests were carried out with three different samples from the Django Reinhardt settling tank having various sample concentrations. The results are given in Table 1. The mass balance is quite good, with errors ranging from 3 to 5%. However, it appeared that concentrations of particles were lower in the settling column than in the sample vessel. In fact, the major part of the initial total mass of particles is divided among the sample vessel M_{br} (more than 54%) and the settled mass M_{dec} (more than 23%). The mass concentration for the initial sample (M_{ini}) and the sample contained in the column at the beginning of the experiment ($M_{dec} + M_{fin}$) have been calculated. Table 2 shows the concentration results obtained.

Table 2 shows prominent divergences between the concentrations obtained. This means that the settling velocity curves obtained from the VICAS protocol are not fully representative of the whole initial sample contained in the bucket. This could be explained by the fact that, during the quick filling of the settling column, all particles in the

Table 1 | Results of the mass balance tests

	Test 1		Test 2		Test 3	
	Mass (mg)	% M_{ini}	Mass (mg)	% M_{ini}	Mass (mg)	% M_{ini}
M_{dec}	3481.2	32%	1663.9	23%	83.5	24%
M_{fin}	87.0	1%	73.0	1%	9.0	3%
M_{br}	6606.8	61%	3952.3	54%	202	59%
M_{hom}	7.3	0%	6.3	0%	0.3	0%
M_s	353.1	3%	1325.1	18%	36.5	11%
Δ	358.6	3%	346.4	5%	13.1	4%
M_{ini}	10,894.0	100%	7367.0	100%	344.4	100%

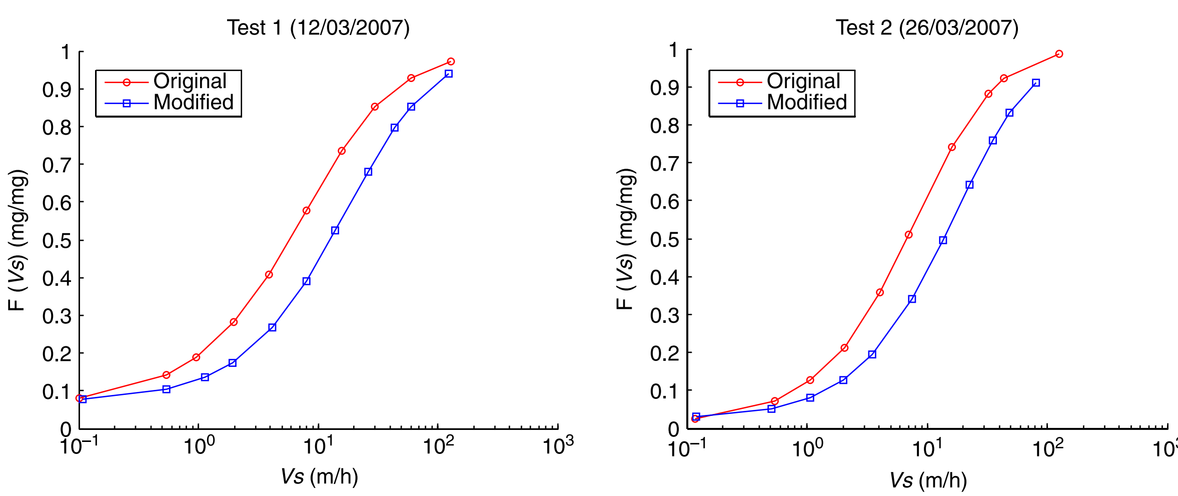
Table 2 | TSS concentrations for three mass balance tests

	Test 1 C (mg/L)	Test 2 C (mg/L)	Test 3 C (mg/L)
M_{ini}	2723.5	1473.4	68.9
$M_{\mathrm{dec}} + M_{\mathrm{fin}}$	1541.2	750.2	40.0

sample vessel have not the same probability to be pumped into the settling column, owing to fast settling occurring in the sample vessel and to some particles segregation. As a consequence, particles with the highest settling velocities could be less represented in the column compared to the sample vessel. Thus actual settling velocities should likely be higher than those the obtained with the VICAS protocol.

