Reclaiming steep-slope coal mines
in the eastern US for successful reforestation

by D. Kumar and R.J. Sweigard

Abstract ■ A methodology has been developed and demonstrated to be effective in reclaiming surface-mined land for a forestry post-mining land use. The forestry reclamation approach (FRA) has been applied, almost exclusively, to flat or gently rolling surfaces. One of the primary steps in the FRA is to loosely grade the top 1.22 m (4 ft) of soil or substitute root growth medium to avoid excessive compaction. Concern has been expressed by regulators and the public that loose grading on steep slopes (i.e., greater than 23°) could lead to slope failures, which is one of the issues that the Surface Mining Control and Reclamation Act of 1977 (SMCRA) sought to correct. A field investigation was conducted at a steep-slope contour operation in eastern Kentucky to test the applicability of FRA in this setting. Final grading was performed according to FRA standards. The surface consisted of two distinct substitute rooting media. One was unweathered gray sandstone and the other was a combination of gray sandstone, brown sandstone, and topsoil. A variety of native hardwoods was planted following the FRA guidelines. The slope was instrumented with 70 survey monuments to monitor for mass movement. The reclaimed spoil was also characterized using bulk density and penetrometer resistance methods. The characteristics of both spoils are similar to those observed on flat to rolling surfaces where the FRA has been used and, after one year, approximately 70% of the trees had survived. During this first phase of investigation, there has been no major mass movement of the slope and slope stability analysis indicates that the application of the FRA has little impact on the overall stability of the slope.

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Introduction

Over the past decade and a half, a considerable amount of work has been done on improving reclamation practices to enhance reforestation success on surface-mined land. For many years following the passage of the Surface Mining Control and Reclamation Act of 1977 (SMCRA), attempts to reforest reclaimed mine sites were largely unsuccessful, due to excessive compaction (Graves et al., 1995). Similar to the problem of reclaiming prime farmland, researchers learned that excessive compaction negatively impacts tree survival and growth. Soil compaction results in increased soil strength and soil density (Dollhopf and Postle, 1998). Much of the recent work has concentrated on minimizing or alleviating soil compaction, but it has also addressed selection of the rooting medium, planting methods and the selection of tree and herbaceous species. There have been many positive results from this work, not the least of which is heightened realization on the part of industry, regulators and the general public of the importance of reforesting surface-mined land and the technical path to success in this area. One of the specific results that has been realized from the recent studies is the formation of the Appalachian Regional Reforestation Initiative (ARRI) (Angel et al., 2005) and the formalization of the forestry reclamation approach (FRA), which recommends only minimal grading of the upper 1.22 m (4 ft) of the replaced rooting medium (Burger et al., 2005). However, the vast majority of research sites that were used to develop and test these minimal grading practices have been either mountaintop removal operations or area stripping operations, where the final surface was relatively flat or rolling. Very few sites even considered minimal or loose grading on steep slopes and none have actually studied the best practices for implementing the forestry reclamation approach on steep-slope highwall elimination operations.

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Certainly, one of the driving forces behind the passage of SMCRA was the problem of unstable slopes caused by unregulated conventional contour mining that was practiced widely in the Appalachian region. The problems of

Figure 1

Experimental site at the Peel Poplar Mine (before highwall elimination).

exposed highwalls and unstable outslopes have effectively been resolved by enforcement of the regulations derived from SMCRA. By necessity, successful highwall elimination requires a considerable amount of compaction, which has negative impacts on tree growth. Tree planting also suffers, because it is difficult to properly plant trees in compacted soil (Torbert **et al. [no Torbert and Daniel in refs]**,1988) . There has been concern expressed by some, both from industry and the regulatory authorities, that the application of FRA on steep slopes may be either impractical or even, under some circumstances, deleterious to the stability of the slope in question.

