

# Utilizing Strain Criteria to Predict Highwall Stability Performance

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## ABSTRACT

Assessments of the stability performance of open pit highwalls have traditionally been based on consideration of surface movement rates. Although generally accepted in industry, this approach presents challenges for establishing appropriate threshold values to allow for safe mining operations and does not address the issue of total strain. Surface movement monitoring data from a limited number of open pit mining operations in North and South America has been evaluated in terms of highwall strain, rock mass quality and inferred mechanism of instability. Threshold strain levels for key stages of highwall stability proposed from previous work have been reviewed and are generally endorsed based on evaluation of additional data. An empirical highwall strain criteria for the assessment of highwall stability performance is postulated based on the observed trends in highwall strain data from the case histories presented.

## INTRODUCTION

Open pit mining results in the extraction of large volumes of rock and accompanying stress relaxation of the rock mass. The amount of stress relaxation that will occur will be governed by the overall geometry of the open pit in terms of the highwall angle, overall depth, and the rock mass quality. The stability performance of a large open pit highwall is affected by stress relaxation as the rock mass dilates and rock mass strength deteriorates, resulting in slope displacements. The amount of displacement that occurs along open pit highwalls is commonly measured using electronic distance measuring devices and survey-monitoring prisms. Surface movement monitoring data can be evaluated to quantify the amount of movement as highwall strain.

### STRESS RELAXATION WITH OPEN PIT MINING

Open pit highwalls undergo unloading during the mining process. Unloading results in stress relaxation, the degree of which depends on rock mass quality (i.e. rock mass structure, strength, and deformability), the extent of unloading (i.e. depth of pit), the geometry of pit (i.e. depth and angle of highwalls) and the initial site-specific in-situ stress regime.

The degree and orientation of fracturing, the strength of the intact rock, and the prevailing groundwater conditions within the rock mass all have an effect on the pit wall movements as mining proceeds. These parameters define the overall quality and deformability of the rock mass, and have a significant effect on the way that the stresses are redistributed within and around the pit highwalls. There are several rock mass classification systems used by the industry today; however, not all of them are suitable for open pit applications. To standardize the various data that has been reviewed, the

rock mass conditions of the open pit highwalls were characterized using the Rock Mass Rating (RMR) system (Bieniawski, 1976).

Stress relaxation occurs as a result of direct unloading with the mining of open pits to extensive depths. Both elastic and non-elastic deformations of the rock mass occur due to mining. Non-elastic relaxation occurs as a result of the dilation of joints within the rock mass. In some cases, heaving of the pit floor can cause extensive loosening and upward dislodgement of rock and can create significant operational problems. Increased seepage inflows may also occur as a result of higher hydraulic conductivity of the rock mass due to dilation.

Stress relaxation can also occur as a result of steepening of highwalls associated with pushbacks and/or modifications as part of optimisation and pit expansion. Steepening of the highwall at depth results in convex slopes that can increase stress at the toe of the slope and reduce confinement of the rock mass in the mid-slope. This generally results in unfavourable stability conditions and further dilation of the rock mass above the working area. Figure 1 shows extensive stress relaxation along the SW highwall of the Lornex Pit at Highland Valley Copper.



Figure 1- Tension Cracks in Upper Slope of Highland Valley Copper's Lornex Southwest Wall

### HIGHWALL MOVEMENT AND STRAIN

#### General

Open pit highwalls undergo varying amounts of movement and resulting strain in response to mining. The amount of movement and strain within each highwall is a function of the overall highwall geometry and the rock mass quality. These geotechnical conditions include the rock type, the degree, nature and orientation of rock mass

jointing, and the amount of groundwater pressure in the slope. The amount of movement within each highwall can also be significantly influenced by the blasting practices at the open pit mine.

Highwall movement is typically monitored at the surface using optical prisms surveyed with instruments such as theodolites or total stations. The required frequency of survey monitoring will depend on the identified or interpreted potential type and size of instability, the progress of mining, and the occurrence of precipitation or runoff.

#### Highwall Movement – Displacement Rates

Mining operations typically monitor displacements and calculate displacement rates to evaluate the stability of the highwalls. Displacement versus time plots can be used to determine if the movements are regressive or progressive, i.e. whether or not the nature of the movements may be tending towards a lesser or greater degree of stability, respectively (Zavodni, 2001). Depending on the type of instability, these displacement rates and their apparent trends can be used, in conjunction with the inferred instability mechanism (i.e. toppling, wedge, planar, rock mass, or some combination of these) to establish displacement rate thresholds to allow practitioners to evaluate stability and decide whether restrictions need to be put on mining in that area. However, it is important to note that these displacement rate thresholds do not reflect the total strain that has been experienced by the highwall. This is considered to be a significant shortcoming of this approach.

