Quantifying the differences in hangingwall conditions

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Synopsis

Underground excavations exhibit different hangingwall conditions in response to varying geotechnical and mining situations. These differences need to be quantified so as to accurately determine the effectiveness of the mining and/or support strategies. A useful tool for the quantification of these differences is hangingwall profiling. Two methods of hangingwall profile measurement are described—termed irregular and periodic methods. Several data analysis techniques are reviewed for these methods and the suitable ones are discussed in detail. For irregular data the suitable techniques are the determination of the length, the average of the profile and the average absolute deviation from the mean of the profile. All of these techniques as well as determination of the moving average of the height and examination of the spectral image of the profile can be successfully applied to regular data. The effect of preconditioning on the hangingwall is discussed as an example and it is quantitatively shown that it results in improvements of conditions. The techniques described allow the engineer to quantitatively identify the appropriate support type or mining strategy and thus represent a valuable decision-making tool. It is suggested that these techniques should be employed on a routine basis by the rock engineers on the mines as part of their geotechnical classification, as well as support manufacturers to quantify the effectiveness of various support types.

Introduction

Not only do poor hangingwall conditions represent a major hazard and are thus important to understand and control, but hangingwall conditions, in general, are also one of the most useful indications of the success or failure of a particular mining strategy. Hangingwall conditions may vary greatly from stope to stope within a mine and even from panel to panel within the same stope. These variations may be due to a number of factors from poor rockmass conditions, due to the adverse influence of geological features, to an improvement due to good mining practice. Underground these differences can often be clearly seen. However, to date no easily applicable method has been available to quantify the condition of a hangingwall. As such, opinions vary on the stability of rough and smooth hangingwalls. Once this empirical feeling has been quantified, suitable rock-mechanics and/or mining strategies can be employed.

Two methods of measuring hangingwall profiles are presented. These are termed *irregular* and *periodic* methods (based on the way the data is collected and its subsequent analysis). An example of how these methods are used to quantify the differences between preconditioned and unpreconditioned hangingwall conditions is given. A step by step procedure of hangingwall profiling is provided in the Appendix.

Data collection methods

Hangingwall profiles are measured by stretching a measuring tape over a particular distance, usually between 5 and 10 m, and then measuring the separation between the tape and the hangingwall at various points along the tape (Figure 1). The dip of the tape and the average dip of the hangingwall need to be recorded so that correction can be made for the difference in their dips. The position and orientation of each profile should also be noted.

The orientation of the profiles is dependent on the information needed. For example, orthogonal profiles in various orientations may be measured for geotechnical characterization of the area. It is, however, generally advisable to measure profiles perpendicular to the mining face as well as perpendicular to the predominant fracturing in the area. These two directions are often coincidental.

Two types of profiles can be measured. The simplest and quickest is where only the peaks and troughs of the hangingwall above the tape are measured. This is termed the *irregular* method. However the uneven data-set produced from this method cannot be analysed

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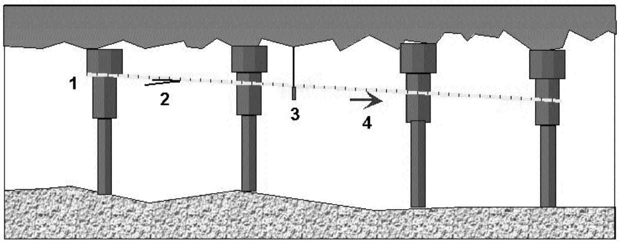

Figure 1—Sketch diagram showing method of data collection. (1) Tape is anchored tautly between two points, (2) Angle of tape and average dip of strata is recorded, (3) Distance between tape and hangingwall is measured (at each peak and trough for irregular profiles and at small regular intervals for periodic profiles), (4) Step 3 is repeated along the profile until the end-point is reached

using more sophisticated techniques such as fractal and spectral analyses. These techniques require a more regular data-set and so a second method, with data measurements taken at small-spaced regular intervals is developed. Data collected using this *periodic* method can be analysed using all the methods applied to the irregular data-sets as well as more sophisticated techniques, but is more time-consuming.

