Soil erodibility prediction for excavated materials
by William S Hartsog

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering
Montana State University

Abstract:
Laboratory erosion studies were conducted to determine the erodibility of soils from four Northern Great Plains surface coal mines. A drop-forming rainfall simulator was used to apply rainfall at a rate of 76.2 mm/hour for one-half hour duration to a 55.25 cm x 55.25 cm erosion plot. Statistical analyses of the laboratory erosion data were done using the BMDP statistics package. Regression equations using interrill and splash erosion measurements as dependent variables were expressed in terms of soil chemical and physical properties and plot slope. These equations can be used to estimate the sheet erosion component for erosion process models. Details on laboratory procedures, statistical analysis, and splash distribution, are presented along with a summary of erosion prediction methods.

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A thesis submitted in partial fulfillment
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APPROVAL

of a thesis submitted by

William S. Hartsog

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Laboratory erosion studies were conducted to determine the erodibility of soils from four Northern Great Plains surface coal mines. A drop-forming rainfall simulator was used to apply rainfall at a rate of 76.2 mm/hour for one-half hour duration to a 55.25 cm x 55.25 cm erosion plot. Statistical analyses of the laboratory erosion data were done using the BMDP statistics package. Regression equations using interrill and splash erosion measurements as dependent variables were expressed in terms of soil chemical and physical properties and plot slope. These equations can be used to estimate the sheet erosion component for erosion process models. Details on laboratory procedures, statistical analysis, and splash distribution, are presented along with a summary of erosion prediction methods.

INTRODUCTION

The Northern Great Plains receives about 25 to 35 cm (10 to 14 inches) of precipitation annually. According to Langbein and Schumm (1958), regions receiving this range of rainfall often have the most severe erosion and sedimentation rates. Particularly severe erosion has been observed in this region on construction sites and mine areas, but few quantitative data are available for prediction of erosion rates. Such data are vital if land managers, regulatory agencies, and industries are to anticipate and control erosion and the degradation of water quality that typically accompanies erosion.

One area of concern is increased erosion resulting from strip coal mining, a major industry in the Northern Great Plains. About 1.05 million hectares are underlain by surface-mineable deposits in the four-state area (Montana, North Dakota, South Dakota, Wyoming). Beneath this area lie 72.8 billion metric tons of surface-mineable coal, representing about 60 percent of the Nation's surface-mineable coal reserve (U.S. Dept. of Agriculture and others, 1975).

Under the Surface Environment and Mining program (SEAM)[1], the USDA Forest Service in 1977 initiated a study into erosion of spoil and topsoil mine materials in the Northern Great Plains. The U.S. Environmental Protection Agency (EPA) along with the Engineering Experiment Station at Montana State University provided funding and support because of the concern over sediment pollution. The objective of this research is to devise a method for predicting erodibility of mined materials in particular. However, the study is applicable to erodibility of excavated materials in general.

The general approach to the study was to collect soil samples from four active strip mines and subject them to simulated rainfall in the laboratory. (Note the broad use of the word "soil" herein to denote either excavated topsoil or spoil material.) The amount of soil displaced was correlated with physical and chemical characteristics of the soil sample and the slope of the soil surface. Factors found to influence soil displacement were quantified for use in equations that predict erodibility.

This report 1) defines sheet erosion, 2) discusses various techniques of erosion measurement, 3) considers the basis for testing and describes the test apparatus,

1. A United States Department of Agriculture, Forest Service, program to provide and apply technology in order to maintain or restore the quality of the environment and surface values on forest and grassland areas subject to mining.

4) presents data analysis, and 5) shows results along with potential uses for prediction of erosion. A separate discussion of splash erosion and distribution is also presented.

THE EROSION PROCESS

Components of Erosion

Erosion is one of the three components in the overall sedimentation process: erosion, transport, and deposition. Erosion due to rainfall and runoff has been the subject of intensive research for the last 50 years. Unfortunately the state-of-the-art in erosion prediction has not progressed to the point where accurate estimates of erosion can be made. Soil erosion by water consists of particle detachment and subsequent movement, with water providing the energy and acting as an entraining medium.

Interrill and Rill Erosion

Upland erosion includes both sheet and rill erosion. The rills are defined as locations of concentrated erosion caused by channelized flow. The remaining land surface between the rills is where more uniform sheet erosion occurs (Meyer and others 1972). Mulcher and Young (1972) showed that raindrop impact was the primary force in soil detachment and transport in sheet erosion.

Sheet erosion consists of interrill erosion and splash erosion. Interrill erosion is defined herein as the portion of the sheet erosion that is entrained in the sheet flow runoff and measured at a rill boundary as sediment in the surface runoff. Splash erosion is that portion of sheet erosion that is airborne and is transported beyond the rill boundary as splash. Interrill erosion provides a mechanism for sediment to be transported as a moving sheet to the rill system where concentrated flow and raindrop agitation are the mechanisms of transport.

Reasons for Laboratory Study

Because erosion prediction is an inexact science and there is a need for basic information, this study is directed toward measurement of both splash erosion and interrill erosion. A laboratory study was selected in order to allow close plot and environmental control while determining factors important to the sheet erosion process. A small plot size was selected so that intensive measurements of sediment in the surface runoff and soil splash could be made. The small plot size eliminates the erosion due to rilling so results can be attributed to interrill and splash erosion. Using the laboratory approach, the factors affecting erodibility of different soils can be determined within reasonable costs.

Process Modeling

Defining the erodibility of soil materials based on soil properties may provide input into current erosion prediction models such as the Universal Soil Loss Equation, U.S.L.E., (Wischmeier and Smith 1978) that have factors to account for other variables such as rainfall, slope, length of slope, vegetation and conservation measures. The basic information on interrill and splash erosion will also be useful to researchers developing new erosion and sediment process models such as the watershed model and road sediment model developed by Simons and others (1976) at Colorado State University, and the CREAMS Model developed by the USDA, SEA-AR and edited by Knisel (1980).

