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Shear strength analysis of grouted coal waste materials to improve mine outslope stability: a laboratory analysis

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Summary

Slope stability problems exist within the Appalachian Basin as a result of the emplacement of coal mine waste materials on mine outslopes. Prevention or elimination of slope instability problems can be costly. In an attempt to test alternative methods of slope stabilization, the United States Bureau of Mines determined some physical characteristics and shear strengths of ungrouted and polyurethene-grouted samples of coal refuse, coal spoil and natural soils collected at a number of mine outslope sites in Pennsylvania and West Virginia. The particle size distribution, per cent field porosity, per cent field water content and shear strengths of the materials were determined in the laboratory. Fifty drained direct shear strength tests were performed with the sample materials using a 0.06 m^3 shear box. Tests were done at field moisture, 100% saturation and grout-infused conditions. Normal loads of 103 kN m^{-2}, 206 kN $m^{-2}$and 416 kN m^{-2} were used. The grout-infused tests generally showed strength increases. An infinite slope model was used to demonstrate the potential effectiveness of *in situ* grouting for a variety of field slope conditions. This modelling suggests that *in situ* grouting has the potential of stabilizing slopes of up to 35° at depths of 14 m for refuse material and 30° at depths of 5 m for spoil and soil materials. The validity of these increases in material strength by grout injection will require field testing for confirmation.

Keywords: Slope stability; coal mine waste; shear strength; grouted fill; mine tip stability.

Introduction

Slope stability problems exist throughout the Appalachian coal region, due in part to coal spoil placed on the mine outslope. Based on recent estimates, direct and indirect costs from slope instability within the Appalachian Basin exceed one billion dollars per year (Schuster and Krizek, 1978). In addition to significant economic losses from slope movements, loss of human life can also be caused by landslides and other types of slope failures (Schuster and Krizek, 1978).

Slope stability problems in the Appalachian Basin are generally associated with contour strip mining where mine spoil was routinely emplaced on the outslope during mining operations (Law Engineering Testing Company, 1981). The Surface Mining Control and

Reclamation Act (SMCRA), which now limits the angle of outslope to less than 20°, reduced the extent of the problem but outslope failures still occur.

The geologic, climatic and topographic conditions within the Appalachian Basin contribute significantly to problems associated with mine outslope stability. Factors affecting the shear strength of mine spoil and its consequent angle of internal friction include the lithology of the parent bedrock, grain size of the material, and the nature of surface and ground water movement through the material (Anderson and Richards, 1987). Water can accelerate chemical and physical degradation of overburden waste material and can also increase internal pore-water pressure, which decrease the material strength (Kenney, 1984). A typical overburden-derived spoil in the Appalachian region consists of varying amounts of sandstone, shale, and siltstone (Okagbue, 1986). Spoil containing high percentages of friable materials, such as shale, generally weathers to produce a high percentage of fine-grained material. As the percentage of finer-grained material increases, its strength generally decreases (Lambe and Whitman, 1969).

Downslope movement of earthen material is a function of the variables that govern shear strength. The fundamental shear strength relationship is given by the Mohr-Coulomb equation:

$$S = c + (\sigma')\tan\phi \qquad (1)$$

where S = shear stress at failure
c = material cohesion
ϕ = angle of internal friction
σ' = normal shear stress.

Numerous classification schemes have been proposed to describe slope movement processes (Hansen, 1984). Most rely on the interrelationships of three factors: material size characteristics, the rate of downslope movement, and per cent saturation of the material. Mass movement of earthen material downslope responds to gravitational forces. These downslope movements are generally attributed to the addition of water within the earthen material matrix, and is characteristic of slope material which experiences an increase in density per unit volume. Because of the abundance of finer-gained material within coal wastes, mining-related slope deformations generally occur at relatively slow rates (Okagbue, 1986). These type of failures are classified as continuous creep (Terzaghi, 1950).

Prevention or elimination of a hazardous slope movement situation is costly. Site preparations, such as clearing vegetation and constructing access roads, may be required to facilitate remediation. Conventional methods generally consist of removing mine spoil material from the site as well as controlling the direction of surface and ground water flows.

