

Soil Erosion Processes and Sediment Sorting at Low Flow Rates

H. Asadi^a, H. Ghadiri^b, C.W. Rose^b, B. Yu^b, and J. Hussein^b

^a Soil Science Department, Faculty of Agriculture, Guilan University, Rasht 41635-1314, Iran.

^b Faculty of Environmental Sciences, Griffith University, Nathan, Queensland 4111, Australia.

Abstract

There is a need to describe sediment sorting where the on-site and off-site effects of soil erosion are studying. There is general agreement among researchers that sediment leaving an area is finer than that of the soil under surface erosion. But in some cases, it has been observed that the coarser particles transported at rates greater than the finer one. This paper describes experiments on different soil types in which the time variation in size distribution of the exiting sediment is measured. The objective was to investigate the processes that control the size distribution of the sediment at the low flow rates. The experiments were carried out on the three soils in the 1 x 6 m flume of Griffith University's large rainfall simulation facility, with overland flow confined to uniform rectangular rills pre-formed in the soil bed. The results supported a selective pattern (bimodal) for transporting of the particles of various size classes, with peaks at the finest class and the size class of 1-2 mm. The particles between 0.1-0.5 mm appeared to resist against transportation. It seems that the presence of different transport mechanisms acting on various size classes (suspension-saltation and rolling) and differences in resistance to transportation (transportability) of various size classes are responsible for selectivity in transportation at the low flow rates.

Introduction

There is a need to describe sediment sorting where the on-site and off-site effects of soil erosion are studying. Many studies in the past have investigated the sediment sorting and tried to simulated and determine the processes that affecting it. There is general agreement among researchers that sediment leaving an area is finer than that of the soil under surface erosion (e.g. Aberts et al., 1980, 1983; Foster et al., 1985). But in some cases, it has been observed that the sediment size distribution is bimodal (Meyer et al. 1980; Loch and Donnollan, 1983). At the steady state condition, many researchers (e.g. Moss et al., 1979; Govers, 1985; Proffitt and Rose, 1991; Hairsine and Rose, 1992a, b) believe that size distribution of the sediment is very similar to the original soil.

There are still some conflicting and unexplained results regarding to the prediction of sediment sorting (e.g. Beuselinck et al., 2002; Rose et al., 2006). The development of accurate erosion prediction models requires more understanding of detachment and transport mechanisms of particles in a wide range of conditions. The existence and importance of mechanisms such as rolling in sediment transport is not clear yet. There is also no any clear reason describing the mechanism of bimodal sediment size distributions mentioned above. This paper describes experiments on different soil types at the low flow rates in which the time variation in size distribution of the exiting sediment is measured.

Materials and Methods

The experimental data used in this paper were obtained using the Griffith University Tilting Flume Simulated Rainfall (GUTSR) Facility. Three contrasting soil types were used for this study. A soil from the Toohey Forest area of Griffith University (Nathan Campus) which was treated by washing the organic waterproof component and much of its clay fraction, the treated soil had 940 gr kg⁻¹ sand; a Krasnozem (red clay) from Redlands Bay Research Station with 430 gr kg⁻¹ clay, and a Vertosol (self-mulching black clay) with 640 gr kg⁻¹ clay. These three soils have been referred as Toohey, Red Earth and Black Earth respectively. The Toohey soil was free of any water stable aggregates.

Five experiments were carried out with overland flow confined to uniform rectangular rills pre-formed in the soil bed, three on Black Earth (R1, R2 and R3), one on Red Earth (R4) and one on Toohey soil (R5). The slope was the same (2 percent) for all experiments. Flow was provided at the top of the flume at a constant rate. Uniform rills were artificially developed in the flume bed that already had been filled with ten centimeters soil, saturated for some hours with Brisbane town water and let to stabilize for a couple of days. Soils were freed of clods greater than about 8 mm and undecomposed organic material (such as grass). The details of the experiments are given in Table 1. Experiment duration was 15 minutes for the Black and Toohey soil and 30 minutes for Red Earth.

