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Dynamics of soil aggregate size in turbulent flow: Respective effect of soil type and suspended concentration

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ABSTRACT

The fate of eroded soil particles impacts soil loss, river engineering and aquatic ecosystems. However, little is known about soil aggregate dynamics within the flow just after their detachment from the soil matrix. The relationship between particle size and turbulence has already been studied but few studies analysed the associated effect of particle concentration. The disaggregation/flocculation of three soils, two badland materials and a well developed calcareous brown soil, was studied by using a grid-stirred tank. An isotropic and homogeneous turbulence was generated to focus on the effects of suspended concentration on particle sizes. Increasing the suspended concentration in the range $1-10\ \mathrm{g\ L^{-1}}$ leads to a decrease of the proportion of the medium size particles and of an increase of the proportion of the smallest particles, as a consequence to enhanced abrasion. The soil aggregates with the largest organic content had the highest strength but were still subject to disaggregation within the turbulent flow, the resulting particle size depending on the suspended concentration. This study demonstrates that soil aggregate characteristics are influenced by concentration, this behaviour being dependent upon the soil type.

1. Introduction

Soil erosion by water is considered to be the main threat to soils in Europe. The concerning extent of 10^6 km^2 of eroded soils (Jones et al., 2012), 16% of Europe's total land area, is expected to increase in the context of global change. In addition to local land degradation resulting in net loss in crop productivity (Collins et al., 2005), the transfer of sediments to rivers is also of great concern for aquatic life and water resources (Owens et al., 2005). It contributes to reservoir siltation and to the export of pollutants such as heavy metals and nutrients to downstream water bodies. Despite modelling efforts undertaken in the last decades, the performance of erosion models remain moderate to low (Jetten et al., 1999, 2003; Boardman, 2006; De Vente et al., 2013). These models therefore cannot be used as tools to evaluate erosion mitigation strategies or the evolution of sediment yield in a context of climatic change.

Wainwright et al. (2008) pointed out that the inability of catchment scale models to correctly reproduce soil erosion could be related to their inability to consider particle travel distances. The maintenance of solid particles in suspension results from the balance between turbulence and particle settling velocity (Winterwerp, 2001). As the settling velocity is mainly dependent on particle sizes, one of the possible misconceptions of mechanistic erosion models may be due to the fact that particle sizes are considered to be stable over time after their detachment from the soil matrix. Conversely, in the conceptual models developed for lowland rivers and estuarine environments, such as the ones proposed by Dyer (1989) or Droppo (2004), it is considered that the particle sizes are mostly controlled by in-channel processes acting upon the suspended particles, i.e. flocculation and disaggregation, each being dependent upon particle concentration and flow turbulence. Headwater hydrosystems are characterized by a high temporal variability of discharges, suspended concentrations (Navratil et al., 2012) and suspended particle sizes (Grangeon et al., 2012). This emphasizes the need to study the effects of turbulence and suspended concentration on soil particles. While particles eroded from the soil matrix are mainly aggregated particles, almost no studies have addressed the dynamic behaviour of soil aggregates within headwater hydrosystems. It was however demonstrated that soil aggregates seem to coexist with newly formed flocs during runoff events (Droppo et al., 2005; Williams et al., 2008). Grangeon et al. (2014) explored this issue through laboratory experiments for three soils within an annular flume. Over an increasing and decreasing sequence of bed shear stress, their observations suggest that soil aggregates were not stable once introduced in the flow, but rather undergo disaggregation and flocculation. Large

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differences in particle size were found between soils during the early stage of the rising limb of the bed shear stress sequence. The differences were smaller in the falling limb suggesting that soil aggregates underwent structural change. However, the intrinsic design of the flume experiments did not allow for dissociating the respective effects of flow turbulence and suspended concentration on particle characteristics, as both varied during experiments due to bed erosion and deposition. The objectives of the present study were therefore to assess i) how the suspended concentration impacts soil aggregate sizes and ii) whether concentration plays a lesser or greater role than the eroded soil type.

2. Materials and methods

2.1. Soil characteristics

The dynamics of soil particles within the flow was explored through the introduction of various amounts of three soils in a turbulent water tank. The three soil types were similar to those studied by Grangeon et al. (2014). They were sampled in the first top 10 cm of bare soil areas. Two of them were collected within the Galabre catchment, located in a sedimentary area of the southern French Alps (Navratil et al., 2012). The Galabre catchment, typical of highly energetic headwater catchment, exhibited high variations of suspended sediment concentrations during runoff events (i.e. from a few g L^{-1} to more than 100 g L^{-1}) (Navratil et al., 2011; Grangeon et al., 2012; Legout et al., 2013). These two materials could not be considered as evolved soils, since they were sampled in badland areas. Therefore they were labelled with the names of the lithological layers they were originated from: black marls and molasses. The third material was collected in a sedimentary area located in southern France within the Cevennes-Vivarais Mediterranean Hydrometeorological Observatory (Boudevillain et al., 2011). It was a cultivated well-developed calcareous brown soil (Le Bissonnais et al., 2007), hereafter referred as clay soil. As shown in Table 1, the clay soil had the highest organic content. All these materials were air dried and sieved using a 1 mm mesh before the experiments.

