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677 South Segoe Rd., Madison, WI 53711 USA

DETACHMENT OF SOIL BY FLOWING WATER UNDER TURBULENT AND LAMINAR CONDITIONS

M. A. NEARING* AND S. C. PARKER

Abstract

Fluid turbulence of water flowing over soil surfaces imparts instantaneous and localized levels of shear stress to the fluid–solid interface that are much greater than the average shear stress of flow. It has been hypothesized that these high levels of instantaneous shear are the driving mechanism for detachment of cohesive soil by flowing water. The purpose of this study was to test the hypothesis that detachment of soil by flowing water at a given shear stress is dependent on turbulence. Detachment rates of three soils were measured in a hydraulic flume at seven combinations of flow depth and bed slope under both turbulent and laminar flow conditions. For all soils and all slope/depth treatments, detachment was dramatically greater for the turbulent case compared with the laminar case. Detachment that occurred under laminar flow conditions was thought to be due in part to localized turbulence associated with pitting of some of the samples.

THE AVERAGE SHEAR STRESS of flowing water that causes detachment of soil in upland areas is commonly of the order of Pascals, whereas soil strengths, even under tensile failure conditions, are of the order of kPa. This apparent paradox has been explained as being due to instantaneous, higher than average levels of shear stress that accompany velocity fluctuations within turbulent flow (Nearing, 1991; Nearing et al., 1991a; Raudkivi and Tan, 1984). Cleaver and Yates (1973) developed a conceptual model based on the mechanics of turbulent flows, and specifically turbulent bursts, which impart high levels of instantaneous shear stress on the soil surface and cause detachment of particles.

Nearing et al. (1991a) performed a series of flume studies to measure the detachment of soil under turbulent flows. Their results would indicate that detachment is not a unique function of average flow shear stress alone. Whereas shear stress is proportional to both flow depth and bed slope, detachment was more sensitive to slope than to flow depth. At equivalent levels of average shear stress at different slopes, more detachment always occurred for the case of the greater slope. Nearing (1991) developed a probabilistic model for detachment by turbulent flow that emulated several aspects of measured data, including the occurrence of detachment even with the wide disparity between average shear stress of flow and soil strength as discussed above and the empirical observation that detachment rates were more strongly affected by changes in bed slope than by changes in flow depth. The model takes into account the difference in the frequency of the turbulent bursting events for shallower flows to explain why the detachment rate was more sensitive to slope than to flow depth.

In spite of the successful application of the probabilistic turbulence model of detachment, the evidence that turbulent fluctuations of shear stress are the driving mechanism for detachment by flow is not conclusive. The purpose of this study was to measure detachment rates of soil by flowing water under laminar and turbulent conditions at equivalent levels of average shear stress. The hypothesis was that in the absence of turbulent shear stress fluctuations, detachment rates would be negligible due to the fact that flow shear stresses would not exceed the strength of the soil.

Methods

Other than for a few exceptions discussed here, the measurements of detachment rates by flowing water were made in a hydraulic flume using techniques identical to those described by Nearing et al. (1991a). The reader is referred to that source for detailed information on the testing technique. The flume was a split flow device. Water entered the upper end of the flume via a curved, gradually narrowing inflow section, and the lower portion of the flow was allowed to pass under the flume bottom, thus eliminating the boundary layer at the entrance. The boundary layer is the portion of flowing water with reduced velocity due to friction between the moving water and the flume bottom. The overall effect was that flow was laminar in the upper section of the flume and passed through well-defined stages of transitional to turbulent flow along the length of the flume.

Tests for detachment were made in either the fully laminar or fully turbulent regions of the flume. The flow rate in the flume was adjusted prior to testing so that the flow for the region being tested was at the desired depth (accurate to ≈0.5 mm). Because flow depth was different for the laminar vs. turbulent region of the same flow rate, each had to be calibrated separately with different rates of flow to obtain the same shear stress levels in the two regions. Only the turbulent regime was used in the study of Nearing et al. (1991a).

Detachment rates were quantified by measuring the difference between the amount of soil in the test cylinder prior to detachment and the amount after the test. Because the amount of soil loss was quite low for the laminar case, the initial flush of sediment was subtracted from the measured soil loss data. For every sample, there is an initial flush of loose sediment that rests on the top of the core and washes off when the water first crosses the sample. This amount was measured separately for each of the three soils with eight replicates, and the average value so obtained was used as the flush amount for each of the soils.

Three soils were used: the Miami silt loam (fine-loamy, mixed, mesic Typic Hapludalf) from central Indiana, the Paulding clay (very-fine, illitic, nonacid, mesic Typic Haplaquept)

USDA-ARS, National Soil Erosion Research Lab., 1196 SOIL Building, Purdue Univ., West Lafayette, IN 47907-1196. Received 15 Nov. 1993. *Corresponding author.

