Transport characteristics of tile drain sediment in clay loam soils

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Abstract Increasing use of subsurface tile drains in agricultural watersheds has created concern for sediment delivery to receiving waters and potential undesirable effects on surface and subsurface water quality. In this study, transport characteristics of sediment from tile drains in predominantly clay-loam soils of a southern Ontario watershed were tested in a rotating circular flume located at the National Water Research Institute, Burlington, Ontario. Tile drain sediments were collected and mixed with river water at different speeds in the flume to study transport processes such as deposition, erosion and flocculation as a function of bed shear stress. Empirical relationships are developed to describe erosion and deposition processes of tile drain sediment. The relationships are in a form suitable for use in the fine sediment transport model developed by Krishnappan (1997) and can be used to predict transport characteristics of tile drain sediment in receiving streams.

INTRODUCTION

Areas of highest sediment yield in the Laurentian Great Lakes basin coincide with agricultural and industrial land use activities in basins with fine-grained glacio-lacustrine parent materials (Stone & Saunderson, 1996). There are management concerns about the effects of irrigation practices on the delivery of cohesive materials to receiving streams (Richards & Baker, 1993) and the role of these materials in the fluvial transport of contaminants (Ongley *et al.*, 1992).

While some information is available on transport properties of cohesive sediment in rivers (Krishnappan, 1997) and lakes (Lick, 1982), much less is known about transport characteristics of fine-grained tile drain sediment in relation to soil texture. Empirical relationships quantifying erosion and deposition processes are required to model the transport and fate of cohesive sediment and associated contaminants. In this paper, transport characteristics of tile drain sediment collected from a southern Ontario agricultural watershed with silt-clay soils are studied in the laboratory using a rotating annular flume. Empirical relationships required for a fine sediment transport model developed by Krishnappan (1997) are determined.

METHODS

The tile drains under investigation are located in a sub-catchment of the Sydenham River near St Thomas, Ontario. Soils at the study site are characterized as the Huron association of the Perth soil series with silt-clay loam soils that overlay a silt-clay loam till. Mineralogy of the tile sediment includes quartz (35%), anorthite/albite (15%), mica (10%), montmorillonite (15%), kaolinite (10%), calcite (5%) and dolomite (5%). Approximately 5 kg of sediment was collected inside the tile drains and approximately 500 l of filtered (0.63 μm) Sydenham river water was used as a suspending medium for flume experiments.

Rotating flume experiments

A circular flume was used to conduct erosion and deposition experiments on tile drain sediment. The flume is equipped with a Laser Doppler Anemometer that operates in back-scatter mode to measure the flow field. *In situ* size distribution of suspended sediment in the flume is measured with a Malvern Particle Size Analyser that operates in continuous flow-through mode. Sediment concentration was determined by the filtration method (Environment Canada, 1988). Complete details of the flume and its flow characteristics are found in Krishnappan (1993). Additional information on the experimental procedure is reported in Stone & Krishnappan (1997).

Two types of flume experiments were conducted. The first dealt with deposition behaviour while the second examined erosion characteristics of the sediment. For the deposition tests, the flume and top cover were rotated in opposite directions at their maximum speeds for 20 min to thoroughly mix the sediment and water and break up flocs. During the high speed operation, sediment concentration was measured every 5 min and the size distribution every 2 min. After 20 min, flume speeds were reduced to a particular bed shear stress and maintained for a period of about 5 h when the sediment concentration and size distribution of sediment flocs were monitored at regular intervals.

For the erosion experiment, the sediment-water mixture was left undisturbed for 65 and 40 h to allow sufficient time for sediment to settle and age on the flume bed. Flume and top cover speeds were increased incrementally to apply shear stress in a stair-case function. Sediment concentration and size distribution of eroded sediment were measured in the flume as a function of time and shear stress.

RESULTS AND DISCUSSION

A total of eight experimental runs were conducted and a summary of the experimental conditions is given in Table 1.