Successful application of FRA in flat or rolling surfaces was the motivating force behind this research in steep slopes. Land is drastically disturbed by surface mining due to removal of native vegetation, soil and exposed overburden. To minimize the environmental and ecological disturbances, SMCRA requires that a coal mining operation should return the affected surface-mined land to the approximate original contour and be able to support the premining land uses or higher uses. After two decades of experience with SMCRA, the Kentucky Department of Surface Mining Reclamation and Enforcement (KDSMRE) recognized that the implementation of SMCRA did not result in successful reforestation. Through several field visits, KDSMRE concluded that excessive compaction of growth media, inappropriate growth media and excessive competition from herbaceous ground covers are the main factors for unsuccessful reforestation on mine lands (Campbell, 1997). In 1997, KDSMRE issued Reclamation Advisory Memorandum (RAM) 124, a forerunner of the FRA.

One of the strongest driving forces behind the passage of SMCRA was the problem of unregulated conventional contour mining operations that were most common throughout the Appalachian region. The problems associated with exposed highwalls and unstable slopes have been regulated after implementation of SMCRA. However, to maintain stability of slopes as required by SMCRA, the mine operators do a considerable amount of compaction of loose spoil, which can have a negative effect on tree growth. The stability concern arises due to the top 1.22 m (4 ft) of loose material on steep slopes.

Objectives

The overall objective of this research is to facilitate the broader application of FRA on steep-slope operations throughout the Appalachian region. This was accomplished by conducting a thorough evaluation of the current regional practices that are used for highwall elimination in steep-slope mines that employ FRA and by assessing the effectiveness from the stability, operational, economical and reforestation potential. Slope stability was a major focus of this investigation and was evaluated through field monitoring and analysis of a reclaimed slope. Following is a list of two more specific project considerations that were evaluated during research:

- Slope stability of the reclaimed mine where the highwall has been eliminated.
- Reforestation potential in terms of selected spoil characteristics such as bulk density and maximum penetration depth, which have been proven to correlate to reforestation success.

Experimental site description

The Peel Poplar Mine of International Coal Group (ICG) was selected for detailed field investigation. The site is located on the Left Fork of Blackberry Creek in Pike County, eastern Kentucky (USA). The site is part of the Matewan Quadrangle of the United States Geological Survey, with latitude 37° 30’ 40” and longitude 82° 13’ 36”. The topography of the Peel Poplar Mine coincides with the Kentucky portion of the Cumberland Plateau. The coal deposit at Peel Poplar is exposed along the contour. The strata consist of layers of sandstone, shale, coal and underclays (little fireclay

Figure 2

Experimental site after final grading.

and fireclay rides).

The climate of the region is humid continental, with an average precipitation of 114 cm (44.9 in.), and an average monthly precipitation of 10 cm (3.9 in.), which ranges from 6-12 cm (2.4 - 4.7 in.). The average temperature is 13° C (55° F), with a mean daily maximum and minimum of 31° C (88° F) and 18° C (64° F) in July and 8° C (46° F) and -4° C (25° F) in January (Hill, 1976) **[do you have more current climatic records?]**. The coal seams are mined using the contour haulback mining method. The mining is done using a combination of hydraulic excavators, front end loader, trucks and dozers. Figure 1 shows the experimental site before highwall elimination.

Experimental site preparation

The highwall was eliminated using a combination of truck haulback and lateral dozer push. For this, a ramp was constructed along the contour bench and spoil was hauled up the ramp and dumped over the edge. Then lateral pushing was done in horizontal passes. Approximately, 581,000 m^3 (760,000 cu yd) of loose material was backfilled to eliminate the highwall by a combination of a Caterpillar 992D loader, 777D trucks and a D11R dozer. Backfilling of the highwall was required by law; however, the final grading method was modified for this experiment.

The first step of the process was to load the trucks using the 992D loader and then haul the spoil up the ramp along contour. Next, the dumped material was pushed in horizontal passes by the CAT D-11R dozer. The last step was grading of the slope from top to bottom using the D11R dozer in a single pass following FRA recommendations (Sweigard et al., 2007 **[which one?]**). After final grading, the area of approximately 1.9 ha (4.7 acres) was naturally divided into two parts based on top spoil material, as shown in Fig. 2. One part consists almost entirely of gray sandstone with some shale mixed in, with an average slope angle of 28°. The other part was a mixture of sandstone, shale and some topsoil dozed down the highwall (giving material its brown color). The gray spoil accounts for around 40% of the total area and the brown spoil accounts for the remaining portion, with an average slope angle of 26°.

