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SLOPE**STABILITY**
in Surface Mining

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CHAPTER 30

Assessment of Embankment Parameters

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30.1 INTRODUCTION

Embankments constructed using mine waste rock typically involve side slopes formed at the angle of repose of the material, in the range of 35° to 40°. As a result, the side slopes cannot be compacted. Even where slopes sufficiently flat to allow compaction are employed, compaction of the side slopes is unusual. Mine site embankments typically are raised progressively in a series of lifts as the development of the mine and mineral processing dictate. This may result in the use of differing construction materials depending on the waste rock materials available at the time of the raising. It can also lead to seepage and stability problems at the interface between raises.

The density of the waste rock used for embankment construction ranges from about 1.6 to 2.2 t/m^3, depending on whether the material is placed loose or compacted to some degree. Over this range, density will have little impact on embankment stability. The natural gravimetric moisture content of waste rock typically ranges from 3% to 7%, and its optimum moisture content for compaction is likely to be on the order of 10% to 15%.

Location of the phreatic surface within a waste rock embankment depends on the use to which the embankment is put and any zoning of construction materials. Where the water level against the upstream face of the embankment is low or is maintained at a low level by the inclusion of drainage within the embankment, the phreatic surface will be low and will have little impact on the stability of the embankment. On the other hand, where the water level against the upstream face of the embankment is high, the phreatic surface will be high and will have a substantial impact on the stability of the embankment.

The foundation beneath a waste rock embankment should be selected to provide adequate strength and low permeability. Proper selection should eliminate foundation failure and excessive foundation seepage.

In the following section, the possible long-term behavior of a waste rock embankment is considered in the light of natural slope angles and hill slope formation processes. Subsequent sections discuss the other waste rock parameters.

30.2 NATURAL SLOPE ANGLES AND HILLSLOPE FORMATION PROCESSES

Distribution of natural slope angles has received some attention in the past and is of relevance in assessing the stability of waste rock embankments in the long-term. Studies during the 1950s, 1960s, and early 1970s in the United Kingdom (Carson and Petley 1970) suggested that natural hillslope angles are grouped about different "threshold values." These are the angle of repose (35° to 40°), half the angle of repose (about 18°), and "slopewash" in the range from 18° down (Figure 30.1). Figure 30.1 highlights the variability of natural hillslope angles. The threshold slope angle depends as much on the diameter of the material on a slope as on the energy of the hillslope formation processes. As the diameter of the material diminishes from weathering over geological time, it becomes possible for the threshold slope angle to diminish (Holtz 1960).

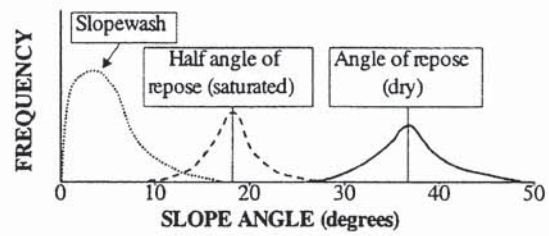

FIGURE 30.1 Schematic frequency distribution for natural hill slope angles

Principles of soil mechanics can be used to explain the observed grouping of slope angles. Loose-dumped, dry, or free-draining granular materials form at their angle of repose. Such slopes subjected to seepage parallel to the angle of repose surface can sustain a slope angle of only about half the angle of repose of the dry material, because of buoyancy effects. Further reduction in the slope angle occurs with the production of further fines. The flow of erosion products on a floodplain results in deposition slopes in the range from 10% (coarse material) to 1% (fine material).

In a similar way, the distribution of slope length, vegetation types and coverage, gully frequency and depth, and so on, may be determined for a given landform. These distributions could be determined both prior to and after mining. It then may be possible for spoil rehabilitation to be designed to achieve distributions similar to premining conditions, based on minimizing the earthworks involved.

The processes involved in hillslope formation include the following:

- *Weathering of the surface materials.* This takes place to a depth and at a rate dependent on the materials and the climate. In the rocks of the United Kingdom coalfields, weathering takes place to a depth of 0.3 to 1.0 m in about 100 years. The fines produced by weathering penetrate the near surface voids, increasing the density of the material, and also flow downslope, resulting in a slight flattening of the slope angle. The buildup of fines also allows the formation of perched water tables, and the possibility of minor surface slumping, exposing underlying material to weathering.

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- *Development of sinkholes as a result of rainfall infiltration through dispersive materials.* This can take place rapidly in susceptible materials but is localized. Apart from the obvious surface expressions, sinkholes result in the localized piping of fines with depth, aiding in the buildup of water.
- *Weathering at depth because of water table fluctuations.* This results in the buildup of fines and water, and densification, with accompanying surface settlement.
- *Increasing saturation of the hillslope material.* As the saturation level rises, the hillslope angle cannot be sustained at the angle of repose (dry) and will revert to about half this value.
- *Accumulation of erosion products out from the base of the hillslope.* The erosion products will be deposited on the floodplain beyond the base of the hillslope.

These processes are likely to occur relatively rapidly (perhaps on a 100-year timescale) in steep, erodable terrain, in a high-rainfall climate; and gradually (perhaps on a 10,000- to 100,000-year timescale) in undulating, stable terrain, in a temperate or dry climate.

30.3 STRENGTH PARAMETERS

There is ongoing confusion about the relationship between the angle of repose of coarse-grained mine waste rock and other granular materials and their strength parameters. The angle of repose is often adopted as the friction angle of the material (Williams 1996).

