Geotech Geol Eng (2013) 31:1261–1274
DOI 10.1007/s10706-013-9648-0

ORIGINAL PAPER

The Low Compaction Grading Technique on Steep Reclaimed Slopes: Soil Characterization and Static Slope Stability

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Received: 20 November 2012 / Accepted: 7 April 2013 / Published online: 17 April 2013

Abstract Since the Surface Mining and Control Reclamation Act of 1977, US coal mining companies have been required by law to restore the approximate ground contours that existed prior to mining. To ensure mass stability and limit erosion, the reclaimed materials have traditionally been placed with significant compaction energy. The Forest Reclamation Approach (FRA) is a relatively new approach that has been successfully used to facilitate the fast establishment of native healthy forests. The FRA method specifies the use of low compaction energy in the top 1.2–1.5 m of the contour, which may be in conflict with general considerations for mechanical slope stability. Although successful for reforestation, the stability of FRA slopes has not been fully investigated and a rational stability method has not been identified. Further, a mechanics-based analysis is limited due to the significant amount of oversize particles which makes the sampling and measurement of soil strength properties difficult. To investigate the stability of steep FRA slopes (steeper than 20°), three reclaimed coal mining sites in the Appalachian region of East Tennessee were investigated. The stability was evaluated by several methods to identify the predominant failure modes. The infinite slope method, coupled with the estimation of the shear strength from field observations, was shown to provide a rational means to evaluate the stability of FRA slopes. The analysis results suggest that the low compaction of the surface materials may not compromise the long-term stability for the sites and material properties investigated.

Keywords Forestry reclamation approach · Slope stability · Mine spoil material · Surface coal mining

1 Introduction

A reclamation method that employs minimally compacted spoils to enhance native forest growth, known as the Forest Reclamation Approach (FRA) is currently being promoted by the US Office of Surface Mining (OSM) (Angel et al. 2007; Sweigard et al. 2007b). Since the Surface Mining and Control Reclamation Act of 1977 (SMCRA), coal companies in the USA have been required by law to restore the land to its pre-mined contours (USDoI 1977). Reclamation activities have traditionally incorporated compaction procedures to augment the strength of the reclaimed material and ensure stability of the restored slopes.

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However, while compaction is important for strength and erosion resistance, it diminishes soil porosity which restricts root penetration and reduces water infiltration with negative impacts on tree survival and grass reestablishment (Angel et al. 2007; Sweigard et al. 2007b). FRA employs a low compaction effort in the uppermost 1.2–1.5 m. The low-compaction grading technique has proven to be successful in encouraging tree growth, and demonstrates the potential for establishing healthy native forests on reclaimed mine lands (Angel et al. 2007; Barton et al. 2007). However, with the exception of Torbert and Burger (1994), most of these demonstrations were conducted on relatively flat lying terrain where stability issues were negligible. The stability of steep FRA slopes, defined as steeper than 20° by the USDoI (2009), and the possible modes of failure have not been investigated and a rational stability analysis method has not been suggested.

Slope stability analysis requires the knowledge of soil properties in terms of density and strength; characteristics not easily determined for reclaimed mine spoil due to the significant amount of oversize material (> 0.3 m). The in situ density of soils consisting of large rock particles can be difficult to measure, which makes it difficult to quantify and awkward to provide proper construction quality control. Sweigard et al. (2007a) have suggested correlations between dry bulk density and shovel penetration; though practical for reforestation efforts they are not appropriate for the evaluation of slope stability. Furthermore, because of the difficulties associated with sampling and testing due to the oversize particles, the shear strength properties are not typically measured in laboratory or field tests. For mine reclamation projects, the design is typically completed well in advance of mining activities and usually based on experience using assumed or traditional regional soil properties (Bell et al. 1989). Naturally, there is uncertainty associated with this practice, especially if low compaction is employed on steep reclaimed slopes. For example, in Kentucky the majority of slope failures in abandoned mine lands have occurred via translational and rotational failure mechanisms through the loose material placed prior to the SMCRA (Iannacchione and Vallejo 1995). The lack of proper compaction is a known cause of failure in constructed slopes, with the stability becoming worse under intense rainstorms (Chen et al. 2004).The failure of Sau Mau Ping slopes in Hong Kong is one dramatic example of the danger associated with poorly compacted slopes and lack of proper engineering design (Abramson 1996; Hong Kong Geotechnical Engineering Office 2007).

The objectives of this paper are to (1) characterize the geotechnical properties of low compacted spoils on steep slopes constructed according to the FRA, and (2) investigate the likely failure mechanisms associated to steep slopes reclaimed using the FRA. This is accomplished using three reclaimed field sites at which the material characteristics are evaluated, and the results will be used to suggest a practical method to estimate the shear strength and evaluate the stability of slopes constructed using the low compaction grading technique.

2 Methods

2.1 Location of Field Sites

To investigate the potential effects on stability resulting from the implementation of the low compaction grading technique, three steep FRA slopes were studied. The three sites, referred to here by the name of the initial coal operator (Premium, National and Mountainside), are located in northeastern Tennessee, with Premium located in Anderson County, National in Campbell County and Mountainside located in Claiborne County (Fig. 1). Each of the mine operators played an instrumental role in the development of the study sites. Each site was divided into four different plots which while not discussed here, were instrumented in order to concurrently investigate the runoff hydrology and sediment yield on the FRA slopes (Hoomehr et al. 2013). Fig. 2 shows the National site during construction of the study plots.