Slope movement monitoring network

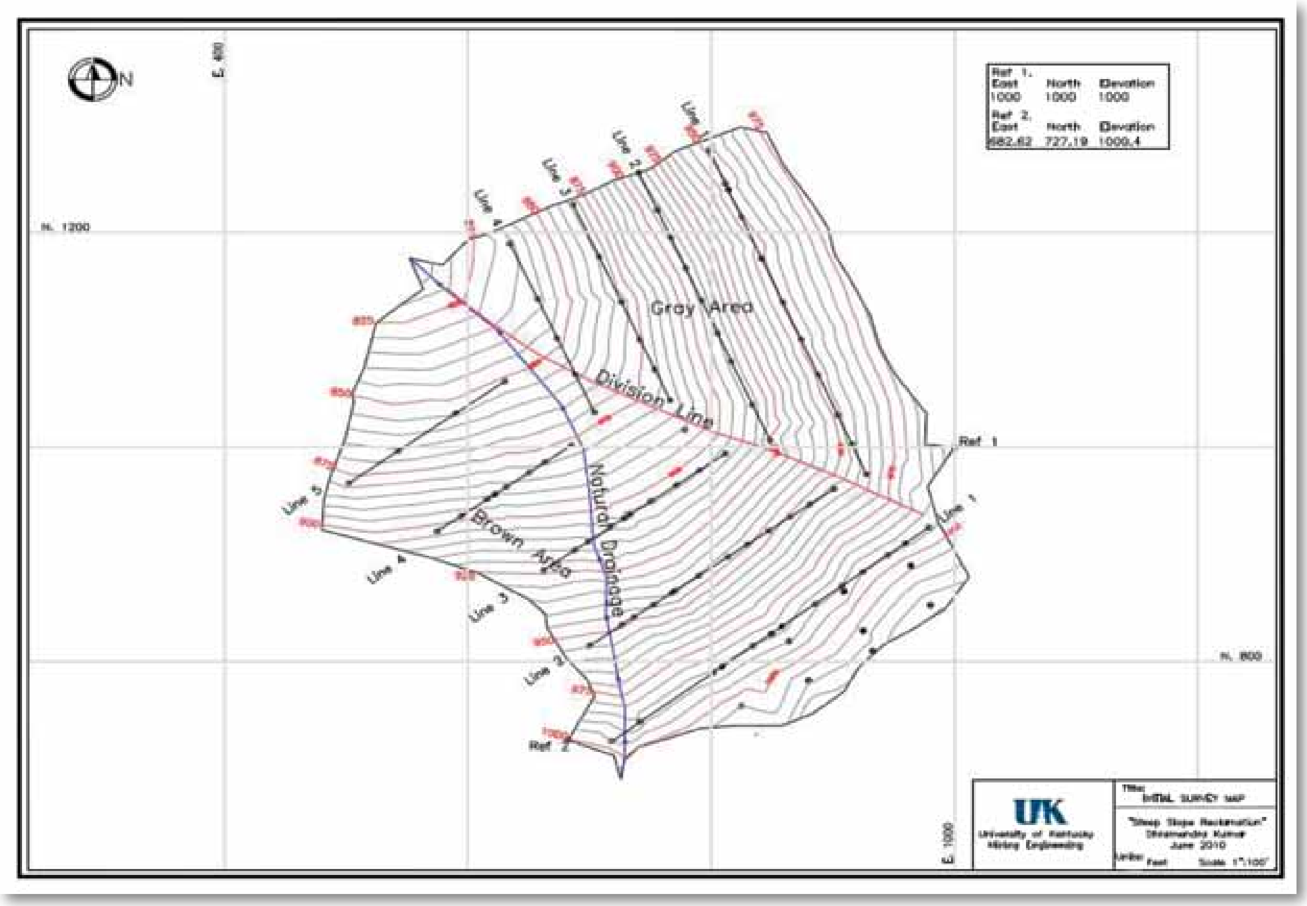
A detailed survey of the experimental site was conducted to locate the boundaries, plot the topographic contours, fix the location of survey monuments and find area, slope angle and volume of backfilled spoil. A combination of a total station (Topcon GTS-229) and reflecting prism was used for the survey work. The locations of the reference points were chosen in such a manner that the relative movement of any unstable area could be monitored. The permanent control points (reference points) were located on stable ground outside the slope area and within view of targets. A drawing of the reclaimed area with monument positions is shown in Fig. 3. After fixing the locations of the monuments by surveying, both the gray spoil and the brown spoil areas were instrumented with 1.25-cm (0.5-in.) diameter and 1.22-m (4-ft) length steel rebars. The monuments were driven approximately 0.92 m (3 ft) below the surface to minimize the effect of freezing and thawing on vertical movement. A total of 70 rebars were driven. A regular rectangular pattern of approximately 25 by 15 m (82 by 49 ft) was used in locating the position of the monuments.