In order to test this hypothesis, specific tests were performed. These tests consist of modifying the way in which the VICAS column is filled. The column was filled by horizontal immersion into the raw sample transferred into a large vessel. Once filled, the column was closed with a special cover. The vacuum pump was then switched on and the column was immediately installed vertically on the assembling support, with the sample vessel previously filled with tap water. Then the special cover was removed and replaced by the first aluminium plate. The cover has a special design which allows collecting the mass settled between the instant corresponding to the filling of the column and the instant corresponding to the setting of the first aluminium plate. Two tests were carried out in order to compare the results obtained with both initial and modified VICAS protocols (Figure 2). In Figure 2 high relative differences were observed between both VICAS protocols. In test 1, relative differences range from 88% (v_{80}) to 134% (v_{20}). In test 2, relative differences range from 78% (v_{10}) to 105% (v_{90}). These results revealed the bias for sediments deposited in settling tanks. However, more tests are required in order to fully assess the modified VICAS protocol in terms of repeatability and uncertainty.

Tests of repeatability with the initial VICAS protocol have been carried out. One example is presented hereafter. Three 5 L sub-samples have been taken from an initial 25 L sample collected on site. Settling velocities have been measured simultaneously with three identical apparatus by one operator. Measurements have been made simultaneously to avoid possible bias introduced by sample storage at 4°C. The results are shown in Figure 3. They are



	Vs orig (m/h)	Vs modif (m/h)	Rel. diff
V10	0.24	0.49	105%
V20	1.09	2.54	134%
V30	2.25	5.18	130%
V40	3.76	8.44	125%
V50	6.12	12.95	112%
V60	9.14	19.87	117%
V70	14.10	28.95	105%
V80	23.79	44.61	88%
V90	48.88	94.64	94%

	Vs orig (m/h)	Vs modif (m/h)	Rel. diff
V10	0.82	1.45	78%
V20	1.89	3.66	93%
V30	3.26	6.42	97%
V40	4.90	9.84	101%
V50	6.89	13.87	101%
V60	10.61	20.02	89%
V70	14.50	28.87	99%
V80	22.78	42.91	88%
V90	37.02	75.90	105%

Figure 2 | Comparison between settling velocity curves obtained from original and modified VICAS protocol for two tests.

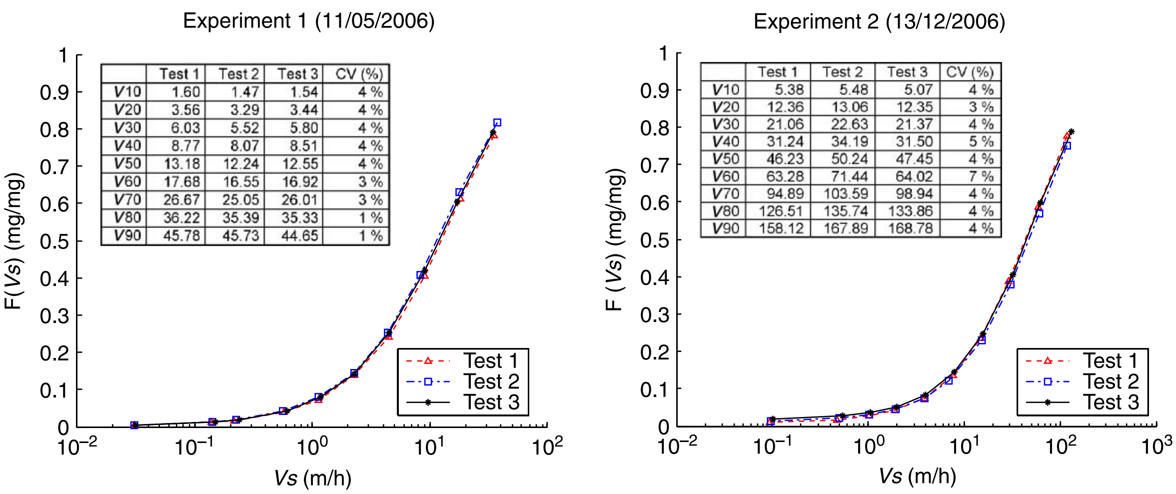


Figure 3 | Example of repeatability tests for the VICAS protocol.

very similar for the three sub-samples, with coefficients of variation up to maximum 7%. Other tests have been carried out (not shown here), giving similar results. This confirms that the VICAS protocol has a good repeatability.