EROSION PREDICTION METHODS; STATE-OF-THE-ART

Universal Soil Loss Equation

Wischmeier and Smith presented the Universal Soil Loss Equation (U.S.L.E.) in 1978 in USDA Agriculture Handbook No. 537. The method currently is widely used in the field; many investigators believe that it represents the state-of-the-art for estimating soil erosion. The equation was developed from over 10,000 plot-years of field data from the Midwest. It was originally formulated on basic erosion principles, but the statistical relationships formed during model development caused the equation to be largely empirical.

The U.S.L.E. was developed to predict combined sheet and rill erosion that is transported to the boundary of an agricultural field. The equation is not intended to cover sedimentation processes such as transport beyond the field boundary and erosion in gullies and streambanks.

The form of the U.S.L.E. is the product:

$$A = R\ K\ L\ S\ C\ P$$

where:

A = the computed sheet and rill soil loss per unit-of-area calculated from the product of six other factors. The estimate represents average annual soil loss (tons per acre) due to rainstorms on a small field-size upland area.

R = the rainfall factor, a measure of the erosive potential due to rainfall for an average year. This factor accounts for differences in rainfall frequency, duration, and intensity by summing the individual storm's erosivity index for a normal 1-year period. Research data show that soil losses are directly related to the erosivity index: the product of a rainstorm's total kinetic energy times its maximum 30-minute intensity.

K = the soil-erodibility factor, a measure of the average soil loss per unit of R under arbitrarily selected conditions (a plot 22.1 meters long, with a uniform 9-percent slope that is in continuous fallow and tilled up and down the slope). Any differences in soil loss under these fixed conditions are explained by differences in the soil-erodibility factor, which is a function of the soil physical and chemical properties.

L = the slope length factor, which accounts for increased surface runoff that accumulates as the length of a field increases. This factor is expressed as the ratio of a field slope length to that of a 22.1-meter slope length with the same soil type and gradient.

S = the slope-gradient factor expressed as the ratio of the soil loss from a field on any given gradient to that from a 9-percent slope.

C = the cropping-management factor accounts for plant or mulch cover and soil surface conditions. C is expressed as the ratio of soil loss from a field with given cropping and management conditions to the loss from a field in a fallow condition.

P = the factor for erosion control efforts, defined as the ratio of the soil loss using terracing, strip cropping, or contouring to losses with up and down slope straight-row farming.

The Agricultural Research Service and Soil Conservation Service and others have done extensive work in an attempt to adapt the equation to the widely varying soil and climatic conditions in the United States. Because the U.S.L.E. is the most commonly used tool presently available, others have modified it for specific uses to estimate erosion under varying conditions, such as construction sites (Wischmeier and Meyer 1973), urban areas (Meyer 1974), and forested areas (Curtis and others 1977).

Likewise, the U.S.L.E. is the accepted method currently available for estimating erosion on strip mines (USDA, SCS, EPA 1977) and can be modified for rough approximations of erosion for portions of a year or single-storm events. In spite of its inaccuracy for short-term estimates, it does provide an erosion model that isolates the contribution of the six factors (R,K,S,L,C,P). This makes it feasible to separate out any one factor and study it in detail as is done in the study reported herein where the K-value or soil erodibility is the topic.

The U.S.L.E. provides a nomographic solution (Wischmeier and others 1971) for estimating K-values based upon soil properties. Accuracy of this method is questionable in areas where it has not been verified, and it is recommended that local values for K be established using field sized plots.

One of the objectives of this study is to provide insight into the possibility of estimating K-values from laboratory tests.

Laboratory Erodibility Factors

Using a laboratory rainfall simulator to estimate soil erodibility for field situations is a questionable method. The laboratory measurements indicate erodibility due to sheet erosion but give no measure of a soil's erodibility due to rill erosion. This indicates that laboratory determined erodibilities will not be directly applicable to field sites where rilling is the dominant erosion process.

Where soils are resistant to rill erosion, Meyer, Foster, and Romkins (1975) show that erosion measured at successive downslope sections approached a constant level as length of slope increased. Thus, this finding shows that the sheet erosion component for these rill-resistant soils is strongly related to the total erosion on a slope. Their results also showed that sheet erosion was approximately equal to total erosion on rill-susceptible soils so long as the length of slope was short enough that rills were not fully developed.

Trott and Singer (1979) showed that laboratory-determined K factors for some soils give better estimates of soil erodibility than Wischmeier's nomograph. These results could indicate that the nomograph erodibility solution is not applicable for the properties of these soils or that interrill erosion is dominant for these soils. With proper understanding of the foregoing, results in this report on the erodibility of mine soils, determined from sheet flow on small plots, may be helpful in estimating K-values for the U.S.L.E.

Erosion Process Models

Erosion: Sources and Transport

The failure to separate the sources of erosion (sheet and rill) and failure to properly understand the sediment transport process are viewed by many scientists as major shortcomings in the U.S.L.E. The U.S.L.E. has proven satisfactory for corn belt soils along with certain other soils that are homogeneous enough to allow the lumping of sheet and rill erosion along with sediment transport into one equation. For areas of widely varying soils, there is no reason to believe that it is feasible to combine the processes of erosion and transport into a simple equation. Combining different processes into a single field-boundary, sediment-yield measurement, as is done with the U.S.L.E., results in an empirical approach that is largely site-specific. Considering the wide variety of soils in the Northern Great Plains and noting that activities like strip mining create soils containing a composite of many different materials, it does not seem practical to estimate each new soil's erodibility using field-sized plots. An alternate approach is to measure sheet erosion on small plots in the laboratory and rely on process-oriented models to predict rill erosion and sediment transport for field-sized areas.