30.3.1 Angle of Repose

On end-dumping from a truck, waste rock ravels (fails) downslope at the angle of repose of the material. The angle of repose of granular material is affected by the following (Rowe 1962):

- Particle size, shape, and surface roughness (increasing with increases in size, angularity, and roughness)
- Specific gravity of the particles (increasing with increasing specific gravity)
- Height of fall (decreasing with increasing height of fall)
- Amount of water present (increasing with the addition of a little water, but decreasing with further saturation)
- Curvature of the slope in plane (concave slopes being more stable than planar and convex slopes because of arching effects)
- Base conditions
- Whether the slope is natural or artificial

Simons and Albertson (1960) presented angle of repose data showing an increase in the angle of repose of granular materials with increasing mean particle size. The more angular the particles, the higher the angle. The data show, for instance, that the effect of scalping to allow laboratory testing may reduce the angle of repose of the scalped material by 6° compared with the field value for the full-scale material. The field value typically is in the range of 37° to 40° for durable, angular mine waste rock.

Rapid dumping leads initially to over-steepening of the upper part of the slope. With continued rapid dumping, the oversteep section of the slope will lengthen, possibly leading to a slip. Over-steepening results from the cohesion of fines hanging up near the crest of the slope, while the coarse particles ravel to the base of the slope.

The angle of repose also is affected by the weathering of particles over time. The production of fines on weathering is accompanied by an increase in the density of the material and a slight flattening of the slope, making it more stable with time. Provided that the slope does not fully saturate, it will remain at this angle in the long-term; although some erosion likely will occur. Saturation gradually reduces the slope angle to perhaps half the initial angle of repose (Stratham 1974).

At large strains (typically greater than 10%) and in a loose state, such as occur on the raveling of coarse-grained mine waste rock down an angle-of-repose slope, the friction angle of the material reverts to its ultimate value. The associated void ratio is termed the *critical state void ratio* (Roscoe, Schofield, and Wroth 1958) and the friction angle is designated the critical state friction angle ϕ_{cv}, numerically equivalent to the angle of repose at which the material ravels.

30.3.2 Friction Angle

The strength of waste rock is characterized by a friction angle and zero cohesion. The value of the friction angle a function of the following:

- Particle size distribution (reducing with decreasing particle size)
- Particle shape and surface roughness (increasing with increasing angularity and surface roughness)
- Strength and specific gravity of individual particles
- State of packing (increasing with increasing density)
- Applied stress level (decreasing with increasing stress, resulting in a curved strength envelope passing through the origin)

It has long been recognized (Holtz and Gibbs 1956; Holtz 1960) that an increase in the proportion of coarse material in an otherwise fine-grained granular soil can result in an increase in friction angle. Alternatively, when the voids within a coarse granular material are filled with fines, its friction angle is increased by as much as 10° (Stratham 1974). The amount of fines required to have a significant effect on the friction angle is relatively small.

Limiting the maximum particle size of a coarse-grained spoil material that can be strength-tested readily in the laboratory will result in a low estimate of the friction angle of the coarser whole material. Over time, the friction angle will increase further as a result of infilling by fine-grained weathering products.

Leps (1970) presented friction-angle data based on triaxial strength testing of large size (up to 200 mm) rockfill particles. These data suggest that the friction angle of durable spoil could be as high as 55° at low stress and is likely to be at least 50° at moderate stress levels. Waste rock would be expected to have a friction angle in the range of 40° to 50°, the lower end of the range corresponding to weathered or crushed, fine-grained material, and the upper end of the range corresponding to fresh, coarse-grained material.

For medium-dense sandy gravel materials, which approximate the waste rock materials used in embankment construction, the value of ϕ_{cv} would be expected to be 4° to 6° less than the peak friction angle (Lambe and Whitman 1979). Together with Leps data, this suggests that mine waste rock would be expected to have a peak friction angle of about 45°.

30.4 OTHER STRENGTH-RELATED FACTORS

30.4.1 Effect of Segregation

Waste rock tends to segregate according to particle size during placement by end-dumping from a truck, because of a combination of Bagnold's grain dispersive pressure and particle kinematics (Middleton 1970). Since the friction angle of granular material tends to increase with particle size, segregation tends to produce alternating weaker and stronger angle of repose layers. As the permeability of the material decreases with mean particle size, alternating layers of lower and higher permeability result. The continuity of the individual layers, however, may be insufficient to produce clearly defined weak layers or preferred seepage flow paths.

30.4.2 Effect of Slope Profile

The stability of a granular slope for a given type of failure depends not only on the slope angle but also on the plan geometry of the slope (Azzouz, Baligh and Ladd 1983). Longitudinally concave slopes (steepest toward the crest and flattest toward the toe) tend to be intrinsically more stable than conventional straight, planar slopes (Schor and Gray 1995). Concave slopes are stable at an angle of about 3° steeper than convex slopes, with planar slopes in between (Rassam and Williams 1999).

30.4.3 Effect of High Water Tables and Rainfall

High water tables reduce the factor of safety for deep-seated slope failures, possibly by a factor of 2. Perched water tables may give rise to surficial failures, which sometimes arise as a result of weathering of the near surface spoil, which produces fines, preventing the infiltration of rainfall. The effect of water near the surface of a spoil slope depends on the direction of any flow. The greatest reduction in the factor of safety (by a factor of up to 2) occurs for flows parallel to the surface of the slope (Gray 1995), which is promoted by the angle of repose layering of waste rock end-dumped by truck.

Slope stability is influenced significantly by intense or prolonged rainfall (Chowdhury and Nguyen 1987). If mine waste rock remains stable on placement, subsequent failures usually are rainfall-related. However, direct correlations between rainfall intensity and the frequency and magnitude of waste rock slope instability have not been established. In dispersive waste rock (Emerson and Seedsman 1982), sinkholes can develop as a consequence of rainfall infiltration (Figure 30.2).