This report describes the effect of polyurethane grout infusion under laboratory conditions on the shear strength of various types of earthen materials associated with mine outslopes, and represents a potential alternative method of stabilizing slopes by localized grout infusion by increasing the inherent *in situ* strength of the earthen material.

The laboratory analysis of the potential strength increase by grout infusion into earthen materials represents a scale model test of 'soil nailing'. The purpose of soil nailing is to reinforce the earthen material by grout injection into the slope headwall such that the grouted cohesive earthen matrix acts as a permeable *in situ* gravity wall, resisting the stresses that develop within and along the slope. The testing results presented in this report provide guidelines to the practicality of *in situ* grouting of outslope coal mine waste to reduce potential slope failures.

Methodology

Soil, spoil and weathered spoil samples were collected at potential and active landslide sites in the vicinity of Charleston, WV. Samples were collected by shovel probe and placed in 19 l plastic lined steel cans and sealed at the site. Two unweathered coal spoil samples were collected from an active strip mine near Connellsville, PA. A weathered coal refuse sample was provided by MSHA (Mine Safety and Health Administration of the US Department of Labor) and an unweathered coal refuse sample was collected from the preparation plant of an active longwall mining operation in Pennsylvania.

Physical characteristics of the samples were determined according to methods outlined by Lambe (1967). These included particle size distribution, per cent field moisture and per cent field porosity for the samples. Summary results of the tests are presented in Table 1.

A direct shear box was used for shear strength testing of the samples (Fig. 1). It is larger than conventional bench-top equipment and its volume is 0.06 m^3. Conventional direct shear testing equipment typically allows for testing of particles less than 2 mm in diameter. However, the larger volume of this box allows for testing of particles of up to 50 mm in diameter. Other advantages of this larger volume shear box are: (1) that polyurethane grout injection could be accomplished directly within the shear box while under an applied normal load; and (2) that box modifications could be made to accommodate drained shear tests under saturated conditions. Sample preparation for direct shear testing followed the methods described by Lambe (1967) and conformed to ASTM standards. Data (horizontal displacement, normal load, normal displacement and time) are collected from a series of transducers connected to the box with the bridge amplifier outputs recorded using a MOD-LOG analog-to-digital converter connected to a micro-computer.

In order to conduct the drained shear tests under saturated and grouted conditions, modifications to the original box design were necessary. Drained rather than undrained shear testing was selected to allow the dissipation of any pore-water pressure that could develop due to the shearing process (Head, 1981). With cohesive earthen material, drained direct shear tests are usually performed with water just covering the sample; a slow shear displacement rate is also selected so that pore-water pressures are effectively zero throughout the duration of the test.

Modifications to permit saturated-drained tests included the drilling of four 2.54 cm diameter holes through the bottom of the shear box. Plastic tubing inserted into each hole from the bottom allowed drainage into collection containers located beneath the shear box. The inside bottom of the box was lined with filter cloth to retain the test material yet allow water to drain. To accommodate the grouting procedure, a 0.64 cm diameter hole was drilled through the centre of the load beam and a 5 cm diameter hole was drilled through the centre of the shear box top plate. A 0.63 cm grout injection rod was inserted through a rubber stopper at the centre of the 0.06 m^3 box.

Grout injection was accomplished by pumping the 2-component polyurethane grout directly into the sample material through the centred grout rod while the earthen material was under the three respective test normal load pressures. An air-powered piston pump was used to inject the grout. A total of 0.23 l of grout was pumped into the material-filled box for

Table 1. Summary of physical characteristics of test materials

Sample	% Field moisture	% > Sand (> 2 mm)	% Sand (2 mm to 63 μm)	% Silt (63 to 2 μm)	% Clay (< 2 μm)	% Field porosity
Weathered refuse A	12.1	27.52	42.80	21.45	8.23	23.0
Unweathered refuse	16.6	39.40	44.70	9.60	6.33	33.7
Spoil A	15.9	16.80	31.98	24.29	26.93	20.0
Spoil 1	14.3	16.10	24.90	37.60	21.40	20.3
Spoil 2	13.1	12.20	34.90	34.30	18.60	18.1
Unweathered shale spoil	22.8	17.80	57.20	15.60	9.40	24.6
Unweathered sandstone spoil	23.6	20.90	44.00	22.40	12.70	23.2
Soil A	13.7	7.41	70.60	15.35	6.65	28.8
Soil 1	13.5	23.50	64.30	7.30	4.90	25.3
Soil 2	10.7	30.70	52.30	10.30	6.70	22.4
Soil 3	12.9	15.80	75.60	6.20	2.40	29.7