Table 1- Rill dimensions and hydraulic characteristics of flow for the rill experiments

Parameter	Rill No.1	Rill No.2	Rill No.3	Rill No.4	Rill No.5
Soil type	Black	Black	Black	Red	Toohey
Mean weight diameter (mm) of soil particles	1.15	1.15	1.15	1.70	0.61
Base width of rill ($m \times 10^{-2}$)	6.5	6.5	8.0	6.5	6.5
Top width ($m \times 10^{-2}$)	7.0	7.0	9.0	7.0	7.0
Depth of rill ($m \times 10^{-2}$)	1.0	1.0	1.5	1.0	1.0
G, flow rate ($m^3 s^{-1} \times 10^{-3}$)	0.052	0.086	0.100	0.040	0.025
Surface flow velocity (m s ⁻¹)	0.286	0.370	0.286	-	-
Reynolds number	701	1160	1096	539	337
Calculated flow depth ($m \times 10^{-3}$)	5.2	7.2	7.0	5.2	3.0
Calculated mean flow velocity (m s ⁻¹)	0.178	0.224	0.210	0.137	0.140
Stream power (W m ⁻²)	0.157	0.261	0.246	0.121	0.076
Steady state sediment concentration (kg m ⁻³)	5.5	10.5	7.1	2.2	4.5

*Manning's n was assumed to be 0.025, 0.025 and 0.020 for calculating of mean flow velocity and water depth for Black, Red and Toohey soil respectively.

For all three soils, the size distribution of soil aggregates or particles was measured by wet sieving after direct fast wetting. The nest of sieves used in wet sieving contained sieves of size 4, 2, 1, 0.5, 0.25, 0.125, 0.075 and 0.038 mm. Wet sieving duration was 10 minutes at a rotation rate of 35 RPM. In all experiments, runoff was periodically sampled to yield measurement of sediment concentration and also (by wet sieving) the aggregate size distribution of eroded sediment leaving the flume during the experiments. After each experiment, the aggregate size distribution of surface soil (rill bed) was also determined by wet sieving. Sampling depth was about 4 mm.

The original uneroded soil was subdivided into *I* size classes each having an equal mass fraction using the wet sieving data (as described by Asadi et al. (2006)). *I* was 10 for the Black and Red Earth and 20 for Toohey soil. The fraction of each of *I* size classes in outflow sediment at different times was then obtained using the size boundaries obtained from subdividing the original soil into equal classes.

Results and Discussions

Sediment size distributions for materials leaving an area could be a function of either aggregate size distribution of original soil, settling velocity of different size classes, selective transport of various size fractions, or a combination of all. The effects of aggregate size distribution of original soil could be eliminate by dividing it to an arbitrary number (*I*) of size classes, with an equal mass of soil in each class using the concepts of GUEST model (Misra and Rose, 1996). Figure 1a, 1b and 1c show the mass fractions of each of the 10 size classes, defined for Black Earth, in outflow sediment at different times for experiments R1, R2 and R3.

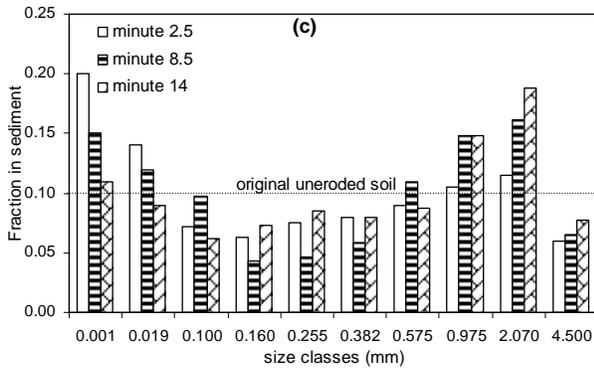
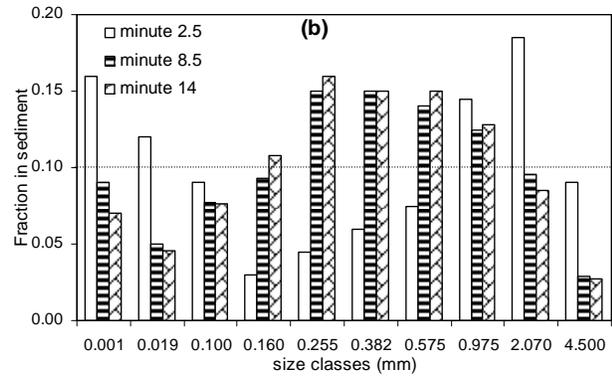
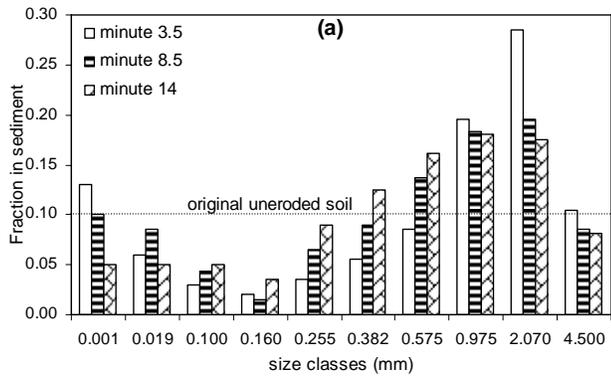


