STABILITY AND EROSION ON STEEP SLOPES CONSTRUCTED BY THE FOREST RECLAMATION APPROACH IN THE SOUTHERN APPALACHIAN REGION[1]

Isaac A. Jeldes[2], Siavash Hoomehr[2], Wesley C. Wright,[3], John S. Schwartz,[4] David E. Lane,[5], Eric C. Drumm[6]

Abstract: The Forest Reclamation Approach (FRA) employing low compaction of the surface materials has been shown to facilitate the establishment of healthy fast-growing forests. However, because low levels of compaction will generally result in reduced strength, it may be detrimental with respect to the mass stability and erosion resistance when employed on steep slopes (steeper than 20 degrees). To investigate the stability and erosion of steep sites reclaimed using the FRA, three research sites in the southern Appalachian region were developed. The sites were reclaimed by three different coal operators in general accordance with the FRA assuring low compaction in the upper 1-2 meters. However, the sites were not seeded according to the recommendations of FRA because the study was designed to test the effects of 3 perennial ground covers on erosion and tree growth; little or no ground cover was established during the first year. Each site was equipped with a full weather station that records precipitation, humidity, wind speed/direction, solar radiation, and air temperature. In addition, at each site four erosion study plots were equipped with H-flumes and stage recorders to measure hydrology, and sediment collection devices to estimate transported course and fine materials. This paper describes the instrumented sites and presents results obtained during the first year after reclamation. A simple method is presented for the stability analysis of FRA reclaimed slopes, and the long term stability of the project slopes shown to be acceptable. The observed sediment yield and the corresponding precipitation records are also shown. The results suggest that while the FRA may benefit the establishment of forests, and the long term mass stability may be sufficient, significant quantities of sediment were produced in the first season when no annual ground cover was established. It is suggested that erosion resistance is not enhanced in FRA reclaimed slopes simply due to the increased infiltration that accompanies the low levels of compaction in the surface layers. Rather, the infiltration and subsequent erosion should be dependent on the intensity and duration of the precipitation event.

Additional key words: slope stability, erosion, sediment

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[2] Graduate Research Assistant, Dept. Civil and Environmental Engineering, University of Tennessee, Knoxville, TN 37996; [3]Research Associate, Dept. of Biosystems Engineering and Soil Science, [4]Associate Professor, Dept. Civil and Environmental Engineering; [5]Civil Engineer, United States Department of the Interior, Office of Surface Mining, Pittsburgh, PA 15220; [6]Professor, Dept. of Biosystems Engineering and Soil Science University of Tennessee, Knoxville, TN 37996.

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Introduction

Surface mining requires the removal of millions of tons of material in order to obtain the desired resource. After the Surface Mining and Control Reclamation Act of 1977 (SMCRA), coal companies were required to restore the land to its pre-mined condition. Methods for reclamation usually include compaction of the reclaimed materials to increase the strength and ensure stability of the restored slope, but compaction also has a negative impact on the tree survival due to decreased root penetration and soil permeability resulting from decreased soil porosity (Sweigard et al., 2007a).

The Forest Reclamation Approach (FRA) is a reclamation method that uses low compaction grading in the surface layers to provide a low density growing medium for trees. Iannacchione and Vallejo (1995) reported that the majority of slope failures in abandoned mine lands in Kentucky occurred in loose material placed prior to SMCRA. The stability of slopes is a function of material shear strength that in turn is a function of void ratio or degree of compaction of the material. Generally, the more dense the material, the higher the strength parameters (internal friction angle and cohesion) (Holtz and Kovacs, 1981; Lambe and Whitman, 1969; Salgado, 2008). On the other hand, quick establishment of soil cover and forest is needed to reduce the amount of produced erosion (Angel et al., 2007; Schor and Gray, 2007; Sweigard et al., 2007a; Sweigard et al., 2007b; Torbert et al., 1994), resulting in a conflict between slope stability and a low density growth medium.

Data on the quantification of runoff and sediment yield during reclamation activities on steep slopes is limited. Several studies have been conducted using rainfall simulators (Gilley et al., 1977; Mitchell et al., 1983; Mostaghimi and Mitchell, 1983) and others on gentle slopes (Mcintosh and Barnhisel, 1993; Mckenzie and Studlick, 1979), but data for natural rainfall and reclaimed material on steep slopes is needed for more accurate erosion prevention and sediment collection control plans.

This paper describes three instrumented field sites in Tennessee and presents results obtained during the first year after reclamation. The sites were reclaimed in general accordance with the FRA, except that the ground cover was not seeded according to the recommendations of FRA because the study was designed to test the effects of 3 perennial ground covers on erosion and tree growth. As a result, little or no ground cover was established during the first year. Results are presented in terms of the supporting site characterization, the initial slope stability determinations, and the observed sediment yield for the corresponding precipitation records. The three sites are referred to here by the name of the coal operator as Premium, National and Mountainside.

Location of Field Sites and instrumentation

Each of the three sites was constructed using the low compaction grading technique. All three sites are in northeastern Tennessee, with Premium located in Anderson County, National in Campbell County and Mountainside located in Claiborne County (Figure 1). All plots in each site were constructed with the help of the local mining company.

