# GEOTECHNICAL CONSIDERATIONS IN SURFACE MINE RECLAMATION

by

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Abstract: Most attention in surface mine reclamation is given to agronomic soils and revegetation, but reclamation success depends on the geotechnical characteristics of the underlying earth. If the soil and rock that underlie the surface are not stable, surface treatments lack the dependable foundation needed for them to succeed. Reclamation practitioners need to understand those geotechnical considerations - material properties, structures, and processes - that affect stability. Properties of rock and soil are altered by mining, and those altered materials together with water and processing waste form often-complex mixtures of materials that must be stabilized in reclamation. Surface mining alters existing landforms and creates new ones such as pit walls, spoil and waste rock piles, tailings impoundments, and earthfills. Those structures need to be constructed or stabilized so that they can endure and support successful reclamation. Processes that affect material properties and landforms include mechanical breakage, accelerated weathering, erosion, and mass movements. Mechanical breakage and the resulting accelerated weathering combine to change material properties, usually expressed as degraded strength, that can lead to instability of landforms. Erosion, especially that related to extreme storm events, and mass movements in the form of slope failures are the most problematic processes that must be taken into account in reclaiming mined lands. These geotechnical considerations are essential in successful reclamation, and practitioners who overlook them may find their work literally sliding down a slippery slope.

Additional Key Words: geotechnical, stability, material properties, structures, processes

## Introduction

In the author's experience, reclamation is usually understood to be those measures taken to turn disturbed, unproductive ground into recontoured, revegetated ground. Thus defined, reclamation is concerned with land surfaces and the soils and vegetation to the depth of root penetration. The underlying ground is assumed to be stable and, therefore, of no consequence in reclamation. Such an assumption can be a big mistake.

There is no other land use that disturbs the earth as deeply and profoundly as surface mining. Land forms are altered or removed, hydrologic regimes are changed, and ecosystems are eradicated during surface mining. Reclamation of the land from such impacts must involve considerations that go beyond the depths to which roots will penetrate. These are the geotechnical considerations - the materials, structures, and processes that support and further shape the surfaces of reclaimed mine lands.

This paper discusses the geotechnical considerations most important to surface mine reclamation, based on the author's experience. An in-depth discussion of these considerations is not possible in this paper, so they are described at a level of detail sufficient only to familiarize the non-engineer with the subject and the importance of identifying and addressing critical geotechnical considerations in reclamation planning. For the engineer this paper can provide a checklist of geotechnical factors to be included in reclamation design.

## Material Properties

All geotechnical considerations in surface mine reclamation start with the properties of the soil and rock affected by mining. Mining changes earth materials by first breaking or loosening them, then

[1] Paper presented at the 1999 Annual Meeting of the American Society for Surface Mining and Reclamation, Scottsdale, Arizona, August 16-18, 1999.

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Proceedings America Society of Mining and Reclamation, 1999 pp 481-489
DOI: 10.21000/JASMR99010481



https://doi.org/10.21000/JASMR99010481

exposing them to chemical alteration by weathering or acid attack.

## Rock Properties

In the discipline of rock mechanics, rock properties are divided into two categories - intact and in situ or rock mass (Johnson and DeGraff, 1988). Intact properties are those related to rock mineralogy and fabric and are important in drilling, crushing, and ore extraction. In situ or rock mass properties are those that characterize the rock mass and are essentially the intact properties reduced or weakened by discontinuities. In situ properties, rather than intact properties, nearly always govern rock mass behavior and greatly influence the geometries of rock excavations.

The rock properties that affect surface mine reclamation are:

- shear strength
- compressive strength
- durability

For in situ rock behavior, strength is important. Shear strength is commonly more important than compressive strength and is usually directly related to sliding resistance along discontinuities. Compressive strength is important where extremely large loads occur (e.g., bridge piers, headframe foundations) and where the likely mode of failure involves breakage through the rock fabric. Durability, an important intact property for rock used for erosion protection, is resistance to abrasion and other largely surficial stresses like weathering.

