CHAPTER 14 HIGHWALL STABILITY

14.1 INTRODUCTION

Contour mining was popular in the Appalachian coalfields prior to the implementation of the surface Mining Control and Reclamation Re-enforcement Act of 1977 (Skelly and Loy, 1979). This type of mining method is normally conducted around the mountain ridge following the elevation contour lines, thereby creating a one bench highwall, as opposed to open pit mining where multiple benches are used.

In drift mines, in which the coal seams outcrop and entries are driven from the exposed areas directly into the coal seam, there is a face-up area, involving a highwall cut to provide a flat ground for surface facilities (Fig. 14.1.1). The highwalls may be either vertical or inclined inby 10^o - 20^o depending on the regulations of individual states and geological conditions.

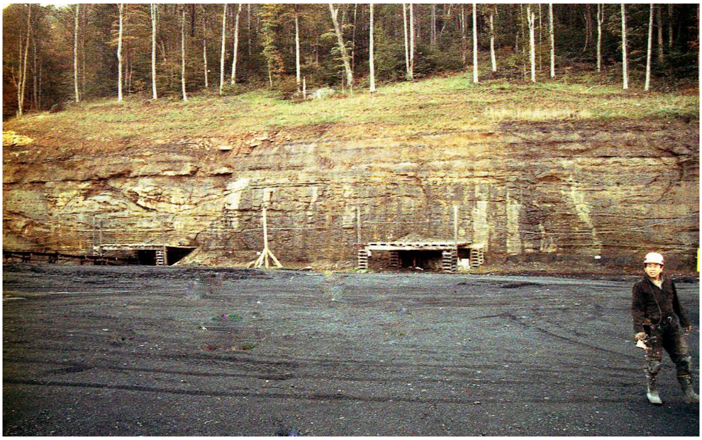


Fig. 14.1.1 Two examples of face-up highwalls in drift mines in Appalachia (Peng, 2007)

In recent years, highwalls mainly are generated by auger mining and highwall mining (Fig. 1.3.19, p. 17) (Walker, 1997). From a ground control point of view, highwall and auger mining involve web pillar design and slope (or highwall) stability. Web pillars are addressed in Section 5.9 (p. 279). This chapter will deal with highwall stability.

14.2 HIGHWALL CHARACTERISTICS

Due to the history of contour mining in Appalachia, the highwalls in highwall mining may involve the following three types (Gardner and Wu, 2002).

1. Unreclaimed highwalls are those abandoned from previous contour mining, including auger mining. Therefore they were most likely not properly sloped or constructed by pre-splitting, which creates a smooth, solid face.
2. Surface mining highwalls are the final bench cut of a surface mining operation. Due to an increased stripping ratio, surface mining becomes less profitably, and highwall mining is a good alternative before transition to underground mining. The **Stripping ratio** is the ratio of overburden thickness to coal seam thickness. The economic limiting ratio is around 17-19 for U.S. mining conditions.
3. Highwall mining highwalls are usually located and designed to optimize stability and productivity.

Among the three types of highwalls, unclaimed highwalls require the most attention from a stability point of view, because from construction, the highwalls may have been degraded due to weathering, groundwater flow, and deterioration of web pillars. Therefore this type of highwall should be thoroughly examined before putting them into use.

14.3 FACTORS AFFECTING HIGHWALL STABILITY

In addition to web and barrier pillars as they apply to highwall mining, other key factors affecting highwall stability include rock type and quality, discontinuities, and ground water.

Just like all other types of mine structures, the quality of rock determines the quality of the highwall. Massive and strong rocks make a stable highwall requiring little or no maintenance (Fig. 14.1.1 upper). Conversely, highwalls made of weak/weathered rocks or unconsolidated materials are less stable, requiring frequent attention (Fig. 14.1.1 lower).

Groundwater is a key source of slope/highwall stability. Groundwater pressure can destabilize a highwall and accelerate weathering. Therefore, seepage, such as springs and seeps, must be effectively controlled. If there are fractures in the highwall, freezing and thawing cycles may eventually destabilize parts or all of the highwall. Surface run-off should be channeled away.

Geological anomalies, mainly discontinuities such as joint sets, planes of weaknesses, or fractures must be carefully mapped. Using a borehole camera has been very effective in mapping geological defects in the interburden (Leisemann and Follington, 1993). Highwall location, direction, and slope should be designed accordingly. In general, the highwall and access entries should intersect the discontinuities obliquely, rather than parallel or perpendicular to them.