#### Highwall Strain

A strain criteria approach has been proposed as an additional means to assess the stability performance of open pit highwalls. The strain criteria approach is based on the correlation of actual strain values from prism monitoring data to observed highwall stability performance. Predicted strain values from stress-deformation models can then be compared to the established correlation to assess expected highwall stability performance and stability for proposed mining geometries. Using this approach, highwall strain ( $\epsilon$ ) is defined as follows:

$$\epsilon \approx \frac{\Delta x}{H}$$

where  $\Delta x$  is the maximum deformation of the highwall, H is the total height of the highwall and strain is presented as a percent value.

#### Threshold Strain Levels

Zavodni (2001) has suggested from experience that highwalls may be subjected to a maximum strain of 0.6% to 1% before moving from a regressive mode to a progressive mode of instability and that strains over 1% may lead to abrupt highwall instability and failure. The data presented in Figure 2 suggests that a threshold strain of about 2 % (Table 1) may be more appropriate as an indicator of highwall failure. However, this could be due to the large number of toppling failures, which typically involve greater strain, that are included in the data presented here. For reference, the suggested strain threshold values are shown in Figure 2. These threshold strain levels are also presented in Table I for identified key stages of highwall stability.

Table I  
Threshold Strain Levels for Key Stages of Highwall Stability (after Zavodni, 2001)

Highwall Stability Stage	Threshold Strain Level, %
Tension Cracks	~ 0.1
Progressive Movement	~ 0.6
Potential Onset of Failure	> 2.0

### HIGHWALL INSTABILITY MECHANISMS AND STRAIN

#### General

Open pit highwalls may undergo different forms of instability, depending on subject to the nature and orientation of rock mass jointing and the presence of any discrete large-scale structural geologic features. The commonly recognized forms of highwall instability and their corresponding letter designation include Planar (P), Wedge (W), Step-path (S), Toppling (T), Rotational/Rock Mass (R), and Complex (C) or some combination of the above.

It is recognized that the deformation behaviour of a highwall can vary significantly subject to the different mechanisms of instability. Accordingly, different levels of highwall strain can be expected to occur and may even be characteristic of the type of instability. For example, relatively high strains are expected for toppling failures in a relatively deformable rock mass, whereas relatively low strains can be tolerated before a planar failure in a brittle rock mass becomes unstable. Brief descriptions of the instability mechanisms and relative strains are presented in the following section.

## Highwall Strain, Instability Mechanism, and Rock Mass Quality

Planar instability only involves movement along a single joint plane and the amount of movement required to initiate failure is relatively small. Therefore instability can be expected to initiate at low highwall strain levels. Rock mass quality does not generally play a large role in this type of mechanism, with geological structure orientation being the critical factor for this instability mechanism.

Wedge instability requires movement to occur along two well defined joint planes and the amount of movement to initiate instability is still relatively small, although higher than for planar failure. Therefore, instability generally initiates at relatively low highwall strain levels. As for planar failure, geologic structure orientation is the most important factor controlling the instability.

Stepped-path instability can occur when the dominant geologic structures do not daylight but are of sufficient continuity and frequency within the rock slope that a failure plane develops by overcoming the strength of intact rock bridges between these structures and then propagates to the surface. This type of instability requires a moderate amount of strain, generally more than planar or wedge instability, before instability occurs. No examples of this type of instability mechanism were available for inclusion in this database.

Toppling instability occurs depending on the presence and orientation of geologic structures in the slope. This instability mechanism can lead to very large strains without catastrophic failure. Highwall strains of up to 20% without catastrophic failure occurring have been documented in the existing database for toppling instability in relatively competent rocks. (Newcomen et al. 2002). The quality of the rock mass, particularly near the toe of the toppling slope, can have a significant impact on toppling.

Rotational or rock mass instability can occur in heavily altered and/or highly fractured rock masses. In general, this type of instability requires relatively deep (>500m) excavations and often involves some form of structural control. Relatively large strains occur and the quality of the rock mass plays a key role in this type of instability mechanism.

Complex instability is defined here as involving a combination of the above types of instability mechanisms. Some of the types of instability observed and included in the database include wedges initiated by upslope toppling (i.e. toppling wedges), nested wedges where bench or inter-ramp scale wedge failures occur within an overall slope wedge instability, and non-daylighting planar/wedge failures that intersect in-dipping structures

or a poor quality rock mass that allow the lower part of the slope to kick out.