Rock mass strength is a function of the intact rock mineralogy, fabric or texture, and the rock mass discontinuities, with discontinuities playing by far the most important role. A rock mass that is unfractured will have essentially intact rock properties, but the same rock mass that is extensively fractured will be substantially weaker and more deformable. Therefore, because ore bodies or coal seams always contain natural fractures, bedding planes, shear zones or faults, these discontinuities will control the behavior of the host rock mass of any surface mine.

Rock mass properties set limits for the stability of openings and slopes cut into the rock. Pit wall heights and slope angles are limited by the discontinuities of the wall rock. For reclamation of pit walls the challenge is to determine the pit wall configuration that, considering the geologic discontinuities and blast damage, will remain stable indefinitely.

## Soil Properties

As used in this paper, soil means any nonlithified assemblage of mineral fragments other than processing waste (tailings). This definition includes naturally evolved soil as well as soil that results from the disaggregation of rock due to mining. The most important geotechnical properties of soils are:

- particle size
- plasticity
- density

For engineering purposes all soils are classified under the Unified Soil Classification System (Casagrande, 1948) primarily according to particle size, both average diameter and distribution of sizes. Size classification provides immediate indication of the types of strength and behavior that the soil can display. Coarse-grain soils (sands and gravels) develop their strengths from density and friction between soil particles. Fine-grain soils derive their strengths mostly from cohesion if they are moderately to highly plastic and from friction if they are nonplastic. Behavior of fine-grained soil is strongly affected by moisture, but moisture content has little effect on coarse-grain soils unless density is low and moisture is near saturation.

Plasticity is a measure of the cohesiveness of soil and is quantified as the difference in moisture contents at which the soil behaves like a liquid (liquid limit) and like a crumbling solid (plastic limit). The larger the difference, the greater the plasticity and cohesiveness of the soil (Terzaghi et al, 1996). Plasticity is also an index of clay content of soil and even of the types of clay present in the soil; highly plastic soils commonly contain a large percentage of smectitic clay.

Density is important in the behavior of both coarse-grain (granular) and fine-grain (nongranular) soils. The higher the density of any soil, the stronger and less compressible it will be. Density is sensitive to moisture content in cohesive soils but much less so in granular soils. In reclamation earthwork, soil density can be manipulated readily when soil is placed and compacted. Fine sands and cohesive soils that are both saturated and loose or soft will densify when drained through the process of consolidation. Likewise, cohesive soils at ground surface will absorb moisture and swell, losing density in this process.

For revegetation purposes it is good to have a mixed-grained soil with both fines and sand. This type of soil also generally makes good structural fill. The engineer will want this soil to be well compacted for structural purposes, but the agronomist/ botanist wants the soil loosened for revegetation purposes. When conflicting objectives like these are encountered, it is important for the different disciplines to understand each others' concerns and reach a mutually acceptable decision.

Effects of Water on Rock and Soil Behavior

As a general rule, water has little or no effect on rock and soil behavior until water content approaches saturation. When saturation is reached, water in the pore spaces participates in response to loads suddenly imposed on the rock or soil by momentarily sharing the load with the solid matrix of the rock or soil. The load placed on the pore water generates excess pore pressure, which reduces effective stress in the rock or soil. Because granular materials depend on effective stress working with friction to generate strength, excess pore pressures reduce strength in soil and rock masses. In free-draining rock masses and soils, the excess pore pressure dissipates rapidly and strength is quickly recovered. However, if excess pore pressures cannot dissipate fast enough, the saturated material will deform, leading to failures described in subsequent sections of this paper.

In rock, water can affect rock mass strength by reducing shear resistance along discontinuities in the rock. This phenomenon is often referred to as lubrication, but this term is correct only if water actually lowers the coefficient of friction along the discontinuity. The lubrication analogy is appropriate for those circumstances in which clay or other hygroscopic mineral coats a sliding surface and loses strength because water weakens the mineral structure, in effect reducing friction within the mineral layer. Otherwise, and more commonly, the reduction in rock mass strength is due to excess pore pressure that reduces the effective stress (rather than the coefficient of friction) along the sliding surface, resulting in reduction in shear resistance.

Reclamationists of all disciplines should be aware of the role that water plays in stability of landforms. Little can be done to alter the physical properties of soil and rock solids easily or economically, but there are usually economical options available to alter rock and soil mass properties by controlling water content and drainage.