CREAMS Model

Recognition of the shortcomings of the U.S.L.E. and other erosion prediction methods has resulted in the development of process-oriented models. The CREAMS Model is a direct result of the U.S.L.E.'s failure to separate the erosion and sediment transport processes. The CREAMS Model and Colorado State University Watershed Model are two possible methods of estimating sediment yields from strip mine or construction areas. Erosion process models are relatively new and have not been refined, especially for a situation as complex as surface mine soils. Nevertheless, a different approach to erosion and sediment prediction is needed as evidenced by the large expenditure of time and money spent on established methods that are not universally applicable. Ideally, a process approach to the erosion problem will result in a better understanding of basic relationships, which is needed to improve erosion prediction and control.

Future of Process Models

Currently there is a large project under way to develop a highly refined new erosion process model based on fundamental hydrologic and erosion processes by the USDA-Agricultural Research Service (ARS). The USDA-Water Erosion Prediction Project (WEPP) is headed by G.R.Foster with the National Soil Erosion Research Laboratory, located at Purdue University and should be completed by the mid-1990's. (General Report, USDA-Water Erosion Prediction Project, January 5,1987.)

The use of process models could greatly reduce the number of field-sized erosion plots required if the models adequately describe the erosion and transport process. This approach will require field verification of rill erosion and sediment transport estimates but may eventually greatly reduce the total number of field-sized studies.

EQUIPMENT AND METHODS

The basic equipment used for these erodibility tests consists of a rainfall simulator, a box containing the soil sample, and a tilting platform that permits variations in slope. Figure 1 shows the equipment as set up in the laboratory. The soil sample was carefully aligned beneath the rainfall simulator to obtain uniform rainfall coverage.

The Rainfall Simulator

The rainfall simulator selected to conduct this study is a "Nevada type" infiltrometer (Figure 2) designed by Meeuwig (1971) and modified by Malekuti and Gifford (1978). This rainfall simulator is similar in concept to the polyethylene drop-forming apparatus presented by Chow and Harbaugh (1965). The plexiglass water chamber is 61 cm by 61 cm, with 23-gauge stainless steel tubes pressed into holes drilled into the lower surface. Raindrops are formed by 518 stainless steel tubes uniformly distributed on a 55.88-cm-square grid pattern. The tubes terminate as needles of 0.012 mm inside diameter. The entire water chamber oscillates on three 2.54-cm-radius cams to better distribute the raindrop pattern. A float system was added to the

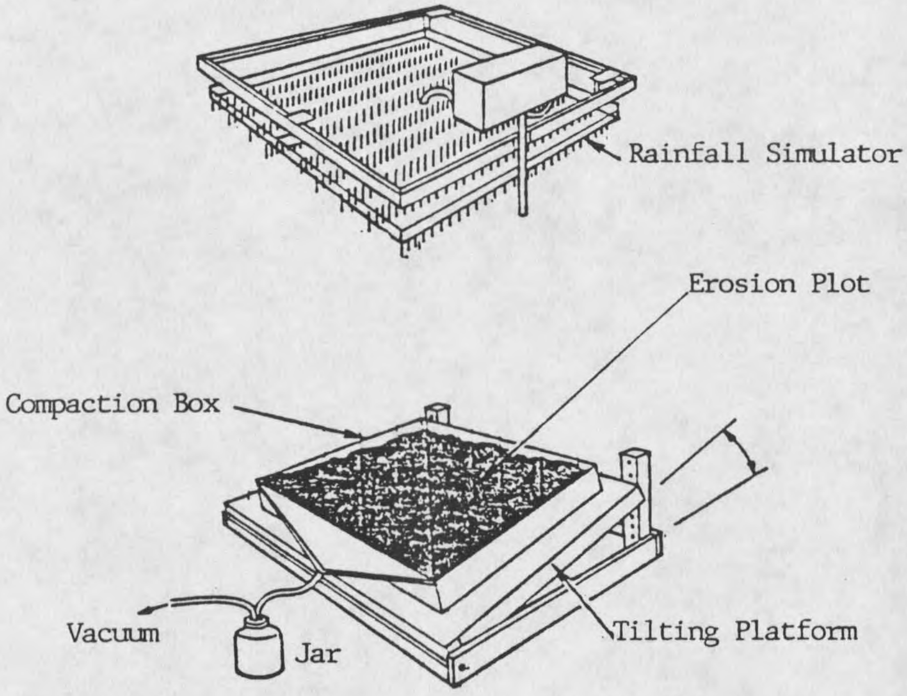

Figure 1. Equipment set up for erodibility tests.

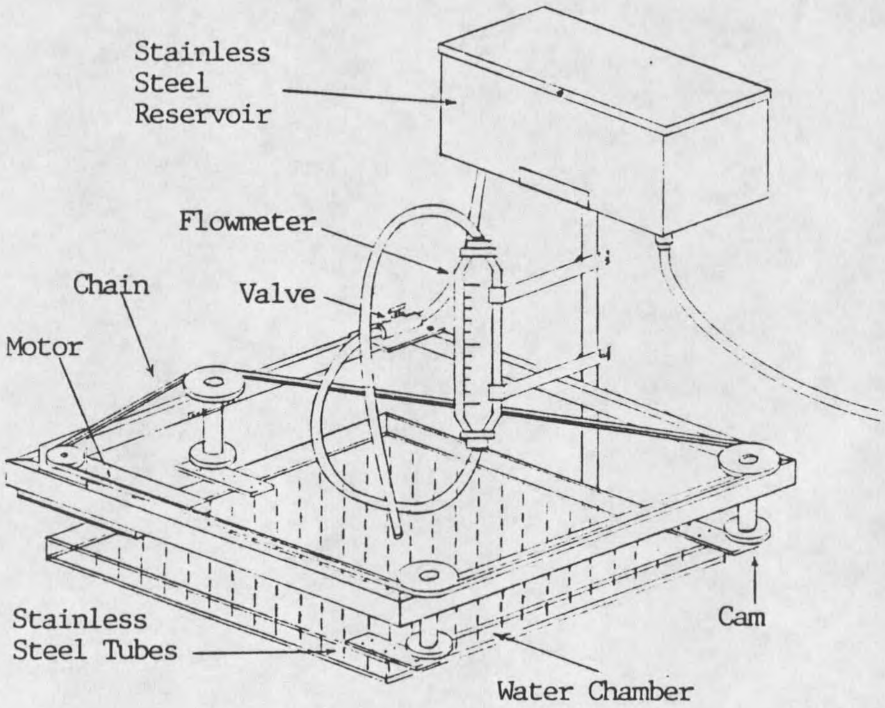

Figure 2. The rainfall simulator.

supply reservoir to maintain a constant head. A flowmeter and valve regulate the flowrate to the water chamber and consequently the rainfall rate.