30.4.4 Effect of Tree Roots

The factor of safety for surficial failures may be increased significantly by the roots of any trees that become established on waste rock slopes (Gray 1995). According to Hubble and Hull (1996), the increase in strength because of the presence of the roots is more than sufficient to offset the extra loading that results from wind acting on the trees, although contrary views have been expressed (Brown and Sheu 1975; Barker 1995). Surficial sliding or planar failures limited to a depth of 250 mm can be stabilized by normal engineering methods, plus vegetation (Lawrance 1995). Removing inappropriate shrub and tree vegetation may result in significant benefits.

Integrated hydrology and slope stability models are required to properly account for the effects of vegetation on slope stability (Collinson, Anderson and Lloyd 1995; Anderson and Lloyd 1991). The factor of safety of bare slopes with high permeability ($> 10^{-5}$ m/s) may be increased by 20% because of the effects of tree cover. Although the factor of safety of a slope with medium permeability (10^{-6} m/s) may be increased by 20% in the long-term as a result of trees, it may be reduced by 20% in the short-term as the tree cover is becoming established. The effects of the tree cover on the slope hydrology also must be considered (Collinson and Anderson 1996).

30.4.5 Effect of Weathering

The generation of clay size fines by physical weathering may reduce the friction angle by 2° or 3° (Seedsman and Emerson 1985). This reduction does not occur gradually, as the clay fraction increases but, instead, relatively suddenly at a clay content of about 10%. At this clay content, the larger particles in the spoil are no longer in direct contact with each other but instead tend to be supported in a matrix of clay-sized particles. The weathering may occur at the surface of the spoil piles to a relatively shallow depth, or deep within the spoil piles because of a fluctuating water table. Chemical weathering reduces the friction angle by 6° to 12°. The physical breakdown of coal mine waste rock, as opposed to chemical processes, is a short-term process (Taylor and Spears 1970; Taylor 1984). Susceptibility to erosion also must be considered.

FIGURE 30.2 Surface expression of sinkholes

30.4.6 Progressive Failure

In waste rock slopes, shear strength may decrease significantly as a result of moisture softening. Moreover, waste rock materials exhibit characteristic brittleness overstressing also can lead to a marked decrease in shear strength. Progressive phenomena are important in such circumstances (Chowdhury, Nguyen, and Nemcik 1986).

Because moisture softening is important in promoting progressive failure, the extent of moisture infiltration, the wetting sequence, and the development of pore water pressures are of considerable importance. Other important factors are the development of tensile failure in the material and the potential for slip at the interface between old and recently placed material.

Delayed waste rock slope failure can be a source of disruption in rehabilitation works. It may be necessary to monitor waste rock slopes over a number of years and use the observational data to update stability analyses. The primary cause of delayed instability is infiltration from rainfall.

30.5 APPROPRIATE FACTOR OF SAFETY

The appropriate factor of safety or probability of failure for the stability of a waste rock embankment depends on the coefficients of variation of the strength parameters (cohesion showing considerably more variation than friction angle) and the waste rock density (which shows relatively little variation) and on the acceptable failure rate. An acceptable annual failure rate may be 1/10,000th of the area of the waste rock slopes, corresponding to "dams" defined by Whitman (1984). However, the acceptable failure rate and the appropriate factor of safety also depend on the consequences of failure, including potential loss of life, damage to infrastructure, and loss of function, both on and off lease. Consequences of the possible failure of waste rock embankments are difficult to assess and have to be site-specific.

Generally, waste rock slopes designed with a factor of safety of 1.10 to 1.15 have only a minor risk of failure (Khandelwal and Mozumdar 1992; Miller et al. 1979). Waste rock slopes designed for a factor of safety of less than 1.10 are subject to a greater risk, even if the input data used are accurate, because of variability in the height of the slope or of the strength of the waste rock material or foundation. These conditions may result in local fluctuations of about 10% in the factor of safety, leaving little safety margin.

The initial failure of a slope composed of loose waste rock is governed by the normally consolidated friction angle of the material. However, the waste rock layers exposed by a failure are overconsolidated. Consequently, following the initial failure, the dilation angle of the material becomes an important influence on

the factor of safety of the exposed failure scarp. Normally, this will increase after each failure, as the degree of overconsolidation and dilation angle increase, even if the failure debris—the presence of which tends to decrease the overall slope angle—is removed. This means that stability is enhanced post-failure. It explains the apparently over-steep failure scarps that remain stable post-failure.

The magnitude of displacement of the waste rock during a slope failure can be a significant safety consideration. For example, large displacements might threaten roads, railways, or other structures. If the debris of waste rock slope failures is removed—by a stream at the toe of the slope, for example—the slope will retreat at the critical angle (the angle of repose for the material, in the absence of groundwater). Otherwise, the slope angle will gradually reduce because of the loss of material from the crest, and the accumulation of debris and erosion products at the toe.

30.6 SAFE OPERATION OF PLANT

Waste rock slope angles of 14° or flatter readily allow machinery to work along the contours, constructing contour banks, seeding, and fertilizing. A slope angle of 18° may be the upper limit for this purpose (Peterson 1987). A D9 dozer can work up and down slope angles of up to 27° (Walker 1987), but operators are more comfortable working on slope angles of less than 22°. Conventional dozers have lubrication problems on steep slopes (Williams 1997).