Fig. 1. Direct shear testing apparatus

A. Top plate with drilled grout rod hole in centre
B. Buckets for retrieval of water during shear testing
C. Normal load hydraulic system
D. Horizonal displacement
E. Shear box
F. Normal load beam
G. Horizontal displacement ram

each test. Two grout injection procedures were used: continuous injection of the 0.23 l of grout into the earthen matrix (Tables 2–4), and a 60 s delay between each pump cycle (Table 5). For each test, the grout was allowed to cure completely within the box for a period of about 18 h after injection prior to shear testing.

Polyurethane grout reacts and expands (up to a 15:1 ratio) when it comes into contact with water; in addition, the strength characteristics of the grout decreases with expansion. Both propagation and strength characteristics are major concerns in determining the engineering design and economical feasibility of using polyurethane grout in stabilizing potential slide zones *in situ*. Thus, it was necessary to observe how the grout propagates in various materials and to determine respective strength characteristics.

A total of 50 direct shear tests were completed (Tables 2–5). Shear displacement distances between 2.24 and 5.08 cm were used for the three types of materials. Shear tests were performed to determine the maximum shear stress and angle of internal friction for the earthen materials. The first set of tests applied three normal loads of 103, 206 and 414 kN m^{-2} under the following conditions: (1) field moisture conditions; (2) 100% saturated conditions; and (3) grouted under 100% saturated conditions (Tables 2–4). These pressures approximate vertical loadings of 4.6, 9.1, and 18.3 m depths, respectively. The second set of tests were conducted under only 103 kN m^{-2} normal loads for field moisture, saturated and grouted conditions (Table 5). The rate of shear displacement in all tests was controlled at 0.05 cm min^{-1}. This particular rate of shear displacement was selected to enable a suitable time for failure to occur under drained conditions (Head, 1981).

Analysis

A graphic plot of the size distribution of the samples is illustrated in Fig. 2. According to Folk (1974) these descriptive classification terminologies are appropriate when samples contain a significant proportion of gravel. Although there is no general classification trend by type of earthen material, the proportion of gravel (>2 mm) varies between about 7 and 40%. The soil samples all had sand-to-mud ratios greater than 1:1 while the refuse samples had sand-to-mud ratios less than 1:1. The spoil samples showed more variability in sand-to-mud ratios (Fig. 2). The per cent field porosity was also similar for the three types of earthen materials (Table 1), and ranged up to 33.7% in the unweathered refuse sample collected from an active longwall site.