Studies by other investigators (Sherard and others 1973) indicate that the chemical properties of eroding water can affect erosion rate, especially in soils that are dispersible due to sodium levels. The rainfall simulator's small size makes it practical to use distilled water in order to more closely simulate the chemical properties of natural rain.

Simulated Rainfall Properties

One of the main advantages of this simulator is close monitoring and control of the energy, intensity, and quantity of rainfall. To obtain useful data on the erodibility of different soils, the physical properties of the artificial rainfall must be known and be reproducible. Therefore drop size, mass, and fall distance are of primary importance. These factors will determine the velocity, momentum, and kinetic energy delivered to the soil. Measured drop size was 2.5 mm, as closely as could be determined using calipers. Chow and Harbaugh (1965) calculated drop size with the 0.012-mm-inside-diameter needles as 2.39 mm, which supports our measurements. The average fall distance for the drops was 2.9 meters. In this distance a 2.5-mm drop will attain a velocity of approximately 5.73 meters per second as determined from Laws' publication (1941). This velocity is 77 percent of the terminal velocity of a 2.5-mm-diameter raindrop.

The kinetic energy produced by this rainfall simulator for a 30-minute event with a 76.2-mm-per-hour intensity, a 2.9-meter fall height, and a 5.73-meters-per-second velocity, is 0.0625 joules per cm^2. The energy in a 30-minute natural rainstorm with a 3-inch- per-hour (76.2-mm-per-hour) intensity was calculated as 1610.9 foot-tons per acre (0.1080 joules per cm^2), using the relationship presented in Wischmeier and Smith (1958):

$$Y = [916 + 331 \, \text{Log}_{10} \, X] \, Q$$

where Y is the kinetic energy in foot-tons per acre, X is the intensity in inches-per-hour, and Q is the total inches of rain at this intensity. The natural storm yields a higher energy, 0.1080 joules per cm^2 versus 0.0625 joules per cm^2 for the rainfall simulator, mainly because natural raindrops have reached their terminal velocity. Therefore, this rainfall simulator produces 58 percent of the energy produced by a natural rainstorm with a 76.2-mm-per-hour intensity. By comparison, a 1/2-hour duration natural rainstorm that produces the same energy as the rainfall simulator (.0625 joules per cm_2) would have an intensity of approximately 47.1 mm per hour.

Laws and Parson (1943) showed there is a relationship between average drop size and rainfall intensity for natural rainstorms. A 2.5-mm mean size raindrop would have an intensity of 50.8 mm per hour. The uniform drop size and lower energy produced by the rainfall simulator makes it impossible to simulate relationships between energy, intensity, and drop size that exist in natural rainstorms. There are other factors such as momentum, depth of water film, and spatial distribution of momentum and energy that further complicate the similitude problem. The 76.2-mm-per-hour rainfall simulator intensity was selected so that the energy per unit time could be kept relatively high, and also because several other investigators working with drop-forming and sprinkler-head type simulators have used similar intensities. The selected intensity should be satisfactory for determining the erodibility of selected materials and also provide data that is comparable with data from other studies.

The Erosion Plot

Simulating Field Conditions

The erodibility study was conducted in a laboratory so that rainfall simulator conditions and other environmental problems such as wind and temperature could be easily controlled. At locations where soil samples were taken, the conditions near the surface were measured in the field and were reproduced in the laboratory. Near-surface moisture contents and soil bulk densities were determined for spoils and topsoil with nuclear moisture-density equipment at each mine site. For each soil the field moisture was reproduced and the field bulk density obtained by compacting the material into a steel compaction box with a Proctor compaction hammer.

Description of Laboratory Plot

The compaction box (55.25 cm x 55.25 cm x 10.16 cm deep), shown in Figure 1 also served as the container for the erosion plot. The box has a pattern milled into the bottom to allow rainfall that infiltrates through the soil to drain from the box. A nonwoven filter fabric used in road construction placed on the bottom of the box prevents plugging of the drainage system. The three upper sides of the box have a beveled lip, raised 2.54 cm above the soil surface. The lip serves as a sharp boundary and deflects precipitation that falls outside the soil plot boundary away from the soil plot. The downslope edge of the box was flush with the compacted soil surface to allow free drainage of surface runoff. This runoff was concentrated into a trough molded to the edge of box and measured at five-minute intervals. The box was placed on a tilting platform beneath the rainfall simulator, and each erosion test was replicated twice at slope angles of 1, 9, and 20 percent. The 1-percent slope was selected as the minimum that would provide adequate control of surface runoff. The 9-percent slope represents the basic slope used in the development of the U.S.L.E. Twenty percent slope was selected as the maximum because mining law requires that reclaimed lands be graded to slopes of 20 percent or less.

Measurements of Soil Splash and Runoff Erosion

The erosion plot was equipped to measure the contribution of soil splash (soil splashed over the plot boundary) at the same time sediment in the surface runoff (interrill erosion) was being measured.