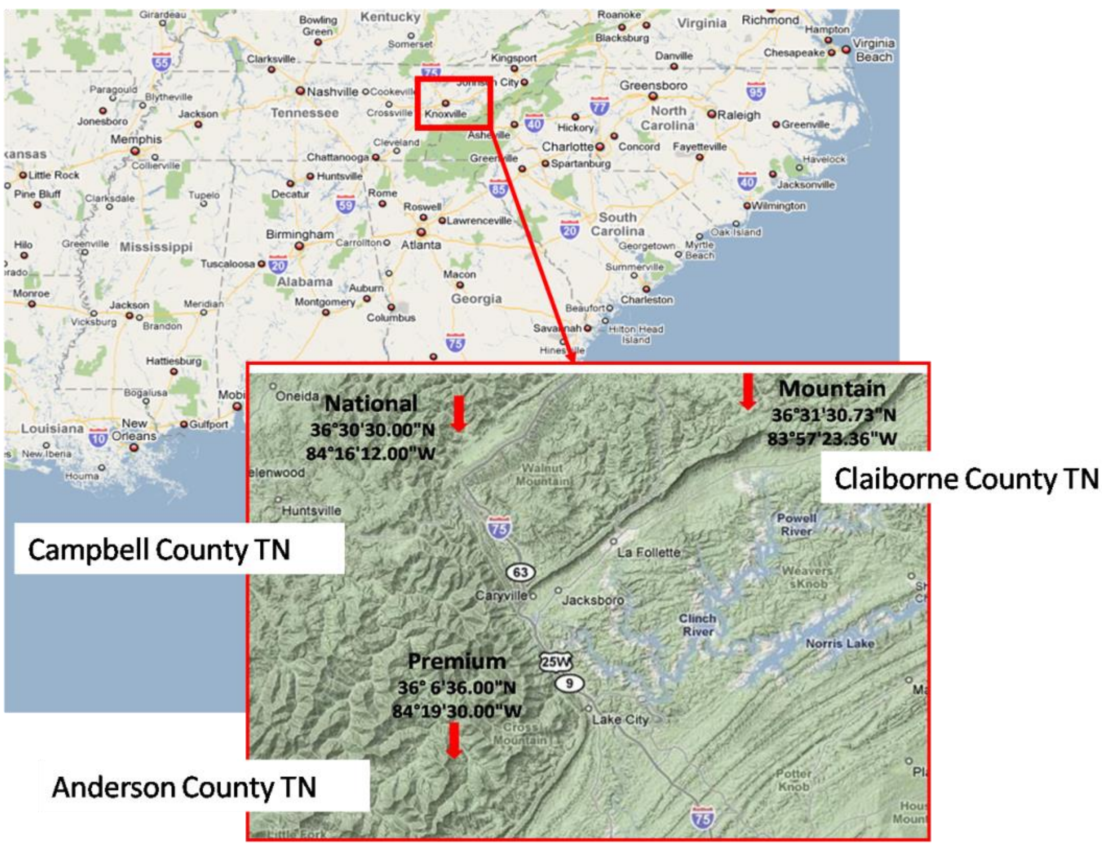

Figure 1. Instrumented field sites location at Northeastern Tennessee referred as Mountainside, National and Premium sites.

Each site consists of four different plots that are being used to study erosion production under four different combinations of ground cover and trees. One of these plots was left in bare conditions (no grass was seeded) to be used as a control plot, while the other received various ground treatments (Table 1). H-Flumes with an automated fluid level indicator (Yoder et al., 1999) were installed at the bottom of each plot to measure the time history of runoff volume, while runoff passing through them is later collected by a pre-sediment tank and water buckets. Each water bucket processes a flow divider that divides the runoff several times yielding a smaller but representative sample that is used for further physical and chemical laboratory analysis (Pinson et al., 2004). Also, each site has a weather station installed, where precipitation, solar radiation, wind speed, wind direction, and temperature is obtained in intervals of 5 minutes (Hoomehr et al., 2010). Figure 2 illustrates the sediment collection system installed at each of the 4 plots at each site.

Table 1 Summary of ground cover application rates and Percent Cover (Klobucar et al., 2009)

Site	Ground Cover	Seeding Rate (lbs/acre)		Average Percent Planted of Ground Cover (%)	Average Percent of Total Ground Cover, Including Volunteer Species Seedling in (%)
National		**May 20, 2009**	**June 18, 2009**	**August 10, 2009**	**2010**
	Alfalfa	9.50	----	2.11	5.24
	Goldenrod	1.00	----	0.01	3.72
	Switchgrass	4.50	----	0.29	5.73
	Bare	----	----	----	4.77
	Rye (arround trees)	----	7.00	----	----
Mountainside		**May 20, 2009**	**June 18, 2009**	**August 7, 2009**	**2010**
	Alfalfa	9.50	----	1.08	12.20
	Goldenrod	1.00	----	0.00	5.62
	Switchgrass	4.50	----	1.47	22.56
	Bare	----	----	----	8.08
	Rye (arround trees)	----	7.00	----	----
Premium		**May 20, 2009**	**June 18, 2009**	**August 6, 2009**	**2010**
	Alfalfa	9.50	----	2.70	3.47
	Goldenrod	1.00	----	0.00	0.99
	Switchgrass	4.50	----	0.06	2.19
	Bare	----	----	----	0.26
	Rye (arround trees)	----	7.00	----	----

Note: The Average Percent Cover values are expected to increase significantly during the 2010 growing season, and evidence of these increases has already been noted during recent surveys.

