2 Quantifying physical disintegration of faeces in sewers: Stochastic model and 3 flow reactor experiments

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10 **ABSTRACT**

11 We present a novel stochastic model for quantifying gross solids (GS) physical disintegration
 12 under varying turbulent flow conditions and used a unique experimental setup for model
 13 calibration and validation. The stochastic deterioration model predicts faeces size evolution
 14 over time. It conceptually entails the two main processes of solid fragmentation, namely
 15 breakage and erosion. Model parameters were calibrated on synthetic faeces and validated
 16 with real human ones. A cylindrical reactor was used, where turbulent flow was forced by an
 17 array of water jets and the physical disintegration of the faeces was monitored using a high
 18 speed camera. Image analysis of breakage experiments obtained under backlight illumina-
 19 tion allowed determination of the evolution of the solids' size over time. The flow field in the
 20 reactor was characterised by particle image velocimetry (PIV) using tracer particles seeded
 21 into the water. We found different disintegration behaviours depending on turbulence in-
 22 tensity and water content of the solid. In conditions of low shear stress, dense solids hardly

disintegrated. Generally, the model predictions mirrored the broad range in the solids disintegration rate imparted by the high variability in flow conditions and in solids characteristics. It is expected that, similar to our experiments, also in real sewer systems both flow conditions and solid characteristics are highly variable and the stochastic model can be tailored to capture this variability. We thus anticipate that the model can be integrated into existing sewer models predicting sewer flows and solids' movement. From these, shear stress, flow velocities and transport of individual solids can be inferred. The integration of the present solids disintegration model may provide better predictions of hot-spots for solids accumulation and blockages in sewers.

KEYWORDS

Backlight illumination image analysis, gross solids, image processing, particle image velocimetry, synthetic faeces, turbulent flow

PARAMETERS AND VARIABLES

$As(t)$	size of a solid s at time point t
Δ	calculation time step
φ	sample break fraction
σ	average shear stress
WF	water content of the solid
$P_{\text{break}}(t, \sigma)$	Solids breakage probability
ρ	erosion rate
ϕ	Parameter of the Beta distribution
λ^*	breakage rate
(α_1, α_2)	Parameters of the hazard rate of a log-logistic distribution
$(\theta_0, \theta_1, \theta_2, \beta_{0\varphi}, \beta_{1\varphi}, \beta_{2\varphi})$	Regression parameters
d_p	mean diameter of the neutrally buoyant polyamide tracer particles
ρ_p	density of the neutrally buoyant polyamide tracer particles

ε	Energy dissipation rate of turbulent kinetic energy
u'	root mean square of the horizontal velocity fluctuations
L	integral length scale
$ s_{ij} $	average magnitude of the fluctuating rate of strain tensor
ρ	density of the fluid
μ	dynamic viscosity of the fluid

36

37 **1 INTRODUCTION**

38 Our understanding of gross solids (GSs) transport, sedimentation and disintegration in sewer
39 systems is still rudimentary (Littlewood and Butler 2003), despite its importance for the de-
40 sign and maintenance of these systems (Butler et al., 2010). GSs are usually defined as solids
41 larger than 6 mm in any two dimensions. Their specific gravity lies in the range of 0.9-1.2 and
42 they include faecal stools, toilet paper and “sanitary refuse” (Butler and Davies., 2010). Sed-
43 imentation of GSs can cause maintenance problems such as blockages and dangerous gas
44 formation such as hydrogen sulphide (Liu et al., 2015). These unwanted phenomena are ex-
45 pected to become more frequent with decreasing water use and higher water use efficiency
46 in many existing systems around the world. Quantification of GSs fate (movement, sedimen-
47 tation and disintegration) in sewer systems provides the means to identify and prevent such
48 undesirable phenomena. Some models predicting GSs transport in sewers can be found in
49 the literature. However, only very few studies focused on their disintegration. Moreover, to
50 the best of our knowledge, none focused on the physical disintegration of faeces, which are,
51 together with toilet paper, the largest mass stored in sewers during dry weather (Spence et
52 al., 2016). In this paper, we present a stochastic model quantifying physical disintegration of
53 faeces that can be integrated in existing sewer models predicting their movement and stag-
54 nation in sewers. It is based on a novel technique to quantify the temporal evolution of GSs

size. Laboratory experiments are presented based on imaging to observe the disintegration of gross solids subject to turbulent flow.

1.1 GS movement, sedimentation and disintegration in sewer systems

Movement, sedimentation and disintegration of GSs vary depending on their location in the sewer system. In upstream locations, within small diameter pipes, GSs are expected to be intermittently transported (Walski et al., 2011; Penn et al., 2017 (a,b)). In downstream sections, GSs are expected to be moved more easily (Staufer et al., 2011; Penn et al., 2017 (a,b)) due to higher flow velocities. Due to deposition and physical disintegration of faeces and toilet paper they are expected to be found mostly in the upper parts of the sewer system (Verbanck *et al.*, 1994; Milne *et al.*, 1996). At downstream links, other GSs such as plastic and sanitary products are expected to dominate (Evans and Eadon 2005). Even though toilet paper and faeces disintegrate faster than other GSs found in sewers (Davies et al., 1998), drains and small sewer pipes are critical sections where disintegration of toilet papers will be limited (Eren and Karadagli 2012).

In many places, solids deposition will most likely get worse due to a trend to produce less wastewater. This may be the result of population decrease - very pronounced, for example, in former East Germany (Schlör *et al.*, 2009). More frequently, in many places the specific water consumption is reduced due to water resources issues (e.g., Target 155 campaign), e.g. as a consequence of a temporary drought. Another contribution is the implementation of novel technologies to enhance water productivity (Grant et al., 2012) and therefore to reduce net domestic water consumption (e.g., Guo and Englehardt 2016; Larsen *et al.*, 2016). A reduction in wastewater streams may increase GSs deposition most prominently in upstream links of the sewer system (e.g. Littlewood et al., (2007); Penn et al. (2013); Mattsson et al. (2015)). In addition, due to lower shear stresses their disintegration may decrease.