Fig. 1- Mass fractions of the 10 size classes in outflow sediment at the different times for the experiments carried out on Black Earth, (a) R1, (b) R2, and (c) R3.

For all three experiments on Black Earth, at the earlier time (minute 3.5 for R1 and 2.5 for R2 and R3), sediment size distribution as shown (Fig. 1a,b,c) appears bimodal, with peaks at the finest class of 0.001 mm and the size class of 2.07 mm, and two minimums at 0.16 mm and 4.5 mm. The size class of 2.07 mm alone included 30% of the sediment at the earlier time for the experiment of R1 (Fig. 1a), at the same time the size class of 0.16 mm is transported at the rate 14 times slower than the 2.07 mm class. At the earlier times, when the erosion event (runon) has not been too progressed to change significantly size composition of the soil bed and then we can emphasize that all 10 size classes has equal mass in the soil, figure 1 shows that the fraction of each class decreases with increasing of size until the size of 0.16 mm, then increases until the size of 2.07 mm and then decreases again.

The mass fractions of the easily transported classes decrease with time (Fig. 1a, b, c) because their fractions in soil surface are reducing with progress of erosion. In contrast, the mass fraction of the hardly transported size classes increase with time due to relative increasing in their fractions at the soil surface. In spite of these changes, sediment size distribution is bimodal through of the event. In this soil and under the above experiment conditions, size class of 0.16 mm seems to have the highest resistance to transportation. The results of experiments on Red Earth and Toohey soil also show similar patterns (Fig. 2 a, b), but with some differences in the peaks and minimums.

The differences between the experiments are due to difference between the hydraulic characteristics of the flow, the rill dimensions and soil type (Table 1). Stream power and consequently sediment concentration are higher, for example for R2 than for two other experiments (R1 and R3) on Black Earth and therefore the changes with time in fraction of various size classes (Fig. 1b) are more for this experiment than two others. On the other hands, Red Earth has the highest MWD and the flow rate used for it (exp. R4) was low in comparing with R1 and R2 (Table 1), and therefore the second peak of the sediment size distribution (Fig. 2a) is not too sharp as it is for other experiments.

To support the above pattern of sediment transport, particle size distribution of the rill bed was determined after each experiment. The hardly transported classes should accumulated in the surface of soil bed, and in contrast soil bed should depleted from easily transported particles. Particle size distribution of the rill beds after the experiments (Fig 3) also supports selectivity in transport of various

particle size classes. The fraction of the finer and the larger particles is relatively low and the fraction of the middle size classes is high. The very low fraction of the coarser class (4.5 mm) is due to this fact that when we sample soil surface for analyzing particle size distribution after experiment, we try to take a sample as thin as possible to shows clearly the effect of erosion. Therefore, the fractions are presented in Fig. 3 are relative values rather than the exact values presented for example in figures 1 and 2. The sampling depth in this study was about 4 mm.