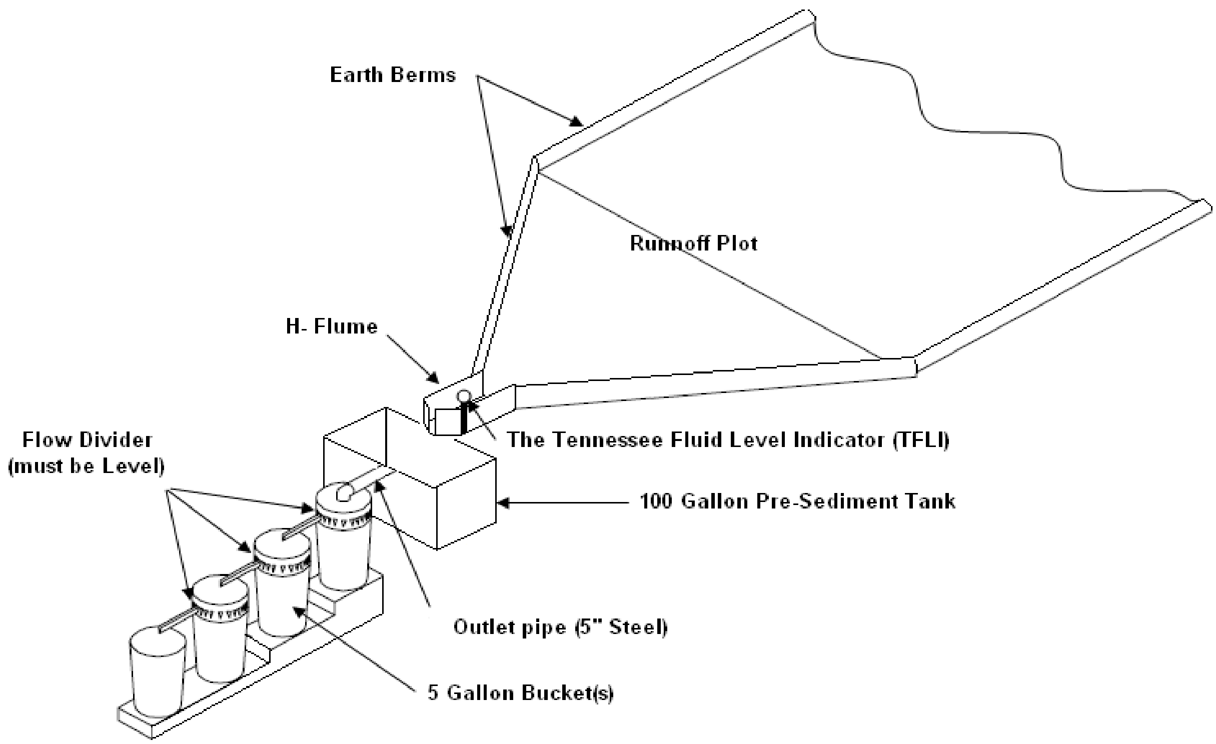

Figure 2. Illustration of the runoff and sediment collection system implemented at Mountainside, National and Premium sites (Hoomehr et al., 2010)

Site characterization and geometry of the slopes

Site Dimensions and Geometry

A topographical survey data was conducted using a Total Station instrument to determine the plot dimensions, and the inclination of the study sites estimated using a Suunto Mechanical Inclinometer model PM-5/360PC (Table 2). With two exceptions, all slope measurements exceed the SMRCA definition of steep slopes (exceeding 20 degrees). The slope inclinations obtained with the inclinometer were later verified from a linear regression of the survey data.

Table 2 Summary slope angles, lengths and widths for the three instrumented sites

Site	Plot	Angle of Slope, Degrees	Length (m)	Width (m) Top	Width (m) Bottom
Mountainside Site	1	27	48.8	21.5	21.5
	2	29	46.0	21.5	25.0
	3	28	44.6	25.1	22.4
	4	27	42.3	25.7	23.3
National Site	1	21	47.6	23.1	19.7
	2	20	48.4	22.1	25.3
	3	19	49.2	23.5	28.4
	4	21	48.2	20.8	28.2
Premium Site	1	28	33.5	24.8	21.7
	2	28	33.3	28.8	27.2
	3	28	33.3	27.7	25.3
	4	30	28.5	31.0	25.7

Determination of Unit Weights

Field determination of unit weights and moisture content of the low compaction surface layer material was conducted at each of the three sites. Data was collected using a nuclear density gauge (NDG) device (Troxler 3411 B) between June, 2009 and August, 2009. Details of the theory, field operation and safety recommendations of the NDG have been reported previously (Farrag et al., 2005; Randrup and Lichter, 2001; Troxler Electronic Laboratories Inc., 1997; Troxler Electronic Laboratories Inc., 2006). In order to avoid disturbance of the seeded plots, all unit weight measurements, were obtained in the bare ground plot, and the results assumed to be representative of the remaining plots. Measurement of the dry density and moisture content allow determination of the wet unit weight which is used in the stability analysis.

It is well known that the density or unit weight measurements obtained with the NDG are subject to errors due to presence of voids or over-dense material; however it is useful for obtaining a large number of measurements to investigate the spatial variability of density. Furthermore, because a measurement of unit weight which includes the presence of large particles is appropriate for use in the stability analysis, a comprehensive testing series was conducted at each site with the NDG was used. A randomized systematic sampling technique to reduce data tendency or bias in the in measurements (Sweigard et al., 2007b). This sample technique allows the subdivision of the data collection area in subareas where the measurement is randomly obtained. In our case, the total area of the bare plot was subdivided in squares of 3m by 3m and the NDG measurement was randomly taken inside the square, assumed to be representative of the complete square area. Figures 3 and 4 illustrate the application of the systematic random technique during NDG measurements on the bare plot at National Site.