To quantify where and how the disintegration and movement of these solids will be reduced by decreased wastewater flows, transport and disintegration models are required. Models describing GSs transport in sewers can be found in the literature (e.g., Butler *et al.*, 2003; Walski *et al.*, 2011; Penn *et al.*, 2018 (a)). However, models of physical disintegration are scarce, and particularly missing for faeces.

In this study we investigate the physical disintegration of GSs with particular focus on faeces. Faeces are the most significant GS type when organic loads and health issues are of concern and represent the largest solids mass fraction in upstream locations of sewers.

1.2 Experiments for the characterisation of solids physical disintegration

Disintegration of toilet paper and other flushable materials was analysed in rotating flasks (Karadagli *et al.*, (2009); Eren and Karadagli (2012); Tang and Jin (2013)). Solids were sampled at specific time points and screened through a series of sieves. The turbulence was characterized by the Reynolds number. These methods are unsuitable for characterising the change of faeces size over time. Screening materials through sieves requires forces to be applied which could potentially contribute additional unwanted disintegration of the faeces. Additionally, detecting and quantifying the physical processes by which the solids disintegrate is impossible. Time resolved measurements of breakage experiments of finite size colloidal aggregates were done by Saha *et al.* (2016). They used three-dimensional particle tracking velocimetry (3D-PTV) to investigate the breakup mechanism of the aggregates in turbulent flow. 3D-PTV allows simultaneous measurement of aggregates trajectories until its breakage, together with the detailed flow field along their path. Hence, by image-based analysis, precise forces acting on the solids during their disintegration can be calculated and the actual mechanism causing the destruction of the aggregates can be assessed.

Our study focuses on faeces, the characteristics of which are known to be highly variable depending on diet, lifestyle and geographical location (Rose et al., 2015). Their variability makes it difficult to execute repeatable experiments. Synthetic faeces, mimicking real faeces by shape, density, viscosity, water content and various chemical properties, provide consistently reproducible substrate and alleviate these challenges (Penn et al., 2018 (b)). In the present study we employed both synthetic and real faeces for the reactor experiments and we tested the hypothesis that their detrition behaviour would be similar. The simulant's water content and density can be adjusted to the ranges found in real human stool. Both of these properties are expected to influence faeces disintegration.

1.3 Mechanisms of solids physical disintegration

Some solids such as toilet paper and faeces disintegrate in short time scales, relative to non-disintegrating solids such as plastics. Previous studies showed that the disintegration rate of such solids depends on turbulence intensities and on the solids' size, density, water content and mechanical strength (e.g., Karadagli et al., 2009; Eren and Karadagli 2012). Disintegration accelerates with increasing water content of the solids and increasing turbulent forces. Wood pulp composite nonwovens wipes of medium size of 7 cm x 7 cm were shown to have the highest disintegration rate (Tang and Jin (2013)). Karadagli et al. (2009) showed that small particles with densities close to that of water tend to move with turbulent eddies and thus may not be exposed to high shear stresses that appear when particles cross different eddies. They estimated that the rate of disintegration should be high for large solids and may approach zero for very small particles. On the other hand, it is known that in turbulence even very small particles are exposed to a velocity gradient and thus shear. However, the strength of small aggregates (i.e. small relative to the Kolmogorov's length scale, which is the scale indicative of the smallest eddies present in the flow at which energy is dissipated) is

found to increase with decreasing size (e.g., Sonntag and Russel 1987; Harshe *et al.*, 2011). Restructuring and breakage of aggregates caused by fluctuating hydrodynamic stresses (such as in turbulent flow), depend on the way an aggregate samples these fluctuations along its trajectory (Babler *et al.*, 2008; Babler *et al.*, 2012). Only intermittently do these stresses overcome a critical stress required for breakage of the aggregate (Babler *et al.*, 2015). Weak correlation was found between the size of small aggregates (larger than the Kolmogorov scale, but significantly smaller than typical inertial eddies) and the shear stress at the time point of breakage, during their exposure to homogeneous turbulent flow (Saha *et al.*, 2016). Aggregates were found to break mostly because of accumulated drag stress over time, causing the aggregates to restructure before their breakage. Even though GSs are clearly bigger than these small aggregates, some of the mechanisms governing the breakage are expected to be similar.

In general, one may expect that also for GSs two main modes of disintegration govern their disintegration, namely, erosion, in which the solid's size continuously decreases, and sudden breakage into two or more fragments of different sizes (e.g., Eren and Kardagli *et al.*, 2012 and Saha *et al.*, 2016)

1.4 Models predicting solids' physical disintegration

In many studies, particle size distribution was used as means to describe GS disintegration (e.g. Eren and Karadagli 2012). Smoluchowski (1916) presented a stochastic population balance equation for describing coagulation processes. Population balance modelling (PBM) was found to be a powerful approach in the field of wastewater treatment modelling (e.g. Nopens *et al.*, 2015). However, these approaches are not suitable for the disintegration of faeces because of the small number of solids observed in our experiments.

This paper presents the development of a stochastic model describing the disintegration of faeces. It should fulfil the following requirements:

- a) model individual solids explicitly,
- b) describe the size of each solid over time (due to erosion),
- c) represent breakage events,
- d) allow the sampling of realistic random realisations of solids disintegration.

From the literature, the disintegration rate is expected to increase with higher shear stress and larger solids water content. However, it is unclear how dominant these effects are compared to other lesser known influencing factors, for example the variability in sewer flow regime or the exact characteristics of the discharged solids. Therefore, these unknown effects introduce 'randomness' that should also be captured by the model.

To obtain calibration data, a novel technique to quantify GS physical disintegration under realistic hydrodynamic conditions was developed. We varied the experimental conditions to match the conditions expected in sewers.

2 MATERIALS & METHODS

2.1 Stochastic disintegration model

Solids larger than 2 cm^2 projection area (see section 2.3.3) were tracked and the model describes their erosion rate and a breakage probability as stochastic processes. If breakage occurs, the size of the new particle is randomly assigned and the model tracks the new solids.

