Overall Performance Index to Characterize Geosynthetic Erosion Control Systems

R. N. Rustom
Islamic University of Gaza, Palestine

ABSTRACT: Soil erosion due to rainfall and runoff is a serious problem that has led to the development of innovative techniques, using geosynthetics, to alleviate it. The diversity and increasing number of geosynthetic erosion control systems along with the lack of a comprehensive method to evaluate their effectiveness has made it difficult for designers and practitioners to select the proper system under different meteorological, topographic, and soil conditions. Therefore, a laboratory experimental system was constructed to evaluate the performance of various erosion control systems on steep slopes under reproducible, controlled conditions. The experimental results obtained represented measurements of surface runoff, a characteristic overland flow hydrograph, and sediment yield resulting from various rainfall intensities.

The analysis is focused on introducing an *overall performance index*, R^*, to characterize the relative performance of geosynthetic erosion control systems. R^* is a measure of the overall performance of an erosion control system in terms of both its hydraulic characteristics and its sediment yield performance. R^* was determined for the various geosynthetic erosion control systems tested. The overall performance index is believed to be a true representation of the behavior of erosion control systems on steep slopes and a promising tool for the design and selection of an effective geosynthetic erosion control system.

1 INTRODUCTION

Soil erosion due to rainfall and runoff is a serious problem that has led to the development of innovative techniques, using geosynthetics, to alleviate it. The diversity and increasing number of geosynthetic erosion control systems along with the lack of a comprehensive method to evaluate their effectiveness has made it difficult for designers and practitioners to select the proper system under different meteorological, topographic, and soil conditions.

2 RAINFALL/EROSION CONTROL EXPERIMENTATION SYSTEM

A rainfall/runoff/infiltration simulation system has been constructed. Figure 1 shows a schematic of Drexel University's Geosynthetic Research Institute (GRI) system. The simulation system is comprised of a rainfall-producing module, a soil/erosion-control-system test flume, and a measurement/data collection system. For a complete description of the system see Rustom and Weggel, 1993.

3 MATERIALS USED IN THE EXPERIMENTAL STUDY

3.1 The soil

Only one soil was used in the experimental study; a fine-grained, silty sand (SM) soil with traces of clay. The soil's grain size distribution is given in Table 1. Its specific gravity is 2.7. Optimum moisture content (Standard Proctor Hammer) is 9.5% at maximum dry unit weight of 19.8 kN/m^3. Its hydraulic conductivity (from a falling head permeameter) is 7.36×10^{-6} m/sec. Atterberg limits are as follows: liquid limit = 18.7, plastic limit = 17.6, and plasticity index = 1.1.

Table 1 Size Distribution of Soil

a) Sieve Analysis			b) Hydrometer Analysis	
Sieve #	Diameter (mm)	Total % Passing	Diameter (mm)	Finer %
4	4.75	100.0	0.0417	36.8
8	2.36	94.8	0.0301	32.8
16	1.18	85.4	0.0192	31.5
30	0.6	67.3	0.0113	28.9
60	0.25	49.6	0.0080	26.9
100	0.15	34.0	0.0057	24.9
200	0.075	26.5	0.0028	23.0
			0.0012	22.3