14.4 TYPE OF HIGHWALL FAILURES

Highwall failures may occur in many forms, slowly or suddenly, and with or without any external intervention. Failures may be due either to a sudden or gradual loss of strength by the soil or to a change in slope conditions. In general, there are five types of slope/highwall failures: raveling, planar, circular, wedge, and toppling. Circular failure occurs if the materials are homogeneous, but since most highwall materials are heterogeneous, non-circular failure surfaces, consisting of a combination of planar and curved sections, are most likely.

14.4.1 Raveling

Raveling is the deterioration of a slope as a result of weathering and erosion, including windblow, cyclic freeze and thaw, and flowing actions of water. Raveling is a problem when the slope is larger than the angle of repose, which is generally about 35^{o} (Bullock et al., 1993). This method of failure is restricted to individual pieces of rock rolling down the slope and accumulating over time on the toe of slope. Raveling failure may be a concern for highwalls with rock that are weathered easily, such as claystone. If the bedding plane dips toward the portal mouth, raveling may be accentuated.

14.4.2 Planar Failures

A planar failure is the failure of a slope along a plane. It occurs in a slope with a thin layer of soil that has relatively low strength in comparison to the bedrock materials. Planar failure requires a predefined failure plane, e.g., a joint plane oriented parallel or sub-parallel to the slope face and a release surface at the top and both ends (Bullock et al., 1993) (Fig. 14.4.1).

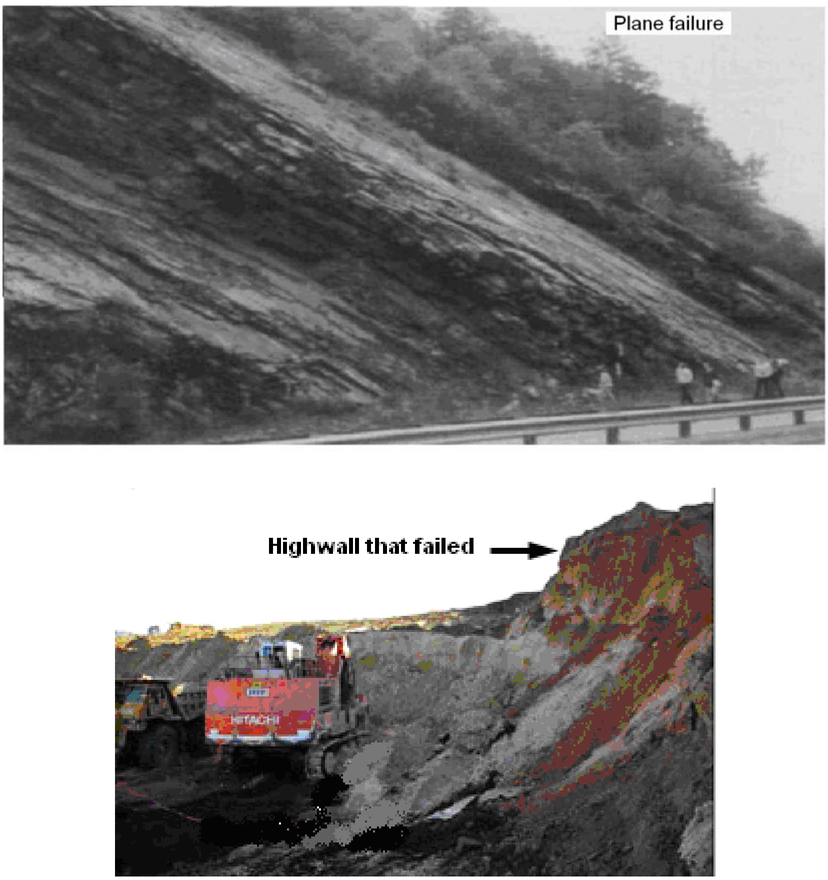


Fig. 14.4.1 Planar type of slope/highwall failure

Planar failures usually involve a tension crack on either the upper slope surface or on the slope face along which the failed block detaches from the slope block and slides down the slope along the plane of failure once the friction resistance is overcome. The tension crack forms as a result of small shear movements within the slope face that are mainly the result of responding to unloading associated with excavation around the slope. When heavy rain occurs, water flowing into the tension crack, thereby reducing the friction resistance of the failure plane, is the primary factor causing the planar failure. Therefore, the location of the tension crack is critical in determining the severity and magnitude of planar failure.

14.4.3 Wedge Failure

Wedge failure occurs when two sets of potential failure planes dip inward and intersect such that the line of intersection is exposed on the slope face. The upper surface of the wedge is normally a bedding plane (Fig. 14.4.2). The failure planes can be either joints or slickensides. Wedge failure may be triggered by mining activities or water flow lubricating and reducing the friction resistance of the potential failure planes.