Data analysis methods

Analysis of irregular data

Cumulative percentage of size of profile steps

Profiles have to be normalized for differences in the dip between the tape and the hangingwall. Each normalized profile is then zeroed by subtracting the minimum y value (height), thereby allowing various profiles to be compared. A cumulative percentage plot can then be drawn up of the heights of the steps in the profile. This method is useful only when the dominant sizes of the steps in the various areas are significantly different and hence shows up as a distinct crest on the cumulative curve.

Fitting a regression line to a profile

It was initially thought that this technique would show the roughness of a profile clearly, as correlation coefficients are good indicators of scatter in data. Correlation coefficients (R^2) were calculated for profiles using Equation [1]. (After Spiegel,[1992]).

$$R^2 = \frac{\Sigma\left(Y_{est} - \bar{Y}\right)^2}{\Sigma\left(\bar{Y} - \bar{Y}\right)} \qquad [1]$$

The numerator is equivalent to the explained variation of each point and the denominator is the total variation of the data. Irrespective of the roughness of the profiles, very low R^2 values are obtained. Profiles have a very small range of y-values (that is, the heights of the peaks and troughs) relative to the x values (distance along the profiles) resulting in a low total variation. This is because the variation in height of the steps is virtually independent of the position along the profile. As such, R^2 values are not a good indication of the roughness of a profile.

Profile length

In this technique, the total length of each profile is determined by calculating the distance between successive points along the profile and summing these distances [Equation 2].

$$Length = \sum_{\substack{i=1 \\ j=i+1}}^{n-1} \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \qquad [2]$$

where n is the number of points, x_i, y_i are the coordinates of the ith point and x_j, y_j are the coordinates of point i+1. The straight-line distance between the first and final points is subtracted from the summed length. The smaller this final value, the smoother the hangingwall, a quantitative description of the condition of the hangingwall can be obtained.

Average gradient

The greater the difference in heights between adjacent points on a profile, the less smooth the profile is. Therefore, a measurement of the change in gradient between points along a profile provides an indication of the roughness of a profile. Gradients between successive points are calculated by dividing the absolute difference in x-coordinates by the absolute difference in y-coordinates and taking the average of these for the entire profile.

Average absolute deviations from the mean

The appropriateness of using the deviation from the mean should first be tested for a profile using Equations [3] and [4] (after Chapre and Canale,[1985]). These equations determine if the average absolute deviation from the mean is an appropriate statistical test for the data.

$$S_x = \sqrt{\frac{S_t}{n-1}} \qquad [3]$$

$$S_{y/x} = \sqrt{\frac{S_r}{n-2}} \qquad [4]$$

S_t is the total variation and S_r is the unexplained variation. If $S_x > S_{y/x}$ then examination of the average of absolute deviations from the mean is a suitable statistical test. This has been found to be the most common case for hangingwall profile evaluation. If, however, $S_x < S_{y/x}$ then a better statistical test would be to examine the average absolute deviation from the trend. The equation for calculating the average of absolute deviations from the mean is given below by Equation [5], where n is the number of points and $\bar{y}$ is the mean.

$$D_{average} = \frac{1}{n}\sum\left(y - \bar{y}\right) \qquad [5]$$

*Analysis of periodic data**

Comparison of moving averages

Moving averages of the heights at various sampling or 'window' lengths can be calculated for a profile. When an increase in the window length no longer results in a major

*Note that all the methods described for the analysis if irregular date are applicable to periodic data