The uncertainty in $F(V_s)$, noted $u(F(V_s))$, has been estimated by applying the law of propagation given by Equation 4:

$$u^2(F(V_s)) = \sum_{i=1}^{6}\left(\frac{\partial f_F}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{5}\sum_{j=i+1}^{6}\frac{\partial f_F}{\partial x_i}\frac{\partial f_F}{\partial x_j}u(x_i, x_j) \qquad (6)$$

with x_i the 6 variables of Equation 3 ($x_1 = b$, $x_2 = c$, $x_3 = d$, $x_4 = t$, $x_5 = M_{dec}$, $x_6 = M_{fin}$.), $u(x_i)$ the standard uncertainty in the variable x_i and $u(x_i,x_j)$ the covariance of x_i and x_j. Standard uncertainties are considered as approximately equivalent to standard deviations.

The time t is measured manually with a chronograph. Settled solids are collected in $p = 1$ to 10 aluminium plates at $t_p = 1$ min, 2 min, 4 min, 8 min, 16 min, 32 min, 64 min, 2 h, 4 h and >12 h. According to experience, the standard uncertainty $u(t)$ is assumed to be equal to 1 s, i.e. time is measured with $\pm 2u(t) = \pm 2$ s with an approximately 95% confidence level.

Standard uncertainties in b, c and d have been evaluated by means of Monte Carlo simulations. N sets of ten elementary masses m_p (m_p is the mass of particles having settled in the column between t_{p-1} and t_p) have been generated as correlated random series (Tu 1998), each m_p series being normally distributed. The method used to define the number N of simulated sets of elementary masses is explained in Bertrand-Krajewski *et al.* (2000, chapter 5). $N = 800$ sets were generated for all VICAS experiments. For each set, b, c and d are determined by means of the least squares method. For the series of N values of b, c and d, mean values and standard deviations are calculated. Figure 4 illustrates, for one example, the correlated random curves simulated and the results (mean value and standard deviation considered equivalent to standard uncertainty) obtained for b, c and d.

As $M_{dec} = \sum_{p=1}^{10} m_p$, its standard uncertainty is calculated from the standard uncertainties in each value m_p, which are themselves calculated from the elementary weighing of dried filters used to separate the particles collected in each aluminium plate. For each weighing, the standard uncertainty is assumed to be equal to the standard uncertainty of the laboratory scale, i.e. 1 mg. A similar calculation is made for M_{fin}, which is determined from the filtration of the water in the settling column at the end of the experiment. As this filtration is long, several filters are necessary, and each elementary weighing is assumed to be made with a standard uncertainty of 1 mg. The standard uncertainty $u(V_s)$ depends on both standard uncertainties $u(H) = 0.5$ mm and $u(t) = 1$ s.

All calculations have been implemented in a MatLab code named UVICAS used for each experiment. An example of uncertainty results is shown in Figure 5. The final