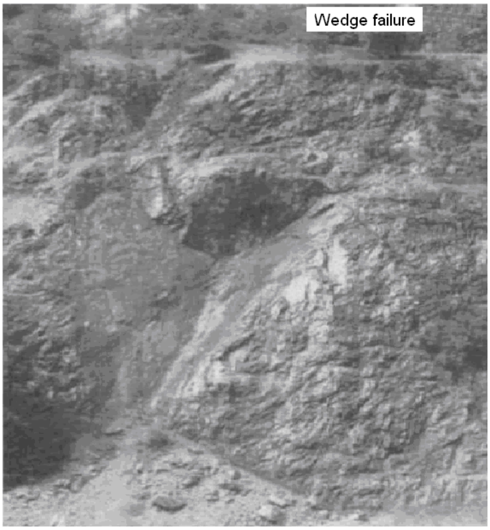


Fig. 14.4.2 Wedge type of slope/highwall failure. Note that portals below the failed block in bottom photo

14.4.4 Circular Failure

Circular failure surfaces are found to be the most critical in slopes consisting of homogeneous materials. Circular failure surface may extend from the crest to the toe or within the slope (Fig. 14.4.3).

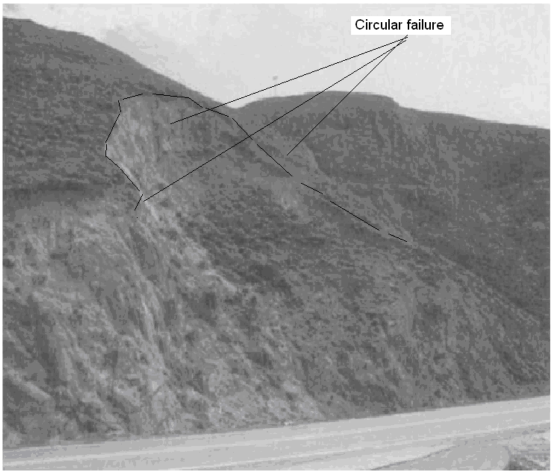


Fig. 14.4.3 Circular type of slope/highwall failure

14.4.5 Toppling Failures

Toppling failure results from propagation of stress-release vertical fractures or joints. In a highwall, the stress component normal to the highwall face vanishes at the face, allowing the highwall to expand toward the free face and resulting in the splitting off of slabs parallel to the surface (Fig. 14.4.4).

Fig. 14.4.4 Toppling type of slope/highwall failure

14.5 FAILURE ANALYSIS

14.5.1 Planar Surface Analysis

For a planar slope failure, three known forces are required in order to evaluate the stability (Fig. 14.5.1): weight, W, mobilized shear force, S_m, and normal reaction force, P, (Abramson et al., 1996). The weight of the wedge is

$$L = \frac{H}{\sin\beta} \frac{\sin(\beta-\alpha)}{\sin(\theta-\alpha)} \tag{14.5.1}$$

$$W = \frac{1}{2}\gamma H^2 \left[\frac{\sin(\beta-\theta)}{\sin^2\beta} \frac{\sin(\beta-\alpha)}{\sin(\theta-\alpha)} \right] \tag{14.5.2}$$

where H is the height of the slope, β is the slope angle from the horizontal, α is the slope angle of the back slope, and θ is the slope angle of the failure plane.

$$P = W\cos\theta \qquad \text{and} \qquad S_m = W\sin\theta \tag{14.5.3}$$

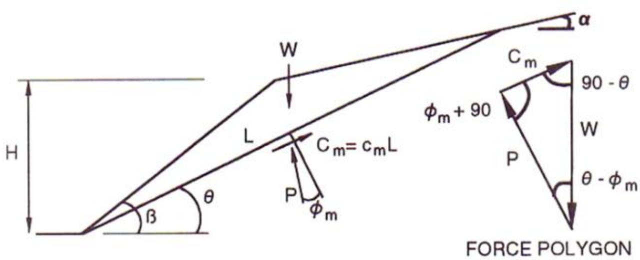


Fig. 14.5.1 Planar failure surface

If the safety factor for cohesion, c, and friction are F_c and F_ϕ, respectively, then the contributions by the mobilized shear force are

$$c_m = \frac{c}{F_c} \qquad \text{and} \qquad \tan\phi_m = \frac{\tan\phi}{F_\phi} \tag{14.5.4}$$

The force causing failure is $W\sin\theta$ and the available resisting strength along the potential failure plane is $c_m L + W\cos\theta\tan\phi_m$

For the slope to be stable, the resisting strength must be equal to or greater than the force causing failure, i.e.,

$$W\sin\theta = c_m L + W\cos\theta\tan\phi_m \tag{14.5.5}$$

Solving for c_m

$$c_m = \frac{W}{L}\left(\sin\theta - \cos\theta\tan\phi_m\right) \tag{14.5.6}$$

Substituting Equations 14.5.1-14.5.3 into Equation 14.5.6

$$c_m = \frac{1}{2}\gamma H\left[\frac{sin(\beta-\theta)(sin\theta - cos\theta\, tan\phi_m)}{sin\beta}\right] \tag{14.5.7}$$

In Equation 14.5.7, the inclination of backslope, α, has been eliminated.