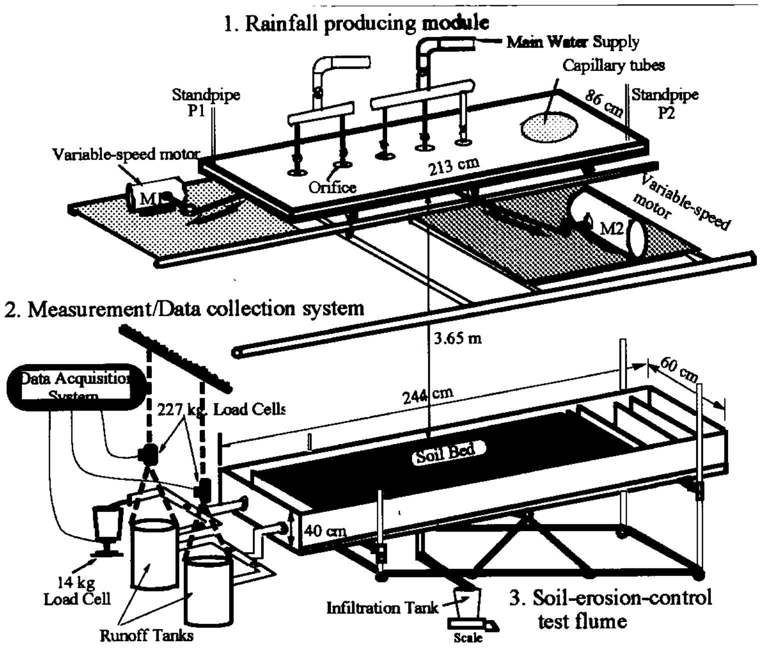

Fig.1 Schematic representation of the experimental system (Rustom and Weggel, 1993)

3.2 Erosion control materials

Twelve different erosion control materials were investigated, geosynthetics as well as natural. Some of these materials require that soil be placed within the product matrix or that soil cover be provided. In this study, all products were tested without soil fill or cover. At some critical stage during installation, prior to filling, or following the removal of fill by erosion, the conditions reproduced in the present tests might occur. The conditions modeled in the present tests generally prevail at the early stages in the lifetime of the erosion control material. The materials requiring soil fill were tested without fill because it is felt that the system would not have performed much differently than unprotected soil. For a material requiring soil cover or fill to perform better than bare soil, a surface layer of soil would have to be eroded away exposing the material to rainfall and overland flow. This would result in initial sediment yields equal to or greater than unprotected soil. Consequently, testing with fill and/or soil cover would give a misleading picture of the overall performance of these products. Recognize that some of these materials are intended for relatively long lifetimes, beyond just the time required for vegetation to take hold. These aspects were not evaluated in this study. Some are designed to hold the root systems together (turf reinforcement) and, therefore, must remain intact for an extended lifetime. Also, these aspects were not evaluated in this study. A brief description of the erosion control materials used in the study follows:

Product 1: a coarsely woven open-mesh fabric of natural jute.
Product 2: a woven meshed fabric made of 100% biodegradable coir fibers.
Product 3: a biodegradable, curled aspen-wood excelsior mat encapsulated in a photodegradable plastic netting. The excelsior fibers are evenly distributed throughout the mat with 80% of the fibers exceeding 15 cm. in length.
Product 4: a 100% biodegradable straw mat encapsulated in a photodegradable plastic netting.
Product 5: a natural coconut fiber mat encapsulated in a non-photodegradable plastic netting.
Product 6: a nylon fiber mat encapsulated in a non-photodegradable plastic netting.
Product 7: a lofty web of polyolefin fibers encapsulated in a non-photodegradable plastic netting.
Product 8: a flexible mat of bonded PVC monofilament fibers.
Product 9: a nonwoven blanket of randomly oriented PVC monofilaments thermally welded together.
Product 10: a flexible composite of nonwoven, isotactic, polypropylene staples in a uniform fiber blanket reinforced with polypropylene netting.
Product 11: a three-dimensional, multi-layered structure of polyethylene netting.
Product 12: a three-dimensional geomatrix of heavy nylon monofilaments fused at their intersections.

4. TEST RESULTS

The experimental results obtained for all the products tested represent measurements of surface runoff, a characteristic overland flow hydrograph, and sediment yield resulting from various rainfall intensities. Figure 2 is a typical S-hydrograph obtained from the experimental system. The outflow curve, comprised of both sediment and water, is easily obtained from the data-acquisition system by directly weighing the cumulative outflow. The outflow is periodically sampled to determine sediment concentration and the sediment yield curve is generated from these data. The sediment yield curve is obtained by multiplying the total outflow by the sediment concentration at each time interval. The runoff curve (overland flow hydrograph) for water alone is found by subtracting the sediment yield curve from the outflow curve.