Tree planting

Tree planting was done in the spring of 2009 following the FRA guidelines for proper planting techniques. Planting was done by a professional contractor, Williams Forestry Services. A total of 4,327 tree seedlings of ten different species were planted in a 1.8 by 1.8 m (5.9 by 5.9 ft) pattern. Table 1 pro-

Figure 3

Figure 3: Position of survey monuments.



vides the inventory of seedlings planted.

Spoil characterization

Thompson et al. (1987), demonstrated that bulk density and penetration resistance are good predictors of root system performance in reclaimed mined lands. Soil resistance to deformation or penetration indicates the soil strength (Jansen, 1990). Dunker et al. (1994) found that severe root impedence occurs when penetration resistance exceeds 2,000 kPa (290 psi) and root elongation is severely restricted at 2,620 kPa (380 psi). As a result of reforestation research at Starfire Mine by the University of Kentucky, it was found that maximum penetration depth (depth of refusal) and bulk density display a strong correlation with tree survival rate (Conrad, 2002). There was less evidence of a correlation between soil resistance and tree survival rate (Conrad, 2002). In the present study, the effect of spoil compaction on the survival and growth rates of trees on steep slopes was evaluated. Shortly after completion of the experimental site, dry bulk density, penetration resistance and maximum penetration depth were recorded in June 2009. These parameters were evaluated again approximately one year later in May 2010.

Table 1

Tree inventory.

No.	Common name	Scientific name	No. of trees
1	White oak	*Quercus alba*	713
2	Black oak	*Quercus valutina*	713
3	Black cherry	*Prunus serotina*	713
4	Sugar maple	*Acer saccharum*	713
5	Yellow poplar	*Liriodendron tulipifera*	400
6	Northern red oak	*Quercus rubra*	297
7	Gray dogwood	*Cornus racemosa Lam.*	236
8	Eastern redbud	*Caercis canadensis*	236
9	White pine	*Pinus strobes*	281
10	American chestnut	*Castanea dentata*	25
Total number of trees			**4,327**

Bulk density. The dry bulk density, wet density and moisture content of the brown and the gray spoil areas were recorded using a Troxler 3440-single probe nuclear density gauge. The field set-up of the nuclear density gauge is shown in

Figure 4

Field setup of nuclear density gauge.

Figure 5

Comparison of dry bulk density at 15 cm depth.

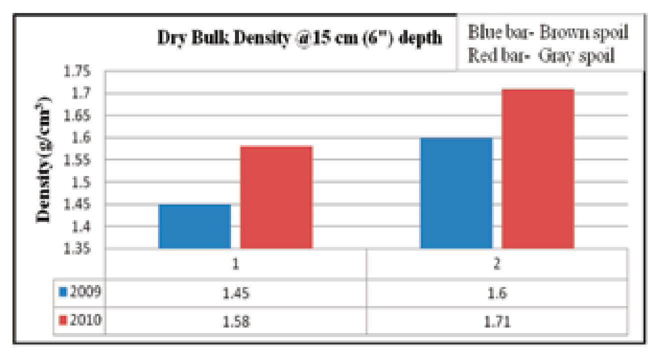


Figure 6

Field setup of the Wildcat dynamic cone penetrometer.