30.7 SETTLEMENT OF WASTE ROCK

30.7.1 Mechanisms and Components

Although the mechanisms of waste rock settlement are not well understood, they include the following:

- Particle reorientation
- Water-induced weakening of interparticle bonding
- Weathering (swell/slake) of high clay-content spoil materials
- Dispersion and transport of fine particles through the spoil or backfill

Components of the settlement of waste rock include primary settlement, creep settlement, and collapse settlement (Geoffrey Walton Practice 1991). Both primary and creep settlements are time-dependent, reducing with time. Collapse settlement is attributable to a reduction in the strength of the spoil materials when they become saturated, and probably results from partial breakdown of the material and/or crushing of weakened point contacts between rock particles. It may occur where water levels rise within the waste rock and happens immediately on wetting. It also can result from mining subsidence or surcharge loading and can be particularly severe when waste rock has been placed with no compaction.

Weathering of waste rock, an important factor in the development of settlement, is highly dependent on the amount and type of clay minerals present (Thomson et al. 1986; Naderian 1997). Rapid weathering occurs near the surface of the waste rock but also can occur at depth in the presence of groundwater.

Self-weight settlement of waste rock is rapid (Naderian 1997). Most of it occurs during placement of the material, and it continues for only a short time thereafter. Groundwater is the most significant agent causing subsequent settlement of the material and any volume change (Charles, Burford, and Hughes 1993; Naderian 1997).

30.7.2 Field Measurements

A review of the literature carried out by Naderian and Williams (1996) indicated a range of measured settlements under dry conditions of between 0.3% and 7% of the waste rock height, with further 1% to 4% settlement on groundwater recovery. Creep or

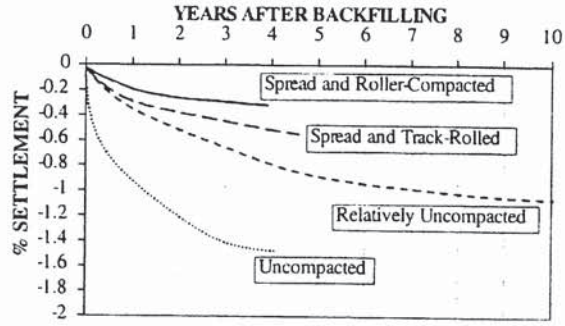

FIGURE 30.3 Backfill settlement versus time (Source: Knipe, personal communication, 1979)

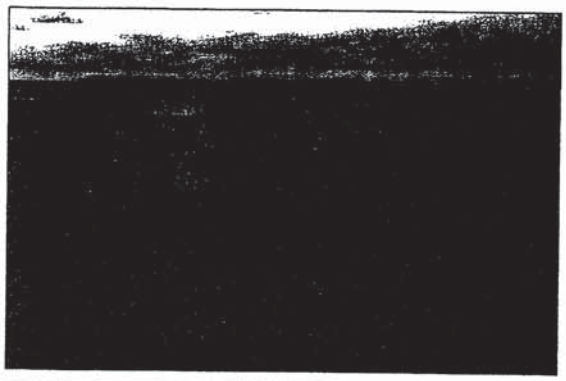

FIGURE 30.4 Loose-dumping over the edge of a 260-m-deep pit

FIGURE 30.5 Differential settlement scarps in loose-dumped waste rock 260 m high

consolidation settlement was shown to continue beyond 10 years after construction. Typical settlement (normalized relative to the initial fill thickness) versus time (after the end of backfilling) plots for waste rock backfilling of open pits in the Midlands coalfields of England are shown in Figure 30.3.

At Kidston Gold Mines in northeastern Queensland, Australia, durable waste rock loose-dumped over the edge of a 260-m-deep pit (Figure 30.4) sustained post-backfilling settlements of about 4 m (1.5% of the waste rock height) and differential settlement scarps 1 to 2 m high, which are a reflection of benches on the pit face (Figure 30.5).

30.7.3 Laboratory Measurements

Naderian and Williams (1996) carried out laboratory compression testing of initially loose sandstone and claystone waste rock

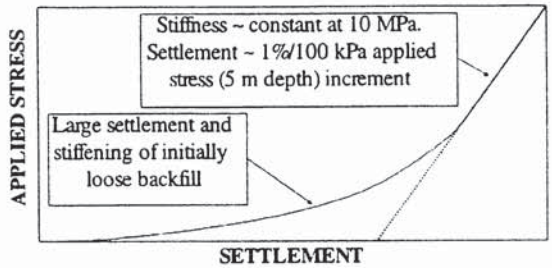

FIGURE 30.6 Applied stress versus settlement (source: Naderian and Williams 1996)

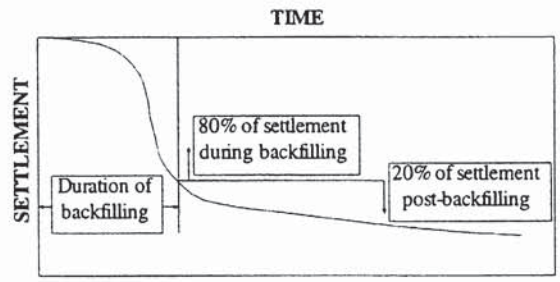

FIGURE 30.7 Settlement versus time (source: Naderian and Williams 1996)

materials from Jeebropilly Colliery, in southeastern Queensland, Australia. They showed that the material initially had little stiffness but became stiffer with increasing applied stress until a constant high stiffness was achieved above about 200-kPa applied stress (equivalent to about a 10-m depth of backfill; shown schematically on Figure 30.6). From 0- to 200-kPa applied stress, the sandstone specimens settled a total of about 4% and 5.5% for dry and saturated specimens, respectively, and the claystone specimens settled a total of about 11% and 20% for dry and saturated specimens, respectively.