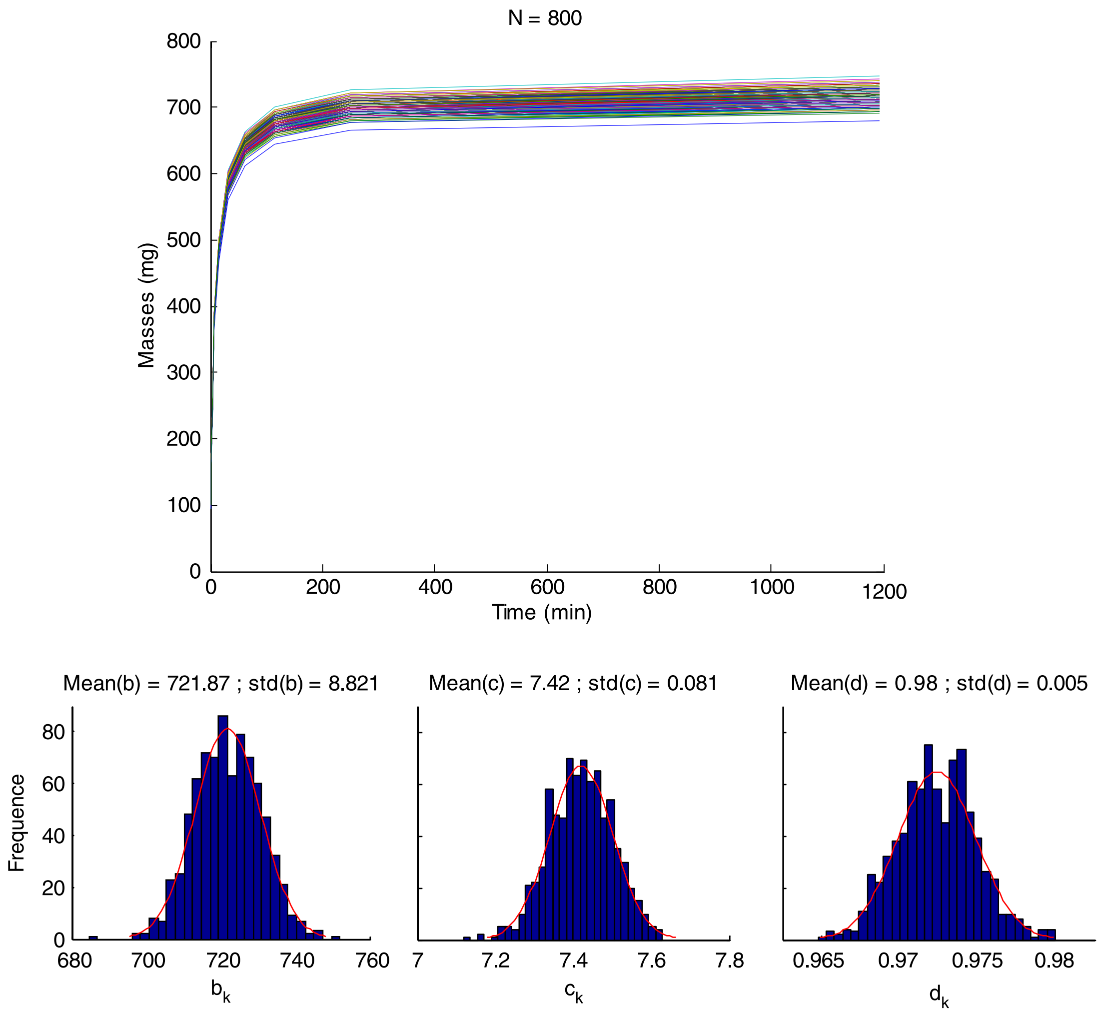
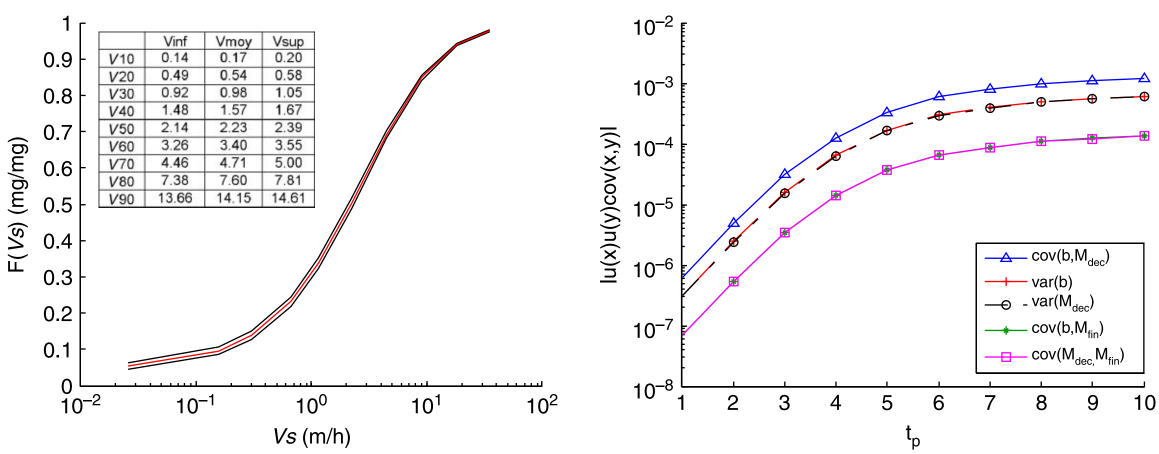