Laboratory Methods

The first replication employed a grid of blotter papers (Figure 3), which caught soil splashed off the erosion plot. Soil splashed onto the middle three rows of blotter papers, centered on the downslope edge of the plot, provided a measure of splash erosion below the lower plot boundary. The process was so time consuming that for the second replication of the tests a neoprene-nylon apron system was used to catch the soil splash (Figure 4). The soil was rinsed off each apron into a sample bottle, which reduced the collection of soil splash to a single measurement for each apron. The neoprene-nylon aprons did not provide data as to splash distance off the plot however. Splashed soil, collected on a 30.5-cm-wide apron centered on the downslope-

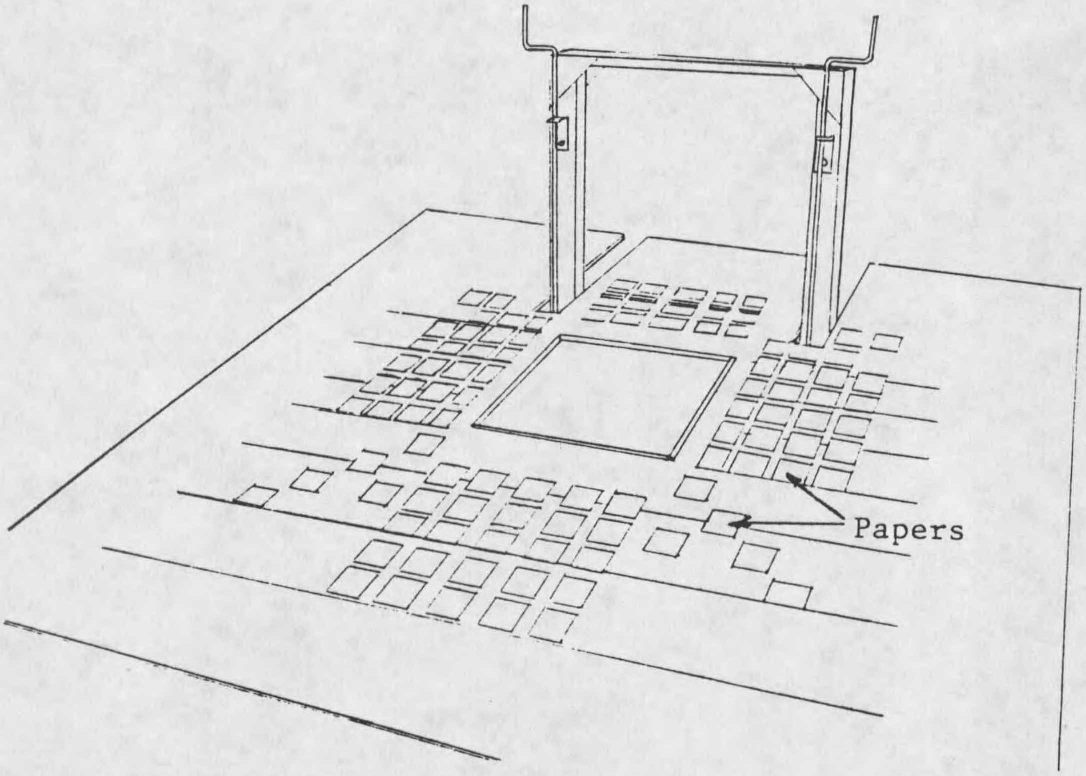

Figure 3. Blotter paper system used to collect splash erosion.

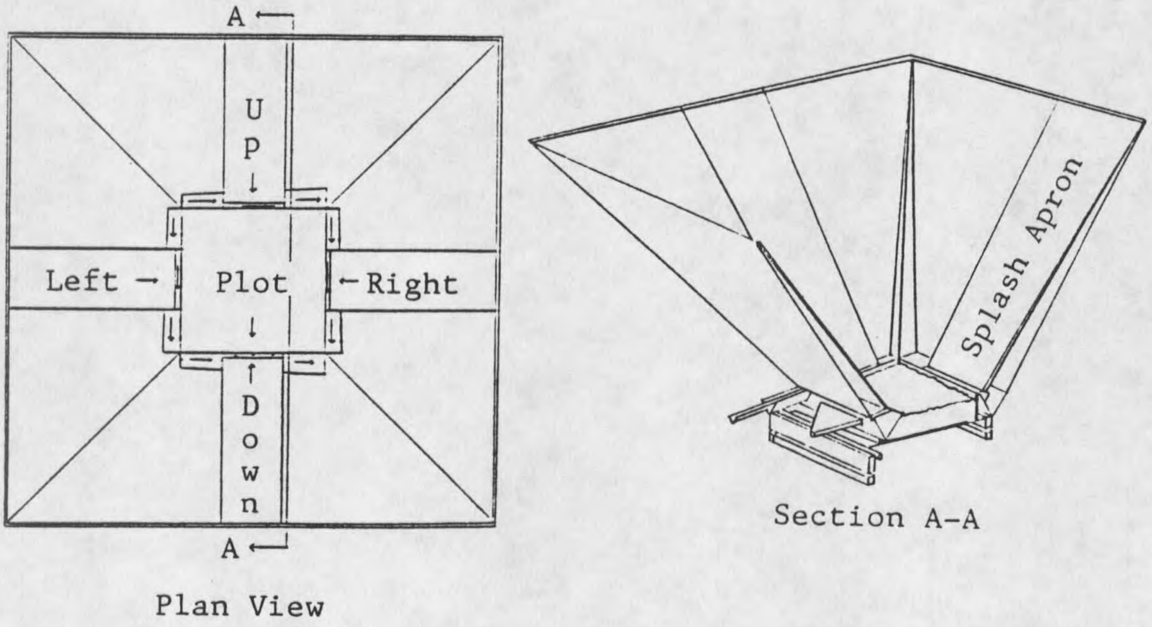

Figure 4. Neoprene nylon apron used to collect splash erosion.

edge of the erosion plot, was used to determine the soil splash erosion below the lower plot boundary.