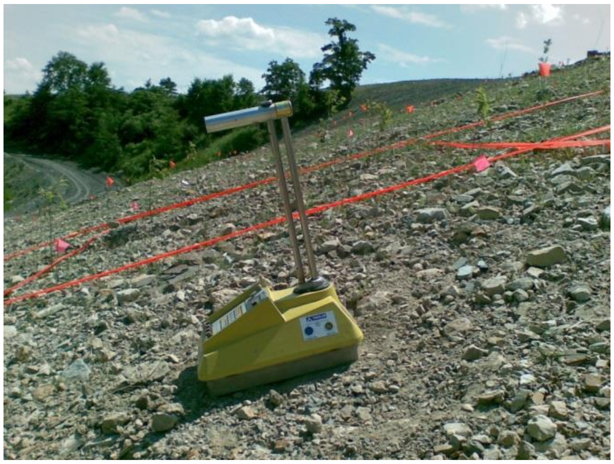

Figure 4 Illustration of NDG ready to measure at National Site

Figure 3 Example of the bare plot subdivided into multiple squares at National Site

The measured spatial distribution of the dry unit weight of the surface layer in the bare plot at the Premium site is shown in Figure 5. Similar interpolation maps were obtained for the National and Mountainside sites, using the spatial analysis tool inside the ArcMap software. A Kriging interpolation method was employed considering the information of 10 neighbors for zones around the center of the plot and at least 4 neighbors for areas located near the edges. Figure 5 suggests a weak tendency for the unit weight to decrease from the top of the slope to the bottom. A similar trend was observed at the National site, while at the Mountainside site the unit weight was higher at the bottom of the slope. This may be explained by the fact that at Mountainside there appears to be substantial number of large (> 1 meter diameter) boulders in the bottom third of the slope with a thinner layer of surface cover. The unit weights of Shale and Sandstone usually range from 23 to 27 kN/m^3, which is close to the measured Unit Weight values in the bottom third at Mountainside.

For general stability analysis purposes, the wet unit weight is of interest, and the value across the slope may be taken as the mean value with little error, since the contribution of a few areas with higher or lower unit weight may not produce any significant difference in the final factor of safety. Table 3 summarizes the average dry and wet unit weights and standard deviations at each site.

Table 3. Means and standard deviations for Wet and Dry Unit Weights for Premium, National and Mountainside.

Sites	**Unit Weight**	**Mean KN/m^3**	**Standard Deviation KN/m^3**
Premium	Dry	16.2	1.3
	Wet	18.5	1.3
National	Dry	18.5	1.0
	Wet	20.3	1.0
Mountainside	Dry	18.9	2.2
	Wet	20.4	2.2

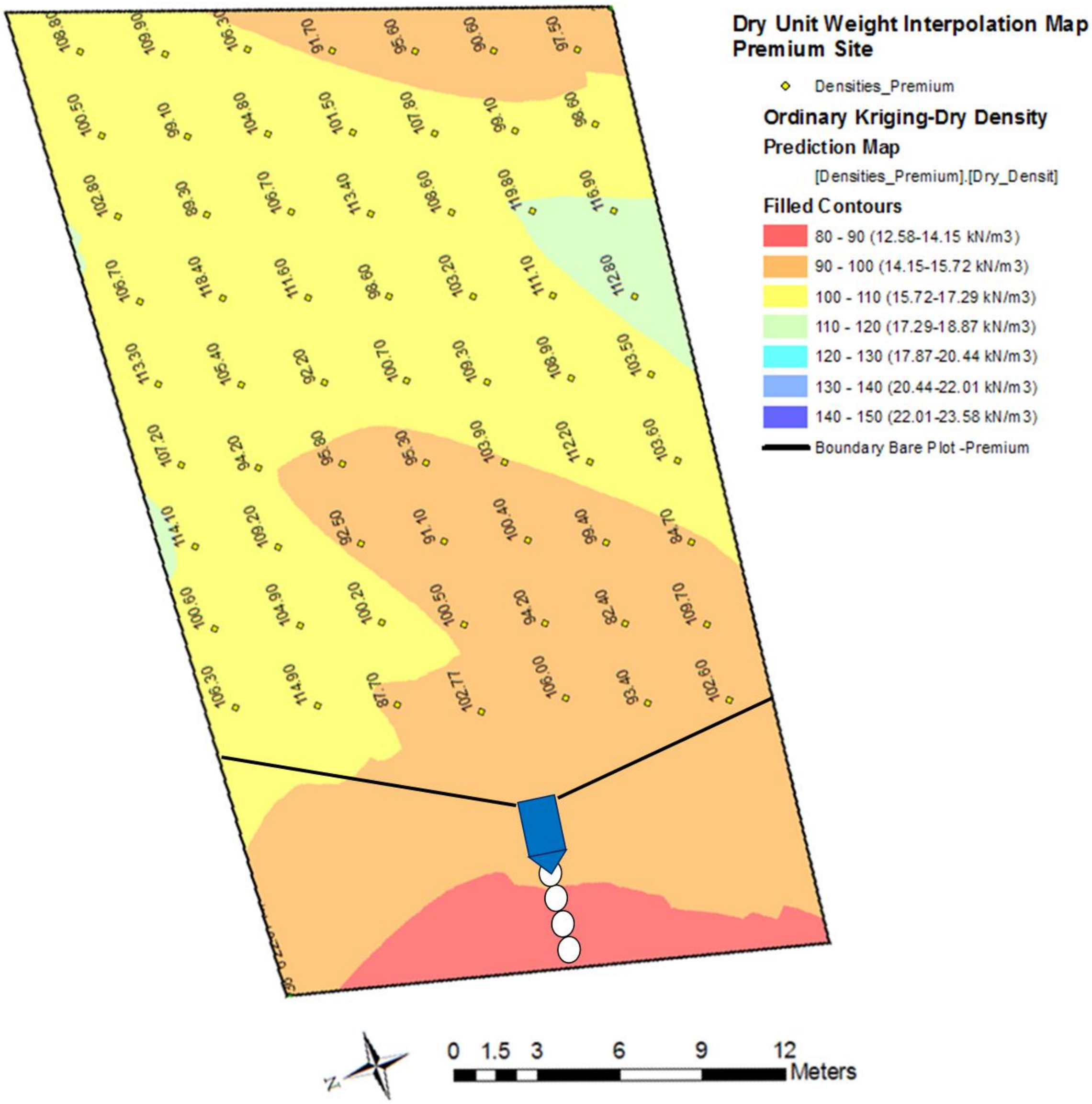

Figure 5. Spatial distribution of the Dry Unit Weight of the surface layer along the bare plot in Premium site (numerical results on figure are shown in pcf)