Figure 4 | Monte Carlo simulations results for $N = 800$ sets of 10 elementary masses m_p.



	Vinf	Vmoy	Vsup
V10	0.14	0.17	0.20
V20	0.49	0.54	0.58
V30	0.92	0.98	1.05
V40	1.48	1.57	1.67
V50	2.14	2.23	2.39
V60	3.26	3.40	3.55
V70	4.46	4.71	5.00
V80	7.38	7.60	7.81
V90	13.66	14.15	14.61

Figure 5 | Uncertainties in $F(V_s)$ (left) and evolution of the 5 most contributing sources of uncertainty in $F(V_s)$ (right) calculated with the UVICAS code (experiment made on 09/04/2006).

uncertainty in $F(V_s)$ is decreasing for increasing values of V_s: $u(F(V_s))$ is ranging from 0.4% for $V_s = 0.03$ m/h to 0.14% for $V_s = 30$ m/h. In this example, the median settling velocity v_{50} has a 95% probability to be between 2.14 and 2.39 m/h, and the 20-percentile value v_{20} is between 0.49 and 0.58 m/h. A more detailed look at the UVICAS calculations allows analyzing the main sources of uncertainties and their evolution during experiments. For the experiment shown in Figure 5 (left), Figure 5 (right) shows the five most contributing sources of uncertainty and their changing values for the different settling times t_p. The main sources of uncertainty are b, M_{dec} and M_{fin} and their covariance. This has also been observed for other experiments not shown here.

CONCLUSIONS

Experiments have been carried out to contribute to the assessment of the VICAS protocol when it is used for deposited sediments in stormwater settling tanks. Samples have been taken in the Django Reinhardt detention and settling tank in Chassieu, France. The main results of these experiments are the following ones: (i) the global mass balance is good, with absolute errors lower than or equal to 5% if all steps of the experiments are accounted for and if all equipments are cleaned meticulously; (ii) the repeatability is good if experiments are made by a trained operator, with coefficients of variation of approximately 4%. These results are coherent with the tests of reproducibility carried out by Chebbo *et al.* (2003*a*); (iii) uncertainties in the final $F(V_s)$ curves have been exhaustively evaluated by Monte Carlo simulations and the law of propagation of uncertainties. Uncertainties in $F(V_s)$ decrease with increasing values of V_s, and, in the example shown in this paper, are below 0.5%. The most contributing sources of uncertainty are the uncertainties in (i) the total mass of settled particles (M_{dec}), (ii) the mass of particles remaining in the column at the end of the experiment (M_{fin}), (iii) the theoretical asymptotic value of $M(t)$ in Equation 2 (parameter b), and (iv) the covariance between the three above factors.

The above elements confirm the interest of the VICAS protocol. Nevertheless, some observations revealed that a significant bias may occur if the protocol, initially developed for suspended solids, is applied to deposited sediments with high settling velocities. In this case, it may happen that the particles are pumped into the settling column with a concentration different from the concentration in the sample vessel. This hypothesis was confirmed by specific tests and a modified protocol was tested to confirm and quantify the bias. The settling velocities obtained with the modified protocol are likely more representative, e.g. in order to design settling tanks, to analyse their functioning and also for modelling purposes.

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