2.2 Site Construction and Reclamation Process

At each of the three sites in this study, the construction procedure followed the contour *haulback method* (Sweigard and Kumar 2010), where a ramp is constructed on the contour bench and spoil is hauled up the ramp and dumped over the edge. The sequence of the construction process can be divided into four major steps (Sweigard et al. 2007b) depicted schematically in Fig. 3: (a) placement and compaction of the materials for the primary backfill core using traditional practices, (b) dumping of the soil that will constitute the loose surface layer (1.2–1.5 m thick),

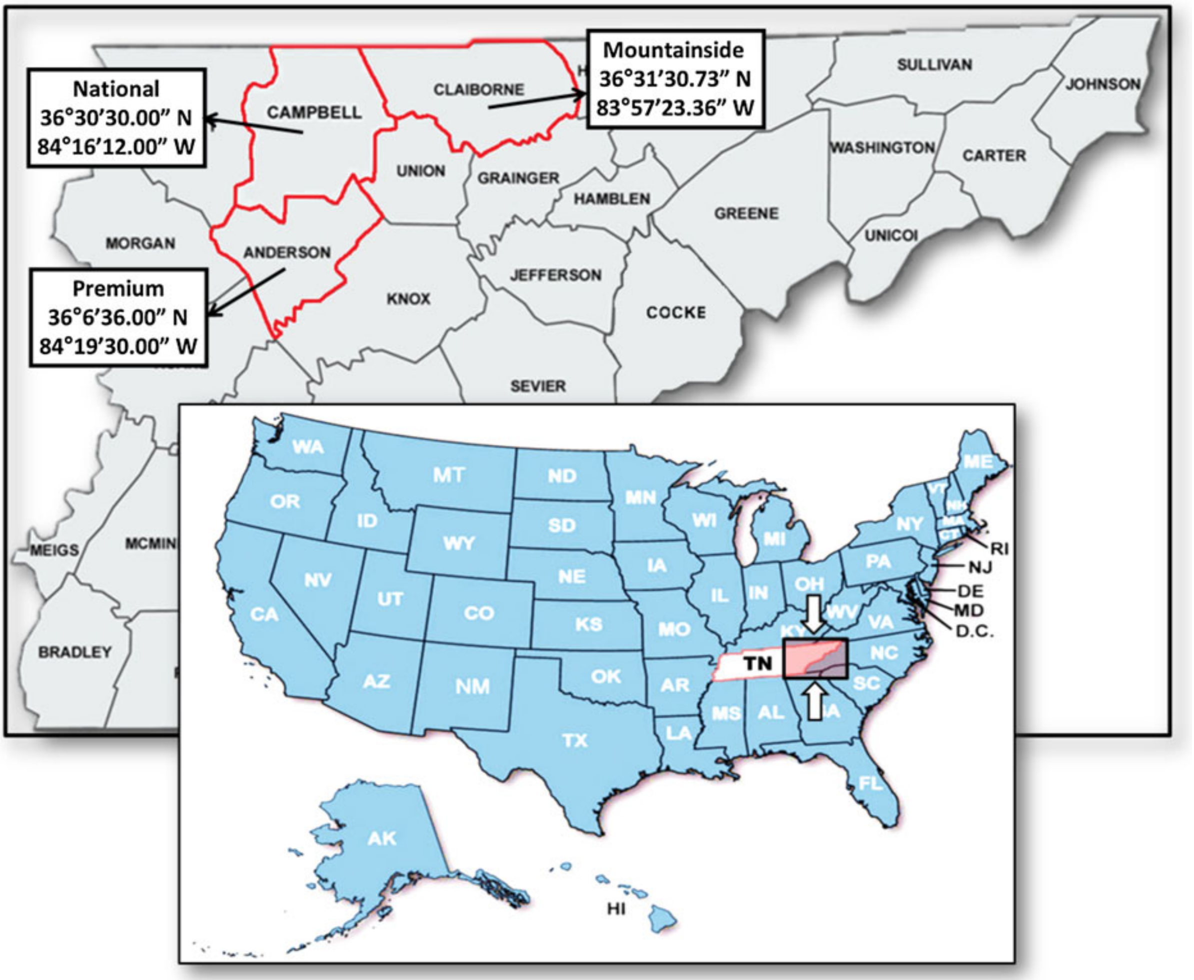


Fig. 1 Location of field sites in northeastern Tennessee, referred to as Premium, National, and Mountainside

(c) grading of the loose soil layer with the lightest equipment available using the fewest passes possible, and (d) reforestation. The three research sites presented a very rough soil surface after the final grading, which is consistent with the FRA recommendations for successful reforestation (Sweigard et al. 2007b). However, because the final layer at all three sites often included boulder-sized material, significant depressions and large rocks were left on the surface of the slope which is a deviation of Sweigard's recommendations for an ideal finished surface.

2.3 Geotechnical Characterization

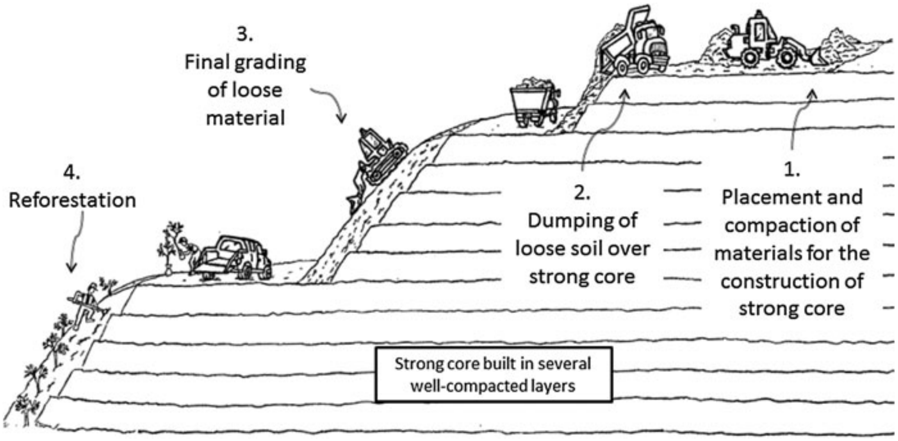
The investigation proceeded with the characterization of the research sites and the analysis of their mechanical stability. The field characterization of the mine spoil included: (a) determination of the site geometry; (b) particle size analysis, index tests, and classification of the materials; (c) determination of unit weight; and (d) estimation of the Mohr–Coulomb (M–C) shear strength parameters.