170 The model calculations are performed according to the following pseudo code where $A_s(t)$
171 denotes the size (in terms of projection area of the solid on the two-dimensional image
172 plane of the camera) of a solid s at time point t :

- 173 1. set $t = 0$ and start with one initial solid
- 174 2. increase time t by Δ
- 175 3. for each solid s , $A_s(t) > 2\text{cm}^2$ do:
 - 176 a. $A_s(t) = \text{erode}(A_s(t-\Delta), \sigma, WF)$
 - 177 b. with probability $P_{\text{break}}(t, \sigma)$:
 - 178 i. sample break fraction φ
 - 179 ii. create a new solid with size = $\varphi A_s(t)$
 - 180 iii. reduce the size of $A_s(t)$ to $(1 - \varphi)A_s(t)$
- 181 4. go back to 2.

182

183 The calculation time step is Δ , the average shear stress and the water content of the solid
184 are denoted by σ and WF , respectively. The fundamentals of the $\text{erode}(A_s, \sigma, WF)$ sub-model,
185 the definitions of $P_{\text{break}}(t, \sigma)$, and the sampling of φ for the breakage are presented in the
186 following subsections.

187 Ideally, the time step Δ of the calculation would correspond to the time interval between the
188 measurements. However, the manual processing (as described in section 2.3.3) resulted in
189 irregularly spaced time steps. Hence, the calculation time step Δ was set to the average time
190 between the experimental time steps (11.57 s). A smaller calculation time step may intro-
191 duce a bias between measurement and model predictions since it is unknown how the solid
192 disintegrates in these smaller intervals.

2.1.1 Erosion model

The erosion sub-model describes the decrease in size over time without producing additional gross solids. Let us denote the projected area on a plane of a solid s at point in time t by $A_s(t)$. The size at the time $t + \Delta$ is then calculated as

$$1) \quad A_s(t + \Delta) = A_s(t) \rho^\Delta$$

where ρ is the erosion rate randomly drawn from $\rho \sim \text{Beta}(\mu(\sigma, WF), \phi)$. The Beta distribution limits the erosion rate ρ to the interval $[0, 1]$ and may be asymmetrically distributed, assuming no coalescence occurs. Hence a generalised linear model with a Beta distribution is a reasonable choice (e.g. Cribari-Neto & Yeilis, 2010). The expected value of the distribution

$$2) \quad E[\rho] = g(\beta_0 + \beta_1 \sigma + \beta_2 WF)$$

depends on the shear stress (σ) and water content of the solid (WF), g is a non-linear link function. The best fit was obtained by using a Cauchy quantile function (see Koenker, 2016 for details) for g .

2.1.2 Breakage model

The breakage model was modelled as a non-homogeneous Poisson process assuming that the breakage probabilities are independent of the previous numbers of breakages. The breakage rate λ^* was parameterized by the shear stress (σ) and solid water content (WF). The formulation used here corresponds to the hazard rate of a log-logistic distribution

$$3) \quad \lambda^*(t; \alpha_1, \alpha_2) = \left(\frac{\alpha_1}{\alpha_2}\right) \left(\frac{t}{\alpha_2}\right)^{\alpha_1-1} \left(1 + \left(\frac{t}{\alpha_2}\right)^{\alpha_1}\right)^{-1}$$

combined with an accelerated life-time model (e.g. Tableman and Kim, 2003, chapter 4.4)

$\lambda(t, \sigma; \theta, \alpha_1, \alpha_2) = \lambda^*(t * \exp[\theta_0 + \theta_1 \sigma + \theta_2 WF]; \alpha_1, \alpha_2)$. This formulation of

$\lambda(t, \sigma; \theta, \alpha_1, \alpha_2)$ allows the probability for a breakage event to first increase and later de-

crease, which showed the best correspondence to experiment observations (explained in the discussion section of the paper). Given the breakage rate, the likelihood function can be derived (see, e.g., Cook and Lawless 2010). The time of the experiment was divided in small time intervals $[t_i, t_{i+1})$. The number of observed breakages within the i th interval was denoted by n_i . The likelihood function for observations n is expressed as

$$4) \quad p(n | \theta, \alpha_1, \alpha_2) = \prod_i f\left(n_i, \int_{t_i}^{t_{i+1}} \lambda(\tau, \sigma; \theta, \alpha_1, \alpha_2) d\tau\right)$$

where $f(n; \lambda)$ denotes the density of a Poisson distribution with rate parameter λ . By maximizing this expression the parameters $\theta, \alpha_1, \alpha_2$ were estimated jointly.

If a breakage event occurs, it “creates” a new solid and reduces the size of the original solid accordingly. The breakage fraction denoted as φ is defined by the ratio $\varphi = A_{after\ break}(t)/A_{before\ break}(t)$ between the new solids after the break and the original solid. The distribution of φ was also modelled with a generalised linear model with a Beta distribution $\varphi \sim Beta(\mu(\sigma, WF), \phi)$ (e.g. Cribari-Neto & Yeilis, 2010), whose parameters were calibrated with maximum likelihood (Equation 5). A similar asymmetric probability distribution was observed in the breakage study conducted on small aggregates by Saha et al. (2016).

$$5) \quad E[\varphi] = g(\beta_{0_\varphi} + \beta_{1_\varphi} \sigma + \beta_{2_\varphi} WF)$$

2.2 Experimental setup

Figure 1 shows a schematic illustration of the experimental setup. Turbulence was created in a transparent cylindrical reactor made out of 8 mm thick PMMA ('Plexiglas'), with a height of 300 mm and a diameter of 200 mm. Flow was forced by injecting water through multiple inlets with a diameter of 3 mm: twenty-four inlets uniformly distributed at the bottom of the reactor produced vertical jets and four clockwise-oriented inlets located immediately above the bottom of the reactor produced tangential jets. A 5 mm grid at the top of the reactor prevented the escape of solids. The resulting flow was approximately homogenous across horizontal planes. The reactor was placed into a rectangular container filled with clean tap-water to minimize optical distortion caused by curved walls. The flow was driven by an adjustable pump (3.8 l/s - 0.2 l/s) and recirculated water through the system. The system was thoroughly cleaned after each experiment, using soap and disinfection by hypochloride solution (to prevent bacterial growth in the reactor and pipes). These substances were thoroughly washed off by subsequently recirculating substantial quantities of tap water.