Deposition tests

Deposition experiments were carried out for five different bed-shear stress conditions. For a bed-shear stress of 0.121 N m^{-2}, two different initial concentrations were tested making a total of six deposition tests (Table 1).

Variation in suspended sediment concentration as a function of time and bed-shear is shown in Fig. 1. The figure shows that after an initial 20 min period during which the flume was operated at high speed to break up the flocs and provide the

Table 1 Summary of experimental conditions.

Test no.	Experiment type	Shear stress (N m^{-2})	Init. concentration (mg l^{-1})	Age of deposit
1	Deposition	0.030	200	n/a
2	Deposition	0.056	200	n/a
3	Deposition	0.121	200	n/a
4	Deposition	0.213	200	n/a
5	Deposition	0.324	200	n/a
6	Deposition	0.121	300	n/a
7	Erosion	n/a	n/a	65 h
8	Erosion	n/a	n/a	40 h

same start up conditions for all runs, sediment concentration decreases gradually and tends to reach a steady state value. Steady state conditions were attained during runs with the highest bed-shear. For the remaining two tests with lower bed-shear, sediment concentration continued to decrease after the 5 h experiment duration indicating that the time to reach steady state is a function of shear stress. For the lowest shear stress test, attainment of steady state is beyond the 5 h and the steady state concentration will be lower than the value measured at the close of the experiment. The critical shear stress for deposition is defined as the bed-shear stress that produces a nil concentration during a deposition test. For the tile sediment, the critical shear stress for deposition is extrapolated as 0.025 N m^{-2}, which is slightly lower than the lowest bed-shear stress (0.030 N m^{-2}) observed in the experimental program.

Deposition characteristics of sediment under constant bed-shear stress with different initial concentrations are presented in Fig. 2. The data show that steady state concentration is a function of initial sediment concentration and for both runs the ratio between the steady state and initial sediment concentration is similar. For the run with lower initial concentration, the steady state concentration is 112 ppm

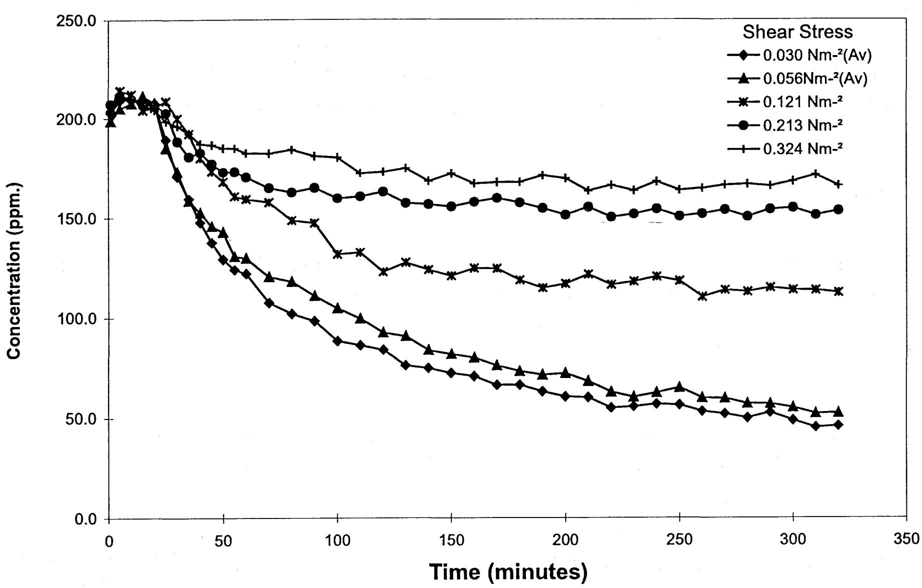

Fig. 1 Sediment concentration *vs* time.

and initial concentration is about 210 ppm. This results in a concentration ratio of 0.533. For the run with the higher initial concentration, the steady state concentration is 175 ppm and the initial concentration is 325 and the ratio is 0.538. Such a result implies that deposition behaviour of tile sediment does not conform to that of non-cohesive sediment for which the steady state concentration is only a function of bed-shear stress and not the initial sediment concentration.