2.3.1 *Geometry*

The geometric characteristics of the research sites were determined via a series of Trimble™ total station topographical surveys. The purpose of these surveys was not only to obtain a more accurate estimation of the slope angles, but also to gather data to geo-reference the instrumented sites allowing an investigation of the spatial variation of material properties.

Fig. 2 National site after the FRA reclamation process and during the construction of the study plots

Fig. 3 Depiction of the reclamation process according to FRA



2.3.2 Particle Size Analyses, Index Tests, and Classification of Reclaimed Materials

Four soil samples of 0.02 m^3 each were randomly taken across the slope at each site for particle size analyses, index tests and classification. All samples were collected from a depth of at least 30 cm below the slope surface to (a) avoid samples with fewer fines due to erosion armoring and (b) avoid surficial soils affected by changes in fabric due to weathering. Particle size analysis (grain size distribution and hydrometer) and Atterberg limits tests were conducted in general accordance to ASTM D422-07 and ASTM D4318–10 respectively, and classification of the materials in general accordance to the Unified Soil Classification System (USCS), ASTM D2487-10. Visual inspection suggested that the materials may contain a large amount of agglomerated fines in the form of large particles, and therefore, traditional dry particle size analysis would indicate a larger amount of coarse material than really exists. We investigated this issue at all three sites by allowing soil samples to soak in water for 14 days. We found very few aggregated fines in the Premium and National soils, but significant aggregated fines at Mountainside. For this reason, a wet preparation of the Mountainside samples was conducted in general accordance to ASTM D2217-85 before conducting the particle size analysis and index tests. The amount of oversize material (> 0.3 m) was estimated on a surface basis. This was accomplished by dividing the plot into multiple squares of 1 m side length; a photograph of each square was used to estimate the percentage of oversize particles per surface area.

2.3.3 *Unit Weight*

An extensive data collection of the unit weight of the loose surface layer at each of the three sites was conducted using a Troxler 3411-B Nuclear Density Gage (NDG), in general accordance to the ASTM D6938-10. The measurements were obtained shortly after each slope was constructed. During the data collection, periodic calibration of the NDG device was conducted at the beginning and middle of each work day, employing the calibration block provided by the manufacturer. A randomized systematic sampling technique (Sweigard et al. 2007c) was used at one plot per site to reduce data tendency or bias in the measurements. The plot was divided into multiple squares of 3 m side length, where single measurements of bulk dry unit weight γ_d, bulk wet unit weight γ_T and moisture content w were taken at random locations inside the squares (Fig. 4). The soil surface was cautiously carved to obtain a planar surface before placing the nuclear gauge device, avoiding air interchange between the gauge base and the soil surface. Then, a hole perpendicular to the slope surface was driven inside each sub-area and the source rod inserted to obtain the readings at 300 mm (which is the maximum length of the source rod of the Nuclear Density Gauge). From previous observations of the materials it was concluded that the amount of hydrocarbons present at each site was very small and unlikely to affect the NDG readings.

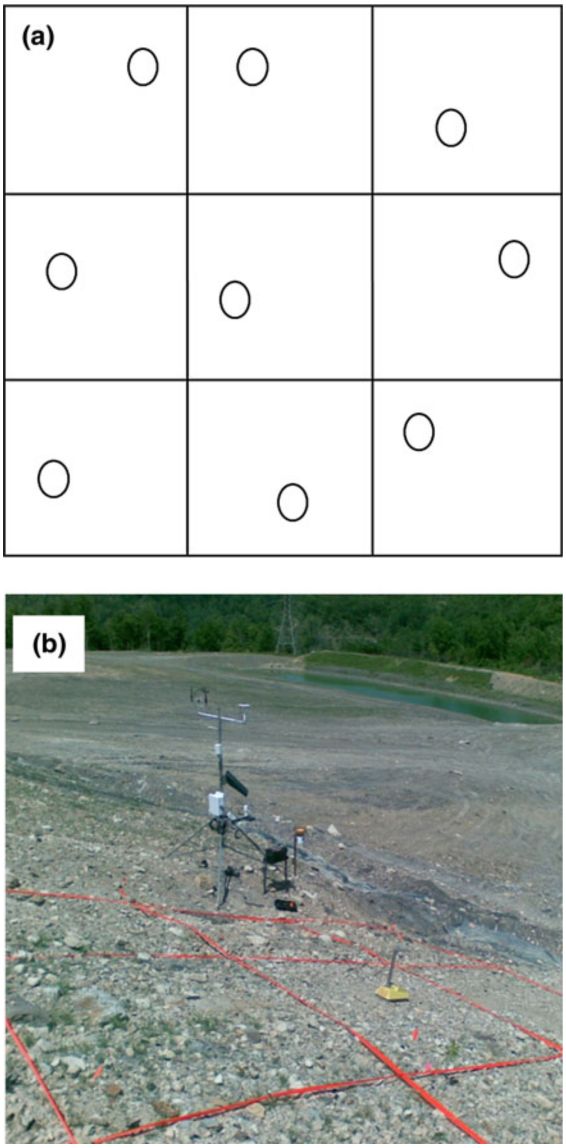


Fig. 4 Randomized systematic sampling technique; **a** area of interest subdivided into small sub-areas (Sweigard et al. 2007c), where *small circles* represent the random measurement locations; **b** application of this technique for NDG measurements at the National site