The magnitude of the "cohesive" force required to satisfy equilibrium can be determined by Equation 14.5.7 for a failure surface inclined at an angle θ. To determine the maximum or critical slope θ_{crit}, differentiate Equation 14.5.7 with respect to θ, holding, γ, β and H as constants, and set it to equal to zero,

$$\sin(\beta - 2\theta) + \tan\phi_m[\cos(\phi - 2\theta)] = 0 \tag{14.5.8}$$

From Equation 14.5.8,

$$\theta_{crit} = \frac{\beta + \phi_m}{2} \tag{14.5.9}$$

Thus, the critical value for c_m is

$$(c_m)_{crit} = \frac{1}{4}\gamma H\left[\frac{1-\cos(\beta-\phi_m)}{\sin\beta\cos\phi_m}\right] \tag{14.5.10}$$

From Equation 14.5.10, the critical height of a slope can be obtained by substituting $c_m = c$ and $\phi_m = \phi$ (i.e., safety factor = 1)

$$H_{crit} = \frac{4c}{\gamma}\left[\frac{sin\beta\, cos\phi}{1-cos(\beta-\phi)}\right] \tag{14.5.11}$$

For a vertical slope or highwall, $\beta = 90^{o}$, and if $\phi = 0$, Equation 14.5.11 gives a critical height of $4c/\gamma$.

14.5.2 Circular Surface Analysis

There are many methods available for determining the critical factors for circular failure including circular arc, friction circle, and slices. Among the methods of slices, there are also many methods available for analysis of slope stability (Abramson et al., 1996). In this chapter only the simplified Bishop method is illustrated.

The Bishop method consists of the following three steps (Fig. 14.5.2) (Clover Associated, 2001),

1. Dividing the cross-section of the slip circle into slices,
2. Resolving and summing forces on each slice to determine the factor of safety,
3. Summing the force on all slices over the entire slope and determining the overall factor of safety.

The overall factor of safety, FS, for the slope is

$$FS = \frac{1}{\sum_{n=1}^{n} W_n \sin\alpha_n}\sum_{n=1}^{1} c[\ell_n + \tan\phi(W\cos\alpha_n - \mu\ell_n)] \tag{14.5.12}$$

where subscript n denotes the slice number. The values for the safety factor commonly used are (Clover Associates, 2001):

1. 1.5 for permanent or sustained loading conditions
2. 2.0 for foundations for a structure
3. 1.25-1.3 for temporary loads
4. 1.15-1.2 for seismic loading

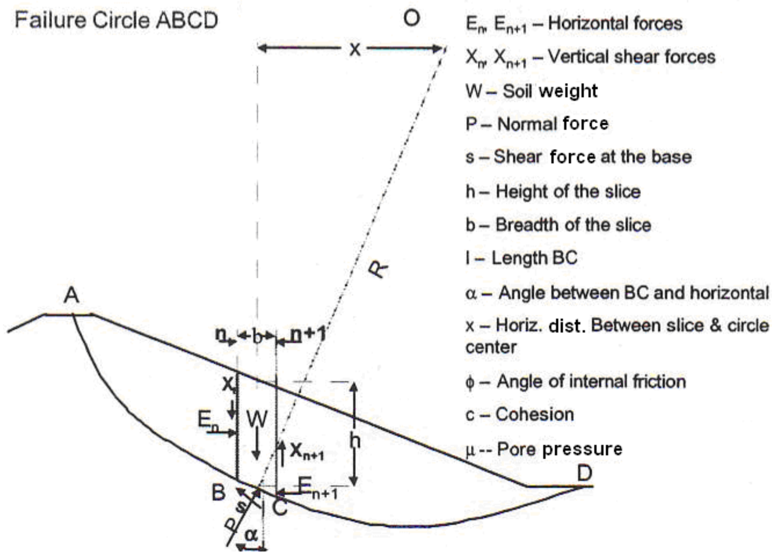


Fig. 14.5.2 Division of potential sliding surface into slices and forces acting on a typical slice