Figure 1. Schematic of the experimental setup

Flow velocity measurements and disintegration experiments were carried out separately.

Turbulence quantification was conducted for different pump settings by means of 2D Particle Image Velocimetry (PIV), a widely used flow measurement technique (Raffel et al. 2007).

This technique is based on a laser sheet (Figure 1) that illuminates neutrally buoyant tracer particles seeded into the water.

In principle, a similar method could also be used to observe larger solids and simultaneously measure the flow field around them (Saha et al. 2016). However, in our setup, the laser-based approach was found inappropriate for analysing the motion of the faeces, their disintegration and the instantaneous flow field around the solids. This was due to the high turbidity conditions prevailing in the reactor resulting from solids disintegration. In those condi-

tions, the illuminated light was strongly attenuated and the solids were not visible clearly enough in the images. Conversely, using backlight illumination images were obtained in which the edges of the solids and their broken pieces could be easily and accurately detected.

2.2.1 Experimental conditions

The physical disintegration of three types of synthetic faeces, containing 65, 72 and 80 wt% water (expected range in real faeces Rose et al., 2015), were examined in varying flow intensities (Table 1). In total, eight turbulence intensities resembling realistic conditions in sewer flows were applied. Each type of solid was examined in five to six different turbulence intensities, according to the water content of the solid. For example, the solids containing 65 wt% water were the strongest ones, i.e., the most difficult to disintegrate and hence they were examined in the five highest intensities. Most combinations of solid's water content and flow intensities were tested once, except for solids with the highest water content (of 80 wt%) and strongest flow intensity (#6). The latter was repeated 4 times to get an impression of the variability under the same conditions, in which highest disintegration was expected. In the experiments, turbulent flow was first activated and a solid was then gently inserted from the top of the reactor. In parallel the recording was started.

Table 1. Experiments specifications

	Flow number	#1	#2	#3	#4	#5	#6	#7	#8
	Average shear stress (Pa)	0.025	0.058	0.06	0.08	0.12	0.15	0.18	0.22
wt% of water content in the artificial solid	80	1*	1	1	1	1	4		
	72			1	1	1	1	1	
	65				1	1	1	1	1
Real faeces							9		

*The numbers correspond to the number of experiments conducted in the corresponding specifications

285

286 2.2.2 Synthetic faeces

287 Synthetic faeces were shaped into 70 g ellipsoids with a diameter of 4 cm and length of 9 cm
288 (i.e. an aspect ratio of approximately 2.25) and a specific gravity of 1.07, corresponding to
289 the specification of the US National Bureau of Standards (NBS) artificial faecal solid
290 (Swaffield and Galowin, 1992). Their detailed recipe was derived from (Penn et al., 2018 (b))
291 and can be found in the supplementary information.

292 2.2.3 Real faeces

293 Real faeces were collected during 5 days from 7 different volunteers. They matched the
294 specification of faeces types 1 – 4 according to the “Bristol Stool Form Scale” (Lewis and
295 Heaton, 1997). Types 3 and 4 are classified as normal stool forms. The stools' water content
296 is found to be ~50, 50-65, 65 – 80 wt% for types 1, 2 and 3-5 respectively (Onabanjo et al.,
297 2016). Types 1 - 4 are considered hard and are expected to disintegrated more slowly than
298 types 5 – 8. Fresh stool samples were stored in the fridge and examined the same day they
299 were produced. In total nine experiments with real faeces were conducted. As water content
300 in the solids was highly variable, all experiments were conducted with the same flow intensi-
301 ty and an average shear stress of 0.15 Pa (Table 1).

302

303 2.3 Measurement methods

304 2.3.1 Faeces water content

305 Prior to placing in the reactor, a mixed sample from three different locations on the stool
306 was taken without deforming the stool's shape. The sample's water content was measured
307 in triplicate using a HE73 Halogen Moisture Analyser with a drying temperature of 105°C.

2.3.2 Flow field analysis

The hydrodynamic conditions in the reactor were analysed by means of two-dimensional PIV, an image-analysis-based nonintrusive whole field flow measurement technique. The flow was seeded with tracer particles moving passively with the water and illuminated by a vertical laser light sheet. Images of these tracer particles were taken by high speed camera placed in front of the reactor. PIV provided space and time resolved 2D velocity vector maps based on analysis of the displacement of tracer particles between subsequent image pairs. The velocity of the fluid phase was measured in a vertical plane spanning the whole cross section of the reactor (Saha et al. 2016). The flow was in statistical steady state and acquired time sequences of velocity maps were used to calculate the turbulent shear. Further details can be found in the supplementary information.

A Photron SA5 camera was used with a recording frequency of 1000 Hz at a resolution of 1024 by 1024 pixels, fitted with a 60 mm lens. The investigation domain was approximately 200 mm by 200 mm. Neutrally buoyant polyamide tracer particles (VESTOSINT 1101 Evonik Industries) with a mean diameter $d_p = 90 \mu\text{m}$ and a density $\rho_p = 1.06 \text{ g/cm}^3$ were used as flow tracers. Further explanation on the suitability of the particles to be used as flow tracers can be found in the supplementary information. A pulsed laser (Darwin Duo 100 M) with an average power of 100 W provided illumination. The beam was shaped into an 4 mm thick light sheet. The light sheet was vertical, perpendicular to the optical axis of the camera, and spanned the entire cross-section of the reactor.