Dependence of steady state concentration on initial concentration has been observed for cohesive sediment by other investigators (Partheniades & Kennedy, 1966; Mehta & Partheniades, 1975; Lick, 1982). An explanation for such a behaviour on the basis of flocculation of cohesive sediments was proposed by Partheniades *et al.* (1968) who argued that cohesive sediments form flocs and that only strong flocs capable of withstanding high shear stress near the bed are deposited while weaker flocs break up at the region of high shear and remain in suspension. Therefore, only a certain fraction of sediment can form stronger flocs and hence the amount remaining in suspension becomes a function of the amount of sediment in the initial suspension.

The tendency of sediment to flocculate during deposition can be inferred from Fig. 3 where the median size (D_{50}) of the distributions measured for different bed-shear stresses are shown as a function of time. The data show that the median size of sediment in suspension changes as a function of time. For low bed-shear stress run (0.030 N m^{-2}), the median size decreases gradually suggesting that the larger particles will settle out leaving finer ones in suspension in a manner analogous to settling of non-cohesive sediment without flocculation (settling as individual particles). However, as shear stress increases, median size of the particles in suspension increases due to flocculation as shown in the run with bed-shear stress of 0.213 N m^{-2} that produced the largest flocs. For this run, median size of flocs grew from an initial value of about 12 μm to about 22 μm at the end of the run but floc size decreased with increasing shear stress. For example, at a shear stress of 0.324

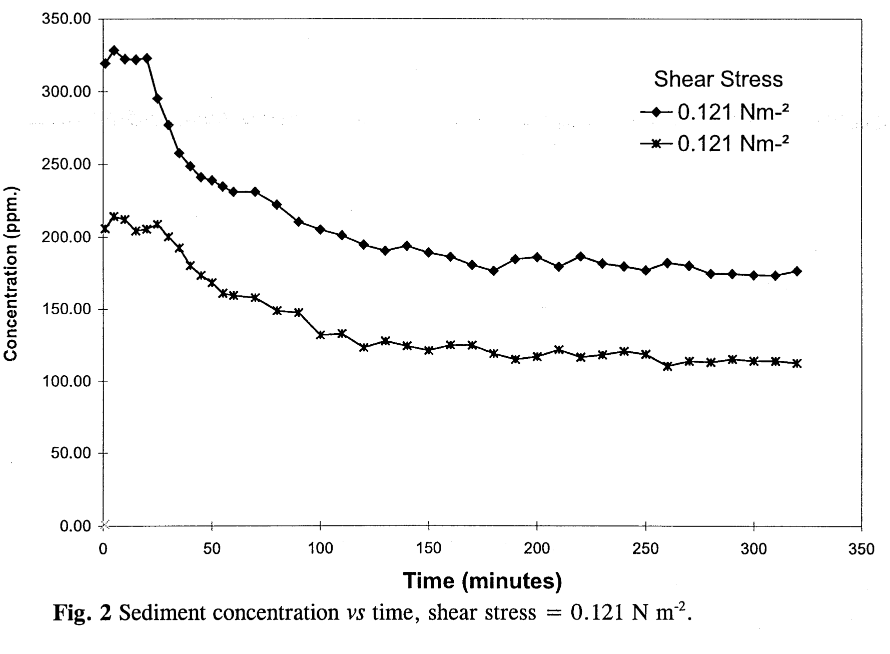

Fig. 2 Sediment concentration *vs* time, shear stress = 0.121 N m^{-2}.

N m^{-2}, the maximum floc size attained was only about 15 μm. At this shear stress flocs cannot withstand the high turbulence and the larger flocs break up. These observations demonstrate that turbulence plays a dual role in flocculation. It promotes flocculation at low shear stress levels and also breaks down flocs at higher levels suggesting an optimum level of turbulence for large floc formation and stability.

