Relationship of Rainfall Induced Erosion to Shear Strength and Compressive Strength

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Abstract

An empirical relationship of soil erosion as a function of rainfall intensity, soil shear strength and soil compressive strength is being developed from a laboratory model to help in predicting soil loss and subsequent increase in total suspended solids leaving a highway construction site during a rainfall event, from simple field measurements. The model consists of a rainfall simulator and a water flume. The rainfall simulator can produce simulated rainfall with intensity as high as 10 inches per hour; the flume is 4.8 meters long and 1.2 meter wide. The relationship is part of a rainfall-runoff-erosion model to allow a highway engineer to evaluate planned temporary sediment controls (TSC) that may be part of a Storm Water Pollution Prevention Plan (SW3P) required for the construction project.

Soil loss is measured on a volumetric basis, then could be converted to mass based on the density. The results of the on-going work will be presented and the usefulness of the model will be compared to data from an actual construction site.

Introduction and Problem Statement

Rainfall and stormwater induced soil erosion is the major source of stormwater solids, and may serve as a transport mechanism for pollutants. High lead and cadmium concentrations are associated with fine grained soils of 20 to 50 microns, and polycyclic aromatic hydrocarbons are associated with particulate in the 6 to 60 micron range (Xanthnpoulous C., et al., 1992). Whipple et. al. (1981) reported that PAHs, heavy metals, and pesticides are common constituents of stormwater runoff and are associated with the particulate portion of the runoff. The topic of soil erosion is well

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studied and many empirical and theoretical relationships are postulated between soil erosion and soil properties. The most widely used method of predicting soil erosion is the Universal Soil Loss Equation (USLE), modified by Evans and Kalkanis (1976),

$$E = A\times R\times K\times L\times S\times C\times P; \tag{1}$$

where, E, is the soil loss in mass per acre; A, is a constant usually taken as 2.24; R, is a rainfall factor related to the kinetic energy of falling rain; K, is an erodibility index; LS, is a topographic factor accounting for the combined effect of slope length L and slope angle S; C is a cropping-management factor and P, is an erosion control factor. While the factors in the equation capture what are thought to be the principal erosion mechanisms, the method requires the use of descriptive site characteristics rather than measurements. This research is attempting to correlate easy to measure soil properties, such as: shear strength, compressive strength and rainfall rate, with erosion volumes, with intent to replace the K and R factor by empirical functions. After that, this relationship, together with the real data from the highway construction site, can allow the highway engineer evaluate the planned temporary sediment controls (TSC) that may be part of the Storm Water Pollution Prevention Plan (SW3P) required for the construction project.

Method and Material

To simulate erosion under controlled conditions, we built a rainfall simulator and a

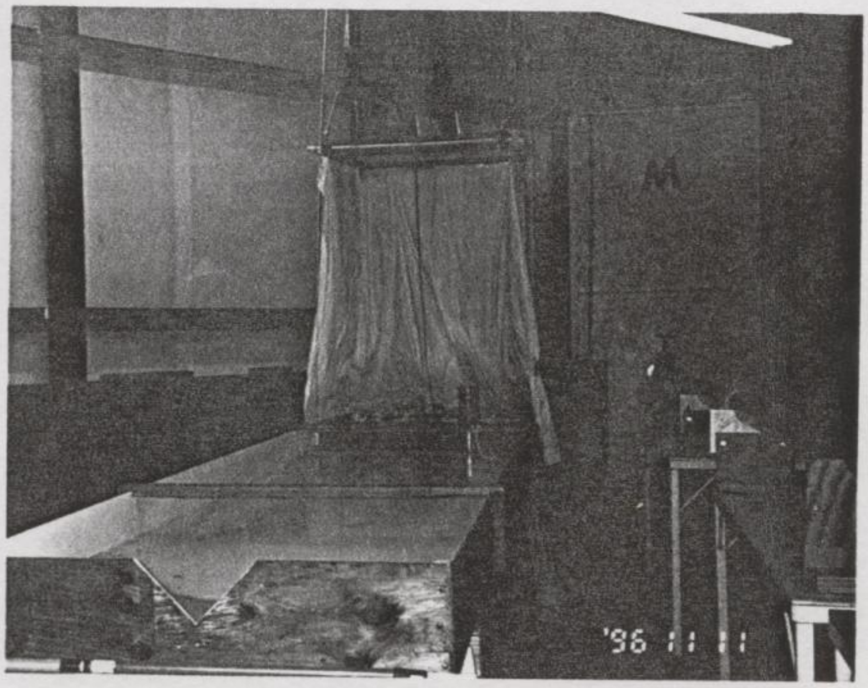


Figure 1. The flume and rainfall simulator.

water flume as shown in Figure 1. The rainfall simulator can produce simulated rainfall with intensity as high as 10 inches per hour; the flume is 4.8 meters long and 1.2 meter wide. Calculations using Stoke's theory for a 1 mm raindrop show that the simulated rain drops could reach approximately 50% of terminal velocity, so the model is expected to under represent the actual rainfall forces encountered in nature.