2.3.4 *Shear Strength Parameters*

Slope stability analysis for long-term conditions assumes that positive excess pore water pressure dissipates during the construction or loading period, and thus, requires the estimation of the drained or effective shear strength parameters. The shear strength of soil is typically described using the M–C yield or failure criterion:

$$\tau_n = c + \sigma_n \tan\phi \qquad (1)$$

where σ_n and τ_n are the normal and shear stresses acting on the failure plane within the soil body, and ϕ and c are the internal friction angle and cohesion.

Outside of mine reclamation, the shear strength material properties ϕ and c are often measured in laboratory or obtained through correlations with in situ tests. However, due to the large particles present in mine spoils, traditional tests are very difficult to conduct. The current practice in mine reclamation is usually based on experience or assumed values of ϕ and c.

As discussed earlier, the FRA technique consists on having a 1.2–1.5 m of loose soil at the uppermost part of the contour, above a well compacted and stable core. Thus, this low density/low strength zone should be evaluated for stability. Since 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), it is suggested as a good representation of the internal friction angle of loose soil layer in a FRA slope. The use of observed angles of repose offers the additional advantage that the overall strength of the mass, including the contribution of the oversize particles, is captured. Angles of repose were obtained by observing the placement of spoils piles, and measuring the angle at which they hold in place. Because these tests were conducted during reclamation activities, we measured the angle via photographs of the fresh piles using a hand held level, for safety reasons. The level helped us to ensure that the picture was taken parallel to the horizon. With a photo editing software the angles of the piles were measured (Fig. 5). Regarding the strength properties of the stronger core material, stability analysis will later show that the most critical condition for stability is insensitive to the selected strength values of the core.

Fig. 5 Typical field determination of the angle of repose at National Site (White et al. 2009). Camera placed on a level and photo taken of material in loose state. Note the large number of oversize (> 0.3 m) particles in the reclaimed material

On the other hand, short-term stability analyses (undrained soil conditions) are often conducted to characterize the behavior of the soil during and immediately after construction, where the loading occurs much faster than the rate of dissipation of positive excess pore water pressure. However, it is assumed that the coarse mine spoil material will not develop significant excess positive pore water pressure under typical loadings (Duncan and Wright 2005); thus, a drained response is expected. This assumption is supported by the grain size distribution of the materials and relatively high void ratios obtained for each site which are reported in the results section. Furthermore, short-term stability is not considered to be important in the reclamation of mine slopes, since any short-term failure would have minimum consequences and would be repaired during construction or routine maintenance.

2.4 Static Long-Term Slope Stability Analyses

The analyses of the mechanical stability focused on long-term analyses of the primary failure modes that are likely to be experienced by FRA slopes: (a) shallow or local failure modes within the loose surface layer and (b) global or deep rotational failure modes of the overall soil mass. Limit Equilibrium Methods (LEM) and the Finite Element Method (FEM) were employed in the analyses assuming 2-D plain strain conditions. LEM analyses were computed using Slide 6.0 (Rocscience Inc. 2011a) with 10,000 critical surfaces analyzed. The FEM analyses were computed using Phase2 (Rocscience Inc. 2011b) employing an elastic perfectly plastic stress–strain behavior and the M–C yield criterion with a non-associated flow rule (zero dilatancy angle) to avoid over-prediction of dilation and failure load for purely frictional materials (Griffiths and Lane 1999). Since the estimation of the factor of safety (FS) has been shown to be not significantly affected by the value of the elastic constants E (Young's modulus) and υ (Poisson's ratio) used in the FEM solution (Griffiths and Lane 1999; Cheng et al. 2007), nominal values of $E = 10^5$ kPa and $\upsilon = 0.3$ were assumed here for the surface and core materials. The model was created with 6-noded triangular elements, with a maximum of 500 iterations solved by Gaussian elimination. Because the geometry and material properties from all sites are reasonably similar, those from Mountainside ($\beta = 28^\circ$ from the horizontal and $H = 21$ m height) will be used here to explore the various failure modes. These values are representative of all three sites and many steep slopes in the southern Appalachian coal fields. The thickness of the low-strength layer (z) was assumed to be 1.5 m.

2.4.1 *Shallow Stability Within the Low Strength Surface Layer*

A shallow failure mode was investigated by assuming that the core was significantly stronger than the surface layer. The methods used were: (a) LEM restricting the analyses to the shallow surface layer via the non-circular Janbu's method and a search block feature, (b) FEM and the shear strength reduction method (Griffiths and Lane 1999; Cheng et al. 2007), and (c) the infinite slope equation for cohesionless soils without seepage ($\mathrm{FS} = \tan\phi/\tan\beta$) and with seepage ($\mathrm{FS} \approx 0.5\tan\phi/\tan\beta$). The infinite slope equation idealizes the surface as an infinite plane with the failure mechanism running parallel to the surface (Skempton and Delory 1957) and it is appropriate when the ratio of depth to length of the sliding surface is small. The geometry of the reclaimed mine slopes constructed according to the FRA is ideally suited for investigation by the infinite slope method.