14.5.3 Direct Determination of Slope Failure Surfaces

The conventional approach stated above requires that the shape and location of the potential slip surface be specified, or the location is determined by different optimization methods, depending on the program algorithms. In order to overcome this problem, Lin et al., (1990) derived the factor of safety by considering available shear strength and mobilized shear stress along an arbitrary failure surface (Fig. 14.5.3). The critical failure surface, which has the minimum factor of safety, is then obtained by adjusting the surface in order to minimize the factor of safety. Minimization of the factor of safety is achieved by an optimization technique. For plane failure

$$c = \frac{c_m}{F} = \gamma\left[\frac{\tan\theta\cdot\tan\beta}{2}\left(\frac{H}{\tan\theta}\right)^2 + H\tan\theta\left(x_n - \frac{H}{\tan\theta}\right) + \tan^2\beta\,\frac{x_n^2}{2}\right] \tag{14.5.13}$$

where c is cohesion, ϕ is the angle of internal friction, $(\mu = \tan\phi)$, γ is unit weight of the stratum, and F is the factor of safety, which for layered highwalls is

$$F = \frac{\sum_{i=1}^{n}\int_{x_{i-1}}^{x_i}\left[c_i\left\{1 + (y'_1)^2 + \gamma_w \mu_i (y_2 - y_1)\right\}\right]}{\int_{x_o}^{x_n}\gamma_w (y_2 - y_1) y'_1 dx} \tag{14.5.14}$$

where γ_w is the weighted average unit weight of all the strata in the highwall, and c_i and μ_i are the cohesion and coefficient of friction for the rock layers in which the failure plane is passing, y_1 = f(x) and y_2 = g(x) are the equations of the slip surface and slope surface, respectively.

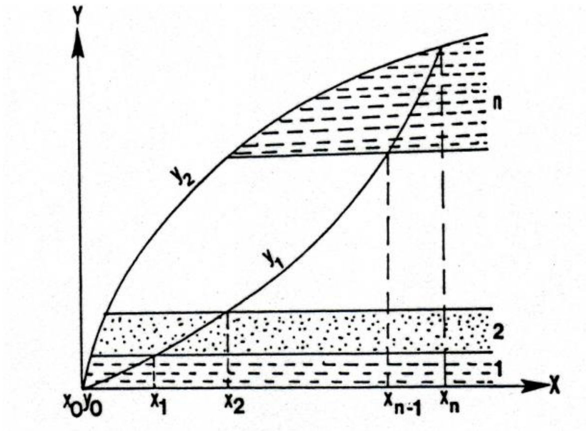


Fig. 14.5.3 Convention for layered highwall (Lin et al., 1990)

In another approach, a local failure surface in a slope can be estimated by applying the Mohr-Coulomb failure criterion and Mohr's circle analysis to the stress distribution in the slope as determined by the finite element analysis (Huang et al., 1989). The failure surface of a potentially unstable slope is determined by directly tracing the points with a calculated safety factor equal to or less than a predetermined value (Fig. 14.5.4).

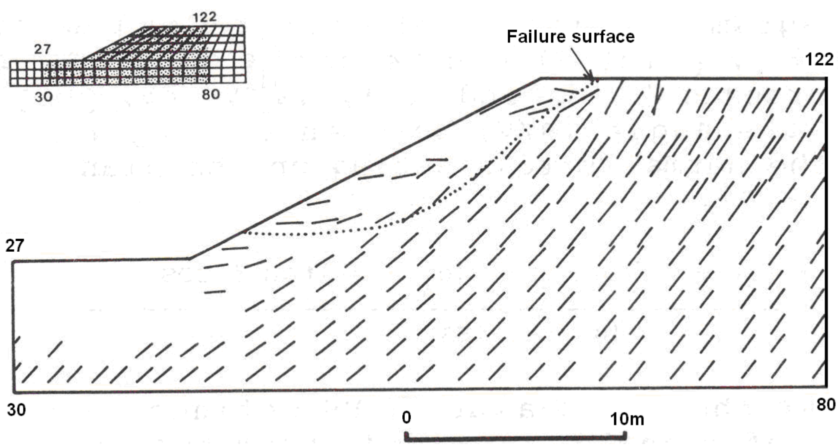


Fig. 14.5.4 A 2:1 model slope showing a curvilinear failure surface using finite element stress analysis (Huang et al., 1989)

14.6 PORTAL STABILITY

14.6.1 Portal Failures

A portal is the near-horizontal surface point of entry to an underground excavation. Portal failures can be classified into 6 major types: overall mass slide, upper slope slide, outer rib slide, upper slope subsidence/collapse, crown face overbreak, and internal crown/rib failure (Figs. 14.6.1 and 14.6.2) (Rogers and Haycocks, 1988 and 1989).