Waste Solids

Waste rock and tailings constitute the largest amount of material that must be stabilized during reclamation. These materials can be classified in the same manner as soil - by particle size, plasticity, and density. However, some tailings will contain substantial concentrations of chemicals from milling that can affect physical properties. Alkaline or acidic salts precipitate in the pore spaces and on particle surfaces of tailings, creating a cement that can strengthen the tailing matrix. The precipitates can also retain moisture, increasing the long-term moisture content and reducing both the effective porosity and the hydraulic conductivity of the tailings.

Tailing fines (slimes) often are the most difficult materials to stabilize during reclamation because of their properties. Clay-rich tailings and tailings containing hydrated salts are often highly compressible and very slow to drain. These slimes also have very low strengths and bearing capacities, making it impossible to work directly on them with heavy equipment. Fine-grain tailings are generally more liquefiable than their natural soil counterparts because the silt- and clay-size tailing fractions are often nonplastic, leaving them with little cohesion to resist liquefaction (Terzaghi et al, 1996). Special attention, in the form of engineered stabilization measures and dewatering schemes, may be required to prepare tailing impoundments for final covering and revegetation.

Waste rock usually has the intact properties of the host rock initially. However, due to fragmentation and weathering, those properties will deteriorate at a rate much greater than in intact rock. Excavated overburden and host rock that is clay-rich or hydrothermally altered can deteriorate very rapidly, in years or decades, into soil material that retains none of the original intact rock properties. The soil material will usually have smaller particle size and lower density than the parent waste rock, giving it lower strength and higher compressibility as well. The deteriorated properties of waste rock/ mine spoil may make re-establishment of approximate original contours both unattainable and undesirable.

## Structures

Surface mining produces structures of soil and rock materials such as pit walls, waste piles and tailing impoundments that must be either removed or stabilized in reclamation. Standard practice has been to create these structures as quickly and cheaply as possible. As a result, pit walls are usually as steep as possible and pile slopes are at angle of repose. These configurations can seldom remain stable indefinitely. Both structural and erosional stability must be considered when planning reclamation of the surface mine structures.

### Pit Walls

Surface mine pit walls are planned and developed to expedite removal of ore or coal, not to facilitate reclamation. Pit walls that remain at the end of mining vary from vertical to steeply inclined, and many have one or more benches in the wall. Regardless of the wall geometry at the end of mining, there will almost always be substantial differences between the end-of-mining geometry and the wall configuration that can remain stable indefinitely or that can be amenable to reclamation measures. Stability analyses provide the means to assess pit wall configurations and to either select measures to stabilize the end-of-mining wall or to design a final wall geometry that can remain stable. The type of analyses needed and the critical stability factors vary according to geologic conditions and the history of the pit. The common pit wall failure modes, analytical methods and critical factors are described below.

Common Pit Wall Failure Modes Pit walls fail when the driving forces (usually from gravity and/or water pressure) exceed the resistance due to friction and/or cohesion along a failure surface. The failure surface is often a geologic discontinuity (fault, shear zone, or fracture) in the wall oriented downward in the direction of the pit. Weathering and seeping water can gradually reduce friction or cohesion along discontinuities, leading to failure years after the pit wall was excavated. Blast damage, stress relief, and ice wedging cau loosen wall rock and cause it to slough off or tumble from the pit wall. In rare instances, weak rock in the pit wall can fail when the weight of the overlying rock exceeds the bearing capacity of the weak rock.

Analytical Methods Finite element, discrete element, and finite difference methods have been developed for computer modeling of mine pit wall stability. Prior to the advent of these methods, analysis relied on hand calculations of driving and resisting forces along potential sliding surfaces, but this type of analysis can be performed by computer very rapidly now to evaluate a large number of sliding surfaces. All analytical methods suffer from limited amounts of data available to characterize the three-dimensional, anisotropic, nonhomogeneous mass that is being analyzed. Because of this, modeling methods should be used with caution by practitioners who are able to apply judgment based on experience in applied rock mechanics.