2.4.2 *Deep Rotational Stability of the Overall Soil Mass*

Because the strength of the compacted core was not known, the deep rotational failure mode was investigated by performing a series of analyses where the strength of the loose surface material was held constant ($\phi = 38^\circ$, $c = 0$) while the internal friction angle of the core was increased. The analyses started with a homogeneous slope with the properties of the weak, loose surface layer analyzed via LEM (the circular Simplified Bishop's method) and FEM. Then, the shear strength of the core was increased such that the ratio $\tan\phi_{core}/\tan\phi_{loose}$ was equal to 1.1, 1.2, 1.3, and 1.4 (ϕ_{core} is the friction angle of the core material and ϕ_{loose} is the friction angle of the loose surface layer).

3 Results and Discussion

3.1 Geotechnical Characterization of Research Sites

3.1.1 *Geometry*

The geometric information of the three sites obtained from the topographical survey is summarized in Table 1. Preliminary information of the slopes angles via a Suunto PM-5/360PC mechanical inclinometer reported angles between 26° and 30° at Premium site, 20° and 22° at National site, and 28° and 29° at Mountainside site (White et al. 2009). These angles, collected shortly after the end of the reclamation process, coincide with the topographic information gathered 15 months later, and suggest no changes in the slope morphology and no slope failures during the study period.

3.1.2 *Particle Size Analysis, Index Tests, and Classification of Reclaimed Materials*

Results from the soil analyses are reported in Table 2. The grain size distribution was conducted on material smaller than 51 mm (2 in. sieve), while Atterberg limits were determined on material smaller than 0.42 mm (No. 40 sieve). According to the USCS, for all the research sites the material classify as clayey gravel (GC) with the exception of one plot at the Premium site that classifies as poorly graded clayey gravel (GP-GC) due to slightly less material finer than the number 200 sieve. Regarding oversize particles, it was estimated that material larger than 300 mm occupies 0–25 % of 1 m^2 at Premium site, 0–10 % of 1 m^2 at National site, and 5–40 % of 1 m^2 at Mountainside site.

Table 1 Average slope length, width and inclination angle for the four plots at the premium, national and mountainside sites

Site	Average slope angle, β (°)	Average slope length (m)	Average slope width (m)	
			Top	Bottom
Premium	28	32.2	28.1	25.0
National	20	48.4	22.4	25.4
Mountainside	28	45.4	23.6	23.1

Table 2 Mean values of Liquid Limit, Plastic Index, soil texture and soil classification (USCS)

Sites	Gravel particles 51–4.75 mm (%)	Sand particles 4.75–0.075 mm (%)	Fines <0.075 mm (%)	Clay particle <2 μm (%)	Liquid limit (LL)	Plastic index (PI)	Soil classification (USCS)
Premium	59	28	13	6	29	13	GC to GP-GC
National	52	28	20	10	27	14	GC
Mountainside	37	22	41	19	32	15	GC

3.1.3 Unit Weight

Results of the unit weight measurements were as follows: the maximum and minimum measured γ_d were 18.8 and 13.0 kN/m^3 at Premium, 21.4 and 14.6 kN/m^3 at National, and 22.8 and 14.9 kN/m^3 at Mountainside. Complementary results from statistical analyses are presented in Table 3. Field measures of density at a similar mine site in Kentucky (Sweigard et al. 2011) indicated similar variations as those found at Premium and National. The largest standard deviations (SD) were observed at Mountainside, which is consistent with the largest range of unit weights, and the largest amount of fines and observed number of oversize particles. At all sites, the spatial variation of unit weight reflects the large range of particle sizes in these reclaimed materials. A single unit weight measurement has a limited ability to represent the state of body forces acting on the complete FRA slope, and thus, mean unit weights with the probable upper and lower bounds (confidence and tolerance intervals) are desired for the mine material characterization. While confidence intervals (C.I.) provide an upper and lower bound of the true mean found at the constructed sites, tolerance intervals (T.I.) provide information of the probable future range of unit weights that each site will have on average. In any case, as discussed later, the determination of the unit weight for static long-term conditions may be of minor concern, but necessary for static unsaturated and seismic stability analyses.

Water and sand cone replacement tests were previously conducted to determine bulk unit weights at random locations on the four plots at each site (White et al. 2009). A comparison of the results indicates that the NDG device gives on average about 25 % higher average unit weights than replacement methods at Premium site, 14 % at National site and 21 % at Mountainside. Since both replacement methods involved the removal of small samples, they did not take into account the effects of large rock fragments that are randomly embedded in the loose surface soil layer. On the other hand, the NDG calculates unit weights based on the velocity travel of gamma rays between the source and the detector, and any denser material that appears on the travel path will be counted in the measurement. In this regard, the collection of a sufficient amount of NDG readings will better represent the wide range of in-place density and provides a more representative average unit weight for stress analyses. Replacement methods may be preferable for the calculation of void ratio and soil porosity due to better representation of the soil matrix. The average void ratio of the loose surface layer calculated

Table 3 Means, standard deviations, 95 % confidence intervals (C.I.), and 90 % tolerance intervals (T.I.) (80 % coverage) for wet and dry unit weights for premium, national and mountainside sites