Flow field analysis was conducted using PIVlab, a PIV toolbox for MATLAB (Thielicke and Stamhuis 2014). Further description on the analysis method can be found in the supplementary information. The resulting flow field had velocity vectors separated by 8 pixels in the

horizontal and vertical directions, which corresponded to a spatial resolution of about 1.5 mm. 5000 images were processed for each turbulence condition.

Turbulent shear stresses vary in both space and time. Energy dissipation rate of turbulent kinetic energy ε represents the strength of the average (in time) turbulent shear stresses experienced by the solids at small scales. It was estimated from Equation 6.

$$6) \quad \varepsilon = (u')^3 / L$$

where u' is the root mean square of the horizontal velocity fluctuations and L is the integral length scale, i.e., the characteristic size of the largest eddies. L was estimated via the Eulerian autocorrelation of the horizontal velocity fluctuations. As mentioned, turbulence is inhomogeneous in vertical direction and statistics (e.g. u' , L and hence ε) vary with vertical direction. For simplicity, we consider here the vertical averages as an estimate of space- and time-averaged shear stresses sampled by GS in the flow domain. In our measurements, L remained relatively constant with change in turbulence intensities, ranging from 9.5 mm at the lowest intensity to 10.5 mm at the highest.

Hydrodynamic conditions were measured at eight pump settings P1 to P8, representing the increasing flow from 0.2 to 3.8 l/s. These conditions correspond to a mean energy dissipation rate ranging from $6 \times 10^{-4} \text{ m}^2/\text{s}^3$ to approx. $4.5 \times 10^{-2} \text{ m}^2/\text{s}^3$ and to a Taylor-scale Reynolds number ranging from 48 to 108 (Figure 2a). The average shear rate due to turbulence fluctuations is given by the average magnitude of the fluctuating rate of strain tensor (Equation 7) it ranged from approx. 24 1/s at the lowest settings (P1) to approx. 212 1/s at the highest intensity of turbulence tested (P8).

$$7) \quad |s_{ij}| = \sqrt{2 \times s_{ij}s_{ij}} = \sqrt{\varepsilon / \nu}$$

Where ν is the kinematic viscosity of the fluid.

The average shear stress due to turbulent fluctuations was estimated as in Equation 8 (Saha *et al.* 2016).

$$\sigma = \sqrt{\rho \mu \varepsilon}$$

where ρ is the density of the fluid and μ its dynamic viscosity. In our measurement σ ranged from 0.025 Pa at pump level P1 to 0.2 Pa at level P8.

2.3.3 Solid size identification

Disintegration measurements were conducted in the same experimental conditions as in the flow field analysis. The 2D projection from the backlight illumination was recorded by the same camera as in the flow measurements. Image processing in Matlab was used to accurately detect the edges of the fragments and to quantify the evolution of their size over time (i.e. its projected area). The length of the recording was limited by the internal memory of the camera to 210 s for a frame rate of 50 Hz. The roughly 11000 images per experiment (table 1) were automatically processed with the image processing toolbox in Matlab, applying the following steps: We (a) smoothed the images to remove noise, (b) masked the areas that corresponded to the walls of the reactor, (c) performed adaptive thresholding to isolate the fragments from the background, and (d) applied a set of morphological erosion and dilation operations to improve image segmentation.

The automatically generated results of the solids size over time were manually post-processed (see results describing Figure 3 for reasoning). All significant high peaks in solid size were manually checked against the image recordings for accuracy. In case of faulty detection, the preceding and following images were checked until an image with a correct ob-

servation was found. The new image was then processed manually to derive the correct solid size. This procedure resulted in 3 to 43 verified observations per experiment (for experiments in which hardly any and high disintegration occurred, respectively).

Particles smaller than 2 cm^2 in projected area were excluded due to the high uncertainty in their measurements. There was a probability that such solids passed the 5 mm grid at the top of the reactor and got dispersed in the pump. Moreover, small particles that were located very close to each other often appeared as bigger aggregates in the images. This phenomenon was quite substantial due to the high concentrations of these particles, their fast movement due to advection by the turbulent eddies, and due to the 2D measurements. These relatively bigger aggregates were nevertheless smaller than 2 cm^2 , hence were as well excluded from the measurement results and did not introduce an additional detection error.

2.3.4 Model implementation and calibration

The stochastic deterioration model and its sub-models were implemented in R V3.4.3 (R Core Team, 2017) and the code can be found in the supplementary information.

The time series of the size development for the largest solid provided the information to calibrate the model. The decrease in size between two subsequent verified observations (without breaks occurring in between) allowed the calculation of the corresponding erosion rate based on Equation 1. Then the erosion model was calibrated with the function `betareg` (of the package “betareg”, version 3.1-0, Cribari-Neto and Zeileis, 2010), using the time difference between observations as weights.

The breakage probability model was calibrated by maximizing the likelihood function of Equation 4 using the function `maxLik` provided by the package `maxLik` 1.3-4 (Henningsen and Toomet, 2017).

Also, if a breakage event was identified, images were processed manually to determine the original size of the solid before and the sizes of both solids after the break (see supplementary information for further details). This allowed the calculation of the ratio of the two solids after the breakage, to which a Beta distribution was fitted using *fitdistr* option from the package MASS 7.3-49 (Venable and Ripley, 2002).

3 RESULTS

3.1 Experimental results

3.1.1 Flow field analysis

Figure 2b shows a snapshot of velocity vectors and the out of plane vorticity component. It reveals patchy, instantaneous turbulent structures on the order of centimetres, consistent with the estimate of L given above. Further, the order of magnitude of the instantaneous vorticity (~ 10 - 100 1/s) displayed in the figure is consistent with the estimate of the average turbulent shear for this forcing condition.

Figure 2c shows the vertical profiles of the root mean square of the velocity fluctuations for the different pump settings. The intensity of the turbulence remained relatively uniform over the height of the reactor at the lowest settings. In high flow conditions strongest turbulence developed in the lower part of the reactor, because inlets are located at the bottom or immediately above and individual jets interact and maximize turbulence production at about 50-60 mm away from the bottom wall. Turbulence intensities gradually decreased in the upper region.