<u>Preliminary estimation of shear strength parameters</u>

Long term stability analysis assumes that all water pressures have been dissipated and thus requires the estimation of the drained shear strength parameters: friction angle and cohesion. White et al. (2009) reported drained friction angles for each of the three sites based on the observed angle of repose of the material. The angle of repose is the "steepest stable slope for loose packed granular material and represents the angle of internal friction at its loosest state" (Holtz and Kovacs, 1981). This approach assumes that the drained internal friction angle of the surface layer is well represented by the angle of repose when the low compaction grading technique is used. White (2009), reported values of angle of repose between 36 and 38 degrees for the National site and between 37 and 39 for Premium and Mountainside. Regarding the drained cohesion parameters, a cohesion value equal to zero is typically used for granular materials (Holtz and Kovacs, 1981; Lambe and Whitman, 1969; Salgado, 2008) and would be appropriate for reclaimed mine spoil. Thus for the stability analysis here, a value of zero is assumed for cohesion, and the angle of repose is taken as the friction angle. To investigate the stability of a generic slope representative of the project sites, the material properties summarized in Table 3 were used.

Preliminary Long Term Slope Stability Analysis

Preliminary Slope stability analysis

A generic slope representative of the most severe conditions at the 3 project sites was investigated. The slope was assumed to have a height of 14 m and an inclination of 28 degrees, with the properties given in Tables 2 and 3 for Premium site. Although there are a number of potential failure modes that should be evaluated, the discussion here only addresses the long term stability of a relatively shallow failure parallel to the surface of the slope. Since the strength parameters for the deeper compacted core materials are assumed to be greater than that for the surface material that received limited compaction, the analysis assumes that failure will occur in the weaker surface layer or at the contact between the surface material and the compacted core materials.

The study was conducted using two different limit equilibrium approaches: a) the infinite slope method and b) a non-circular method using a block search feature available in the software XSTABL (XSTABL, 2008). The surface layer was assumed to run parallel to the slope, with a uniform thickness of 1.5 m. To limit failure through the core material in the computer analysis, an arbitrarily high value of the cohesive strength parameter was assigned to the core materials. Additional analyses demonstrated that when the analysis is focused on the surface layer, the stability is insensitive to the assigned value of cohesion in the core material.

The factor of safety against failure is determined from the infinite slope method as (Lambe and Whitman, 1969):

$$FS = \frac{tan\phi}{tan\beta} \quad \textbf{(1)}$$

Where ϕ = angle of internal friction or angle of repose (cohesion assumed to be zero)

α = slope angle.

Note that the unit weight does not appear in the infinite slope expression, which increases its utility when applied to materials for which the unit weight or density is difficult to determine.

When the infinite slope method was applied to the generic project slope, the obtained FS for long term stability was 1.47. This means that the observed shear strength along the slip surface is 47% greater than that required to maintain equilibrium or stability. This result is valid only in the absence of internal pore pressures or seepage forces. In cases where water movement is present through the surface layer, the infinite slope equation include a coefficient of 0.5 (Lambe and Whitman, 1969). Thus, the infinite slope equation with seepage considerations reduces the computed factor of safety to 0.74, indicating that the resisting forces are lower than destabilizing forces and the slope is not stable. Although this condition is unlikely and assumes complete saturation and downslope water flow through the complete thickness of the surface layer, it should be considered for materials capable of large infiltration rates under high intensity storm events.

Taking advantage of the block search feature in XSTABL the FS for long term stability was found to be 1.477, which shows very good agreement with the FS obtained from the simple infinite slope analysis. Figure 6 shows a schematic section of the slope (the 1.5 m thick surface layer is so small with respect to the height of the slope that it cannot be distinguished from the slope surface) and the potential trial failure surfaces investigated. The circled areas are enlargements intended to show some of the 4000 failure surfaces at the top and bottom of the slope that were evaluated. The results from the infinite slope, infinite slope with seepage, and the XSTABL analysis are summarized in Table 4.

Using the software ArcGIS, the spatial distribution of factors of safety was constructed using the infinite slope equation, to graphically show distribution of Factor of Safety. Even though the assumption made in infinite slope method is that the ratio of depth to length of the sliding surface is small (or a very large surface length), this map can give some preliminary insights about the spatial variation of the Factor of Safety (due to the local variation of inclination). Figure 7 shows the distribution of factor of safety calculated using infinite slope method. The orange zones correspond to the areas with higher local failure potential (FS < 1), white zones represent stable but less than desirable transition areas (FS between 1 and 1.3) and blue zones represent stable areas (FOS>1.3).