Contour maps of splash intensity from the blotter paper replication showed that data from the center 30.5-cm strip were almost completely free of the edge effects of the plot. The splash data for both replications were then multiplied by a correction factor (plot width/strip width) so that the splash erosion and interrill erosion data both would be based on a 55.25-cm-wide plot. For both replications, the splash erosion was determined from the oven-dry weight of splashed soil. Soil sediment in the surface runoff (interrill erosion) as oven-dry soil weight was determined by filtering and oven drying the runoff samples.

Test Duration Considerations

Eight soils (topsoil and spoils from four mines) were tested for 30 minutes in a dry condition and wet condition at each of the three selected slope angles. The dry condition test had the same soil moisture content as when it was compacted into the sample box (field moisture content). The wet-condition test was the condition of the soil sample 24 hours after the 30-minute dry-condition rainfall simulator run.

Detailed erosion tests with the rainfall simulator were conducted to refine experimental procedures. The 30-minute duration for the test was chosen after studying time distribution of erosion. Rainfall simulator runs of six hours or longer were made on several of the soils at the nine percent slope. These runs indicated that 30-minute erosion tests on soils initially in the wet condition were more representative of the constant erosion rate reached during the longer term six-hour runs. High erosion rates at the start of the initially dry runs were thus eliminated. The values of interrill and splash erosion, resulting from 30-minute runs on soils in the wet condition are the basic measures of soil erodibility in this paper.

In addition to the basic runoff and splash measurements made below the lower plot boundary during the erosion tests, data on soil splash in all directions was collected. A later section, "Splash Distribution," summarizes the results of these additional measurements.

Methods of Describing Soil Properties

Soil Sampling Sites

This study specifically concentrates on unvegetated topsoil and spoils from four coal strip mining sites in the Northern Great Plains region. Two mine sites are in south-central Montana on the western edge of the extensive Fort Union Formation that encompasses much of the Northern Great Plains. Another site on the eastern Montana border is near the center of the Fort Union Formation, and the fourth mine site in west-central North Dakota is near the eastern edge of the formation. Soils in this formation generally become more fine-grained from west to east. The mines are not identified at their request, since the results cannot be considered as representative of an entire mine. Materials selected for this study can only be considered to be typical of the topsoils and spoils in the small area sampled at each mine location. Through laboratory tests and data analysis, erodibility of these soils is correlated to slope and the physical and chemical properties of these materials. Test results yield erodibility measurements directly related to the four study sites and provide information that may be useful for estimating the erodibility of other soils in the area based on soil properties.

Topsoil and Spoil Properties

Topsoil and spoil material were analyzed for physical and chemical properties. A list of soil properties that other investigators had found to be related to soil erodibility was compiled. Many of these came from Veon and Miller's (1978) review of soil erodibility.

Soil properties used in this study were limited to those easily determined or commonly measured on coal strip mines and are defined in the following list.

EI - Interrill Erosion: the oven-dry weight of soil sediment collected in the surface runoff from the erosion plot. Raindrop impact is the primary erosional force in soil detachment, and this sediment is transported to the lower plot boundary in the surface runoff. Sediment transport capacity of the surface runoff is greatly enhanced by raindrop agitation of the sheet flow.

ES - Splash Erosion: the oven-dry weight of soil splashed over the lower boundary of the erosion plot. Soil splash was measured separately since it passed over the runoff collection trough at the lower plot boundary. Splash erosion provides loose material for the interrill erosion process, and it also transports material directly into rills or gullies.

SL - Slope: the gradient of the erosion plot expressed as a percentage.

INF - Infiltration: the number of centimeters of water absorbed into the soil.

GT3 - The proportion by weight of particles in a soil that are larger than 3.0 mm diameter expressed as a percentage.

GT2 - The proportion by weight of particles in a soil that are larger than 2.0 mm diameter (fine gravel) expressed as a percentage.

SA - The proportion by weight of particles in a soil that are between 61 microns and 2.0 mm in diameter (sand) expressed as a percentage.

LT61 - The proportion by weight of particles in a soil that are less than .061 mm diameter (silt plus clay) expressed as a percentage.

MWD - Mean Weight Diameter (in mm) = $\Sigma x_i * w_i$ (Farmer and Van Haveren 1971), where: x_i is the mean diameter in mm of each size fraction, w_i is the proportion of the total sample weight in the corresponding fraction, and the summation is over the total number of size fractions into which the sample is partitioned.

FMWD - LT61 divided by MWD (Farmer and Van Haveren 1971).

BD - Bulk Density: oven-dry weight of a soil sample divided by the volume of the sample (gm/cc).

SAR - Sodium Adsorption Ratio: a ratio for soil extracts used to express the relative activity of sodium ions in exchange reactions with soil:

$SAR = Na/[(Ca + Mg)/2]^{.5}$ where Na, Ca, and Mg are expressed in milliequivalents per liter.

EC - Electrical Conductivity of the soil water extract expressed in mmhos/cm.

OC - Organic Content: the percentage of the total dry weight of a soil that is organic matter.

LL - Liquid Limit: the maximum moisture content that a soil can have and still possess a slight shear strength.

PH - pH is a measure of the acidity (or alkalinity) of a soil expressed as the negative logarithm of the hydrogen ion activity.

SG - Specific Gravity: the ratio of the density of the soil grains in a sample to the density of water.

CLAY - The proportion by weight of particles in a soil that are less than 0.002 mm (clay) in size expressed as a percentage.

SILT - Silt content as defined in the U.S.L.E.: the proportion by weight of particles in a soil that are between 0.002 mm and 0.10 mm in diameter expressed as a percentage.

SAND - Sand content as defined in the U.S.L.E.: the proportion by weight of particles in a soil that are between 0.10 mm and 2.0 mm in diameter expressed as a percentage.

M - The M soil parameter defined in the U.S.L.E. as: M = (SILT) (SILT + SAND), the product of silt content and the sum of silt plus sand content using the U.S.D.A. soil classification and Wischmeier's (silt + sand) definition.