2.2. The grid stirred tank

The experiments were conducted in a grid stirred tank. The tank is a square plexiglass box 53 cm wide and 90 cm high. The grid is made of seven square 1.5 cm bars, with a mesh size of 7.5 cm. It is fixed horizontally on a vertical bar that serves as a guide for stirring. The grid oscillates with a stroke (twice the amplitude) $S = 4.3$ cm and at a controlled frequency $f = 4$ Hz. The mean grid position is located at $h_g = 5$ cm above the bottom of the tank, and the z axis is defined upward with the origin O at the mean grid position (Fig. 1). Additional description of the experimental set-up can be found in Gratiot and Manning (2004) and Gratiot et al. (2005).

The grid stirred tank device generates a homogeneous and isotropic turbulence with an intensity depending only on the distance to the oscillating grid (Hopfinger and Toly, 1976). Matsunaga et al. (1999) proposed universal laws of turbulence decay with the distance to the grid for clear water (without sediment). Michallet and Mory (2004) later used a k–ε model (including equations for the turbulent kinetic energy k and the dissipation rate of turbulent kinetic energy ε) to study steady states of fine sediment suspensions in oscillating grid turbulence. They showed that the turbulence abruptly vanishes at some distance above the grid, leading to the formation of a sharp concentration interface called lutocline. Gratiot et al. (2005) experimentally confirmed that there is very little stratification below the lutocline. The dissipation gradient of turbulence $G = \sqrt{\varepsilon/\nu}$, where ν is the fluid kinematic viscosity, has been evaluated by Gratiot and Manning (2004) for similar experimental conditions, reaching an order of magnitude of 100 s^{-1} close to the grid and decreasing to 19, 7 and 3 s^{-1} for distances of 15, 20 and 25 cm respectively. Those values are typical of many natural flows and laboratory devices (Jarvis et al., 2005).

2.3. Experimental protocol

A set of 12 experiments were performed (Table 2). For each soil, three different amounts of material were introduced in the tank in order to maintain different levels of concentration ranging from 1.6 to 10.9 g L^{-1}. The tank was first filled ($H = 40$ cm) with tap water and the grid stirring was started. Dry material was then introduced at the top of the tank at time $t = 0$ min and the experiment lasted 40 min. Two 1 m long vinyl flexible hoses were installed at $z = 15$ cm allowing to collect simultaneously by gravity two suspended sediment samples. This sampling position has been chosen to be far enough from the grid to minimize local convection effects and to remain under the lutocline for all the experiments. Samplings were done at $t = 1$, 5, 10, 20 and 40 min. Each sampling lasted 20 s. At the end of each experiment (after 40 min) the vinyl hoses were lifted at $z = 20$ cm and $z = 25$ cm and additional samples were collected in order to evaluate potential stratification effects. For each time and position, one sample was used to measure the suspended concentration and the other one was used to measure particle size distributions (PSDs) by laser diffraction.

2.4. Measurements

Samples were weighed after collection, oven dried at 105 °C for 24 h and then reweighed in order to measure the suspended sediment concentration (SSC). The position of the lutocline z_l above the central position of the grid was visually tracked during each experiment, as done by Gratiot et al. (2005). Particle size distributions (PSDs) were measured with a laser diffraction sizer (Malvern, Mastersizer 2000) operating in the range $0.01 - 2000$ μm. An equivalent spherical volume hypothesis is considered to calculate PSD from the diffraction data (Andrews et al., 2010). In case of elongated or complex particle shapes, the laser sizer device measures both the small and large axes of the particles and an equivalent volume is attribute to both sizes (Graham et al., 2012). For each sample, a first PSD measurement, referred as to the aggregated PSD, was performed during the first thirty seconds without sonication and with stirring and pumping at half of their maximum levels (i.e. 500 and 1250 rpm respectively). This procedure was developed and validated by Grangeon et al. (2012, 2014) to minimize sample disturbance. Then sonication was activated, stirring and pumping were increased at their maximum levels. PSD was then measured each minute to record the disaggregation dynamics. The measurement performed after 10 min was assumed to be the dispersed PSD corresponding to physical dispersion. This duration corresponds to the time to which maximal physical dispersion was obtained through the protocol. As mentioned in Grangeon et al. (2012) both the aggregated and dispersed PSDs are not the same as those obtained by other methods in the literature. Indeed the use of chemical dispersion could have dispersed aggregates much more than the flow shear stress would have

Table 1
Soil characteristics. All contents are in g·kg^{-1}.

Soil	Sampling latitude	Sampling longitude	Clay content (0–2 μm)	Silt content (2–50 μm)	Sand content (50–2000 μm)	Organic carbon content
Molasses	44°11′50″N	06°12′57″E	326	477	197	20
Black marls	44°10′18″N	06°12′56″E	182	566	252	18
Clay soil	44°34′48″N	04°29′44″E	341	413	246	27