Figure 7

Comparison of depth of maximum penetration for brown and gray spoil area with depth of refusal at 35 blows.

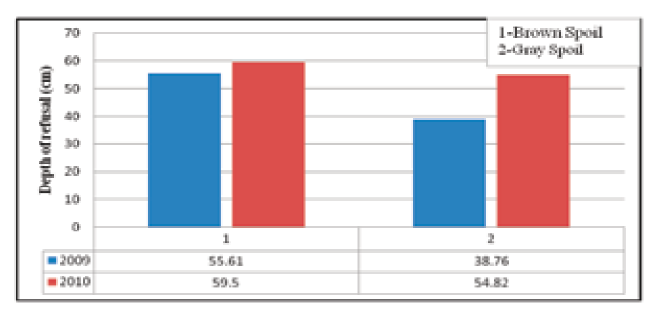


Fig. 4. A total of 70 readings were recorded (near each survey monument). Readings were recorded at depths of 5 cm (2 in.), 15 cm (6 in.) and 30 cm (12 in.).

Conrad (2002) stated that, with time, the growing medium in loose-dumped areas consolidates and, hence, results in an increase of dry bulk density. The dry bulk density results for both the brown and the gray spoil areas at 15 cm (6 in.) for June 2009 and May 2010 measurements are shown in Fig. 5. The bulk density results follow the same trend at other depths (e.g., 5 cm and 10 cm). It was observed that the bulk density values increased slightly in one year, which is consistent with research results by Conrad (2002) at the Starfire Mine.

Spoil penetration resistance. To measure the effect of spoil resistance for growth and development of roots in the growing medium, the average penetration resistance and maximum penetration depth were evaluated in June 2009 and May 2010. If the number of blows per increment with the penetrometer exceeded 35, this was taken as an indication of refusal or maximum penetration depth. Prior experience with the Wildcat dynamic cone penetrometer indicated that, if no advancement was observed after 35 blows, additional blows had no discernable impact (Hunt, 2007). A total of 35 readings were recorded near alternating monument locations. A field setup of the dynamic cone penetrometer is shown in Fig. 6. Only the results of maximum penetration depth or refusal depth are discussed in this paper.

Maximum penetration depth. The maximum penetration depth (depth of refusal) results for the brown and gray spoil areas for June 2009 and May 2010 are shown in Fig. 7. It is observed that with time, maximum penetration depth or refusal depth decreases. To properly correlate tree survival

Table 2

Tree survival rate.

No.	Area	Planted trees (April, 2009)	Surviving trees (April, 2010)	Survival rate
1	Brown spoil	2,412	1,715	71.1
2	Gray spoil	1,731	1,088	62.9

Figure 8

Maximum downward slope movement for each survey line after one year.

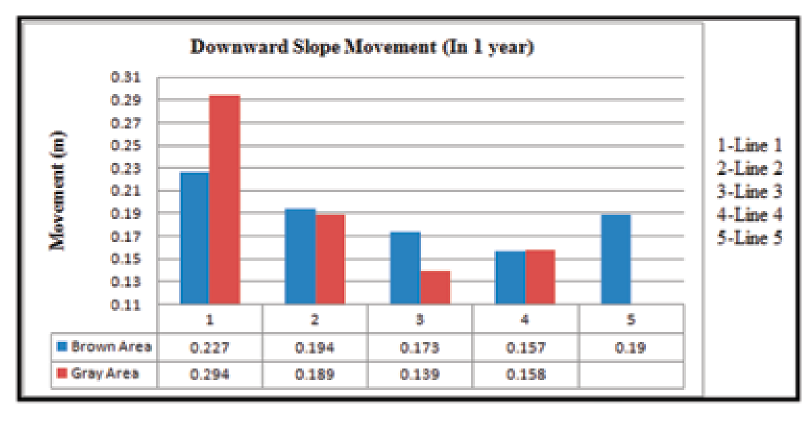
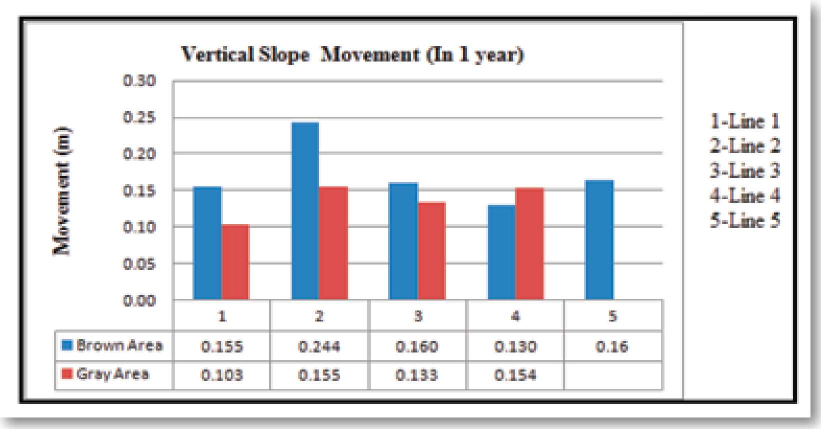