Critical Factors in Pit Wall Stability Judgment and experience are essential in evaluating critical stability factors and selecting analytical methods. A knowledge of geology, especially structural geology and petrology, is needed to identify critical factors aud assign numerical values to them. Because failure occurs when driving forces exceed resisting forces, the critical factors are the physical features that affect those forces, namely:

- rock mass (in situ) properties
- large-scale discontinuities - fracture systems, faults, bedding planes
- hydrologic conditions - water table, seepage paths, moisture content
- pit wall configuration - shape, height, slope

These critical factors can usually be identified, sometimes quantified, seldom changed, but often treated. In civil works such as tunnels and dams, a variety of rock treatments are available to improve rock mass properties or reinforce rock masses, but such treatments are usually too expensive for use in mine reclamation. Hydrologic conditions can be altered in some circumstances by implementing drainage measures or reducing infiltration. Pit wall configuration was created by mining, so it may seem reasonable to assume that wall configuration can be changed as readily as it was created. However, in pits that are hundreds of feet high, changing wall configuration is no small task and usually impractical.

### Waste Piles

Waste piles, whether temporary or permanent, are part of every surface mine site. When rock is excavated it takes up more volume than it occupied in situ; this volumetric expansion or swell is commonly 25-35% of the original volume. Therefore, even if waste rock is use to backfill the pit, some waste rock will remain.

Waste rock is usually dumped in piles without any specific compaction or side-slope design. The dumped rock forms side slopes that assume the angle of repose of the waste rock material. This angle - a function primarily of the rock type, size and shape - is approximately equal to the friction angle of the broken rock and ranges from about 25 to 50 degrees. However, the effects of infiltrated moisture and weathering degrade the broken rock properties over time. Degradation can be especially rapid and severe if sulfide minerals are present. When the rock fragments break down into smaller sizes or are chemically altered into weaker minerals, the angle of friction decreases. If this loss of friction is not offset by increase in cohesion of the waste rock, the angle of repose of the slopes will also decrease. Under such circumstances, the waste pile slopes are steeper than the altered waste rock can sustain, and slope failure occurs.

Weathering of waste rock piles can also change the hydrologic conditions within the pile. Weathering reduces particle size, which in turn reduces hydraulic conductivity of the waste rock. Infiltrating rain water leaches soluble minerals from the rock and carries them deeper into the pile. Preferential pathways then develop, and seepage can become concentrated enough to saturate portions of the pile. The net result is that the waste pile becomes less free-draining, higher in moisture content and weight, and more susceptible to seepage pressures and piping that further destabilize the slopes.

Dealing with the foregoing problems of waste rock piles in ways that ensure long-term stability and successful revegetation is expensive, so there is an understandable tendency to try to revegetate pile slopes as they stand at the end of mining. The reclamationist should be very wary of this approach and needs to be aware that the waste rock pile with angle-of-repose side slopes is not likely to remain a stable landform, even if revegetation is successful in the short term.

Tailing Impoundments

Tailings are usually discharged as a slurry into impoundments contained within berms. Solids in the slurry settle out, with coarser sizes near the point of discharge and finer particles (slimes) deposited farther away. As a result, the slimes, which are slower draining and more compressible, are concentrated in one part of the impoundment.

Consolidation and Settlement. Consolidation and settlement of tailing slimes is a major obstacle to stabilizing and completing reclamation of tailing impoundments. Settlement occurs in response to consolidation of compressible tailings, mostly slimes. Consolidation is the time-dependent process of densification in which water drains from the pores of the material, and the vacated pore space compresses under the weight of the overlying material. Consolidation of the slimes depends on removing pore water, so consolidation and the settlement that results from it can occur only as fast as the slimes dewater. Natural rates of drainage of slimes, which have hydraulic conductivities in the range of $10^{-6}$ to $10^{-7}$ cm/sec, do not fit most schedules of reclamation, so drainage enhancement measures are often necessary.

If final contouring and cover placement on tailings cannot be completed until the primary settlement of the impoundment has been achieved, the rate of settlement determines the critical path for tailing reclamation. Modern design provides for measures to dewater and consolidate tailings during operations, but many older impoundments now being reclaimed contain no such measures. Consequently, these impoundments retain water for many years after mine closure, releasing water at rates too slow for timely reclamation.