1. Overall mass slide

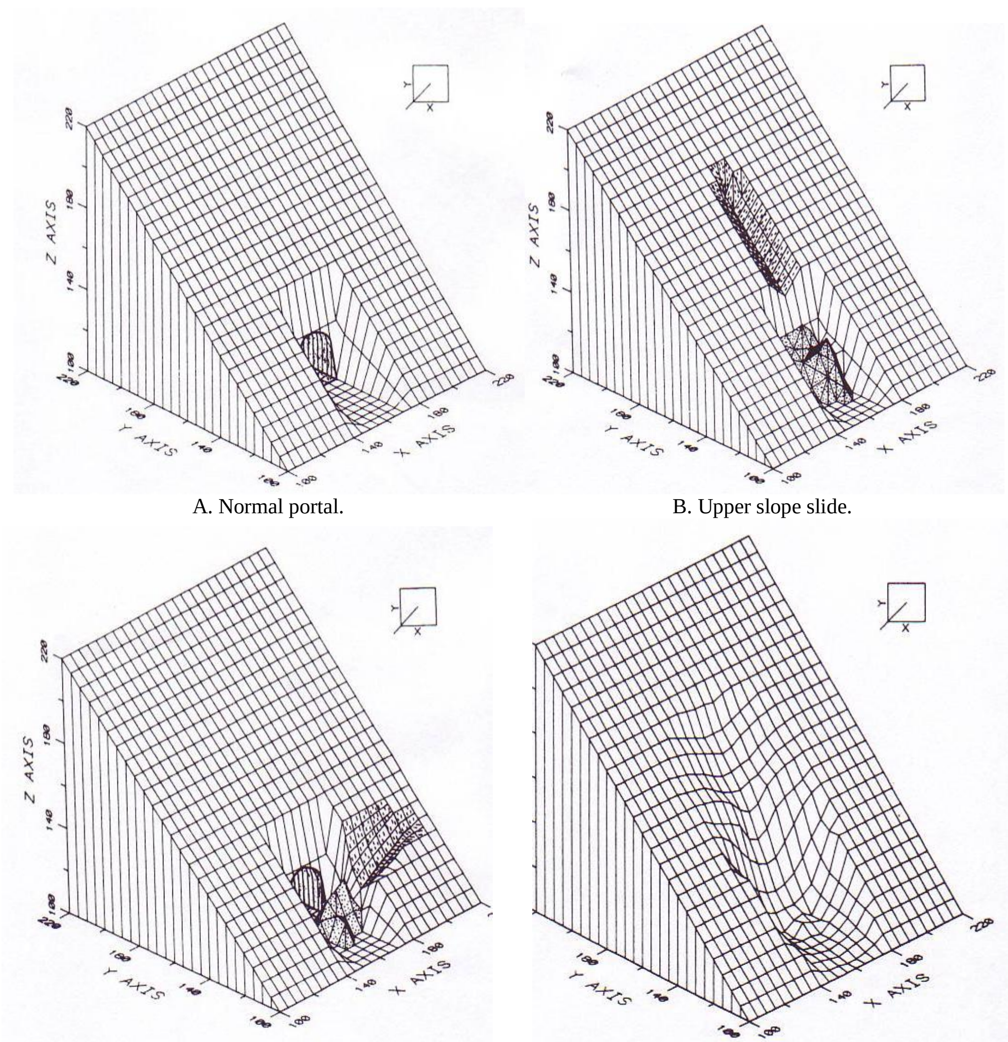
Overall mass slide means the entire slope or highwall surrounding the portal falls. This is the most severe portal failure when it occurs.

2. Upper slope slide

An upper slope slide is initiated by undercutting of a slope and usually extends from the crown face to a break in the upper slope face. The break may be a joint or tension crack (Fig. 14.6.1B). All major types of slope failures are found here.

3. Outer rib slide

An outer rib slide refers to a slide occurring on both side ribs of the portal entrance but before entering underground (Fig. 14.6.1C). All major types of slope failures are found here.



A. Normal portal. B. Upper slope slide.

C. Outer rib slide. D. Upper slope subsidence/collapse.

Fig. 14.6.1 Types of portal failures (Rogers and Haycocks, 1988)

4. Upper slope subsidence/collapse

Upper slope subsidence/collapse extends from the outer ribs to a point on the upper slope where overburden inhibits further deformation (Fig. 14.6.1D). This type of failure normally is sufficiently large to block the portal entrance.

5. Crown face overbreak

Crown face overbreak is the most common type of portal failure. The failure starts at the roof of the portal's underground entrance and may proceeds upward to some point on the crown face (Fig. 14.6.2 A and C).