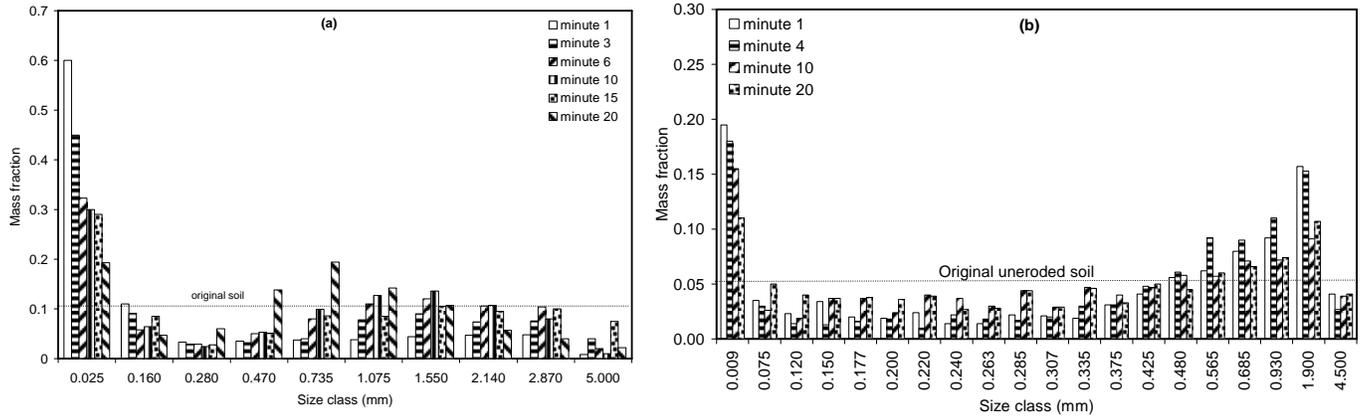


Fig. 2- Mass fractions of the *I* size classes in outflow sediment for the experiments on (a) Red Earth, and (b) Toohey soil at the different times.