Erosion tests

The concentration and median size of the eroded sediment as a function of time and applied shear stress are shown in Fig. 4. The data show that sediment re-suspension did not occur until the bed shear stress reached a value of 0.121 N m^{-2}. The shear stress that initiates sediment erosion is called the critical shear stress for erosion. For tile sediment this value is considerably larger than the critical shear stress for deposition. The inequality between the critical shear stresses for erosion and deposition is a special character of cohesive sediment that causes erosion and deposition processes to be mutually exclusive. For non-cohesive sediment, these critical conditions are equal thus erosion and deposition processes can occur simultaneously (Mehta & Partheniades, 1975; Parchure, 1984; Lau & Krishnappan, 1994).

The size distribution data in Fig. 4 suggest that sediment erosion begins as larger sediment flocs are removed from the bed. Initially, the size distribution is coarse but as bed shear increases these materials (flocs) break up and the size distribution becomes finer.

Transport functions for the tile drain sediment

The present experiments allow transport functions for deposition and erosion of the tile drain sediment to be determined. From the deposition experiments, it was shown

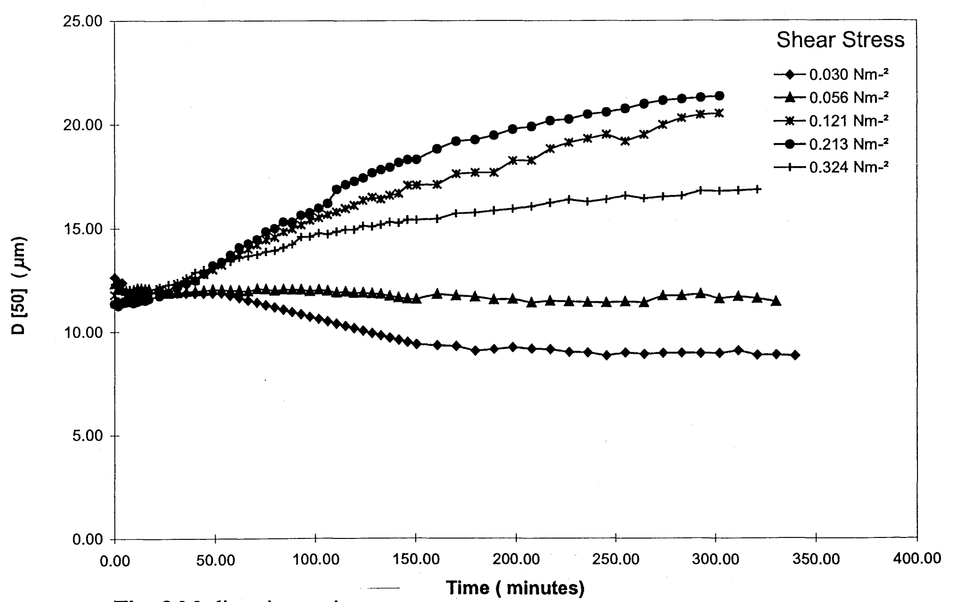

Fig. 3 Median size *vs* time.