Figure 9

Maximum vertical slope movement for each survey line after one year.



rate and maximum penetration resistance, at least two more years of data are required, as demonstrated in Conrad, 2002.

Assessment of tree survival

The survival rate of trees planted on both the gray and the brown spoil areas was monitored one year after planting. The survival rates provided additional data to verify the relationships previously developed between spoil characteristics and tree survival rates. Survival rates one year after planting are shown in Table 2. Chemical analysis of both the brown and the gray spoil samples show that the brown spoil is slightly acidic (pH = 6.71) and the gray spoil is slightly alkaline (pH = 7.78). Prior research demonstrated that acidic soils are more suitable for tree growth compared to alkaline soils (Conrad, 2002). This fact is supported by Table 2, where the brown spoil area has a greater survival rate compared to the gray spoil area.

Slope movement monitoring

Reclamation scientists and industry personnel have expressed concern that loose dumping of the top 1.22 m (4 ft) of material with minimal grading, as recommended by FRA, could compromise the stability of the slope. Hence, the practice necessitates the close monitoring of loose spoil on steep slopes for any type of mass movement. In this study, the focus was only on monitoring for mass movement. The soil erosion due to rain was not taken into consideration. There were some expectations for vertical settlement and frost heave; however, downward movement of the slope was the primary focus of this investigation. To measure mass movement, a well-defined survey network was used as shown in Fig. 3. To monitor slope movement, a regular survey of the monuments using a Topcon GTS-229 total station was done approximately quarterly (June 2009, August 2009, March 2010 and May 2010). One survey, which was scheduled for December 2009, was missed due to inclement weather conditions in December 2009 and January 2010. After each survey, the results were plotted to analyze horizontal and vertical mass movement and were compared with previous survey plots.

Slope movement analysis. The survey results from the base line survey (June, 2009) and the final survey (May, 2010) were plotted and analyzed by line for movement of monuments down the slope and vertical settlement or heaving. The results of maximum downward slope and vertical slope movement are shown in Figs. 8 and 9, respectively. In some parts of the slope, heaving of the monuments due to freezing and thawing was recorded. The maximum downward movements of 0.227 m (0.74 ft) in the brown area (Line 1) and 0.294 m (0.96 ft) in the gray area (Line 1) were recorded. The maximum vertical slope movement of 0.244 m (0.84 ft) in the brown area (Line 2) and 0.155 m (0.51 ft) in the gray area (Line 2) were recorded. These small slope movements are verified by the stability analysis computer models. The overall slope has not exhibited any significant mass movement, even after two prolonged rain storms, which caused flooding the region. The minimum downward movements of slope were 0.10 m (0.325 ft) in the gray area (Line 4) and 0.089 m (0.290 ft) in the brown area (Line 5).