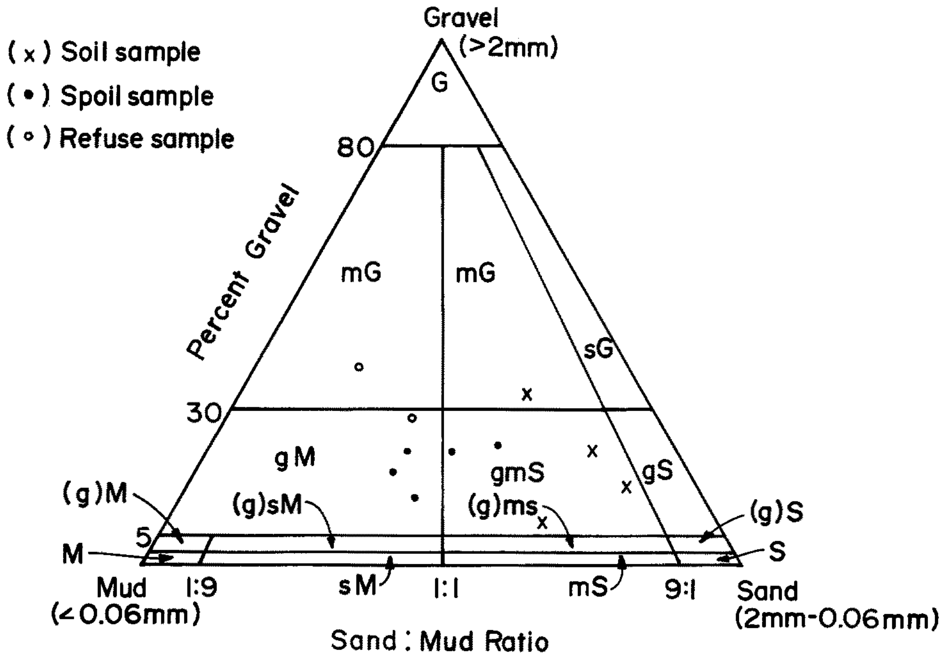

Fig. 2. Particle size relationships. G, gravel; g, gravelly; (g), slightly gravelly; S, sand; s, sandy; M, mud; m, muddy

Although abrupt shear failures for the materials tested were not observed, strength trends for some ungrouted materials similar in size to those tested in this report were also found by Wancheck and Fowkes (1973) and Okagbue (1986). It is also recognized that some of the measured angles of internal friction for some tests are extremely low (Tables 2–5). While the intent was to test the materials under 'drained' conditions, the results indicate that in some tests, positive pore pressures were present during the shearing. This being the case, the reported values for these tests should be viewed as indicators of the impact of the grout injection on the shear resistance rather than the actual shear strength for these particular materials.

Refuse material

For the 103 and 416 kN m^{-2} normal load tests, the grouted shear strengths increased considerably in comparison to the field moisture and saturated tests under the same normal loads (Table 2). The continuous method of grout injection into weathered refuse material had the greatest effect in increasing shear strength at a normal load of 416 kN m^{-2}. These increased shear strengths are also reflected in changes of the angle of internal friction. With exception of the 103 kN m^{-2} test, the maximum shear forces were lower under saturated conditions.

Table 2. Weathered refuse A tests

Normal load (kN m^{-2})	Shear stress (kN m^{-2})	Angle of internal friction (degrees)	Horizontal displacement (cm)
Field moisture			
103	0.7	0.3	2.24
206	27.6	7.6	3.76
416	22.1	3.1	2.54
Saturated			
103	6.2	3.2	2.79
206	14.5	3.9	2.59
416	11.0	1.5	2.59
Grouted (Continuous injection)			
103	24.8	13.3	2.72
206	–	–	–
416	304.1	36.3	3.71

Comparison of the results of the 103 kN m^{-2} tests for the 60 s interval grout injection conditions with the unweathered refuse also showed an increase in shear strengths (Table 5). The grout which infused into the refuse material for these three tests assumed a bulbous shape (Fig. 3b).

Spoil material

Continuous grout injection into the spoil material had little effect upon shear strength for saturated conditions with the exception of the grouted 416 kN m^{-2} test (Table 3). This particular test showed a strength increase of 1.4 times over the saturated 416 kN m^{-2} test. However, unlike the refuse material, the shear strength of the 416 kN m^{-2} field moisture condition test for the spoil was greater than the 416 kN m^{-2} grouted condition by about 3.6 times. The angle of internal friction displayed no appreciable increases other than those associated with the increased normal loading tests for saturated and grouted conditions (Table 3). Observations following the continuous grouting procedure indicated that the spoil material and grout did not adhere well and that the grout egressed through the top of the shear box in an uncured state. Strength decreases were observed in this higher mud content material under saturated conditions (Table 3).