Even though the *local* turbulent shear stress can be strongly variable as exemplified in Figure 2c, for our analysis below we consider space- and time-averaged values. As shown below

and explained in more detail in the discussion, averaging over time provided the best fitting measure for relating flow and breakage measures.

Figure 2. (a) Time- and space-averaged turbulent energy dissipation rate ϵ (black) and root mean square of the horizontal velocity fluctuations (red) in the PIV measurement plane for the eight pump settings. **(b)** Flow velocity field (vectors) and magnitude of the vorticity (color) for one single time step at pump level P8. **(c)** Vertical profiles of the root mean square of the horizontal velocity (u'_{rms}) fluctuations in the PIV measurement plane for the eight pump settings P1 to P8. Values are time- and space-averaged within bins of 2 mm height.

433

434 3.1.2 Faeces physical disintegration

435 Figure 3 illustrates the time evolution of the disintegration processes, for a synthetic faeces
436 with a water content of 65 wt% and average shear stress of 0.18 Pa. Raw image snap shots
437 from the backlight illumination recording and the processed images are shown in panels a
438 and b of the figure, respectively. During the disintegration process, the large faeces were
439 found to mostly erode, a process in which small fragments (defined as $< 2 \text{ cm}^2$) continuously
440 detach from the GSs. In addition, a few breakage events occurred. Panel c of the figure pre-
441 sent the automatically and manually processed data (grey and green dots connected by or-
442 ange lines respectively), where the red vertical lines represent instances in which a breakage
443 event occurred. The high fluctuations in solids size observed in the grey lines (automatically
444 processed data) are due to the solids' rotation in the flow and the change in its projected
445 area. Also, the automatic segmentation of individual solids was not without ambiguities:
446 sometimes two large fragments were segmented as a single one, and in conditions of high
447 turbidity the detected area was sometimes smaller than the solids' actual size. Therefore,
448 the automatically generated results were manually post processed (as explained in the ma-
449 terials and methods section). High reductions in solids size were mainly observed as intense
450 and continuous erosion and not necessarily as breakage events. Many detachments were
451 smaller than 2 cm^2 and therefore defined as erosion. The figure also shows a typical break-
452 age behaviour, where the most area is lost in the first part of the experiment (when solids
453 are relatively big) but not at the onset of the experiment. This means that it takes some time
454 for the solid to experience intense flow events. Another possible reason could be that at the
455 onset of the experiment the solids absorb moisture from the water surrounding them and
456 thus experience a reduction in their strength.

457

458

459 **Figure 3.** Sequence of images at different times illustrating the disintegration of solid con-
 460 taining 65 wt% water exposed to an average shear stress of 0.18 Pa, (a) original images of
 461 the fragmented synthetic faeces from the reactor with backlight illumination (b) processed
 462 images of the segmented solids. Only solids larger than 2 cm² are coloured – orange for the
 463 largest solid whose size is tracked and blue for the detached smaller piece. (c) raw and man-
 464 ually processed measurements of the biggest solid size throughout the experiment. The black
 465 lines are the highly fluctuating, automatically processed data; the green lines are the manu-
 466 ally adjusted results and the red vertical lines represent moments in which breakage oc-
 467 curred.

468

Figure 4. (a, b) Changes in synthetic faeces size over time (a) Solid containing 65 wt% water in five different flow intensities (b) the three type of solids in a flow with shear stress of 0.18 Pa (c) breakage probability for each water fraction- the lines show the estimated breakage probability for different experimental conditions (i.e. average shear stress in the reactor). The dots mark breakages observed in the experiments. (d) Breakage fraction probability – lines show estimated probability; dots mark fractions observed in the experiments

The temporal evolution of the size of the biggest fragment of the synthetic faeces are presented in Figure 4 (a & b) for various experiments.

As expected, for the same type of solid (65 wt% water content) the disintegration rate increased with an increase in flow intensity (Figure 4a). For the same flow intensity (shear stress = 0.18 Pa) the disintegration rate increased with an increase in the water content of

the solid (Figure 4b). In low shear stress conditions, dense faeces (low water content) hardly disintegrated. Such tenuous disintegration was observed at shear rates of 0.08, 0.06 and 0.025 Pa for solids with 65, 72 and 80 wt% water, respectively.

3.2 Model predictions

As shown above, faeces were found to mostly erode with occasional breakage events. We observed that if the shear stress was below a certain value, hardly any disintegration occurred. With higher water content, a lower shear stress threshold (for breakage) was observed with 0.025, 0.06 and 0.08 Pa for solids with water contents of 80, 72 and 65 wt%, respectively (Figure 1 supplementary information). If the shear stress is equal or above the next higher shear stress conditions measured (0.058, 0.08 and 0.12 Pa for solids water content of 80, 72 and 65 wt%, respectively, table 1) the model confirms a slight linear increase in erosion with higher shear stress. However, this linear relationship does not necessarily hold between these values and the thresholds (i.e., between 0.025 and 0.058, between 0.06 and 0.08 and between 0.08 and 0.12 Pa for solids water content of 80, 72 and 65 wt%, respectively). In order to identify the relationship in this range more experiments will be needed. Only data from experiments with these erosion rates and above (i.e. cases in which appreciable disintegration occurred) were used for model calibration.

Table 2: Estimated parameters of the erosion and the breakage model.

	Coefficients	estimation	p-value ($H_0: =0$)*
Erosion model	β_0	-154.18	<2e-16

		β_1 (water content)	1.2	<2e-16
		β_2 (shear stress)	260.76	<2e-16
		ϕ	76.41	
Breakage model	Breakage probability	α_1	18.13	-
		α_2	0.54	-
		θ_0	4.85	0.047993
		θ_1 (shear stress)	12.82	< 2e-16
		θ_2 (water content)	0.10	.51e-4
	Breakage fraction	$Shape1^{**}$	2.40	-
		$Shape2$	4.47	-

*Parameters that are part of the regression ($\beta_0, \beta_1, \beta_2, \theta_0, \theta_1, \theta_2$) were tested for their significant difference from zero. For the other parameters no meaningful null hypothesis can be defined.