Sites	Unit weight	Mean (kN/m^3)	SD (kN/m^3)	95 % C.I. for the mean		90 %/0.8 T.I. for the mean	
				Lower (kN/m^3)	Upper (kN/m^3)	Lower (kN/m^3)	Upper (kN/m^3)
Premium	Dry	16.2	1.3	15.8	16.5	14.2	18.1
	Wet	18.5	1.3	18.2	18.8	16.6	20.4
National	Dry	18.5	1.0	18.3	18.7	17.2	19.9
	Wet	20.3	1.0	20.1	20.5	18.9	21.7
Mountainside	Dry	18.6	2.2	18.1	19.1	15.5	21.7
	Wet	20.4	2.2	19.9	20.9	17.2	23.6

Table 4 Summary of internal friction angle and cohesion for reclaimed mine materials

Author	Origin of material tested	Type of test	Sample dimensions (mm)	Internal friction angle ϕ (°)	Cohesion c (kN/m^2)
Ulusay et al. (1995)	Limestone, claystone and marl (Turkey)	In situ SPT test	N/A	31–38	N/A
Ulusay et al. (1995).	Limestone, claystone and marl (Turkey)	Direct shear test	N/A	34 (peak) 33 (residual)	12 (peak) 9 (residual)
Ulusay et al. (1995)	Limestone, claystone and marl (Turkey)	Triaxial (CD) test	Diameter = 191 Height = 382	23-35	0–10
Stormont and Farfan (2005)	N/A (San Juan, Colorado)	Direct shear test (large laboratory box)	Length = 762 Width = 762 Height = 457	37	5
Gutierrez et al. (2008)	N/A (Northern New Mexico)	Direct shear test	Length = 51 Width = 51 Height = N/A	42–47 (peak) 37–41 (residual)	0
Kasmer and Ulusay (2006)	Limestone and mar (Turkey)	Direct shear test	N/A	31–34 (peak) 24–33 (residual)	18–34 (peak) 6–10 (residual)
Sweigard et al. (2011)	Sandstone and shale (Pike County, Kentucky)	Triaxial (CU) test	N/A	37	0
FRA research sites (this study)	Sandstone and shale (Northeast Tennessee)	Angle of repose	N/A	38	0

via replacement methods was 1.0 at Premium, 0.6 at National and 0.7 at Mountainside. The largest void ratio was calculated for the soils found at Premium, which is consistent with the lowest NDG unit weight measured. Overall, relatively large void ratios were obtained for all three sites, which is consistent with the FRA requirements for healthy tree growth.

3.1.4 Shear Strength Parameters

The angle of repose of the looser soil layer was found to range between 37° and 39° at Premium and Mountainside, and between 36° and 38° at National site. Zero cohesion is usually employed for long-term analysis on coarse granular soils (Lambe and Whitman 1969; Holtz and Kovacs 1981) and normally consolidated fine soils (Skempton 1964), and would be appropriate for reclaimed materials receiving minimum compaction effort. While even a small amount of compaction will increase the density and strength of the soil, the angle of repose is a conservative estimate of the friction angle. Similar values of ϕ and c for loose spoils in the Appalachian region were reported by Sweigard et al. (2011), while similar values for reclaimed spoils outside the Appalachian were found in the literature (Ulusay et al. 1995; Stormont and Farfan 2005; Kasmer and Ulusay 2006; Gutierrez et al. 2008; Sweigard et al. 2011) as summarized in Table 4.

3.2 Static Long-Term Slope Stability Analyses

3.2.1 Shallow Stability Within the Low Strength Surface Layer

Results from the limit equilibrium, finite element, and infinite slope analyses are summarized in Table 5. From a practical perspective, all the analyses yielded very similar FS's (approximately 1.47), implying that the shear strength along the most critical slip surface is about 47 % greater than that required to maintain equilibrium in the long-term. For all cases, the most critical failure mechanism is shallow and is consistent with the assumed failure mechanism in the infinite slope method. Fig. 6 shows the FEM model of the shallow failure mode with a section of the slope enlarged (the 1.5 m thick surface layer is small with respect to the size of the model and may not be clearly distinguished in the full model). It also shows nodal displacement vectors. Larger strains are observed at the interface of the weak surface and core materials, with the displacement vectors acting parallel to the surface suggesting a planar failure mechanism. The obtained long-term FS's are valid for drained conditions in the absence of seepage forces due to transient flow. However, since the occurrence of downslope water flow through the complete thickness of the loose layer is highly unlikely, this condition represents a lower bound or worst case value for the stability of FRA, and would reduce the FS by a factor of 2.

3.2.2 Deep Rotational Stability of the Overall Soil Mass

The results from LEM and FEM analyses of the deep failure mode of the homogeneous slope yield a FS = 1.48, which is consistent with that obtained from the shallow stability analyses. Fig. 7 shows the results of a FEM analysis when the core strength was 30 % stronger than the loose layer (i.e. $\tan \phi_{core} / \tan \phi_{loose} = 1.3$). Here two possible failure mechanisms were observed in the form of shear bands; a deeper mechanism through the core material with a FS = 1.94, and a shallow mechanism with the lowest FS = 1.48 and highest shear strains at the interface of the materials. The FS of the shallow mechanism is equal to those obtained from the shallow analyses

Table 5 FS obtained for long-term static stability focused on low strength surface layer

Analysis method	Assumptions	FS	Critical failure mode
(a) Limit equilibrium	Rigid core and search block—non-linear Janbu's method with 10,000 critical surfaces analyzed	1.48	Shallow planar failure surface
(b) Finite element method	Core much stronger than loose surface layer, shear strength reduction method to determine FS, with 500 iterations solved by Gaussian elimination	1.47	Shallow planar failure surface
(c) Analytical	Infinite slope equation (no seepage)	1.47	Shallow planar failure surface

Slope stability analysis results for generic slope ($\beta = 28°$, $H = 21$ m, $\phi = 38°$, $c = 0$, $\gamma_T = 20.4$ kN/m^3)