6. Internal/rib failure

The roof and rib falls occur inby the portal underground entrance (Fig. 14.6.2B).

14.6.2 Portal Support

Three types of portal supports are used: canopy, canopy and rock reinforcement, and rock reinforcement.

A canopy is most frequently used (Fig. 14.1.1 bottom and Fig. 14.6.2C) and in many instances is the only support required and is mainly for personnel protection against raveling.

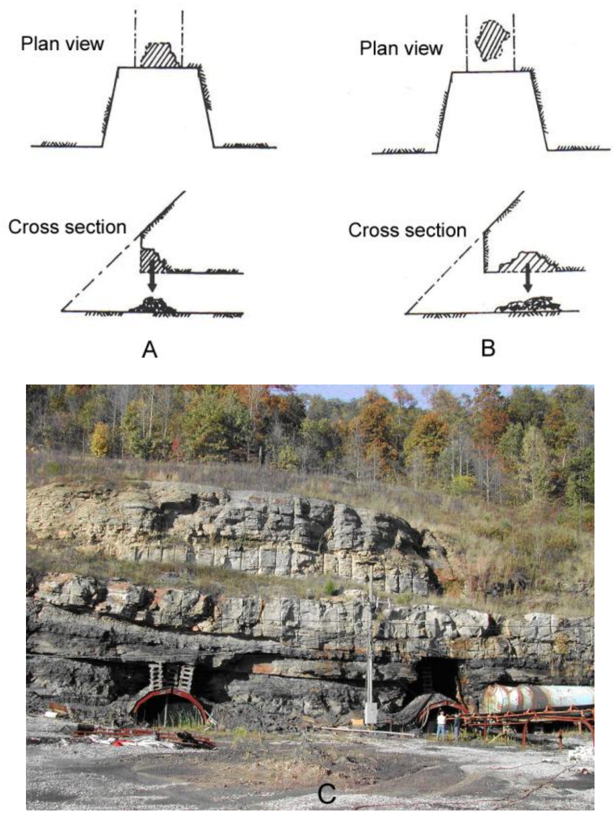


Fig. 14.6.2 A, crown face overbreak, B, internal crown/rib failure (Rogers and Haycocks, 1988), and C, photo showing crown face overbreak (Peng, 2007)

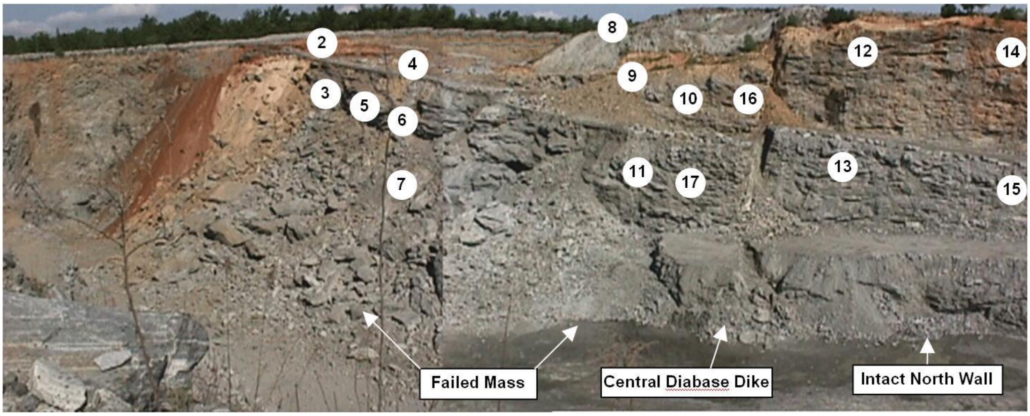
When the portal is under sufficient cover, and the exposed strata are weak, both canopy and rock anchors may be needed. Rock anchors of sufficient length can be installed horizontally into the crown face and upslope areas for stability.

When poor strata conditions exist, systematic design of rock anchors to stabilize the crown face and upslope areas are needed (Rogers and Haycocks, 1989).

14.7 MONITORING OF SLOPE MOVEMENT

In order to provide a safe working environment at a highwall mine site and predict impending slope failure, highwall or slope monitoring is recommended.

Kelly et al., (2002) described a slope-monitoring case in which a major slope failure occurred, and in order to ensure that the slope failure was finished, a systematic monitoring of slope movement on both the failed and intact areas of the slope was performed. Fig. 14.7.1 shows the monitoring site covering both the failed area (left) and the intact highwall (right). A conventional electronic distance meter (EDM) was used to survey the position of each prism station. The survey data were reduced in the form of plots of the magnitude and bearing of the cumulative resultant horizontal displacement (CRHD), the magnitude and plunge of cumulative resultant vertical displacement (CRVD), the total cumulative resultant displacement (TCRD), and the incremental cumulative resultant velocity (ICRV) for each prism station. From these plots, the stability of the failed mass was evaluated.