A variety of methods have been used to dewater tailings. Horizontal drains, vertical drains, and pumping wells in various configurations have been used with varying degrees of success. Selection of a method should be based on thorough characterization of the physical properties of the tailings, the hydrologic regime within the impoundment, and the chemistry of the tailings solution. The selected method should be implemented initially on a small scale and its performance monitored. If performance data show that the method works, it can then be applied fully to the whole impoundment.

Monitoring of the dewatering progress (piezometric levels and system discharges) as well as settlement monitoring are needed to track the consolidation process. When the rate of settlement becomes asymptotic to a certain value, the end of primary settlement can be confidently predicted, allowing the final contouring and closure of the impoundment to be scheduled. Consolidation and settlement can take many years, so it is important to monitor the progress of dewatering and settlement closely enough to know the rates and time lines that must be included in reclamation planning. Predictions of total settlement and settlement rate using classic soil mechanics procedures (Terzaghi et al, 1996) are seldom useful because the physical model assumed in the Terzaghi approach is not applicable to most tailings impoundments. A rough estimate of total settlement can be made based on volumetric compressibility if the impoundment can be adequately characterized, but the rate of settlement cannot be predicted until some settlement data have been collected over a period of months.

Liquefaction. Saturated nonplastic tailings fines (fine sand and silt) can liquefy when subjected to dynamic loading such as earthquake shocks and blast vibrations. The dynamic load causes a sudden increase in pore water pressure that, if it exceeds the effective stress in the fines (the buoyant weight of the fines), will result in the tailings losing all strength and turning liquid. Liquefaction is possible only as long as the tailings are saturated, so dewatering and consolidation will eventually eliminate the potential for liquefaction. Although plastic fines are not likely to liquefy, even minor disturbances of saturated plastic slimes can cause them to shear extensively and lose most or even all strength. These materials will also gain strength as they dewater.

Sludge Ponds

Mining and milling operations that use chemicals for mineral recovery from ore or coal cleaning produce liquid waste streams. Often this liquid waste is used as the liquid component of the tailings slurry, but in some cases the liquid waste is discharged separately into ponds for evaporation. The sludge of super-saturated liquid, gels and solids remaining after evaporation requires removal or stabilization in place. The former can be prohibitively expensive. The latter can present major challenges because the sludge can be literally too thick to pump and too thin to handle as a solid, can be very hazardous, and will often be very soluble.

The method selected to stabilize sludge in place should be based on the volume and physical and chemical properties of the sludge and the available site resources. Because the primary obstacle to sludge stabilization is material handling, the selected method should be one that can change the sludge properties enough to solidify it or at least allow it to be handled with conventional equipment. This change involves either some means to remove moisture from the sludge or the addition of enough solid material to create a relatively dry mixture. Soil or crushed rock for the latter approach is often available on site, and a thorough characterization of site resources will identify candidate materials that could be used for sludge solidification.

Earthfills

Earthwork, involving excavation and placement of rock or soil, is part of site preparation and development of many mines. Earthworks at mine sites include dams and berms for tailing and liquid containment, cuts and fills for road construction, and fills for structure foundations. If an earthfill has been designed according to engineering principles and constructed with quality control, it should remain stable for an indefinite period of time. However, many earthfills on mine sites were neither designed nor constructed with such standards of care; they were put in place as expediently as possible without concern for long-term performance. It is not extraordinary to find foreign material such as scrap wood and metal buried in these earthfills.

It is often impossible to know the history of a mine-site earthfill. Records of construction were sometimes never made, other times not retained. At a minimum, a visual inspection by a geotechnical engineer should be made of all earthfills that will be retained in reclamation. Any earthfill that will serve a key role (e.g., a diversion levee) should be further investigated as needed to determine if the earthfill has the necessary structural integrity.

## Processes

Both the properties and the structures of soil and rock on mine sites are subject to processes that can alter both in ways that can compromise reclamation. Some processes are man-induced and related directly to mining, and some are natural processes that may be accelerated by mining. The processes that affect reclamation are mechanical breakage, weathering, mass movements, and erosion.

Mechanical Breakage

Mechanical breakage is as essential to surface mining as planting is to farming - there is no way to get to the mineral or coal without breaking rock.