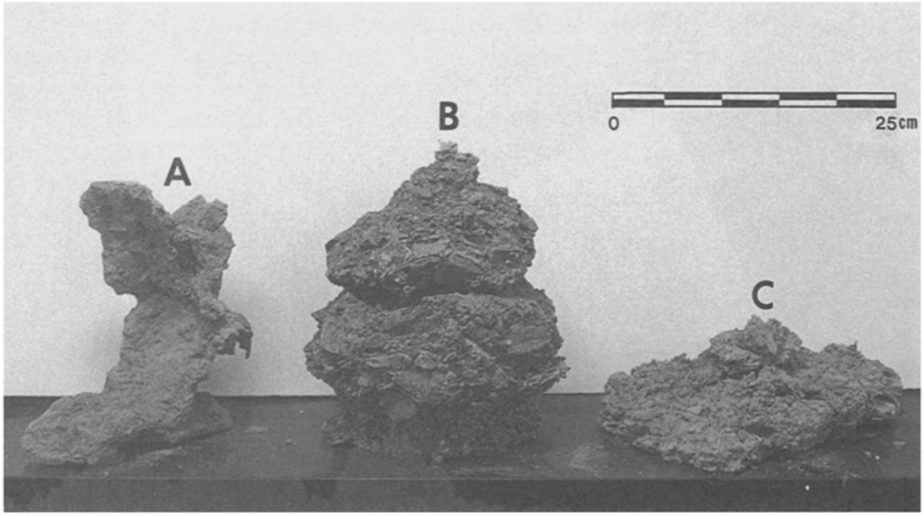

Fig. 3. Shape of cured grout after injection. A. Soil injection; B. Refuse injection; C. Spoil injection

Table 3. Spoil A tests

Design normal load (kN m^{-2})	Shear stress (kN m^{-2})	Angle of internal friction (degrees)	Horizontal displacement (cm)
Field moisture			
103	63.5	31.6	5.08
206	115.8	29.2	5.08
416	278.6	33.9	5.08
Saturated			
103	14.5	7.8	4.65
206	28.9	8.0	5.08
416	54.5	7.5	5.08
Grouted (continuous injection)			
103	17.2	9.4	5.08
206	33.1	9.0	5.08
416	75.2	10.4	5.08

The results of 60 s interval grout infusion into the spoil samples at 103 kN m^{-2} normal load conditions are presented in Table 5. In all tests, there was an increase in shear strength for the grouted tests. Grout diffusion through the spoil material was not uniform and showed an irregular diffusion of grout through the sediment matrix (Fig. 3c).

Soil material

Similar to the refuse material strength tests, continuous grout infusion increased the shear strength of the soil material for the 103, 206 and 416 kN m^{-2} tests (Table 4). The corresponding angle of internal friction of the shear strengths for the soil remained within a relatively narrow range for each respective test condition.

Table 4. Soil A tests

Normal load (kN m^{-2})	Shear stress (kN m^{-2})	Angle of internal friction (degrees)	Horizontal displacement (cm)
Field moisture			
103	53.8	27.3	4.90
206	115.1	29.1	5.08
416	254.4	31.6	5.08
Saturated			
103	46.9	24.4	4.29
206	122.7	30.7	4.75
416	268.2	32.9	4.06
Grouted (continuous injection)			
103	82.7	38.7	5.00
206	120.7	30.3	5.00
416	282.0	34.3	5.08

Shear strengths generally increased with the 60 s interval grout injection for the soil samples with the exception of soil sample 2 (Table 5). Diffusion of the grout through the soil samples assumed a dendritic shape (Fig. 3a).

Discussion

Polyurethane grout injection into refuse samples appears to increase its natural shear strength. For all refuse tests, the grout injection increased the natural shear strength of the refuse. Both continuous and 60 s interval grout injection at 103 kN m^{-2} normal loads show good increases in strength (Tables 2–5). These increases are believed to be related to the fairly uniform diffusion of the grout through the coarse-grained refuse material.

The low sand-to-mud ratio of the spoil material is believed to be the primary reason for the lower increases in shear strength after continuous grout injection. The spoil material generally had the lowest sand-to-mud ratios and lowest per cent gravel of the three materials tested, as well as the lowest porosities (Table 1).

For the 60 s grout injection interval 103 kN m^{-2} tests, considerable increases in shear strengths over field moisture and saturated test conditions were realized for the spoil. Although the physical characteristics of the spoil samples were similar for both types of grout

Table 5. Shear strength characteristics of materials[a]