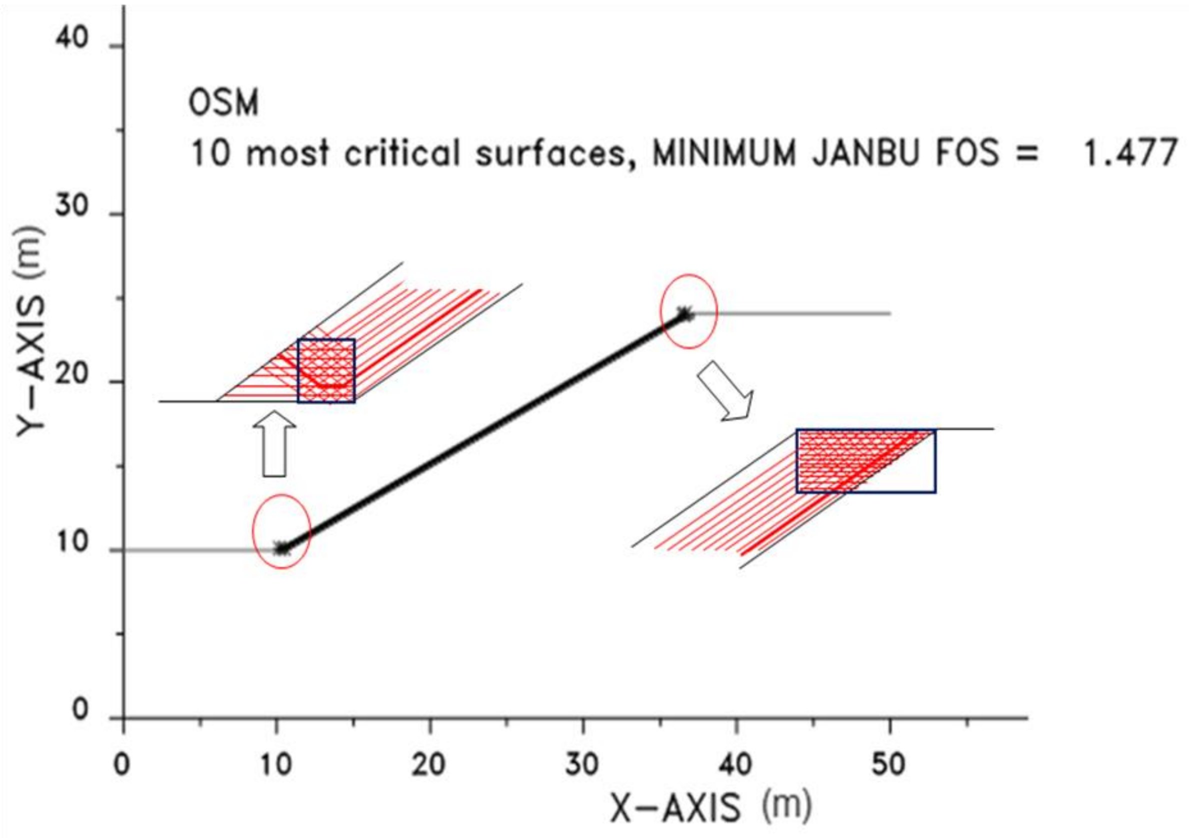

Figure 6 Slip surfaces analyzed with the block search feature of the software XSTABL for the drained analysis. Enlarged areas of the toe (left) and head (right) of the slope are illustrated

Table 4. Summary of considered soil properties for Slope stability analysis

	Material Layer	Friction Angle (φ), Degrees	Cohesion (c), kN/m^2	Unit Weight (γ), kN/m^3	Slope Stability f Analysis results (Factor of Safety)		
Sliding mass with planar failure along surface layer (Long Term Analysis)	Surface layer	38	0	18.4	Search Block (XSTABL) (no seepage effects)	Infinite Slope (no seepage effects)	Infinite Slope (with seepage effects)
	Foundation or core material	0	1000	18.4	**1.477**	**1.47**	**0.74**