Slope stability analysis

Field measurement of slope stability was done using the slope monitoring network and computer modeling of slope stability was performed. In this particular study, the static equilibrium (limit equilibrium) method was used for slope stability analysis. The main objective of any type of stability analysis is the prediction of an accurate slope factor of safety. Stresses, gravity loading, rock mass strength, geology and pore pressure are the main factors contributing to slope failure problems (Girard and McHugh, 2000). The widely used Mohr-Coulomb failure criterion is used in this analysis.

Limit equilibrium method. The limit equilibrium methods are the most commonly used approach for analyzing the stability of slopes. The fundamental assumption of this method is that failure occurs through the sliding of a block or mass along a slip surface (Roc News, 2004). The limit equilibrium methods are popular in geotechnical practice due to their relative simplicity and ability to evaluate the sensitivity of stability to various input parameters. At the condition of limit

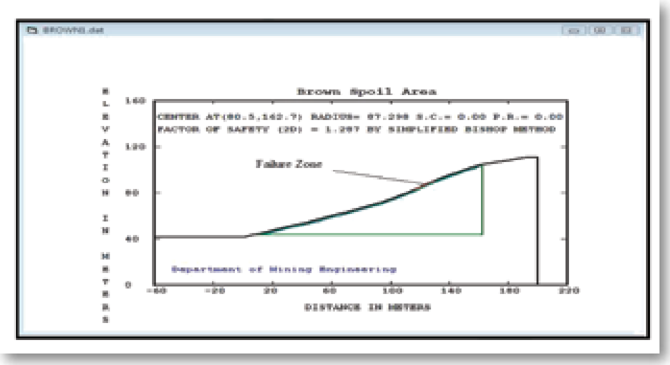
Table 3

Input material properties.

Soil type	Unit weight, kN/m³	Cohesion, kN/m²	Friction angle (°)	Poisson's ratio	Young's modulus N/m²
	(*γ*)	(*C*)	(Φ)	(*v*)	(*E*)
Top brown	15.5	0.0479	36	0.3	7.89E+04
Top gray	16.7	0.0479	37	0.3	8.46E+04
Gray	19.62	0.0479	38	0.3	1.00E+05
Rock	35.316	9.58	42	0.1	1.00E+10

Figure 10

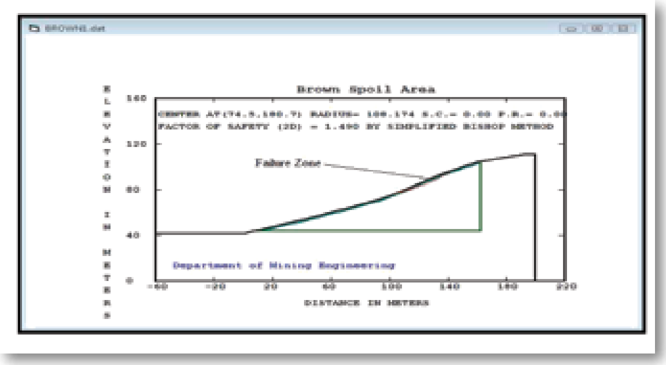
REAME model (with top 1.22 m loose material).



CENTER AT(80.5,162.7) RADIUS= 87.298 S.C.= 0.00 P.R.= 0.00
FACTOR OF SAFETY (2D) = 1.287 BY SIMPLIFIED BISHOP METHOD

Figure 11

REAME model (with top 1.22 m loose material and 3 m DMIN).



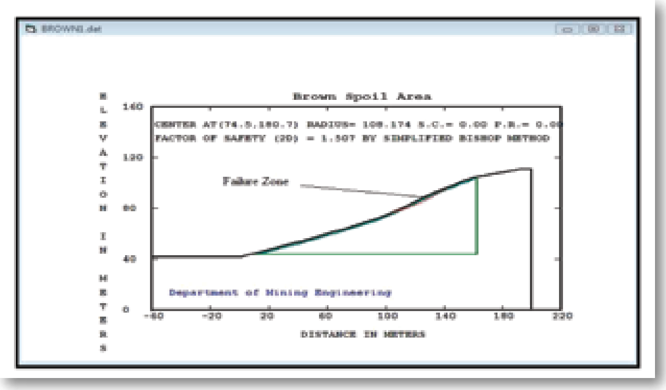
CENTER AT(74.5,180.7) RADIUS= 108.174 S.C.= 0.00 P.R.= 0.0
FACTOR OF SAFETY (2D) = 1.490 BY SIMPLIFIED BISHOP METHOD