**shape1 and shape2 are the parameters of the Beta distribution; they are functions of the expected value and standard deviation

3.2.1 Parameter estimation

The empirical models for the erosion rate and the breakage probability both contained parameters that describe the influence of water content and shear stress. The estimated value of these and the other parameters are listed in Table 2. For the regression parameters p-values are given (under the null hypothesis that the parameters are equal to zero).

3.2.1.1 Erosion model

The parameter estimation was based on 241 observed erosion rates. The parameters show that a higher solid water content and a higher average shear stress in the reactor leads to higher erosion rates. Both effects are statistically significant (low p-value for β_0, β_1 , and β_2 Table 2). Nevertheless, these dependencies explain only a small part of the observed variability (the R-squared as defined by Ferrari & Cribari-Neto (2004) is 0.0608).

3.2.1.2 Breakage probability

The model was calibrated with 36 confirmed breakage events. The calibrated model parameter indicate more and earlier breakages of solids for larger shear stress, and higher water content (low p-value for θ_0 , θ_1 and θ_2 Table 2), presented in the curves of Figure 4c. It was observed that more breakage events occurred in the first part of the experiments compared to its initial stages (dots in Figure 4c).

To the best of our knowledge, no literature nor reasonable argument can be found to correlate the breakage fraction with the water content of the solid or the flow shear stress. This non-dependency was confirmed by regression analysis (found in the SI). The fitted Beta distribution is asymmetric, which means that breakages in unequally sized parts are more likely (Figure 4d). This result is similar to the asymmetric probability distribution observed for small aggregates by Saha et al. (2016).

3.2.2 Simulation results

Monte-Carlo simulations for the size of the biggest solid over time as well as measurements for the synthetic faeces are shown in Figure 5. In most scenarios measurements fall well within the 90% quintile interval of model predictions. Note that the observed as well as the real time-series show a strong auto-correlation. Hence, once a series steps out of the prediction intervals, it is likely to stay there for some time (Figure 5.3 and 5.4).

It was further observed that even though the erosion rates are represented well by a Beta distribution for a few individual experiments, the fit was not as good (see supplementary information Figure 2). This imperfect fit creates some bias between measurements and model predictions.

Even under identical conditions (i.e., same average shear stress in the reactor and water content in the solid) the size of the solids may evolve very differently, as can be seen in Figure 5b. The capability to capture such variability is one of the main advantages of the stochastic model compared to a deterministic one. It can be observed that all replicate experiments fall well within model predictions.

Figure 5. Model predictions for biggest solids size of 100 Monte-Carlo simulations (light brown coloured lines), three model realisation (for each scenario) (darker lines) and 90 % quintiles of model predictions (thickest lines). The blue dots represent processed measurements of the size of the biggest solid (synthetic faeces). (a) all scenarios (b) repeatable experiments

3.2.3 Model validation

Experimental results with real faeces were not used for model calibration. The results mostly fall within the 90% quintiles of model prediction (Figure 6). However, as with artificial faeces, the model was not able to predict cases when hardly any disintegration occurs. Threshold values from which real faeces do not disintegrate will need to be adjusted, due to their more complex structure compared to the simulants (Figure 6 a and d). The effect of this complex and inhomogeneous structure of real faeces is further exemplified in panels d and e of Figure 6. Despite similar experimental conditions (same shear stress and solid water content), the solids' disintegration displayed a wide variability.

Figure 6. Measured evolution of the biggest real faeces size (not used in the model calibration; blue dots) in front of the backdrop of 100 Monte-Carlo simulations (light brown coloured lines) and 90 % quintiles of model predictions (thickest lines).

4 DISCUSSION

The solids' size reduction predicted by the model was represented well for the synthetic faeces used and for the majority of experiments with real faeces. This highlights its potential to be integrated in models predicting gross solids movement and stagnation in sewer pipes. Existing hydrodynamic simulators of sewer flows (e.g., SWMM, Rossman, 2004) and for gross solids transport (e.g., Simba#, Ifak, 2013; Penn et al., 2018 (a)) provide calculations of shear stress, flow velocities and movement of solids in sewer pipes. In combination with these models, faeces disintegration can now be simulated as well. While the required shear rates can be calculated by the hydrodynamic simulators, water content for each solid can be sampled from ranges found in the literature (Rose et al., 2015).

The results show that high disintegration occurred in the first part of the experiments when solids are relatively big. This is consistent with previous experiments that noted that shear strength increases with decreasing size, i.e. large particles are weaker than small ones (e.g. Zacccone et al. 2009, Saha et al. 2016). Additionally, with increasing shear stresses more breakage events occurred. This is consistent with previous findings showing that the disintegration of solids increases with increasing water content in the solid, increasing solid size and increasing turbulent forces (e.g., Karadagli et al., 2009 and Harshe et al., 2011, Saha et al., 2016).

It was further observed that in low shear stress, dense faeces with a low water content hardly disintegrated. Separate sewer pipes are designed for minimum bed shear stress of 1 to 2 Pa (Vongvisessomjai et al. 2010). Since the shear stress in the bulk region of sewer pipes can be one order of magnitude lower than that found near the wall (Babler et al. 2015), the shear stress values obtained in this study's measurements (i.e., 0.025 – 0.22 Pa) are comparable to those found in the logarithmic or bulk region of sewer pipes with moderate flow rate and inclination angle. This result implies that in sewers with low flows (as a result of e.g., implementation of water saving measures) and with low slopes, solids may not disintegrate. Additionally, in these cases where flow rates are low, bed shear stress, flow velocities and water depth are decreased. In these conditions, solids may also not be transported and may accumulate. Their accumulation without disintegration may cause blockages and dangerous gas production. Integration of the developed model described in this paper with sewer models can support the prediction of such undesired phenomena. It can thus enable better planning and managing of such systems.