## CASE HISTORIES

### General

Surface movement monitoring data from a limited number of open pit mining operations in North and South America where the authors have been involved, and data provided by other open pit mining practitioners, is presented in terms of highwall strain, rock mass quality and inferred mechanism of instability in Figure 2. Specific case histories are discussed in the following sections. These case histories represent a wide range of instability mechanisms in a variety of geotechnical environments, and are shown with a corresponding case history number in Figure 2. For reference, the threshold strain levels shown in Table I are highlighted in Figure 2.

### Case History #1: Large-Scale Planar Instability (P), Smoky River Coal Mine, Grande Cache Alberta, Canada

This unbenched footwall slope was approximately 100 m high in the lower portion of the slope, which failed catastrophically approximately two months after mining was completed. The footwall slope was anchored, however, the failure occurred as one intact block behind the depth of the anchors and as such, this failure has been defined as a ploughing type planar failure (Piteau Associates, 1987). The onset of movement was associated with an estimated total movement at the crest of approximately 30mm when the slope was approximately 75 m high. The estimated highwall strain at that time was approximately 0.04 %. Movements continued during mining at a rate of movement of 0.01 mm/day. The rate of movement increased to 0.04 mm/day and to 0.07 mm/day in the two months prior to failure. The estimated highwall strain at the time of failure was approximately 0.9 %. Figure 3 illustrates large-scale planar instability of Case History # 1.