The difference between the dry and saturated settlements for each material indicates the magnitude of the potential for settlement on groundwater recovery. Inundation settlement or collapse occurs rapidly. For the sandstone, inundation collapse was about 40% of the dry settlement as a result of application of the stress, whereas the corresponding figure for the claystone was about 80%.

Above 200-kPa applied stress, the sandstone and claystone specimens, whether tested dry or saturated, attained a constant stiffness of about 10 MPa, implying a settlement of 1% for each additional 100-kPa (5-m depth of backfill) increment of applied stress (Figure 30.6).

Naderian and Williams (1996) modeled numerically (using Fast Lagrangian Analysis of Continua [FLAC]) the backfilling of a typical 60-m-deep pit at Jeebropilly Colliery with randomly distributed, equal volumes of sandstone and claystone. The backfilling method employed at Jeebropilly was end-dumping from trucks without compaction. The results indicated typical total (dry) settlements of about 2.5% of the backfill depth and differential settlements on the order of 1% of the backfill depth. Inundation settlements were calculated to be on the order of 0.4% of the depth of saturated backfill but would occur gradually over the time it took for groundwater recovery.

The analysis indicated that about 80% of the total (dry) settlement would occur during the 6 months it would take for the backfill to be placed (as shown schematically on Figure 30.7); that is, total and differential (dry) post-backfilling settlements of only 0.5% and 0.2% of the backfill depth, respectively. Inundation settlements of the order of 0.4% of the saturated backfill depth would occur post-backfilling, giving a total potential post-backfilling backfill settlement of up to about 1% of the backfill depth. The settlement rate would decrease after the end of backfilling, reaching a constant rate of about 0.02% per year one year after the end of backfilling. In the long-term, settlement would continue at roughly a constant rate per log cycle of time.

Settlement measurements carried out at Jeebropilly after the completion of backfilling and surface recontouring averaged about 6.4 cm over a 2-year period (0.05%/y). This rate agrees with the results of the numerical analysis.

30.8 BEARING CAPACITY OF WASTE ROCK

Plate bearing tests conducted by Naderian and Williams (1997) showed that the bearing capacity of mine waste rock is mainly a function of the compaction it has undergone, not its age. The compaction of backfill afforded by mine vehicle traffic seems to be sufficient to provide a reasonable bearing capacity and the ability to support ordinary lightweight structures. The densification the material undergoes upon loading results in an increase in its bearing capacity. Limited testing has shown that waste rock is capable of supporting stresses of up to 200 kPa, while sustaining settlements of the order of 5 mm and 17 mm for traffic-compacted and freshly placed waste rock, respectively.

30.9 EROSION PARAMETERS

Erosion rates are difficult to measure and even more difficult to predict with any accuracy. The accuracy of estimated erosion rates is often little better than 100% (So 1999). Data on erosion rates available in the literature are presented and discussed in the following sections.

30.9.1 "Natural" Erosion Rates

The history of ancient upthrust zones of the earth's crust, such as the MacDonnell Ranges in central Australia, gives an indication of "natural" erosion rates. The MacDonnell Ranges were formed about 310 million years ago to an estimated height of about 9 km. They now are an average 1 km high. Allowing for isostasy (the raising of the crust's surface as the weight of overburden is reduced by erosion), this is equivalent to an average erosion rate of 0.05 mm depth/y (about 0.74 t/ha/y, assuming a dry density of 1.5 t/m^3). This figure fits within the range of soil formation rates typically quoted from 0.01 to 0.10 mm/y.

30.9.2 Erosion Rates from Developed Land

The average river sediment yield for Australia has been variously estimated at between 0.32 t/ha/y and 0.45 t/ha/y (0.022 mm/y and 0.030 mm/y; Rieger and Ogilvie 1988). Raudkivi (1990) indicated erosion rates from mixed pasture and woodland generally in the range of 1.5 to 3.0 t/ha/y (0.10 to 0.20 mm/y), with a maximum rate of about 4.0 t/ha/y (0.27 mm/y). The erosion rate increases for arable land, but seldom exceeds 7.5 t/ha/y (0.51 mm/y) (Raudkivi 1990). For agricultural land use in the Darling Downs of South East Queensland, Australia, the "allowable" erosion rate is 15 t/ha/y (1.0 mm/y; Bell 1994).

Erosion rates from construction sites in Maryland and Virginia, range from 120 to 500 t/ha/y (8.1 to 34 mm/y) (Chen 1974). The erosion rate of bare soil in the humid tropics on a 4° slope is 100 to 170 t/ha/y (6.8 to 11.5 mm/y; Kirkby 1980). Erosion rates for unvegetated mine waste rock could be in the same range as for construction sites, perhaps even higher for highly erodable spoil. However, few observations have been made of erosion rates from angle-of-repose waste rock slopes.