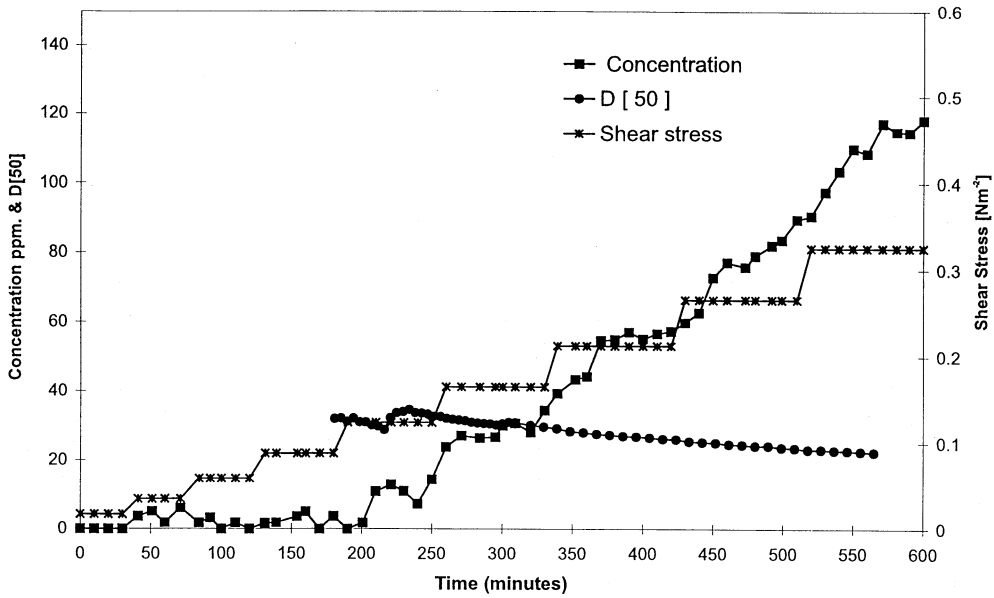

Fig. 4 Concentration, shear stress and median size *vs* time.

that the amount of sediment deposited under steady state conditions for a given bed shear is a function of the amount of sediment initially introduced to the system and the fraction of sediment deposited is constant when bed shear is held constant. This information can be used to establish a relationship between the fraction of sediment deposited and bed shear stress. This relationship is shown in Fig. 5 where the bed shear is expressed in terms of the critical shear stress for deposition. The data show that when bed shear is at or below the critical shear stress for deposition, the fraction of sediment deposited takes a value of unity and this fraction decreases with increasing bed shear. When bed shear is about 20 times the critical shear stress for deposition, the fraction deposited becomes zero and all of the initially suspended sediment stays in suspension. A power law relationship between the fraction deposited and the ratio of bed shear stress to the critical shear stress for deposition was fitted and presented as a solid line in Fig. 5. The relationship takes the following analytical form:

$$\begin{aligned} f_d &= 1.0 - 0.33(\tau_0 / \tau_{cd} - 1)^{0.373} && \text{for } \{1 < \tau_0 / \tau_{cd} < 20\} \\ f_d &= 1.0 && \text{for } \{\tau_0 / \tau_{cd} < 1\} \\ f_d &= 0 && \text{for } \{\tau_0 / \tau_{cd} > 20\} \end{aligned} \tag{1}$$

where f_d is the fraction deposited, τ_0 is bed shear stress and τ_{cd} is the critical shear stress for deposition.

The erosion experiments show that at each shear stress step, the variation of sediment concentration with time was similar; a steep increase as the shear stress was applied followed by a gradual increase towards a steady state concentration. The magnitude of the steady state concentration at a particular shear stress step was lower than the steady state concentration during the deposition experiment with the same bed shear stress. For the maximum shear stress (0.324 N m^{-2}) tested, not all deposited sediment was re-suspended. The maximum concentration reached was only