In five of the eight cases, there was not enough soil to prepare three soil samples (one for each slope 1%, 9%, and 20%) required to complete the second replication. When this occurred, enough soil was gathered in the same area of the mine as the original sample to complete the second replication. These samples were also tested because of the variation in soil characteristics.

Chemical Properties. Chemical analyses (L.E. Allison and others 1969) were made on each soil to determine pH, electrical conductivity, cations (calcium, magnesium and sodium) and sodium-adsorption-ratio (SAR) and organic content (J.R. Sims and V.A. Haby 1970).

Physical Properties. Physical analyses to characterize the topsoil and spoil material from each mine included grain size analysis, specific gravity, and the Atterburg limits (liquid limit, plastic limit, and plasticity index). Because erosion tests deal with wet soil, a wet-sieve analysis was conducted on the coarser fractions of each sample. Materials passing the number 10 sieve were tested using hydrometer procedures to determine the distribution of the finer grains. The wet-sieve analysis and the hydrometer method were combined to give the complete grain size distribution. Specific gravity was measured with an air pycnometer. Atterburg limits (Means and Parcher 1963) are measures of soil moisture content under specific conditions that are related to engineering properties of the soil. The liquid limit is the highest moisture content at which a soil still possesses a small degree of shear resistance. The plastic limit is the lowest moisture content at which a soil behaves plastically and does not crumble. The difference between the liquid limit and the plastic limit is defined as the plasticity index. Preliminary screening of these variables using correlation methods showed that liquid limit was the only Atterburg quantity related to erosion measurements.

Laboratory Erosion Data

Table 1 presents the more relevant physical and chemical soil properties that were compiled for each mine topsoil and spoil, as determined from the results of the physical and chemical tests.

Table 1. Data Used in Interrill and Splash Erosion Analyses.

	CODE	EI	ES	SL	INF	GT3	GT2	SA	LT61	MWD	FMWD
1	1S1	127.2	24.3	1	0.13	2.0	3.0	25.0	72.0	.383	188
2	1S1	254.7	41.0	9	0.15	2.0	3.0	25.0	72.0	.383	188
3	1S1	292.9	49.2	20	0.16	2.0	3.0	25.0	72.0	.383	188
4	1T1	127.2	22.4	1	0.19	2.3	3.5	43.0	53.5	.376	142
5	1T1	258.4	35.3	9	0.20	2.3	3.5	43.0	53.5	.376	142
6	1T1	436.7	59.4	20	0.22	2.3	3.5	43.0	53.5	.376	142
7	1S2	130.3	18.3	1	0.39	6.0	7.0	31.0	62.0	.394	157
8	1S2	269.0	61.4	9	0.27	6.0	7.0	31.0	62.0	.394	157
9	1S2	445.9	107.7	20	0.20	6.0	7.0	31.0	62.0	.394	157
10	1T2	110.8	23.0	1	0.4	1.0	1.5	13.5	85.0	.223	381
11	1T2	260.0	59.8	9	0.39	1.0	1.5	13.5	85.0	.223	381
12	1T2	345.1	77.8	20	0.32	1.0	1.5	13.5	85.0	.223	381
13	2S1	81.8	21.1	1	0.16	3.7	4.0	41.0	55.0	.341	161
14	2S1	136.9	29.6	9	0.18	3.7	4.0	41.0	55.0	.341	161
15	2S1	214.0	47.2	20	0.19	3.7	4.0	41.0	55.0	.341	161
16	2T1	105.8	24.5	1	0.07	4.0	4.5	39.0	56.5	.348	162
17	2T1	136.6	33.6	9	0.16	4.0	4.5	39.0	56.5	.348	162
18	2T1	132.6	33.9	20	0.12	4.0	4.5	39.0	56.5	.348	162
19	2S2	81.4	17.2	1	0.62	3.7	4.0	41.0	55.0	.341	161
20	2S2	149.7	34.6	9	0.72	3.7	4.0	41.0	55.0	.341	161
21	2S2	267.2	64.3	20	0.50	3.7	4.0	41.0	55.0	.341	161
22	2T2	74.5	27.0	1	1.04	1.5	2.0	53.0	45.0	.32	141
23	2T2	121.6	50.8	9	0.98	1.5	2.0	53.0	45.0	.32	141
24	2T2	191.1	74.5	20	0.96	1.5	2.0	53.0	45.0	.32	141
25	3S1	34.2	7.7	1	0.36	1.0	1.3	29.7	69.0	.199	347
26	3S1	52.2	6.3	9	0.37	1.0	1.3	29.7	69.0	.199	347
27	3S1	112.8	38.9	20	0.38	1.0	1.3	29.7	69.0	.199	347
28	3T1	49.7	31.3	1	0.57	1.2	1.8	24.2	74.0	.233	318
29	3T1	63.1	34.1	9	0.55	1.2	1.8	24.2	74.0	.233	318
30	3T1	232.0	103.5	20	0.56	1.2	1.8	24.2	74.0	.233	318
31	3S2	43.0	8.7	1	0.74	1.0	1.3	29.7	69.0	.19	347
32	3S2	100.4	25.6	9	1.04	1.0	1.3	29.7	69.0	.19	347
33	3S2	99.0	42.2	20	0.79	1.0	1.3	29.7	69.0	.19	347
34	3T2	65.4	24.7	1	1.5	10.5	11.8	26.8	61.5	.956	64
35	3T2	133.5	50.9	9	1.33	10.5	11.8	26.8	61.5	.956	64
36	3T2	184.0	77.2	20	1.29	10.5	11.8	26.8	61.5	.956	64
37	4S1	82.2	37.8	1	0.03	0.2	0.5	51.5	48.0	.17	282
38	4S1	275.5	35.3	9	0.07	0.2	0.5	51.5	48.0	.17	282
39	4S1	519.3	48.9	20	0.06	0.2	0.5	51.5	48.0	.17	282
40	4T1	103.8	34.3	1	0.08	0.7	1.0	61.0	38.0	.375	101
41	4T1	240.9	74.6	9	0.34	0.7	1.0	61.0	38.0	.375	101
42	4T1	504.1	104.7	20	0.32	0.7	1.0	61.0	38.0	.375	101
43	4S2	144.2	28.1	1	0.07	9.5	11.0	40.8	48.3	.791	61
44	4S2	231.9	48.9	9	0.05	9.5	11.0	40.8	48.3	.791	61
45	4S2	331.6	56.4	20	0.02	9.5	11.0	40.8	48.3	.791	61
46	4T2	103.3	19.4	1	0.89	0.7	1.0	61.0	38.0	.375	101
47	4T2	152.5	58.6	9	0.99	0.7	1.0	61.0	38.0	.375	101
48	4T2	331.9	97.9	20	0.89	0.7	1.0	61.0	38.0	.375	101