The Queensland Department of Mines and Energy (QDME) target erosion rate for rehabilitated mine sites is 12 to 40 t/ha/y (0.81 to 2.7 mm/y; QDME 1993). This range is much higher (by typically 30-fold) than natural erosion rates and river sediment yields, higher than erosion rates from agricultural land by typically

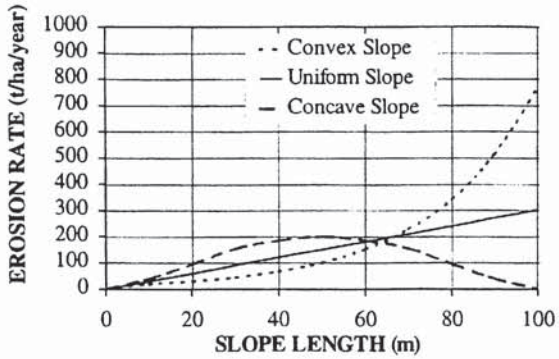

FIGURE 30.8 Form of variation of erosion rate with slope profile (source: Meyer and Kramer 1969, in Lal 1990)

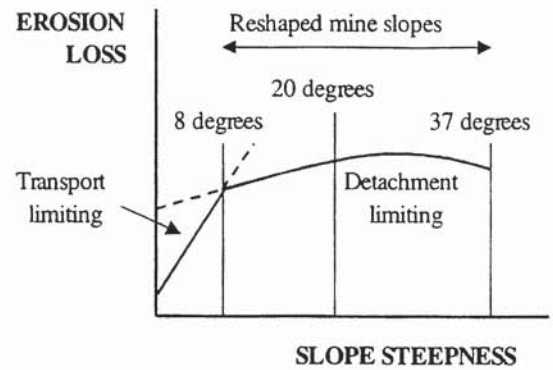

FIGURE 30.9 Erosion loss versus slope steepness up to angle of repose (adapted from Haan et al. 1982, in Lal 1990)

4-fold, but lower than erosion rates from construction sites by about 10-fold.

The erosion rate is strongly influenced by the reconstructed slope profile (Meyer and Kramer 1969 in Lal 1990). Concave slopes deliver water to the toe of the slope with less erosion than uniform slopes of the same average slope (Loch 1999). Convex slopes display an exponentially increasing erosion rate with increasing slope length. The erosion rate on uniform slopes tends to be more proportional to slope length, and the erosion rate on concave slopes peaks at intermediate slope lengths (on the order of 50 m) before decreasing for longer slopes. The effect of slope profile is shown diagrammatically on Figure 30.8.

Haan et al. (1982) in Lal (1990) suggested that the relationship between erosion loss and slope steepness over a large range of slope angles up to angle of repose, as shown schematically in Figure 30.9. In reality, there is a family of curves for different materials, stress histories, and climatic histories. Figure 30.9 identifies two regimes. For slope angles up to about 8° (14%), erosion loss is "transport-limited"; the supply of erodable materials is plentiful and erosion is limited by the carrying capacity of the runoff.

Under this regime, which applies to agricultural land use on relatively flat land, the erosion loss is directly proportional to the slope steepness. For slope angles steeper than about 8°, erosion loss is limited by the ability of the runoff to detach particles from the slope. This regime is described by a flat parabola, indicating that erosion loss is not strongly dependent on the slope steepness for slope angles greater than about 8°, which are typical of reshaped mine slopes.

Although supporting evidence for the form of the relationship given in Figure 30.9 is not readily available, the Chamber of Mines South Africa (1995) stated that erosion loss from coal mine waste rock reaches a maximum for slope angles of 25° to 35°. Relatively little erosion occurs on slopes flatter than 20° or steeper than 40°. Clearly, Figure 30.9 has implications for erosion loss from the relatively steep, final, mine waste rock slope angles.

30.9.3 Effect of % Surface Cover

The % surface cover (which could include grasses, trees, litter, and rock) on soil erosional loss is dramatic, particularly where the surface cover comprises large elements (So et al. 1998). For vegetative cover alone, 50% or more cover is required to dramatically lower erosion loss.

30.9.4 Erosion Prediction Based on USLE

The universal soil loss equation (USLE) (Hudson 1981) remains the most commonly used means of estimating soil erosion rates (Gray 1995). The equation, however, is based on US data from agricultural slope angles in the range from 0° to 5° (Barker 1995). Mine waste rock slopes typically are graded to 8° or steeper, well outside this range.

The USLE is used to predict the long-term average soil loss in runoff resulting from the combined effects of sheet and rill erosion (Wischmeier and Smith 1948). It does not take account of gully erosion and does not attempt to predict sediment deposition or transport within a catchment. The USLE is given by Evans, Aspinall, and Bell (1991) as

$$A = RKLSCP \qquad \text{EQ. 30.1}$$

Where:

- A = computed annual loss per unit area (t/ha/y)
- R = rainfall factor as an erosion index EI
- K = soil erodability factor measured using a standard plot 22.13 m long sloping at 9%
  - = function of wet density, particle size distribution or texture and organic matter content
- L = slope length factor
- S = slope steepness factor generally lumped with L as the topographic factor LS
- C = cover and management factor
- P = conservation practice factor

The US Department of Agriculture Soil Conservation Service Curve Number Method (Boughton 1989; Schroeder 1994) has been traditionally used in Australia for estimating runoff from rainfall on small rural catchments and has been applied to mine waste rock by Schroeder (1994).

The factors in Eq. 30.1 may be estimated for the Bowen Basin coalfields in central Queensland, Australia, using data from Hudson (1981) and Evans, Aspinall, and Bell (1991). Average annual rainfall for the region is 600 to 750 mm, and R (or EI) may be taken as 335. Few measured data are available for K. Typical K values are 0.34 for topsoil and in the range of 0.05 for both sandy and heavy clayey spoil to 0.25 for silty clayey spoil.

The erosion loss increases with both increasing slope length and increasing slope steepness, but not linearly. Several effects are involved, and it is usual to combine the factors L and S into a single topographic factor LS. Estimates of LS derived from Evans, Aspinall, and Bell (1991) are given in Table 30.1 for slope angles of 8° and 15°, for both spoil peaks and ramps. Two cases were considered for each case. In the first, a spoil slope initially 20 m high was regraded to a maximum height of 10 m. In the second, a spoil area was regraded to a maximum height of 30 m without intermediate benches or contour banks. Johnstone (1992) reported that for the Curragh Mine, the length between benches is 70 m for a slope angle of 8°, corresponding to an LS value of 7.