	Shear force ($kN\ m^{-2}$)	Angle of internal friction (degrees)	Horizontal displacement (cm)
Soil-1 (N)	11.7	6.5	5.08
Soil-1 (S)	11.0	6.1	5.08
Soil-1 (G)	19.3	10.6	5.08
Soil-2 (N)	10.3	5.7	5.08
Soil-2 (S)	8.9	5.0	5.08
Soil-2 (G)	31.0	16.7	5.08
Soil-3 (N)	13.8	7.6	4.45
Soil-3 (S)	8.3	4.6	4.45
Soil-3 (G)	13.8	7.6	5.08
Spoil-1 (N)	5.5	3.1	5.00
Spoil-1 (S)	11.0	6.1	4.45
Spoil-1 (G)	22.8	12.4	4.80
Spoil-2 (N)	6.2	3.4	5.08
Spoil-2 (S)	6.2	3.4	5.08
Spoil-2 (G)	19.3	10.6	5.08
Unweathered shale spoil (N)	101.4	44.4	5.08
Unweathered shale spoil (S)	71.7	34.7	5.08
Unweathered shale spoil (G)	128.9	51.3	5.08
Unweathered sandstone spoil (N)	86.2	39.4	5.08
Unweathered sandstone spoil (S)	83.4	38.9	5.08
Unweathered sandstone spoil (G)	92.4	41.8	5.08
Unweathered coal refuse (N)	9.7	5.3	5.08
Unweathered coal refuse (S)	14.5	7.9	5.08
Unweathered coal refuse (G)	51.7	26.6	5.08

[a] All tests were conducted at 103 $kN\ m^{-2}$ normal load pressure.
N = Field moisture saturation test.
S = 100% saturation test.
G = Interval grouting tests.

injection tests, the 60 s interval test provided increases in shear strength. Apparently, the time interval allowed between grout injections gave the grout an opportunity to cure partially before the next portion of grout was injected by sealing additional matrix pore space.

The soil material used for the continuous grout injection tests had a higher sand-to-mud ratio than either the refuse or the spoil material (Table 1). Examination of the differences in shear strengths after continuous grout injection did not reveal any significant changes among field moisture, saturated and grout-injected conditions for any of the 103, 206 and 416 $kN\ m^{-2}$ tests. The consistent angle of internal friction observed (Table 4) suggests that this material acted more like sand than a soil.

Examination of the strength changes in the three soil samples after 60 s interval grout injection shows that the samples with lower sand-to-mud ratios had increases in strength while soil sample A with the highest sand percentage showed no appreciable change (Table 5).

Technical evaluations and recommendations

Polyurethane grout infusion into earthen materials associated with mine outslopes has generally shown increases in direct shear strengths on a laboratory test scale. For refuse and soil materials, grout injection at either the continuous or 60 s interval rates appeared to increase shear strengths by the same relative magnitude over the corresponding field moisture and saturated strength tests. However, grout injection into spoil material at the 60 s interval rate increased the shear strength in comparison with similar tests under the continuous grout injection procedure.

Although there is not a strong relationship between the sediment characteristics and shear strengths, the coarse grained (30% gravel) refuse appears to have had better grout diffusion throughout its matrix. For sandy soils (>70% sand), strength increases are marginal. Relatively muddy spoil samples show strength increases of 2 to 5 times after 60 s interval grout infusion compared to corresponding strength tests under ungrouted saturated conditions.

Given these laboratory test results for the three types of earthen materials, it appears appropriate to consider a field procedure that would test the potential effectiveness of coal waste slope stabilization from *in situ* grouting.

Using an infinite slope analysis model, the average potential increase in strength of the grouted slopes can be predicted at various depths. With this model, the soil properties and pore-water pressures at any given depth below the slope surface are assumed constant. Thus, a typical slope element can be considered representative of the slope as a whole. If the slope surface is geomorphically irregular or depth to bedrock varies, each slope segment or element can also be treated independently with the infinite slope model (Ward *et al.*, 1980) to provide strengths along particular slope locations.

The equation for infinite slope analysis is given by:

$$\frac{S}{V_t H_c} = \cos^2 i\left(\tan i - \frac{V_b}{V_t}\tan\phi\right) \qquad (2)$$

where S = shear stress
V_t = unit weight of slope material
H_c = depth to the failure plane
i = slope angle of stratum base
ϕ = angle of internal friction
V_b = buoyant unit weight of slope material.

Comparisons among the three types of earthen materials using infinite slope analysis are presented in Fig. 4. This analysis provides stability relationships between the overburden depth and the existing natural slope angle.