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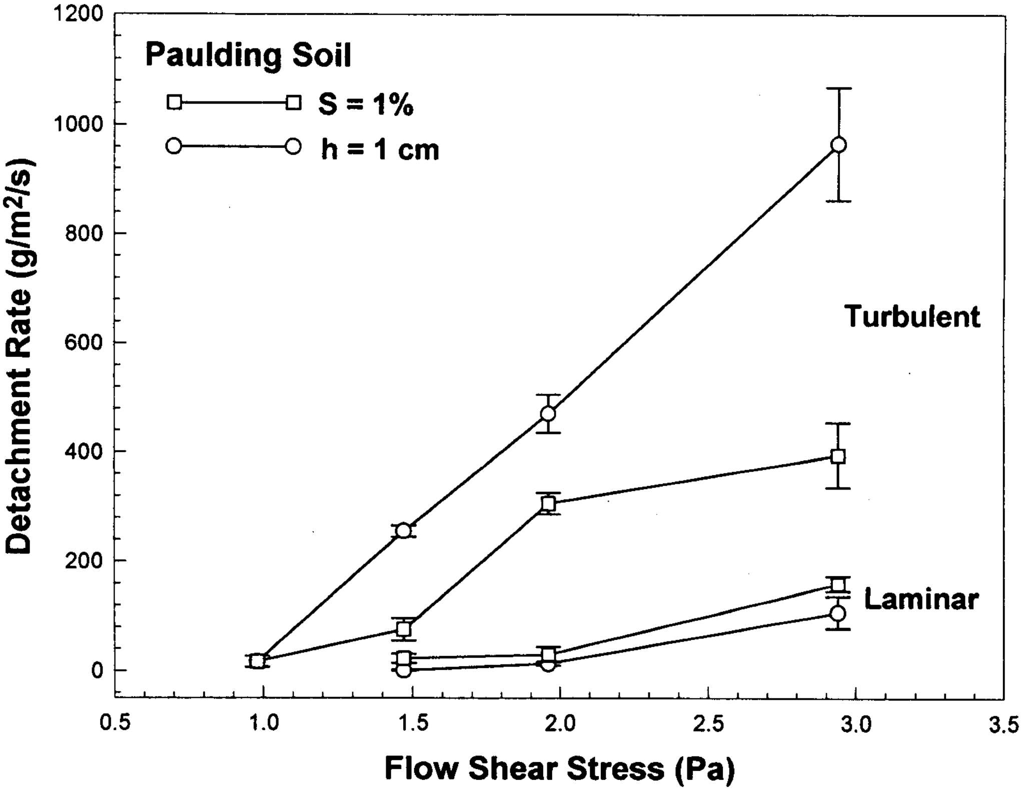

Fig. 1. Detachment rate vs. flow shear stress for turbulent and laminar flow conditions with (i) constant bed slope (S = 1%) and variable flow depth, and also (ii) constant flow depth (h = 1 cm) and variable bed slope for the Paulding soil. Error bars represent 95% confidence interval.

from northwestern Ohio, and the Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult) from northern Georgia. The Miami contained 223 g clay kg^{-1}, 684 g silt kg^{-1}, and 93 g sand kg^{-1}. The Paulding had 535 g clay kg^{-1}, 370 g silt kg^{-1}, and 95 g sand kg^{-1}. The Cecil had 102 g clay kg^{-1}, 154 g silt kg^{-1}, and 744 g sand kg^{-1}. The Paulding and Miami

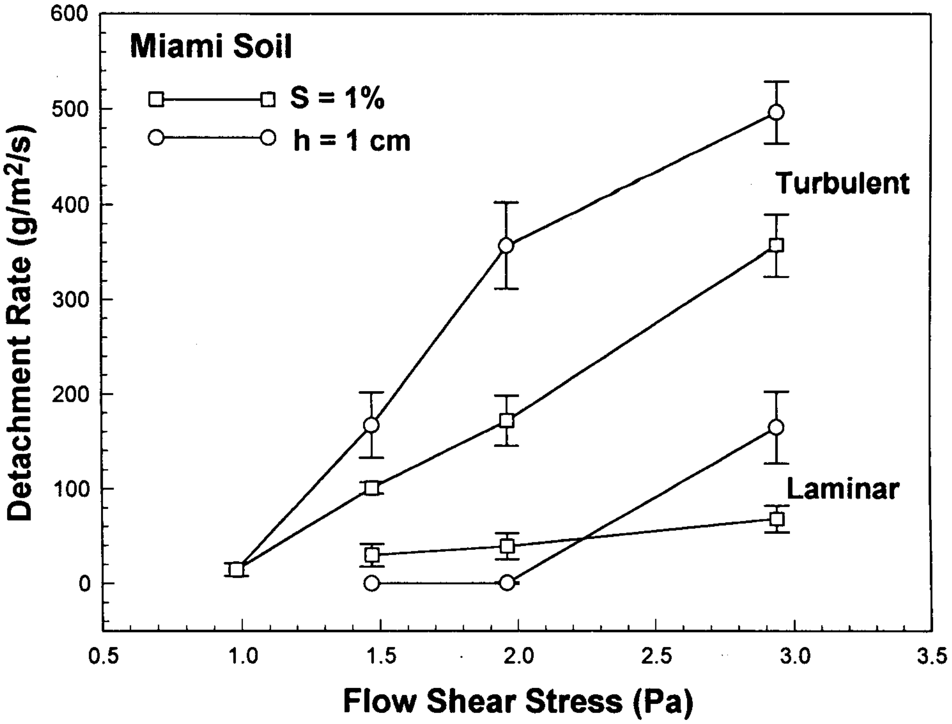

Fig. 2. Detachment rate vs. flow shear stress for turbulent and laminar flow conditions with (i) constant bed slope (S = 1%) and variable flow depth, and also (ii) constant flow depth (h = 1 cm) and variable bed slope for the Miami soil. Error bars represent 95% confidence interval.