Blasting, ripping, loading, hauling and crushing make little pieces out of big pieces of rock, and in so doing the properties of the rock are substantially altered. It is clear that the principles of soil mechanics apply to the behavior of severely broken and crushed rock taken from the pit, but it is not so obvious what mechanical principles apply to the pit wall rock that has been fractured by blasting but is still in place. However, to plan any reclamation of the pit, the extent and effects of blast fracturing in the pit walls must be determined. The extent of such mechanical breakage will affect not only the stability of the pit walls but also the rates of infiltration and weathering in the wall rock.

If it is determined that fractured wall rock is too unstable for safe reclamation, measures must be taken to remove the unstable rock or reinforce it. The latter is seldom an economical option but can be used when only small areas are involved or no other options are available. Removal of unstable rock from relatively short walls or benched slopes is fairly routine and involves dislodging of loose rock using excavators. Long, high pit walls and unbenched slopes are beyond the reach of standard equipment and require special equipment and methods selected on a case-by-case basis.

Accelerated Weathering

Weathering is natural and virtually unpreventable, involving combinations of chemical and mechanical processes. Mining tends to accelerate these processes by exposing more surface areas and mineral surfaces to the climatic effects and by removing the vegetation and surface soils that shielded the substrata before mining. The weathering processes most important for reclamation are oxidation, freeze/thaw, and swell/shrink. At mine sites where acid mine drainage (AMD) occurs, AMD can be a powerful weathering agent, as well.

Oxidation. Exposure of sulfide minerals, so common in coal and metal ores, to air and moisture leads to accelerated rates of oxidation. Mineral composition and structural changes result from oxidation, generally accompanied by increases in volume, compressibility and solubility and by decreases in strength. The net result is that oxidation tends to drive a soil or rock mass toward instability, a fact that should be considered in reclamation design by use of measures that retard oxidation.

Freeze/thaw In locations where temperatures routinely reach freezing and snow or rain is common, cyclic freeze/thaw can play a significant role in the mechanical breakdown of rock and loosening of soil. Water entering rock fractures or soil pores freezes and expands, wedging the openings larger with each cycle. This process can be especially important in highly fractured pit walls or in earthfills that are not well compacted. Freeze/thaw makes the affected rock or soil more susceptible to erosion, as well.

Swell/shrink Soils that have a significant percentage of plastic clays are susceptible to swell/shrink, a process in which the clay mineral lattice adds water molecules and expands when water is available, then shrinks when free moisture is absent and evaporation occurs. The effect on the soil mass is familiar to everyone as the pattern of polygonal cracks that form on the surface of dried mud - the soil mass breaks up along shrinkage cracks into separate blocks. Swell/shrink in a soil cover drastically reduces the effectiveness of the cover, and on any ground surface the swell/shrink cracks can disrupt runoff and cause rapid infiltration.

Mass Movements in Slopes

Mass movements in slopes include all gravity-driven displacements of masses of rock or soil and include slides, slumps, and mud flows. They can be large or small and occur very rapidly or at imperceptible rates, depending on causes and driving mechanisms. Mass movements are very common in nature, especially in terrains of weak sedimentary or highly fractured and weathered rock. Surface-mined terrain is also susceptible to mass movements because of the processes described above.

Slides and slumps are characterized by translational or rotational displacement of earth materials that remain solid throughout the time of movement. The displacement occurs whenever the driving forces exceed the resisting forces along an existing or potential failure surface. Failure surfaces in soil or highly weathered or broken rock are typically circular or curvilinear in shape and concave in the direction of the slope surface. In hard rock, failure surfaces are usually defined by structural discontinuities in the rock mass such as bedding planes and natural joints.

Mud flows are saturated mixtures of soil or rock and water. They may initiate as slumps or slides in saturated material but suddenly lose all strength through shearing and increase in pore water pressure caused by the initial movement. The saturated mass then behaves like a viscous liquid rather than a solid, flowing down slope and beyond the bottom of the slope.

Mass movements result from one or more of the following conditions:

- oversteepening of the slope
- change in properties of the slope material
- dynamic disturbance
- increase in phreatic surface or seepage pressure

<u>Oversteepening of the Slope.</u> It is common practice in mining to stack waste rock and other earth materials as steeply as possible; i.e. at the angle of repose of the material, the maximum angle that loosely dumped material can sustain. If the toe of the slope is removed, by erosion or excavation, the angle of repose is exceeded and the oversteepened portion of the slope displaces downward and outward until the overall slope gradient is once again no greater than the angle of repose.