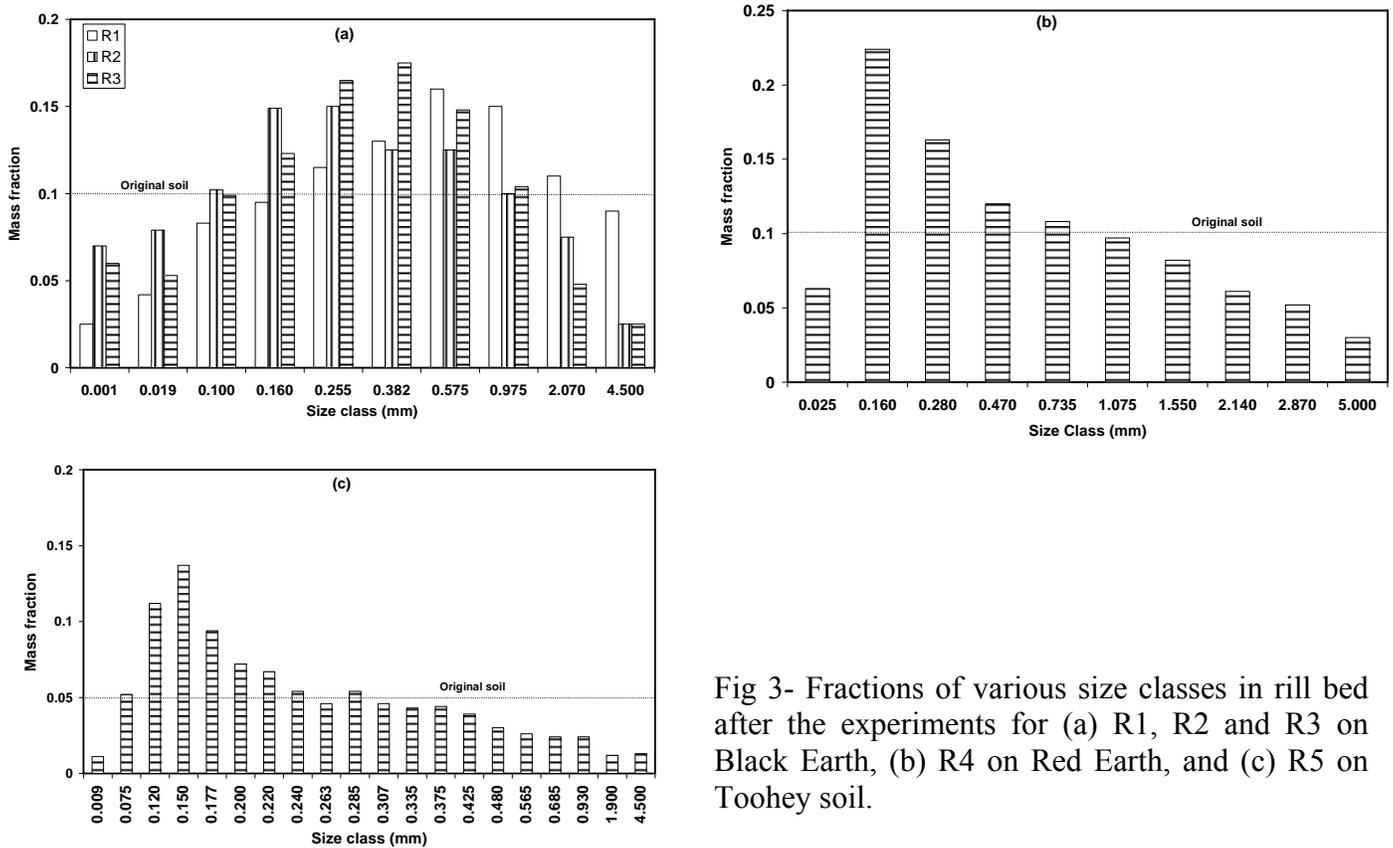


Fig 3- Fractions of various size classes in rill bed after the experiments for (a) R1, R2 and R3 on Black Earth, (b) R4 on Red Earth, and (c) R5 on Toohey soil.

Selective transport of various size particles:

Differences between the mass fractions of *I* size classes in the sediment and their changes with time (Figs. 1 and 2) and also the fraction of each class in the soil bed (Fig. 3) supported a selective pattern for transporting of the particles. Selective transport of various size classes could be due to either presence of different transport mechanisms acting on various size classes, differences in resistance to transportation (transportability) of various size classes, or both.

1- Different mechanisms of sediment transport:

The bimodal selectivity pattern of the transported sediment shown in figures 1 and 2, especially at the earlier times, shows the presence of at least two different transport mechanisms. The first part of the pattern, could be interpreted by the concept of suspension-saltation mechanism (e.g. 7, 8, 9, 14), in which the processes of entrainment and re-entrainment suspended all particle sizes unselectively and deposition returned the larger particles selectively. This theory has two outcomes. First, the continuous action of these processes leads to outflow sediment be enriched of finer particles at the earlier times. Second, the sediment leaving an area of sheet or rill flow should be finer than the original soil and especially each size class should transported at a rate less than the finer classes and higher than the coarser classes. The size classes finer than 0.1-0.5 mm appear to transport mainly as suspended load by suspension-saltation mechanism. The mass fraction of this size classes decrease with increasing in class size because of increasing in deposition rate due to their higher settling velocities.

On the other hands the second part of the pattern could not be interpret using the suspension-saltation theory. The size classes coarser than about 0.5 mm probably transported more as bed load by rolling mechanism. The acting force for this mechanism could be drag force that increases with particle diameter as shown by the following equation.

$$D_r = 3\mu\pi d_p V \quad (1)$$

where μ is dynamic viscosity of water, d_p is particle diameter and V is flow velocity. Therefore in this range of particle size, transportation of the particles increases with particle diameter up until the weight of particle becomes high enough to prevent transportation. This has been occurred for the size class of 4.5 mm for example in this study.

Moss et al. (1979) noted that sediment transport can be divided into suspended, saltating and contact (rolling) loads, each normally being broadly associated with particular sediment size ranges. The boundary for suspended load was adapted to 0.02 mm by Loch and Donnollan (1982). They also indicated a transition from saltating to contact load in the size range of 0.125-0.250 mm. If we consider suspended load and saltating load as a unique mechanism (suspension-saltation), as discussed above, our size analysis suggested 0.16, 0.28 and 0.25 mm as boundary between bed load transport and suspended load for Black Earth, Red Earth and Toohey soil respectively. Then the size boundary between suspension and bed load transport seems to be related to soil type. It is also depended to flow shear stress as shown by the Shields-type entrainment curves.