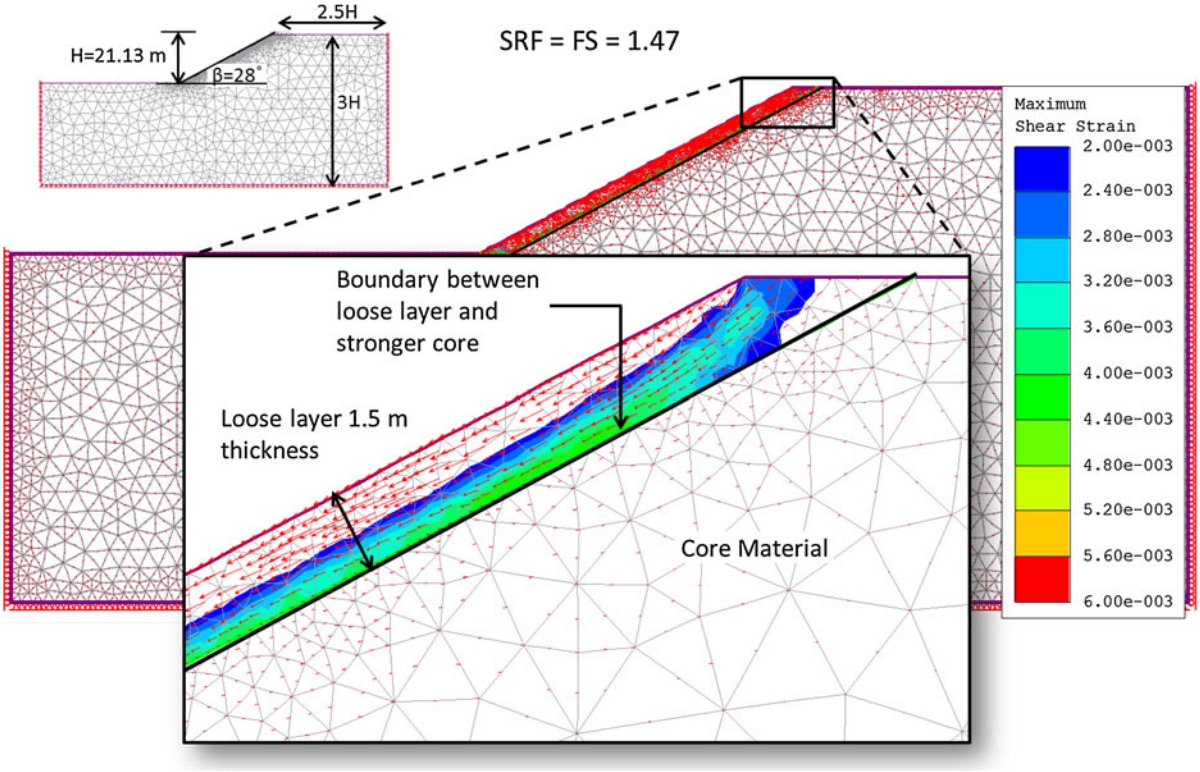


Fig. 6 Shear strains and nodal displacements obtained from the FEM analysis assuming a very strong core. *Upper left corner* illustrates the geometric dimensions employed for LEM and FEM analyses

above. A similar trend is observed for cases when $\tan\phi_{core}/\tan\phi_{loose} = 1.1, 1.2,$ and 1.4 (Fig. 8). As the strength of the core increases, the FS of the deeper mechanism increases; however, the lowest FS is found to be constant with a consistent shallow failure mode and dependent only on the strength level of the loose surface layer. Additional analyses at angles of inclination of 20° and 35° yielded similar results and confirm that the critical failure mode is a surface failure.

These results are consistent with the observation that the failure mechanisms through the loose surface layer will govern and the determination of the strength parameters of the stronger dense core are not important for FRA slope design. Furthermore, since the infinite slope method adequately approximates the shallow failure mode, and accurately predicts the FS, it can be taken as a simple and reliable method to evaluate the performance of FRA slopes and more sophisticated computer analyses are not necessary for most applications. The use of the infinite slope method also simplifies the field characterization of materials and disregards the unit weight determination, because it only requires ϕ_{loose} and β for long-term conditions. The simplicity of the method is appropriate for design of reclaimed mine slopes which are typically designed in advance of mineral extraction with assumed overburden properties. Accordingly, the lowest FS for drained or long-term conditions at each instrumented site using the infinite slope equation is approximately 1.47 for Premium, 2.07 for National and 1.47 for Mountainside.

4 Conclusions

- Characterization and stability evaluation of three FRA slopes in northeastern Tennessee with inclinations as high as 28° were conducted. A large number of oversize particles were found in the reclaimed materials. In general, the material finer than 51 mm classified as clayey gravels with the average Plasticity Index (PI) ranging from 13 to