Bare soil has a C value of 1, reducing to 0.005 or lower for good pasture. In the Bowen Basin, 40 to 50% vegetation cover is

TABLE 30.1 Estimates of LS applicable to the Bowen Basin spoil

Location	Slope Angle (deg)	Slope Length (m)	LS
Spoil peak to 10 m	8	7	7
Spoil peak to 30 m	8	212	12
Ramp to 10 m high	15	41	3.5
Ramp to 30 m high	15	124	6.3

TABLE 30.2 Estimates of erosion loss A for Bowen Basin spoil areas

		A (t/ha/yr)					
		Topsoil		Sandy or Heavy Clayey Spoil		Silty Clayey Spoil	
Slope Angle (%)	Slope Length (m)	Bare	50% Vegetated	Bare	50% Vegetated	Bare	50% Vegetated
14	71	399	199	59	29	293	147
14	212	683	342	101	50	503	251
27	41	199	100	29	15	147	73
27	124	359	179	53	26	264	132

reasonably stable against erosion. Erosion also is reduced by stony ground. For spoil rehabilitation in the Bowen Basin coalfields, C might range from 1 (bare ground initially) to 0.5 (vegetated). A standard 22.13-m-long, 9%, bare soil slope, cultivated up and down, has a P value of 1, reducing to 0.5 for contour cultivation and possibly even further for rehabilitated mine waste rock.

Inserting the best-guess estimates for the various factors into Eq. 30.1 yields the estimates of erosion loss A for Bowen Basin spoil areas given in Table 30.2, for two slope angles and lengths, various surface materials, and for initially bare and at least 50% vegetated conditions.

Based on the A values in Table 30.2, only the combinations highlighted would meet the QDME target erosion rate of 12 to 40 t/ha/y. Sandy or heavy clayey spoil cover comes close to achieving this in most of the cases considered. The vegetated silty clayey spoil comes close to achieving the target erosion rate for the shortest slope length, and the topsoil, whether bare or vegetated, is unlikely to achieve an acceptable erosion loss.

Table 30.2 shows that, for slope angles of 14% and 27%, increasing the slope length three-fold increases the erosion loss (for all materials) 1.7 and 1.8-fold respectively confirming that slope angle alone has little impact on erosion. The steeper the slope, the shorter it will be for a given height, decreasing the catchment size. Table 30.2 suggests that steepening—and hence shortening—the slope 1.8-fold halves the erosion loss (for all materials) for a given slope height (that is, a 3.6-fold effect overall). Based on this simplistic assessment, topsoil is the most erodable, silty clayey spoil is 73% as erodable as topsoil, and sandy and heavy clayey spoil are only 15% as erodable. Establishment of a reasonable vegetation cover reduces the erosion loss by about 50%. Although topsoil may facilitate vegetation, it is highly erodable prior to the establishment of vegetation.

30.9.5 MINErosion Program

In tropical environments, most of the erosion is the result of a limited number of high-intensity storms (Fairbairn and Wocker 1986). The spreadsheet program MINErosion is a single-rainfall, event-based model, giving an estimate of the erosion rate for a rainfall event of a particular recurrence interval (So et al. 1998). MINErosion applies to unvegetated Bowen Basin soil or spoil. The program was based on the results of rainfall simulator tests carried out in a tilting flume on 16 soil types and 17 spoil types from 16 Bowen Basin mine sites. The flume was 3 m long and tests were carried out at slope angles of 5%, 10%, 15%, 20%, and 30% (3°, 6°, 8°, 11°, and 17°). Up to three replicate tests were carried out on each material, with typically 25% agreement being achieved between replicates. Both inter-rill erosion from simulated rainfall and rill erosion from simulated runoff were measured.

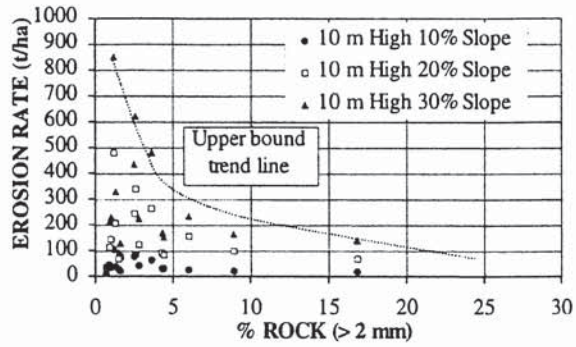

FIGURE 30.10 Erosion rate versus % rock for Bowen Basin soil materials

The measured data were extrapolated to cover slope angles from 0% to 50% (0° to 27°) and slope lengths from 0 m to 100 m, using available erosion prediction equations. The extrapolated results are presented in the program as sets of curves of erosion loss (in t/ha) versus slope length (to 100 m) for slope angles of 10%, 20%, and 30%, for a particular soil or spoil type, rainfall intensity and duration, rill spacing, and infiltration rate. The erosion rates given in the program have not been fully calibrated against large-scale field measurements, and their accuracy is unknown. However, erosion rates are difficult to predict and the accuracy of predictions is often little better than 100% (So 1999).

To gauge the effects on erosion rate of a number of key parameters, calculated data points have been taken from the sets of curves presented in the MINErosion program. Initially, the rainfall intensity was set at 100 mm/h, the rainfall duration at 30 min, and the rill spacing at 1 m. Data points then were read off the curves for all 16 soil materials and all 17 spoil materials, for 10-m-high slopes at slope angles of 10%, 20%, and 30%.