We considered average values of the turbulence shear stress over time and space despite the strong variations observed in the experimental set-up. Averaging over time provided the best fitting measure for relating flow with breakage measurements (since these experiments were conducted separately). Moreover, it can reasonably be assumed that the accumulated stresses over time and integrated in space govern the disintegration process. This is because the size of the gross faeces is much larger than the scale of the smallest and even inertial range eddies. Additionally, the developed model is intended to be integrated in sewer models, where shear stress is mostly likely considered with average values (i.e. models are generally one-dimensional and the turbulence is represented by the friction factor). It is very difficult to evaluate the actual local shear stress due to the high variability prevailing in sew-

ers. Therefore, implementing a more accurate shear will probably not much increase the accuracy of model predictions, which already account quite well for experimental results. It is worth noting that inertial, finite size solids carried by a turbulent flow may react back to the flow and modulate the turbulence. For example, it has been reported that the large eddy structures lose energy faster, i.e. become slower, than those in single-phase flow, because they are disrupted by the large solids that drag the surrounding fluid in their direction (Lucci et al. 2010). At the same time, solids may generate, in their downstream direction, new smaller sized eddies. These processes seem to modify the kinetic energy spectrum, attenuate the turbulent kinetic energy and increase the dissipation of turbulent kinetic energy compared to single phase flow (Lucci et al. 2010). However, these modulation effects are more appreciable when the density difference between the solids and the fluid is significant and mass loadings moderate to high, which is not the case in the present study. We therefore expect that our quantification of bulk turbulence properties without solids to be well representative of the conditions during breakage experiments.

The stochastic nature of the model was capable of capturing the high variability of the experimental results, despite state of the art experimental control. We hypothesise that this stochasticity is an inherent property of faeces disintegration – as it is not feasible to characterise the mechanistic effect of stochastic shear events on the given inhomogeneity of faeces. This is especially true for the intended purpose of predicting faeces disintegration under high variability of flow conditions and solids characteristics found in real sewers.

Several experiments with real faeces could not be described by the model properly (very low probability of the measured disintegration trajectory). The interpretation for this failure lies probably in the much larger inhomogeneity of the physical structure compared to synthetic faeces. Real faeces appear to have an outer layer that contains more water and has a weaker

632 structure than the inner dryer, more condensed layer. As a result, in some experiments with
633 real faeces, flow conditions in the reactor already became very turbid in early stages of the
634 experiment, making the detection of the solid's size difficult. In spite of these highly turbid
635 conditions it was clearly visible that the inner part of the solid often remained compact. In
636 contrast, with the same flow conditions, synthetic solids showed higher erosion. Additional-
637 ly, threshold values below which synthetic faeces do not disintegrate did not match the ob-
638 servation for real faeces.

639 These differences emphasize the need to better understand and characterize the complex
640 and highly variable structure of real faeces. Such understanding can add explanatory varia-
641 bles to the model and improve its predictions. The advantage of using synthetic faeces is
642 therefore in the ability to adjust its parameters, and hence reflect the high ranges observed
643 in real faeces.

644 Better understanding of the complex characteristics of real faeces may contribute to the
645 improvement of model structure. Additionally, in a real sewer solids may experience higher
646 variability of flow conditions compared to our experiments. To investigate this effect further
647 research is needed.

648 The impact of the gross solid disintegration on wastewater treatment is unclear. Qualitative-
649 ly, it is obvious that disintegration and especially erosion decreases the probability of the
650 faeces to be eliminated in the mechanical treatment. Consequently, it might be hypothe-
651 sised that the flow conditions in the sewer have an impact on the load of the biological
652 treatment step. The empirical observations during the experiments with real faeces showed
653 that already at the onset the turbidity in the reactor was substantial and increased signifi-
654 cantly over time due to erosion. However, we did not quantitatively investigated the conse-

quences of this erosion, e.g. characterisation of dissolved fraction, particle size, biological degradability, etc. With reduction in sewer flows (due to e.g., implementation of water saving measures) these characteristic may change and affect the various processes in the plant. The effect of changes in flows on their transport in the sewers and consequently on their part in the composition of the influent to the WWTP is in need of further investigation.

5 CONCLUSIONS

A novel stochastic model was developed to predict the irregular physical disintegration behaviour of faeces. The stochastic nature of the model represents the variability of internal mechanistic processes with the only two observable dimensions of erosion and breakage. The experimental set-up provided a suitable trade-off of reproducibility and variability in terms of hydrodynamic conditions as well as faeces composition.

Erosion and occasional breakage events were both found to be dominating mechanisms of faeces disintegration in turbulent flow. The need for the stochasticity of the model is rooted in the displayed high variability of the disintegration results under the different flow conditions and solids characteristics. Although most disintegration behaviours of real faeces were able to be captured by the model, the higher physical heterogeneity of real faeces compared to synthetic ones represented a challenge and made it more difficult to model their disintegration behaviour. This also shows the limitation of synthetic faeces, used for the experiments, to represent the full complexity of real ones.

We anticipate that the presented experimental approach may also be adapted to quantify the disintegration of other types of GS. Further development of these techniques may enable the characterisation of GS physical disintegration along their movement in real pipes, for example, by using multiple cameras along the stream-wise direction. Measurement accuracy

can be increased by 3D photography and object tracking. Additionally, model predictions for real sewer conditions can be improved by better understanding of the complex structure of real faeces. Investigation of the effects that higher variability in flow conditions, as expected in real sewers, may have on the disintegration process, could further increase the accuracy of model predictions.

Integrating the developed model with models predicting sewer flows and solids transport can support prediction of hot-spots in sewers where solids may accumulate. Consequently, these predictions can serve as means to prevent operational and maintenance problems in sewer systems, especially in those subject to reduction in sewer flows. Additionally, the experimental setup and the results presented in this paper can potentially enhance the evolving research on faecal sludge management for decentralised wastewater systems. It hence may contribute to an increase in the sustainability of wastewater systems and water use.

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