Table 1. (Continued).

	CODE	BD	SAR	EC	OC	LL	PH	SG	CLAY	SILT	SAND	M
1	1S1	1.5	10.7	6.0	4.4	40.0	7.7	2.88	33.0	49.5	14.5	3168
2	1S1	1.5	10.7	6.0	4.4	40.0	7.7	2.88	33.0	49.5	14.5	3168
3	1S1	1.5	10.7	6.0	4.4	40.0	7.7	2.88	33.0	49.5	14.5	3168
4	1T1	1.5	7.0	3.8	1.1	28.0	8.0	2.79	18.0	45.0	33.5	3533
5	1T1	1.5	7.0	3.8	1.1	28.0	8.0	2.79	18.0	45.0	33.5	3533
6	1T1	1.5	7.0	3.8	1.1	28.0	8.0	2.79	18.0	45.0	33.5	3533
7	1S2	1.5	14.4	1.4	0.5	36.6	8.7	2.49	14.5	58.0	20.5	4553
8	1S2	1.5	14.4	1.4	0.5	36.6	8.7	2.49	14.5	58.0	20.5	4553
9	1S2	1.5	14.4	1.4	0.5	36.6	8.7	2.49	14.5	58.0	20.5	4553
10	1T2	1.5	5.5	1.25	1.3	36.3	8.6	2.75	28.5	60.5	9.5	4235
11	1T2	1.5	5.5	1.25	1.3	36.3	8.6	2.75	28.5	60.5	9.5	4235
12	1T2	1.5	5.5	1.25	1.3	36.3	8.6	2.75	28.5	60.5	9.5	4235
13	2S1	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
14	2S1	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
15	2S1	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
16	2T1	1.5	0.3	0.95	1.5	25.2	7.8	2.72	18.5	53.5	23.5	4120
17	2T1	1.5	0.3	0.95	1.5	25.2	7.8	2.72	18.5	53.5	23.5	4120
18	2T1	1.5	0.3	0.95	1.5	25.2	7.8	2.72	18.5	53.5	23.5	4120
19	2S2	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
20	2S2	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
21	2S2	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
22	2T2	1.5	0.1	0.55	1.5	19.8	8.0	2.53	9.0	49.0	40.0	4361
23	2T2	1.5	0.1	0.55	1.5	19.8	8.0	2.53	9.0	49.0	40.0	4361
24	2T2	1.5	0.1	0.55	1.5	19.8	8.0	2.53	9.0	49.0	40.0	4361
25	3S1	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
26	3S1	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
27	3S1	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
28	3T1	1.5	0.7	0.45	2.6	31.0	7.8	2.85	17.2	71.0	10.0	5751
29	3T1	1.5	0.7	0.45	2.6	31.0	7.8	2.85	17.2	71.0	10.0	5751
30	3T1	1.5	0.7	0.45	2.6	31.0	7.8	2.85	17.2	71.0	10.0	5751
31	3S2	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
32	3S2	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
33	3S2	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
34	3T2	1.5	0.2	0.9	2.4	26.6	7.3	2.69	8.2	60.5	19.5	4840
35	3T2	1.5	0.2	0.9	2.4	26.6	7.3	2.69	8.2	60.5	19.5	4840
36	3T2	1.5	0.2	0.9	2.4	26.6	7.3	2.69	8.2	60.5	19.5	4840
37	4S1	1.5	31.4	3.3	1.1	60.8	7.8	2.84	27.0	28.5	44.0	2066
38	4S1	1.5	31.4	3.3	1.1	60.8	7.8	2.84	27.0	28.5	44.0	2066
39	4S1	1.5	31.4	3.3	1.1	60.8	7.8	2.84	27.0	28.5	44.0	2066
40	4T1	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
41	4T1	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
42	4T1	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
43	4S2	1.5	29.5	5.5	0.8	39.9	8.3	2.77	26.0	28.5	34.5	1796
44	4S2	1.5	29.5	5.5	0.8	39.9	8.3	2.77	26.0	28.5	34.5	1796
45	4S2	1.5	29.5	5.5	0.8	39.9	8.3	2.77	26.0	28.5	34.5	1796
46	4T2	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
47	4T2	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
48	4T2	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871

DATA ANALYSIS

This chapter includes a discussion of the general approach to the data analysis and the statistical methods used to analyze the erosion data. Equations are first developed for interrill erosion using erosion test data. This is followed by a parallel development of splash erosion equations from splash erosion data.

Methods of Analysis

The soil properties in Table 1 provide the independent variables for a multiple regression analysis that attempts to relate the amount of soil eroded to soil properties and slope angle. Dependent variables are interrill erosion (EI) and splash erosion (ES). The problem was approached by analyzing interrill erosion and splash erosion as two separate models. Erosion predicted by each model can be summed to estimate the total sheet erosion if desired.

A stepwise multiple regression program (BMDP2R) from the BMDP (April 1985) package was used to analyze the data. Throughout this study a five percent probability level of significance was selected to evaluate whether or not an individual independent variable would be included in the