The laboratory experiments are conducted in two phases. Phase I is studying loose soils, using 4 kind of soils: (1) Sieve 20-40 washed pure sand; (2) Pure bentonite power; (3) 30% bentonite and 70% sand mixture (volume ratio) and (4) real soil from highway construction site at NASA Road 1 in Houston, Texas. The soils are subjected to three rainfall rates: 2 in./hour, 4 in./h and 8 in./hr (which is: 5.08 cm/h, 10.16 cm/h and 20.32 cm/h). The flume is operated at three slopes: 0.1%, 0.5% and 1.0%; relatively steep from a hydraulic point of view, but not uncommon at a highway construction site. Care is taken to keep the surface of the soil parallel to the bottom of the flume. Table 1 shows the result for the nine experiments completed to date. The bentonite results are useless, and this experimental series will be repeated. Phase II will study compacted soil, to allow for comparison to a roller compacted highway construction site.

The experimental procedure includes: (1) Measurement of shear strength, by Vane Sheer Test Kit, 10 points for each simulation, using the average. (2) Measurement of compressive strength, by Pocket Penetrometer, 10 points for each case, using the average. (3) Sampling for Bulk Density, measured after the rainfall simulation. (4) Measurement of initial height of soil. (5) Applying rainfall for thirty minutes, using the standard rain gauge to measure the rainfall rate. (6) Measurement of the final height of the soil in the flume. (7) Data analysis. The calculation of erosion volume uses the product of the original and final height difference and the area. In addition to these tests, we also conducted the following tests, sieve analysis, free swell and liquid limit tests.

Results (to date) and Conclusion

From the data in Table 1, the shear strength shows a difference between the sand, mixture, and clay; sand has the least shear strength. The shear strength of pure bentonite is about twenty times higher than that of sand, and the mixture has a shear strength in between the two "pure" soils. The bentonite also has higher compressive strength, while the sand and clay mixture has much less compressive strength.

The erosion volumes of three cases of pure bentonite are negative values, because swell was not complete before the experiments were run. Although soil was observed to erode when the rainfall was applied, the apparent soil volume increased. Figure 2 shows a plot of shear strength versus erosion volume. A trend can be inferred, but more data are required to firmly establish the trend. As expected, the soil with higher shear strength exhibited slightly lower average erosion. Because shear strength is

Table 1. Measurement and calculation data for 9 cases of simulation.

Case No.	Soil	Slope (%)	Shear Strength (N/cm^2)	Compressive Strength (N/cm^2)	Dry Density (g/cm^3)
Case 2	20-40 Washed Sand	0.5	0.785	0.799	2.565
Case 3	20-40 Washed Sand	0.5	0.856	1.012	2.565
Case 4	20-40 Washed Sand	0.5	0.861	0.918	2.565
Case 5	Powdered Bentonite	0.5	20.580	1.561	2.194
Case 6	Powdered Bentonite	0.5	15.985	1.425	2.194
Case 7	Powdered Bentonite	0.5	15.555	1.391	2.194
Case 8	30-70 Bent.-Sand Mix.	0.5	4.604	0.452	2.576
Case 9	30-70 Bent.-Sand Mix.	0.5	3.716	0.404	2.576
Case 10	30-70 Bent.-Sand Mix.	0.5	4.078	0.413	2.576

Table 1, (Cont'd)

Case No.	Bulk Density (g/cm^3)	Void Ratio	Water Content (%)	Rainfall Rate (cm./30 min.)	Volume Change (cm^3)
Case 2	2.19	0.319	0.124	7.21	1669.8
Case 3	2.06	0.474	0.184	4.47	1959.7
Case 4	2.12	0.393	0.153	5.36	2411.6
Case 5	1.32	2.723	1.237	6.48	-2306.9
Case 6	1.26	3.624	1.647	3.68	-393.5
Case 7	1.31	2.785	1.266	4.88	-6.5
Case 8	1.53	1.965	0.760	4.72	1550.4
Case 9	1.74	1.126	0.436	3.51	1248.6
Case 10	1.64	1.461	0.565	6.91	2725.6

related to the interparticle attractive forces in the soil, the higher shear strength, the greater traction stress required to dislodge the particles.

Figure 3 is a plot of rainfall intensity versus soil erosion. As expected, the higher rate produced more erosion. This result can be explained by the higher traction forces expected when the water runs off the model at higher rates (and higher flow velocities) and because there are many more individual drop impact forces at higher rainfall intensities.

Future Work

The present work is only the beginning of the first phase of the rainfall-soil erosion simulation. The experiment with pure bentonite were not successful. This experiment will be repeated after the bentonite has been fully swelled. A factor analysis will be used between shear strength, compressive strength, rainfall rate, slope and soil erosion based on the laboratory experiments.