Station 1 EDM survey instrument (not shown)
Prisms 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 16, 17 - placed in failed mass
Prisms 12, 13, 14, 15 - anchored to intact portion of north wall

Fig. 14.7.1 Survey prism locations on the north wall of Monroe county quarry (Kelly et al., 2002)

The slope monitoring system (SMS) used by Martin (1996) consists of two components: SMU (slope monitor unit) and central computer and radio (Fig. 14.7.2). The SMS used an automated wire line extensometer to monitor the slope movement. The slope displacement and current temperature are transmitted to a central computer via a packet radio telemetry system at a pre-set interval. The computer receiving the data continuously provides updated displays of active slope monitors and generates audible and visual alarms if movement exceeds user specified values.

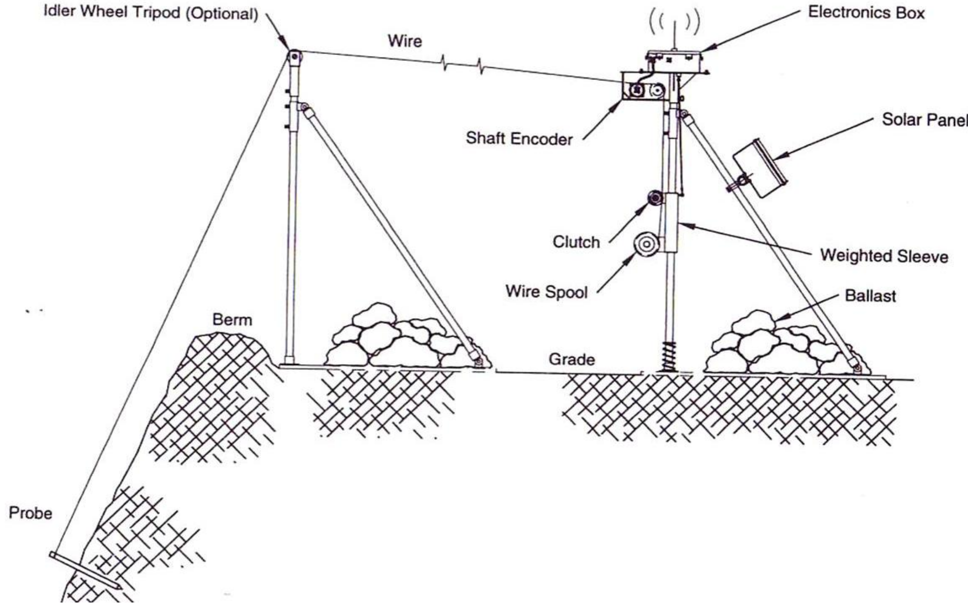


Fig. 14.7.2 Slope monitor system (Martin, 1996)

14.8 SURGE, SPOIL, WASTE, AND TRUCK-BUILT STOCKPILES

In coal mine surface facilities around a coal preparation operation, there are many man-made rock and coal piles, including surge piles, rock-built stockpiles, spoil piles, and waste piles. There are slope stability problems associated with these piles (Fredland et al., 1993).

Surge piles are coal piles that feed material onto a conveyor that runs in a tunnel beneath the piles. Along the underlying conveyor, there are a few draw-off point. When drawing is activated, the material begins to flow into the draw-off opening forming a cone, the slope angle of which may vary from 35^o to 45^o for dry granular material and up to 65^o for compact, wet, and fine materials. It is dangerous if machines are working around the cone area where materials are moving toward the cone and the weight of the machine may cause the cone to collapse drawing the machine into the draw-off openings. In order to avoid the danger, workers should stay away from the cone area and devices indicating the location of draw-off points and the activated feeder must be clearly displayed.

In many cases, material is stored simply by dumping it on the ground without a draw-off point. The angle of the pile normally assumes near the angle of repose of the material. Material is typically reclaimed by loading it out at the toe of the pile. To avoid danger of triggering slope failure, material should not dump directly over the edge of the pile. The best practice is to dump the material with the truck at least one-truck length back from the edge of the pile.

Problems associated with spoil and waste piles occur when materials are dumped directly over the edge of the pile, because the zone of fine particles is less stable. So knowing the nature of the spoil materials, and how they are distributed after dumping, is critical in determining the optimum dumping points around the edge of the piles. Software is available for analyzing the influence of a haulage truck operation on slope stability (Michalowski and May, 1990).