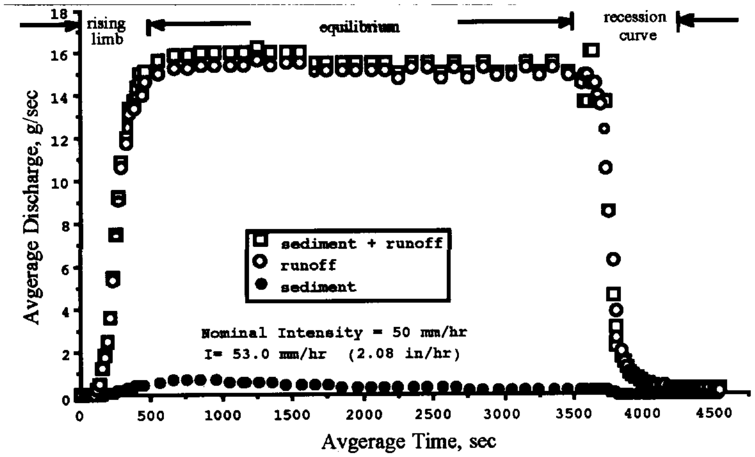

Fig. 2 Typical S-Hydrograph of overland flow and sediment yield from an erosion protected soil on a 1:2.5 slope.

All products were tested at nominal rainfall intensities of 50, 125, and 200 mm/hr. and at a 40% slope (1 vertical on 2.5 horizontal). The values of the average sediment concentration up to the start of equilibrium discharge, $C_{(te)}$, and the average sediment concentration for a period up to 40 minutes following the start of equilibrium discharge, $C_{(t40\ -\ te)}$, are used to compare the performance of the various erosion control products. $C_{(te)}$ is indicative of erosion conditions during the early minutes after the start of rainfall while $C_{(t40\ -\ te)}$ is indicative of erosion conditions during the equilibrium stage of runoff. $C_{(te)}$ is determined as the cumulative weight of sediment collected during the early minutes of rainfall up to time t_e, divided by the cumulative weight of runoff (q) during that time period. Therefore, $C_{(te)}$ is an average weighted concentration during t_e calculated by,

$$C(t_e) = \frac{\int_0^{t_e} C(t)q\ dt}{\int_0^{t_e} q\ dt} \qquad (1)$$

$C_{(t40\ -\ te)}$ is determined as the cumulative weight of sediment collected between t_e and 40 minutes into the test, divided by the cumulative weight of runoff during that time period. Therefore, $C_{(t40\ -\ te)}$ is an average weighted concentration during equilibrium flow calculated by,

$$C(t_{40} - t_e) = \frac{\int_{t_e}^{t_{40}} C(t)q\ dt}{\int_{t_e}^{t_{40}} q\ dt} \qquad (2)$$

In general, q is constant at equilibrium. Therefore, the q's cancel in Equation 2.

The hydraulic performance of an erosion control product is measured by the intensity factor I^* (or equivalently, a runoff factor when infiltration is small) where I^* is defined as,

$$I^* = \frac{I}{gt_e} \qquad (3)$$

Retardance of overland flow, surface velocity, surface storage and water depth are among the factors that involved in I^*. Larger values of I^* indicate poor hydraulic performance (lower retardance of overland flow, higher surface velocity, lower surface storage and water depth).

As a measure of the overall performance of erosion control systems (sediment yield as well as hydraulic characteristics), a mean sediment yield index is introduced. The mean sediment yield index during the early stages of rainfall, $R^*_{(te)}$, is the product of the sediment concentration $C_{(te)}$ and the intensity factor I^*. Therefore,

$$R^*_{(te)} = C_{(te)} \times I^* \qquad (4)$$

Whereas, the mean sediment yield index during equilibrium stages of runoff, $R^*_{(t40\ -\ te)}$, is calculated as,

$$R^*_{(t40\ -\ te)} = C_{(t40\ -\ te)} \times I^* \qquad (5)$$

Erosion control systems with higher R^*'s exhibit, overall, poorer performance when compared with those of low R^*'s. Higher R^*'s indicate higher sediment yields, poorer hydraulic characteristics, and less erosion protection. Table 2 summarizes the values of the sediment concentrations, $C_{(te)}$ and $C_{(t40\ -\ te)}$, intensity factor, I^*, and the R^* factors, $R^*_{(te)}$ and $R^*_{(t40\ -\ te)}$, for each erosion control system. Results obtained for each erosion control system are compared with results measured during Run 2 on unprotected soil (Soil-R2). Thus Soil-R2 forms the benchmark condition against which each product's performance is compared.