equilibrium, all points on a failure plane are on the verge of failure (Charles, 1999). At the failure point, the driving forces (stresses or moments) are just equal to the resisting forces (stresses or moments). Hence, the factor of safety is equal to unity. If the resisting forces of a slope are greater than the driving forces, the factor of safety is greater than unity and the slope is stable. However, when the resisting forces are less than the driving forces, the slope becomes unstable. In limit equilibrium methods, a failure surface is assumed and a state of limit equilibrium is said to exist. The Office of Surface Mining (OSM) recommends that the factor of safety should be greater than 1.5 for reclaimed steep slopes.

Computer models. Two-dimensional computer models for stability analysis were developed using Rotational Equilibrium Analysis of Multilayered Earthworks (REAME-2008 Version). The Simplified Bishop Method was used for analysis. Three different soil layers: bedrock, gray spoil and top gray or top brown (1.22 m loose material) were considered in the analysis. The use of a curved envelope has proven that these shallow circles are not critical and should be eliminated by using a DMIN (minimum depth of tallest slice) (Huang, 1983). The spoil area was almost dry and no seepage was found in any part of the slope; hence, an assumption of zero pore pressure was used. The input material physical properties are listed in Table 3. Two types of REAME analysis for each spoil area were done: the first considering the top 1.22 m (4 ft) of loose material (with and without fixing the minimum depth of tallest slice) and the second considering total backfilled material with the same properties. The first two models resulted in factors of safety equal to 1.287 and 1.490 as shown in Figs. 10 and 11, respectively. The model without the top loose 1.22 m spoil resulted with factor of safety of 1.507 as shown in Fig. 12, which satisfies the OSM requirement for stable steep slopes.

Figure 12

REAME model (without top 1.22 m loose material and 3 m DMIN).



CENTER AT(74.5,180.7) RADIUS= 108.174 S.C.= 0.00 P.R.= 0.0
FACTOR OF SAFETY (2D) = 1.507 BY SIMPLIFIED BISHOP METHOD

Summary of stability analysis. All three REAME model results for both brown soil and gray soil indicated that only the upper part of the slope where the slope inclination is highest (near 30°) shows any signs of instability. The results without 1.22 m (4 ft) of loose material are very close to the results obtained with 1.22 m (4 ft) of loose top material. The results of this study demonstrated that the application of FRA in steep slopes does not cause any additional stability problems that would not otherwise exist for very steep (e.g., greater than 30°) slopes. The results of this stability analysis were verified by the survey results of slope movement monitoring. Furthermore, any minor stability issues associated with the loose material are isolated to the upper 1.22 m (4 ft) and do not contribute any mass instability. These instability conditions can be prevented through careful grading of final slope angles. Here, careful grading refers to visual inspection of slope during grading for any type of bumps or ridges on the slope. For better control of final grading, the stability analysis can be performed in advance and grading should follow the slope survey process.

Conclusion

From the field investigation and the computer-based stability analysis, the following conclusions can be drawn concerning the application of the FRA on steep-slope operations:

- Physical characteristics of the root growth medium, such as bulk density and maximum penetration depth, on the steep-slope reclamation site in the study were very similar to the values obtained for loosely compacted materials on flat or gently rolling surfaces, as shown at Starfire mine by Conrad, 2002.
- The tree survival rate on steep slopes is also comparable to the survival rates found on flat surfaces at Starfire mine. The lower survival rate also corresponded to the gray spoil area, which had inferior characteristics compared to the brown spoil area.
- It was found that the top 1.22 m (4 ft) of loose material was not causing any significant stability problems. Lower factors of safety were observed for very steep portions of the slope (greater than 30°), but these areas were not significantly affected by the upper 1.22m (4 ft) of loose material. Any instability associated with the loose material was minor and did not result in mass instability. ■

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