Figure 30.10 shows the predicted erosion rate versus percent rock (> 2 mm) for the soil materials. Although there is considerable scatter, the erosion rate clearly decreases with increasing percent rock, with apparently little erosion for >30% rock.

The calculated data points for a 10-m-high slope in a range of Bowen Basin spoil materials are plotted against slope angle on Figure 30.11, together with possible extrapolations to angles up to the angle of repose of the material (75% or 37°). The extrapolations include the trend lines for the calculated data points and an alternative extrapolation based on Figure 30.9. Clearly, there is a strong need to collect erosion data for slope angles in the range of 30 to 75%.

Limited erosion data from waste rock slopes at an iron ore mine in the Pilbara region of Western Australia also are included on Figure 30.11. These lend support to the flat parabola suggested by Haan and co-workers for steeper slopes; that is, a roughly constant erosion rate for a range of slope angles. These erosion data are converted to an erosion rate per unit slope width and plotted against slope height on Figure 30.12. Figure 30.12 demonstrates that, for a given slope height, steeper slopes will erode less than flatter slopes, as the catchment length decreases with increasing slope steepness. The Pilbara waste rock exhibits a threshold slope height below which there is negligible erosion. This threshold slope height is strongly dependent on the age of the material. For recently placed waste rock, the threshold slope height for no erosion is about 13 m, whereas for old spoil that has undergone self-armoring, the threshold slope is about 43 m.

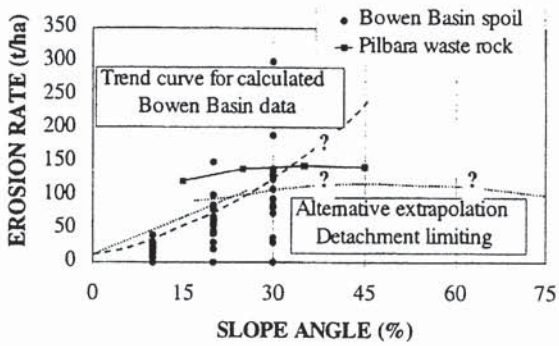

FIGURE 30.11 Erosion rate versus slope angle for Bowen Basin spoil materials

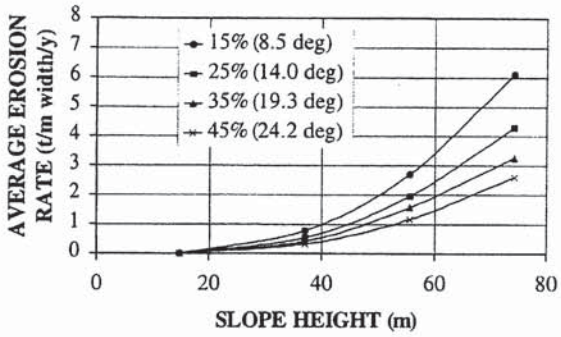

FIGURE 30.12 Erosion rate per unit slope width versus slope height for Pilbara waste rock slopes at different angles

The effects on erosion rate of some of the other parameters are highlighted in Table 30.3. The relative effect on soil and spoil materials is about the same in all cases. Overall, increasing the rainfall intensity has the most dramatic effect on erosion rate, followed by rainfall duration, rill spacing, and infiltration rate.

At Kidston Gold Mines, limited erosion rates have been monitored since 1996/1997 on various durable waste rock slopes either at angle of repose (37° to 40° or 75% to 84%) or regraded to 20° (36%), and with various surface covers. Annual rainfall totals were 524 mm, 623 mm, and 475 mm for the 1996/1997, 1997/1998, and 1998/1999 years, respectively. The results are summarized in Table 30.4, which highlights the negligible erosion from durable waste rock either at angle-of-repose or half-angle-of-repose slopes, the high erosion from erodable oxide waste rock covers without vegetation or with limited vegetation, and the greatly reduced erosion from well vegetated slopes.

30.10 CONCLUSIONS

This chapter has dealt with the assessment of material parameters relevant to the use of mine waste rock or spoil in the construction of embankments. The parameters considered include the geometry of the embankment, and the strength, density, moisture content, settlement, bearing capacity and erosional characteristics of the waste rock and cover materials. Location of the phreatic surface and the foundation conditions also have been briefly considered.

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TABLE 30.3 Effect of other parameters on erosion rate

Parameter	Effect on Erosion Rate	
	10% Slope Angle	30% Slope Angle
Rainfall intensity:		
2-fold increase from 50 to 100 mm/hr	4-fold increase	3-fold increase
Rainfall duration:	Linearly related	Linearly related
Rill spacing:		
2-fold increase from 1 to 2 m	1.2- to 1.4-fold increase	1.35- to 1.55-fold increase
Infiltration rate:		
2-fold increase from 15 to 30 mm/hr	25% decrease	35% decrease

TABLE 30.4 Measured erosion rates from Kidston waste rock embankment slope

Description	1996/1997		1997/1998		1998/1999	
	Vegetative Cover (%)	Erosion (t/ha/yr)	Vegetative Cover (%)	Erosion (t/ha/yr)	Vegetative Cover (%)	Erosion (t/ha/yr)
20°, no oxide cover or vegetation	0	1	0	0	0	0
20°, oxide cover, no vegetation	0	386	0	186	0	425
20°, oxide cover, vegetation	33	359	41	112	48	68
37°, no oxide cover or vegetation	0	0	0	0	0	0
37°, oxide cover, vegetation	10	68	15	1.8	15	19
17°, oxide cover, 1991 vegetation	> 50	23	> 50	0.4	> 50	5.6
37°, oxide cover, 1991 vegetation	> 50	31	> 50	0.3	> 50	2.2

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