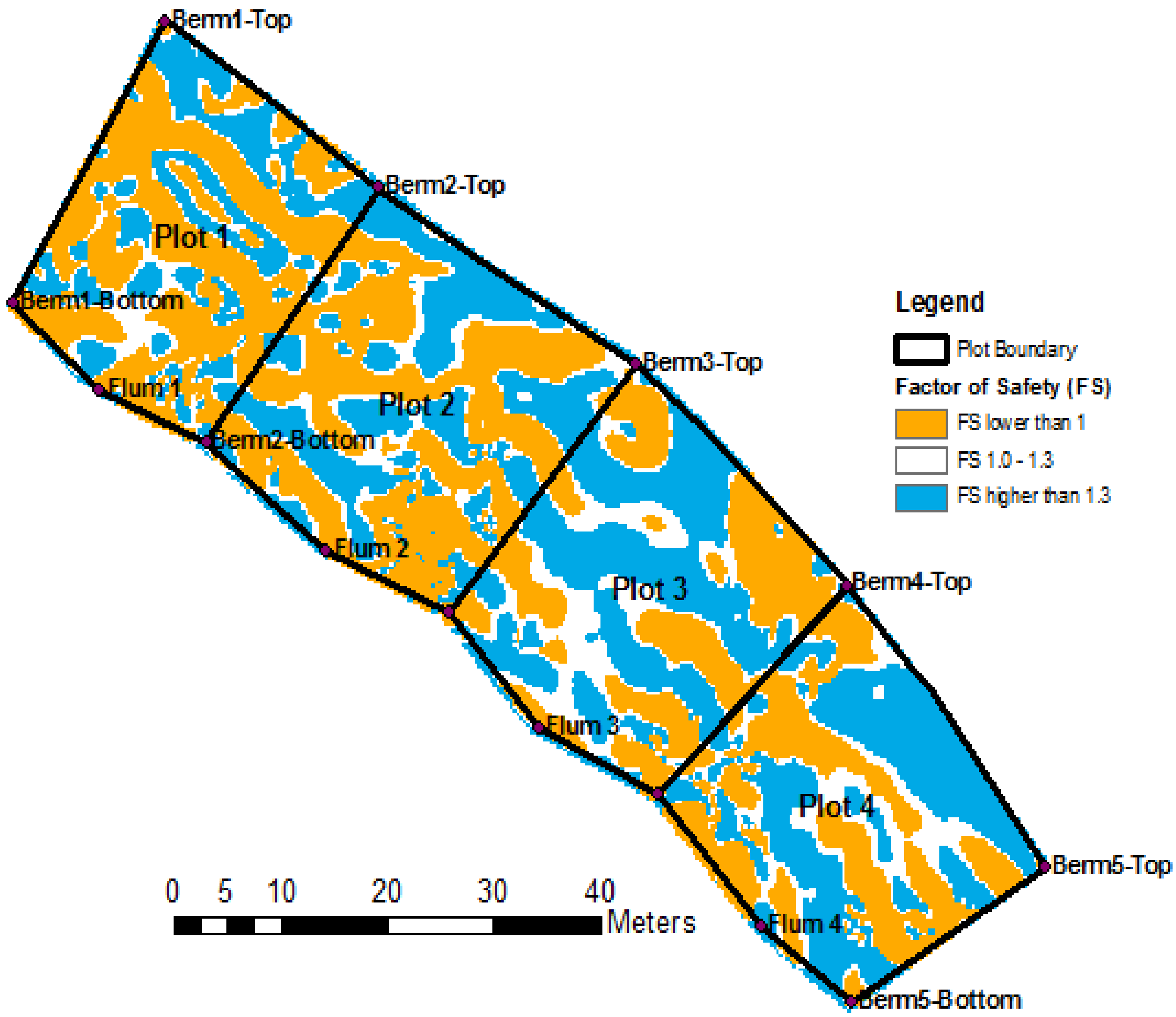

Figure 7 distributional map of factor of safeties calculated using infinite slope method at Premium Site

Soil Erosion and Sediment Yield Preliminary Studies

Maximum five minute rainfall intensity at each site is presented in Figure 8. In general, the Premium site had lower rainfall intensities while the Mountainside and National sites had higher intensity rainfall events. It was also found that Premium usually has longer rainfall duration events than National and Mountainside. During the first year of the instrumented sites, there were numerous rainfall events with 5 minute intensities greater than 50 mm/hour, with some as high as 100 mm/hr.

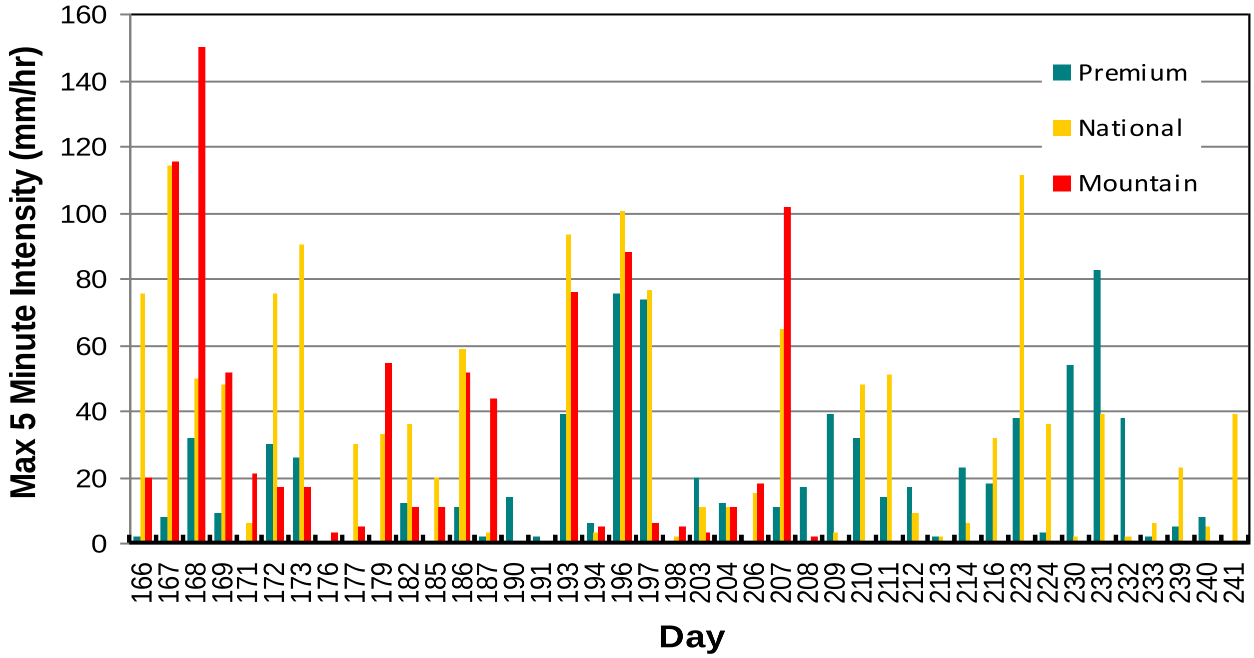

Figure 8 Maximum five minutes rainfall intensity at each site (Hoomehr et al., 2010)

Sediment was collected in the sediment traps and divider buckets to estimate sediment yield from the measured rainfall events. The measured sediment yield is presented in Figure 9 in terms of the mass per surface area of the field plot, with the results shown as the mean of the sediment collected in the four plots. Since the ground cover was not well established during this period, the results from the seeded plots and the bare ground plots are shown together.