The model illustrates stress conditions required for equilibrium of soil strata at depth for various slope angles. For average refuse, slope stability occurs at a minimal depth of about 10 m at an angle of 15°. Based on the laboratory results, the refuse material will remain stable at a minimum depth of about 14 m at an angle of 35° after grouting. The ungrouted soil and

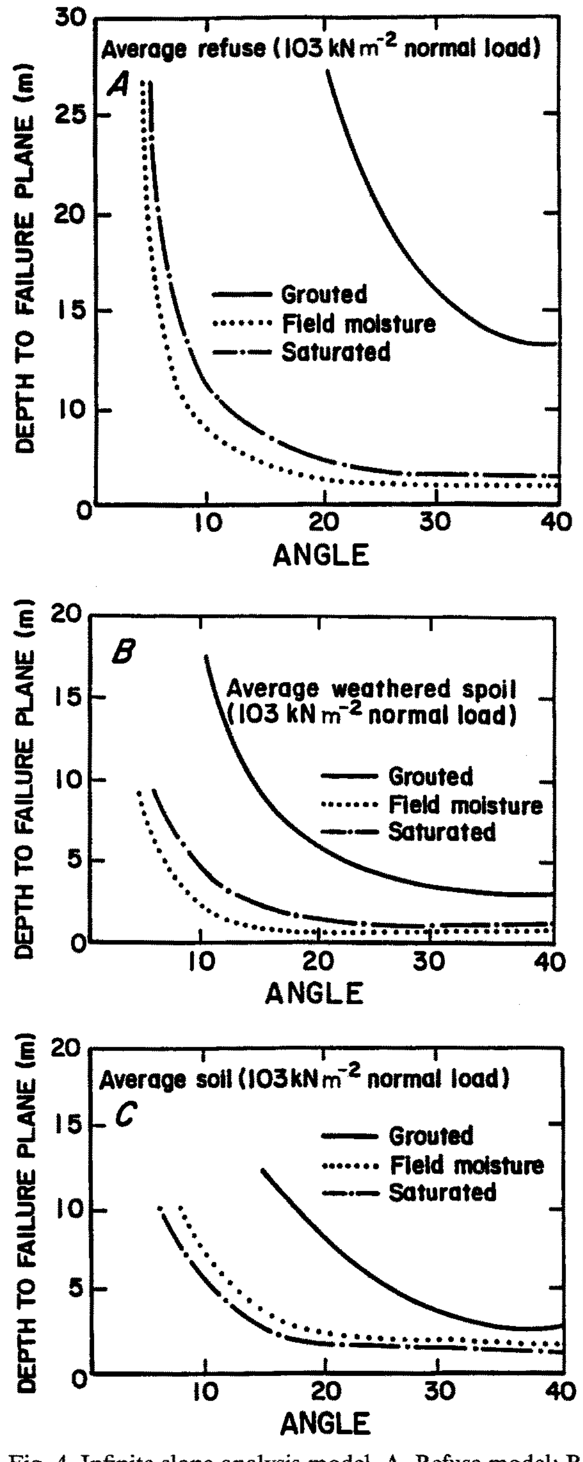

Fig. 4. Infinite slope analysis model. A. Refuse model; B. Spoil model; C. Soil model

spoil samples both show similar equilibrium trends. Both of these materials achieve stability at depths of about 3 m at slope angles of 15°. Slope stability should however occur within these materials after grouting at depths of 5 m at slope angles of about 30°.

The model suggests that considerable improvement in stability relationships is possible after grouting for each type of earthen material. It should be noted however that the calculations are based on the average characteristics of the respective types of earthen materials. Site specific conditions should be considered prior to grouting.

In summary, the laboratory strength of earthen materials associated with mine outslopes is generally increased after polyurethane grout injection. The results of the laboratory tests strongly suggest that this method can provide a possible alternative to conventional slope stabilization and that field testing of grout injection into potential slide areas is warranted. Although slope failures generally occur at the contact between the bedrock and overlying earthen material (Okagbue, 1986), the optimal depth of grout injection should be dependent upon the thickness of the overlying slope material to the bedrock and other potential failure surfaces within the overburden strata. To accomplish this, the grout rods could be drilled and anchored into the bedrock, with grout injected into the slope material by using timed interval grouting at various depths. This would enable proper curing and adequate diffusion of the grout through the proximal earthen material matrix. Field testing should include an analysis of the three-dimensional variances in soil density, permeability, moisture content and per cent grade, as well as spatial considerations of the grout rod pattern and the grouting depth.

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