<u>Change in Properties.</u> When pile slopes or pit slopes are first created, the exposed rock material is usually fresh and relatively unweathered. At that time the angle of repose is the largest it will ever be. Large fresh angular rock particles will maintain slopes of 40-45 degrees (Nelson et al, 1986). However, as particle size breaks down or mineral constituents chemically weather (by oxidation, hydration, etc.), the rock material becomes weaker and will not sustain such steep slopes. Slopes like these are gradually reduced by erosion and dislodgment/ tumbling of individual rock fragments, but if these gradual processes don't keep pace with reduction of properties, the stability of the slope decreases to the point of imminent failure, requiring only a small additional change to trigger mass movement. For this reason it is a mistake to assume that a waste pile outslope will remain stable indefinitely just because it has not yet failed.

<u>Dynamic Disturbance.</u> A slope that is oversteepened or weakened by change in materials properties and, therefore, is at the point of imminent failure, may then be caused to fail by dynamic disturbance. Earthquake shocks, blasting, or even vibrations from heavy equipment may provide the additional stress needed for a slope to fail.

<u>Increase in Phreatic Surface or Seepage Pressure.</u> Water is more than an obstacle in mining; it also contributes to many slope failures. When the water table or phreatic surface rises in a rock or soil mass, it has the effect of reducing the effective stress that, in combination with friction, holds slopes in place. Seepage exerts pressure along its flow path that can be high enough to displace particles, causing a phenomenon called piping. Left unchecked, piping can lead to sudden failures that are potentially catastrophic if they occur in dams or tailing impoundments.

<u>Erosion</u>

Erosion is a process well known to reclamation practitioners and needs no explanation here. Erosion is a concern not just for its effects on revegetation efforts but also for its impacts on surface water quality, landform stability, and contaminant containment systems. While wind erosion is important in some areas, particularly in the arid West, it is not primarily a geotechnical consideration and is not covered in this paper.

Erosion of soil by runoff receives a great deal of attention in reclamation planning, with the focus chiefly on annual rates of erosion expressed in terms such as tons of soil loss per acre. Well established erosion prediction models such as the Revised Universal Soil Loss Equation (RUSLE) (Yoder et al, 1992) and newer approaches like the Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995) provide useful tools for this type of erosion analysis. This gradual erosion process is certainly important, but erosion that can lead to breach of covers and other containment measures is also important

Erosion that occurs in covers and other containment systems in response to extreme runoff conditions is a concern not because of the tons of soil lost but because of the localized damage that can result from concentrated flow and high shear stress associated with extreme-storm runoff. Where reclamation performance standards for a site include resistance to erosion, there is usually a design storm event specified (e.g., a 24-hour, 100-year storm) for which erosion protection must be able to prevent significant erosion under peak runoff conditions.

The geotechnical engineer must design slopes, soil covers, riprap and other protective measures to resist the stresses that are developed during design runoff events. The design will typically be based on worst-case assumptions; e.g., no vegetation and no infiltration of rainfall. Time is not a factor in the design analyses because the critical design parameter is shear stress at peak runoff, which occurs at one point in time when shear resistance of the soil or rock must at least equal the peak shear stress. Several methods are available for these analyses, the most widely used of which are probably those developed by the U.S. Army Corps of Engineers (1970, 1971).

## Conclusion

For reclamation practitioners with backgrounds in biological or agronomic sciences, the importance of geotechnical considerations in reclamation planning and design may not be apparent. This paper can only touch on the most important of these considerations and in doing so, make reclamation practitioners at least aware that geotechnical engineering has a critical role to play in reclamation of surface mines. For geotechnical engineers, the foregoing information may provide some insights into the many applications of their skills required in surface mine reclamation. For mine owners and regulatory people, this paper may encourage some extra attention to the earth mechanics that underpin the durability and long-term success of reclamation. Finally, for everyone interested in surface mine reclamation this paper should underscore the multidisciplinary nature of reclamation and the importance of practitioners acquiring knowledge of disciplines other than their own.

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