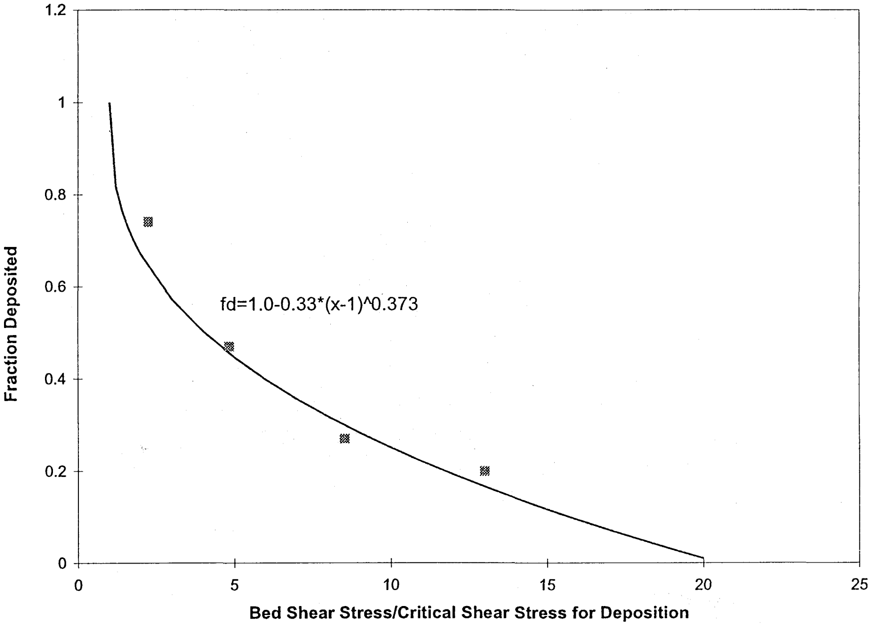

Fig. 5 Deposition function.

about 60% of the total concentration that would have resulted from complete re-suspension. For complete re-suspension, a shear stress 30 times larger than the critical shear stress for deposition would have been required. From the erosion experiments, the fraction of re-suspension was determined for various bed shear

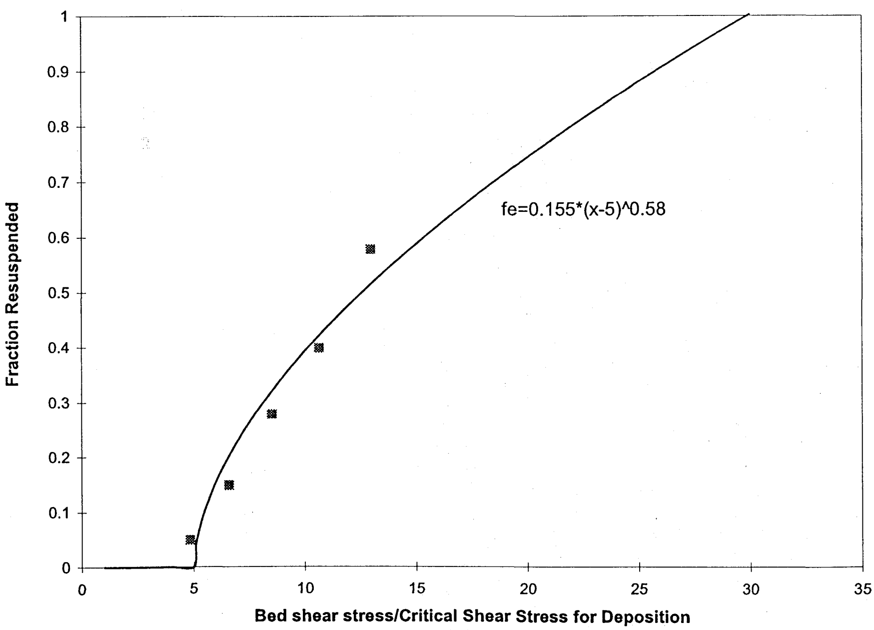

Fig. 6 Erosion function.

stresses and plotted in Fig. 6. A power law relationship was fitted through the experimental points. The form of the power law is shown below:

$$\begin{aligned} f_e &= 0.155(\tau_0 / \tau_{cd} - 5.0)^{0.58} && \text{for } \{5.0 < \tau_0 / \tau_{cd} < 30\} \\ f_e &= 0 && \text{for } \{\tau_0 / \tau_{cd} < 5.0\} \\ f_e &= 1 && \text{for } \{\tau_0 / \tau_{cd} > 30\} \end{aligned} \tag{2}$$

where f_e is the fraction of sediment re-suspended. For a sediment fraction that is deposited at a shear stress different from the critical shear stress for deposition, the above function can still be used with the following modifications: (a) the critical shear stress term has to be replaced by the shear stress at which the deposition occurred and (b) the upper limit of the shear stress has to be maintained at the original value of 30 times the critical shear stress for deposition. Using the two functions given by equations (1) and (2), the transport characteristics of tile drain sediment can be investigated using models for cohesive sediment transport such as the one developed by Krishnappan (1997).

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