Figure 3 shows the overall sediment detachment performance of the erosion control systems investigated. An erosion control system with low $C_{(te)}$ and $C_{(t40\ -\ te)}$ provides better protection than a system with high $C_{(te)}$ and $C_{(t40\ -\ te)}$. Low $C_{(te)}$ and $C_{(t40\ -\ te)}$ means low sediment concentration and thus low erosion. Moreover, when an erosion control system exhibits equal sediment concentrations at both early, $C_{(te)}$, and late stages, $C_{(t40\ -\ te)}$, the system is said to have a balanced performance ($C_{(te)} \approx C_{(t40\ -\ te)}$). Balanced performance is obtained when the rate of sediment detachment is constant over time.

R^* is a measure of the overall performance of an erosion control system in terms of both its hydraulic performance and its sediment yield performance. Figure 4 shows the overall performance of all erosion control systems investigated. Erosion control systems with low $R^*_{(te)}$ and $R^*_{(t40\ -\ te)}$ perform better than those with high $R^*_{(te)}$ and $R^*_{(t40\ -\ te)}$. An erosion control system that exhibits equal sediment yield indices at early and late stages of testing has balanced performance ($R^*_{(te)} \approx R^*_{(t40\ -\ te)}$). Balanced performance is obtained when the overall hydraulic performance and sediment yield performance are constant over time.

5 CONCLUSION

R^* is a measure of the overall performance of an erosion control system in terms of both its hydraulic characteristics and its sediment yield performance. The overall performance index is a good representation of the behavior of erosion control systems on steep slopes and a promising tool for the design and selection of an effective geosynthetic erosion control system. However, further research is still needed to see the effects of long term performance of erosion control systems on R^*.

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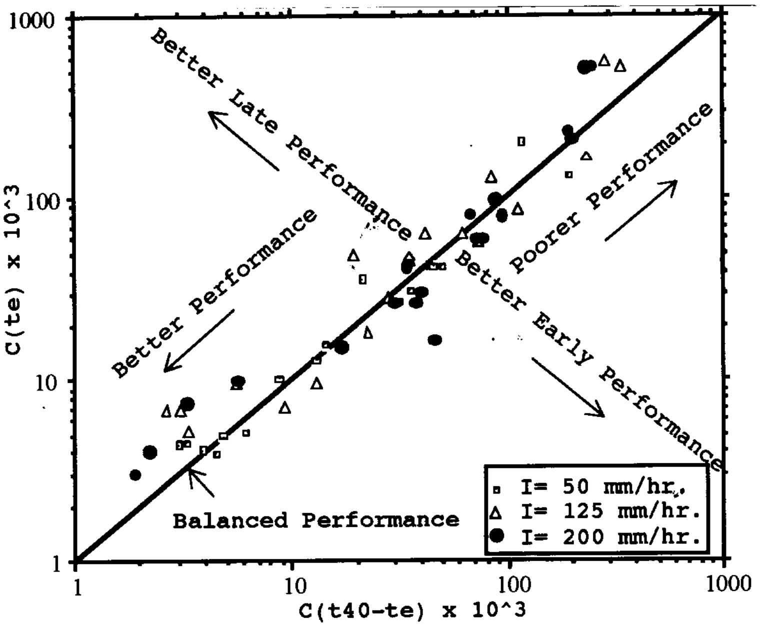

Fig. 3 Criteria for sediment detachment performance (Rustom, 1993)