2- Difference in Transportability of Various Size Classes:

An alternative explanation to that given here for the type of observation illustrated in figures 1 and 2 could be differences in transportability of various size classes. Various particle size classes may have different resistance to transportation (cohesion) rather than exposing to different forces. Cohesion due to water bond may play an important roll in transportation of particles. Cohesion changes with particle size and usually decreases with increasing in particle size. Particle size classes in the range of 0.1-0.5 mm seem to have the highest resistance to transportation, particles finer than this range because of suspension and particles larger than this range because of lower cohesion transported easier than the particles in the range of 0.1-0.5mm. The largest particles, i.e. 4.5 mm, also resists to transportation probably due to their very high weight.

References

- 1- Alberts, E. E.; W. C. Moldenhauer, and G. R. Foster. 1980. Soil aggregates and primary particles transported in rill and interrill flow. *Soil Sci. Soc. Am. J.* 44: 590-595.
- 2- Alberts, E. E.; R. C. Wendt, and R. F. Priest. 1983. Physical and chemical properties of eroded soil aggregates. *Trans. ASAE* 26: 465-471.
- 3- Asadi, H.; H. Ghadiri; C. W. Rose, and H. Rouhipour. 2006. Interrill soil erosion processes and their interaction on low slopes. *Earth Surface Processes and Landforms*, (under press).
- 4- Beuselinck, L.; P. B. Hairsine; G. C. Sander, and G. Govers. 2002. Evaluating a multiclass net deposition equation in overland flow conditions. *Water Resource Research*, Vol. 38 (7): DOI 10.1029/2001WR000250.
- 5- Foster, G. R.; R. A. Young, and W. H. Neibling. 1985. Sediment composition for nonpoint source pollution analysis. *Trans. of the ASAE*, 28(1): 133-139,146.
- 6- Govers, G. 1985. Selectivity and transport capacity of thin flows in relation to rill erosion. *Catena* 12: 35-49.
- 7- Hairsine, P. B., and C. W. Rose. 1992a. Modeling water erosion due to overland flow using physical principles, I. Sheet flow. *Water Reso. Res.* 28(1): 237-243.
- 8- Hairsine, P. B.; and C. W. Rose. 1992b. Modeling water erosion due to overland flow using physical principles, II- Rill flow. *Water Reso. Res.* 28(1): 245-250.
- 9- Hairsine, P. B.; G. C. Sander; C. W. Rose; J.-Y. Parlange; W. L. Hogarth; I. Lisle, and H. Rouhipour. 1999. Unsteady soil erosion due to rainfall impact: A model of sediment sorting on the hillslope. *J. Hydro.* 199: 115-128.
- 10- Loch, R. J., and T. E. Donnollan. 1982. Field rainfall simulator studies on two clay soils of the Darling downs, Queensland. II. Aggregate breakdown, sediment properties and soil erodibility. *Aus. J. of Soil Res.* 21: 47-58.
- 11- Meyer, L. D.; W. C. Harmon, and L. L. McDowell. 1980. Sediment size eroded from crop row sideslopes. *Trans. of the ASAE*, 23: 891-898.
- 12- Misra, R. K., and C. W. Rose. 1996. Application and sensitivity analysis of process-based erosion model GUEST. *Euro. J. of Soil Sci.* 47:593-604.
- 13- Moss, A. J.; P. H. Walker, and J. Hutka. 1979. Raindrop-stimulated transportation in shallow water flows: An experimental study. *Sediment Geol.* 22: 165-184.
- 14- Proffitt, A. P. B., and C. W. Rose. 1991. Soil erosion processes: II. Settling velocity characteristics of eroded sediment. *Aus. J. of Soil Res.*, 29:685-695.
- 15- Rose, C. W.; B. Yu; H. Ghadiri; H. Asadi; J. Y. Parlange; W. L. Hogarth, and J. Hussein. 2006. Dynamic erosion of soil in steady sheet flow. Submitted to *J. of Hydrology*.