Mountainside and National produced the highest amount of daily sediment yield, with about 35 Kg/m2 collected over a period of about 0.2 year, while only about 15 Kg/m2 was produced at

Premium over this period. This is consistent with reports from the literature that rainfall intensity is more closely related to sediment yield than rainfall duration (Renard et al., 1997). It is difficult to compare these results with published annual sediment yield since only data from a partial year is available, but the period shown in Figure 9 corresponds to the time of year with the highest rainfall. Observations by others (Carroll et al., 2000; Espigares et al., 2009) of sediment yield occurring on reclaimed coal mine sites suggests erosion rates ranging from 40-120 ton/ha/year (4 - 12 Kg/m2/yr). Thus, the sediment measured from these sites is somewhat higher than that

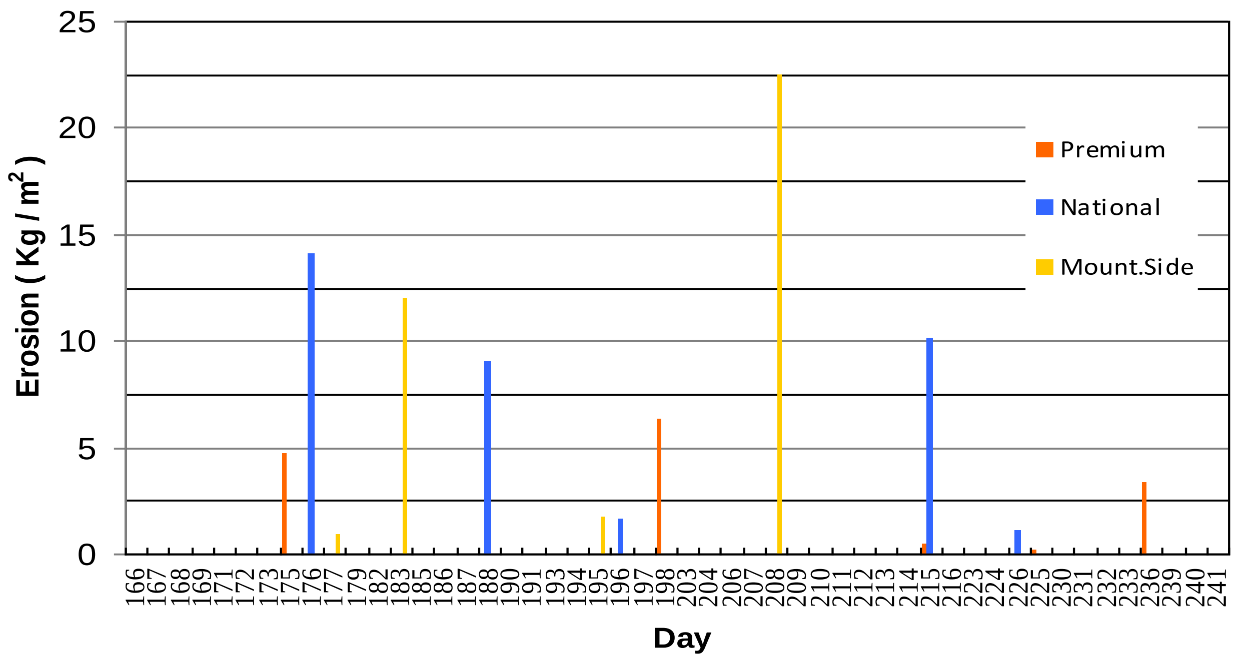

Figure 9 Average erosion rate from each site (Hoomehr et al., 2010)

suggested in the literature, which might be expected since the field plots had limited ground cover and somewhat higher sediment yield would be expected from sites reclaimed using the FRA. Data continues to be collected and the results presented here can be considered to be preliminary.

Discussion and Conclusions

Factors of safety obtained for the weak layer analysis show that for long term stability of the slopes in this study with inclinations as much as 28 degrees, the observed shear strength along the slip surface is 47% greater than that required to balance the destabilizing forces and the slopes should be stable in the long term. It is important to mention that the conditions in this analysis are applicable only when there is no excess pore water pressure developed in the material, or with no water movement through the upper weak layer. On the other hand, a lower bound, worst case scenario analysis with seepage acting in the surface soil layer suggests that the slopes may be unstable. These conditions require the entire surface layer to be saturated with downslope flow (e.g. large and intense rainstorm) but suggest that the surface materials encountered in FRA applications need to be evaluated for this type of instability. The paper also provides a means for estimating the drained shear strength of the surface materials, and suggests that the results from the simple "Infinite Slope" stability calculations are consistent with the more typical limit equilibrium solution for the likely failure mode when the failure passes through the weak surface layer. The Infinite Slope method may be appropriate for long term stability analysis for slopes constructed using a low compaction grading technique, due to its simplicity and in consideration of the typical absence of strength measurements. The short term or undrained stability of the slopes was not addressed.

Regarding the erosion and sediment yield observations, the presented results will be used to create hydrologic and sediment model parameters, which can be used to predict the sediment yield and design appropriate soil erosion control plans on sites with similar geometric and morphologic characteristics. The research program described was designed to investigate the relationship between erosion rates and rainfall intensity for these sites. Many practitioners of the FRA assume that the low compaction grading results in higher infiltration which will in turn limit erosion. While this may be true for rainfall events below some threshold intensity, at higher rainfall intensities the infiltration capacity of the surface materials will be exceeded resulting in surface flow and erosion. Because the low compaction materials are not as resistant to erosion as more highly compacted materials, the erosion rates may be greater. It is suggested that a complex relationship exists between rainfall intensity, infiltration, slope inclination and erosion, and that the frequent assumption that higher infiltration assures reduced erosion may not always be appropriate. The results from this study contribute to the understanding of factors to be addressed when the FRA is applied to steep slopes. Application of the FRA will help the establishment of healthy forests provided the slopes are stable, considerations for erosion are made, and appropriate tools are used to predict and capture the sediment produced.

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