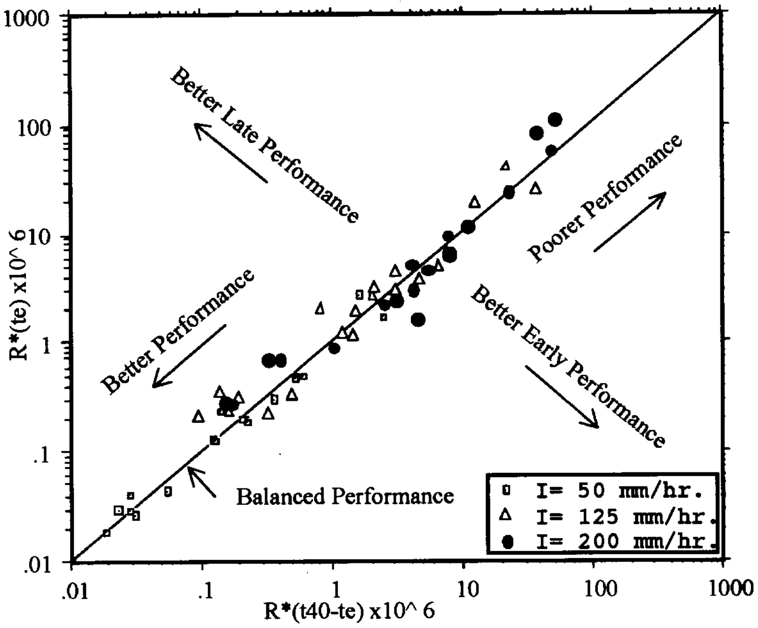

Fig. 4 Criteria for overall sediment control performance (Rustom, 1993)

Table 2 Test results of sediment concentration, intensity factor, and mean sediment yield indices for nominal rainfall intensities of 50, 125, and 200 mm/hr.

Product	C(te) g/kg	C(t40-te) g/kg	I* x 10^ 6	R*(te) x10^6	R*(t40-te) x10^6
1. Nominal rainfall intensity = 50 mm/hr					
Soil- R1	200	119	14.0	2.77	1.65
Soil- R2	133	193	13.0	1.73	2.51
Soil- R3	-	-		-	-
1	5	5	3.9	0.02	0.02
2	10	9	13.8	0.14	0.12
3	4	5	6.9	0.03	0.04
4	5	6	9.0	0.05	0.06
5	4	3	9.7	0.04	0.03
6	4	4	7.4	0.03	0.03
7	16	16	12.7	0.20	0.21
8	36	21	6.7	0.24	0.14
9	43	43	11.8	0.50	0.51
10	5	3	7.0	0.03	0.02
11	41	45	11.5	0.47	0.52
12	27	32	11.3	0.31	0.36
2. Nominal rainfall intensity = 125 mm/hr					
Soil- R1	165	235	160.0	26.34	37.53
Soil- R2	556	287	76.2	42.34	21.86
Soil- R3	522	345	36.8	19.24	12.70
1	7	3	51.7	0.35	0.14
2	48	19	42.3	2.04	0.81
3	9	13	36.9	0.35	0.49
4	7	9	33.7	0.23	0.32
5	5	3	48.8	0.25	0.16
6	9	6	34.0	0.32	0.19
7	47	35	58.9	2.77	2.07
8	44	35	44.3	1.96	1.55
9	58	74	65.6	3.80	4.88
10	7	3	31.6	0.21	0.10
11	128	85	36.6	4.68	3.11
12	62	42	51.1	3.17	2.16
3. Nominal rainfall intensity = 200 mm/hr					
Soil- R1	227	194	256.6	58.29	49.85
Soil- R2	511	231	164.8	84.23	37.98
Soil- R3	519	248	210.4	109.12	52.17
1	7	3	97.6	0.71	0.33
2	30	40	79.5	2.38	3.19
3	26	30	84.9	2.25	2.56
4	15	17	61.5	0.92	1.05
5	3	2	91.3	0.27	0.17
6	10	6	72.6	0.72	0.41
7	42	34	123.2	5.12	4.20
8	60	76	104.6	6.27	7.98
9	96	89	124.9	11.97	11.07
10	4	2	72.1	0.29	0.16
11	60	72	76.4	4.57	5.51
12	81	67	116.6	9.39	7.86