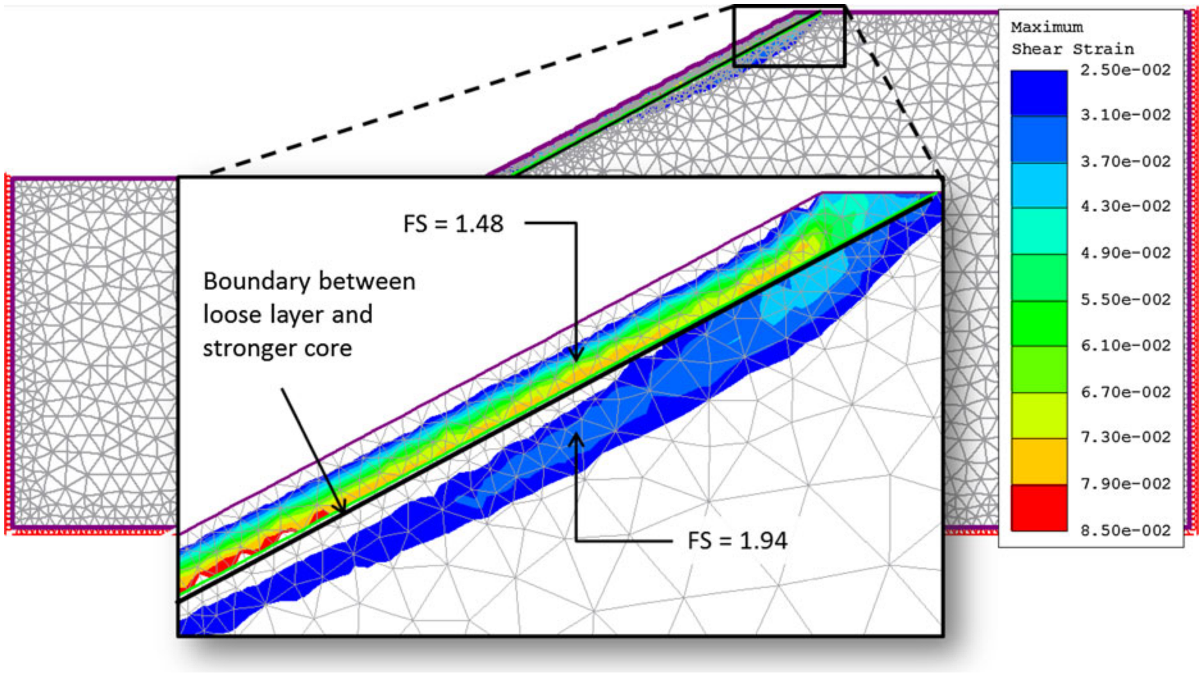


Fig. 7 Failure mechanisms and FS's obtained from FEM stability analysis for $\tan\phi_{core}/\tan\phi_{loose} = 1.3$. The $FS = 1.94$ shown for the deeper failure mechanism was obtained when the strength reduction factor (SRF) search was restricted to be outside the zone where the shallow mechanism occurred. Shear strains showed for $SRF = 2.02$ to emphasize failure mode

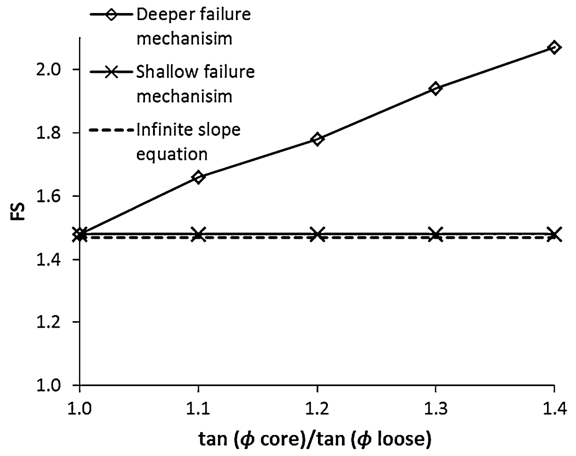


Fig. 8 FEM analyses of the global stability for various values of $\tan\phi_{core}/\tan\phi_{loose}$ and the infinite slope equation

15, suggesting that the physical characteristic of the soils are similar across the three research sites.

- Unit weights determined using a Nuclear Density Gage were found to be higher than those determined by replacement methods, yet vary significantly across the study plots. NDG measures are preferred for stability analyses because they better capture the effect of oversize particles on the in situ state of stresses of FRA slopes. It also allows more measurements to characterize the wide range of in-place density. Tolerance intervals were constructed to reflect the probable future range of unit weights that each site will have on average.
- The analysis of several potential modes of failure suggests that the governing failure mode is shallow and contained within the weak, loose surface layer. The determination of the strength parameters of the core is not important for FRA slope design.
- Because the infinite slope method adequately approximates the shallow failure mode and accurately predicts the FS, it may be an appropriate method to evaluate the performance of FRA slopes and more sophisticated analyses are not necessary for most applications. Since the unit weight of the material is not considered in the infinite slope expression, field measurements of the highly variable unit weight are not required for long-term analyses.
- The angle of repose was suggested to be a conservative estimate of the internal friction angle and it is consistent with the loose nature of the FRA material. This provides a means to quantify the

friction angle of the mine spoil, which has been traditionally assumed based on experience.

- The shear strength along the most critical slip surface, for the typical FRA slope investigated, is at least 47 % greater than that required to maintain static equilibrium in the long-term. In case that the entire loose surface zone becomes saturated with downslope seepage and no infiltration into the core, the FS is reduced by a factor of 2, suggesting that the slope would be unstable. However, these conditions are very unlikely and provide a lower limit to the factor of safety.
- The likely conditions would suggest that the FRA has no negative impact on slope stability, and the benefits of faster forest establishment in terms of reduced erosion and sediment delivery make the FRA very attractive for future reclamation work.

Acknowledgments This research was conducted as part of a project funded by the US Office of Surface Mines, Applied Science Program Grant CA No. S08AP12822, 2008. The authors gratefully appreciate the support and guidance provided by OSM staff David Lane, P. E., and Vic Davis, and the field assistance provided by Patrick White, Wesley Wright, Esteban Zamudio, Mitch Groothuis and Siavash Hoomehr.

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