Figure 2. Relationship between the Shear Strength and Soil Erosion

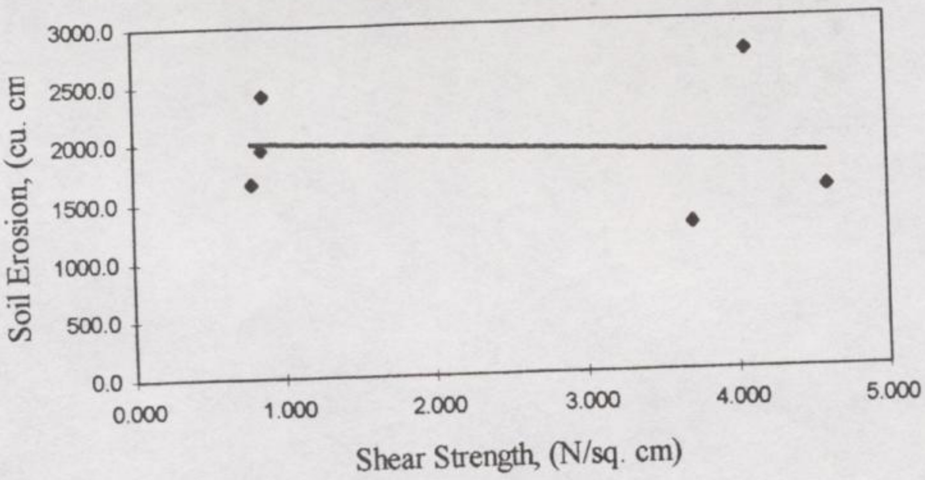
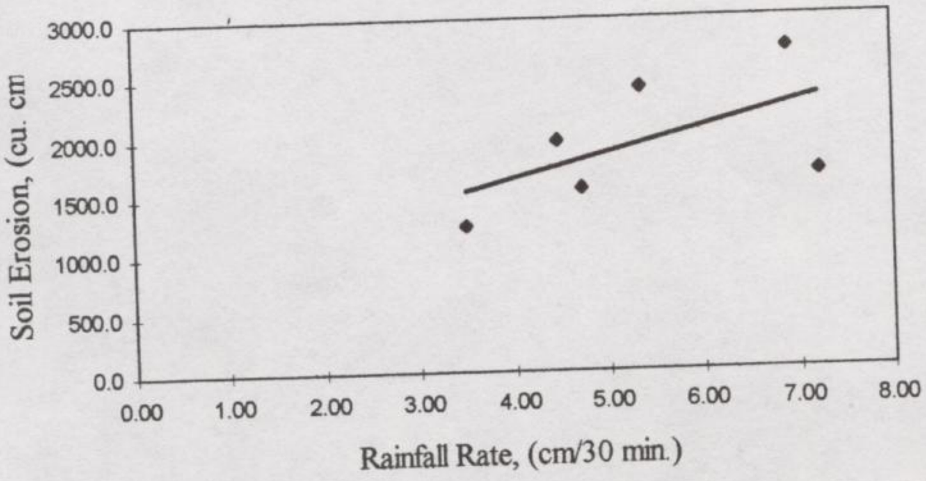


Figure 3. Relationship between Rainfall Rate and Soil Erosion



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References

Daniel M. Katz, Frederick J. Watts, and Edward R. Burroughs, (1995). "Effects of Surface Roughness and Rainfall Impact on Overland Flow", Journal of Hydraulic Engineering, July, 1995.

Das, B. M. (1985). Principles of geotechnical engineering. PWS Publishers, Boston, Mass.

Evans, W. R. and Kalkanis, G., "Use of the universal soil loss equation in California, Soil Erosion : Prediction and Control", Soil Conservation Society of America, 1976, pp. 31-40

Geoffrey E. Blight, 1987. "Erosion of the slopes of Gold Tailings Dams." Geotechnical Practice For Waste Disposal, '87, pp 294-305.

Gilley, J. E., and Finkner, S. C. (1985). "Estimating soil detachment caused by raindrop impact." Trans. ASAE, 28(1), 140-145.

Parker, D. B., Michel, T. G. and Smith, J. L, (1995). "Compaction and Water Velocity Effects on Soil Erosion in Shallow Flow", Journal of Irrigation and Drainage Engineering, Vol. 121, No. 2, March/April, 1995.

Wischmeier W.H. and L. V. Mannering (1969) : Relation of soil properties to its erodibility. Soil Science Society of American Proc., Vol. 33, pp 131-137.

Xanthopoulos, C., and A. Augustin, 1992. "Input and Characterization of Sediments in Urban Sewer Systems." Water Science and Technology, Vol. 25, No. 8, pp 21-28.

Y. Le Bissonnais, M. J. Singer and J.M. Bradford (1993). "Assessment of soil erodibility: the relationship between soil properties, erosion processes and susceptibility to erosion." Farm land erosion: temperate plains environment and hills. Pp 87-96.