Figure 3 – Case History #1 - Planar Instability

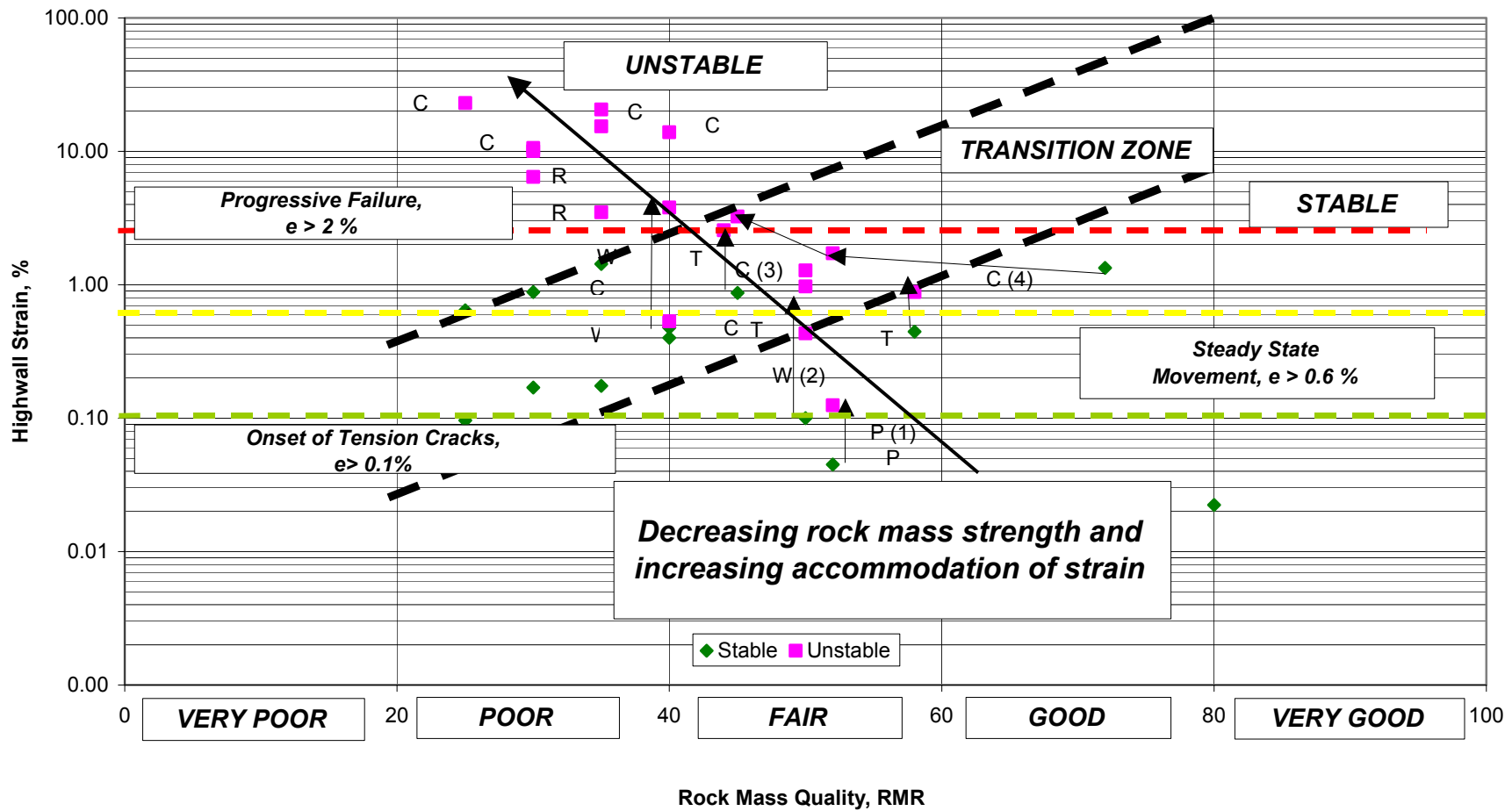


Figure 2 – Case History Highwall Strain Data and Empirical Highwall Strain Criteria.

Case History #2: Large-Scale Wedge Instability (W), Confidential

A large wedge instability of approximately 8 million tons occurred at a small open pit mine. The instability was preceded by the initial identification of tension cracks, monitored movements during subsequent mining, increased extent and size of tension cracks with further mining followed by increased rates of movement up to the time of failure. The onset of the original tension cracks was associated with an estimated total movement at the crest of approximately 600 mm and a highwall strain of approximately 0.15 %. Movements continued with mining at a rate of 3.5 mm/day. The rate of movement increased with continued mining to 20mm/day. The estimated highwall strain at this time was approximately 0.45 %. The rate of movement increased progressively to 60-100 mm/day one month prior to failure. Increasing rockfalls and raveling occurred prior to failure and the rock mass was observed to dislodge as a series of v-shaped wedges out of the highwall. The estimated maximum highwall strain at the time of failure was approximately 0.95 %. Figure 4 illustrates the Case History #2 instability.



Figure 4 - Case History #2 – Wedge Instability

Case History #3: Large-Scale Planar Toppling (C) Instability, Cassiar Asbestos Mine, British Columbia, Canada

A slope failure involving approximately 18 million tonnes occurred involving the final 340 m high slope of squeezing soft deformable serpentinite rocks in the toe of the slope which allowed planar or wedge sliding and toppling of the more competent sedimentary rocks in the upper section of the slope (Martin et al. 1993). Total movements of over 7m were measured over the duration of the instability, with movement rates of up to 150mm/day observed during the final phases of mining. The onset of progressive failure was observed at approximately 0.9% strain, with catastrophic failure occurring when the total strain reached approximately 3.3%.

Case History #4: Large-Scale Toppling Instability (T), Lornex Pit, Highland Valley Copper Mine, British Columbia, Canada

Tension cracks were observed at the top of this slope when the slope was only 56 m high, with a maximum movement of about 0.75m (1.34% strain) measured at that point in time. The RMR of the upper slope was estimated to be 72. The onset of progressive displacements was observed when the slope was approximately 116 m high and maximum displacements of about 2 m (1.72% strain) were measured. A significant decrease in the rock mass quality was observed in the lower slope, with an RMR of 52 estimated. The current slope height is approximately 175 m and approximately 4.5 m of total movement (2.56% strain) has occurred. The rock mass quality has further decreased in the Lornex Fault zone at the current toe and is estimated to be 44. It is noteworthy that catastrophic failure of this pit has not occurred, although significant disruption of the benches have been observed. Figure 5 illustrates the large-scale toppling failure at the Lornex Pit.



Figure 5 - Case History # 4, - Toppling Instability

### Case History #5: Complex Rock Mass Failure (C), Open Pit Gold Mine, Peru

A catastrophic failure of approximately 700,000 tons occurred in April 2002. The failure was triggered by persistent infiltration of rainfall, and maximum movement rates measured during the failure reached up to 6m/day, with an average of about 2.2m/day. The height of the slope at the time of failure was only 100m, with regressive stage strain of about 1.4%. The RMR of the fault zone was estimated to be 28. The RMR of the andesite and the quartz alunite were estimated to be 32 and 56, respectively, with an average of 35 back-calculated for the entire slope.

### CONCLUSIONS

Surface movement monitoring data from a limited number of open pit mining operations in North and South America has been evaluated in terms of highwall strain, rock mass quality and inferred mechanism of instability. Threshold strain levels for key stages of highwall stability proposed from previous work are endorsed based on evaluation of additional data. An empirical highwall strain criteria for the assessment of highwall stability performance is postulated based on relatively consistent trends in highwall strain data.

Open pit mining practitioners are encouraged to contribute data in an effort to further evaluate the applicability of an empirical strain criterion as an appropriate approach for the assessment of open pit highwall stability. The verification of such an approach, along with complementary predictive numerical modelling of strains, may be useful for the evaluation of proposed highwall modifications and pit expansions during open pit mine design and long term planning.

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