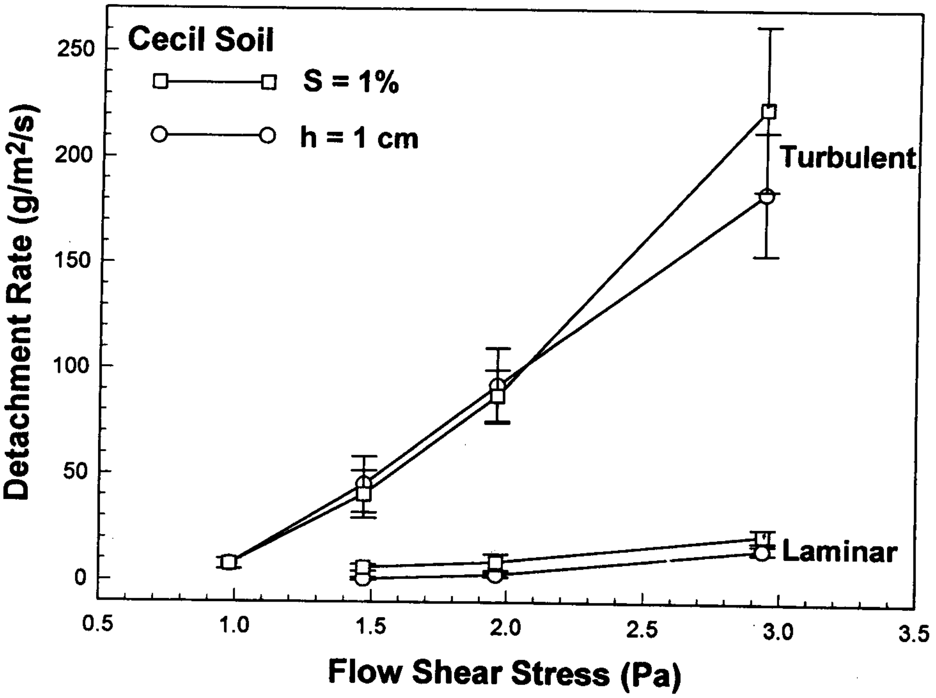

Fig. 3. Detachment rate vs. flow shear stress for turbulent and laminar flow conditions with (i) constant bed slope (*S* = 1%) and variable flow depth, and also (ii) constant flow depth (*h* = 1 cm) and variable bed slope for the Cecil soil. Error bars represent 95% confidence interval.

soils were very similar to the Paulding and Russell soils, respectively, used by Nearing et al. (1991a). The dry soil was sieved to remove aggregates >4 mm prior to testing. Tensile strengths for these soils have been measured. The tensile strength for the Miami soil ranged from 1.1 to 1.3 kPa (Nearing et al., 1991b), for the Cecil soil from 1.0 to 1.3 kPa (Nearing et al., 1991b), and for the Paulding soil from 1.1 to 2.0 kPa (Nearing et al., 1991a). As in the study of Nearing et al. (1991a), treatments were replicated eight times, with some loss of individual samples due to handling.

Results and Discussion

Results for measured detachment rates vs. shear stress are plotted in Fig. 1 to 3. As was the case in previous studies, detachment occurred at levels of average hydraulic shear that were much less than the measured tensile strengths of the soils. For each soil and each shear stress level, detachment by turbulent flow was much greater than for laminar flow. Detachment rates for the laminar condition were very low. It was apparent during the experiment that under laminar flow conditions, very little observable detachment occurred unless the top of the core became pitted. If a piece from the top of the core was removed so that a pit developed, a localized area of swirling would develop and the rate of detachment appeared to increase dramatically. The soil samples on which this process was observed had higher loss of soil than the other replicates of the same treatment. Thus, some of the detachment that was recorded as being taken under laminar conditions is thought to be due to localized turbulence associated with pitting of some of the samples.

Detachment rate increased more with an increase in shear stress through bed slope than with an equivalent increase in shear due to flow depth increase for the Miami and Paulding soils. This results is consistent with the results of Nearing et al. (1991a) for the Russell and Paulding soils. The Cecil soil behaved differently, however. Detachment was a unique function of shear stress for the Cecil. Detachment rate at 2.94 Pa when slope was 1% and depth was 3 cm was not statistically different ($P = 0.05$) than when slope was 3% and depth was 1 cm. Apparently, the form of the relationship between soil detachment rate, bed slope, and flow depth is dependent upon soil type.

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