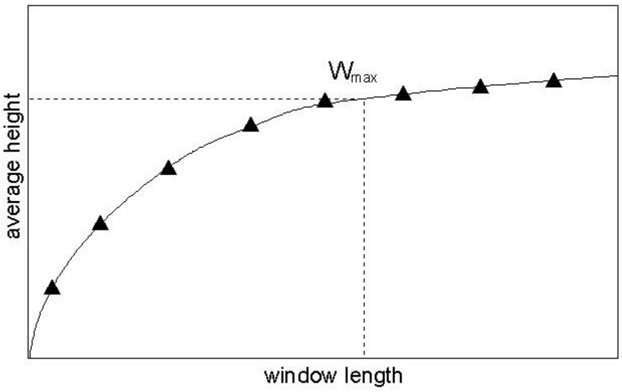

Figure 2—Hypothetical variogram plot of average profile heights for different window lengths. After W_{max}, there is no longer a major increase in the average height. Profiles of this length should therefore have included a sample of the dominant steps in the hangingwall in that area

increase in the average height, all the major steps in that profile have been included. A theoretical example of this variogram analysis is shown in Figure 2. Passing this sort of filter over the data can indicate the minimum suitable length for profiles in a certain area as, once point W_{max} (Figure 2) has been passed a representation of all the sizes of the steps in the area has been included.

Spectral analysis

Hangingwall profiles have a similar pattern to seismograms recorded from seismic events, with the height (y values) of a step in a profile being equivalent to the amplitude of a seismogram and the distance along the profile (x values) equating to the wavelength of a seismic pulse recorded on a seismogram. Using Fast Fourier Transformation (e.g. Sokolnikoff and Redheffer,[1966]) the data can be converted into the frequency domain. The spectra from profiles in different areas can then be compared to see how the intensity and the depth of fracturing varies.

Fractal analysis

Although this method has not yet been proved successful, it is proposed that, due to the scale invariance of many fracture patterns, it should be possible to describe their distribution in terms of a fractal dimension. The easiest way of determining a fractal dimension of a line (such as a hangingwall profile) is the divider method, first described by Mandelbrot (e.g. Mandelbrot,[1986]). It involves measuring the length of the line (L_r) using mathematical 'dividers' (or 'rulers') of different lengths (r). If the line (or profile) has a self-similar fractal dimension then, (After Power and Tullis,[1991]).

$$L_r = Fr^{(1-D)} \qquad [6]$$

with D being the fractal dimension. The simplest way to determine the fractal dimension is to plot a log-log graph of L_r versus r. If the data fits a straight line on this graph then the profile has a self-similar fractal dimension equal to the slope of the graph. Alternatively the profiles could be described by a self-affine fractal dimension, in which one of the dimensions of the original line being examined are multiplied by a constant, for the data to fit a fractal dimension. Once this multiplier has been found and applied to the data, the same log-log plot of line length versus ruler length can be used to determine the fractal dimension.

An example: Quantifying the effects of preconditioning

One of the beneficial side effects of preconditioning, where the main objective is to reduce the incidence of face-bursts in highly stressed stopes (Kullmann *et al.*[1996]) is an improvement in hangingwall conditions (Figure 3). Hangingwall profiling was used to quantify this change as well as determine the area of influence of the preconditioning holes. A brief discussion of the results is given below as an example of how the techniques, described before, can be used.

Not all of the techniques described previously showed the contrast in hangingwall conditions between preconditioned and unpreconditioned areas clearly. The most useful techniques (previously dealt with under their appropriate headings) are profile length, average gradient, and average absolute deviation from the mean for the irregular profiles and spectral analysis, and moving average of heights for the periodic data. Twenty irregular profiles (that is measuring only the peaks and troughs in the hangingwall) each of 10 m in length were recorded in preconditioned and unpreconditioned stopes adjacent to one another. A further six periodic, 5 m long profiles (sampling every 2 cm) were measured. In addition fifteen short (1 m) periodic profiles were measured on a regular grid around preconditioning sockets to determine the area of influence of the preconditioning blast.

The average profile length (as determined from the irregular data) was 115.5 cm in preconditioned areas (that is the length greater than the straight-line distance of 1000 cm), whereas in unpreconditioned areas the excess length was 154.8 cm (Figure 4). The average gradient of profiles was also much lower in preconditioned areas, 0.84 versus a value of 1.15 for unpreconditioned areas. The gradient and profile length increase slightly between preconditioning holes (Figure 5) and it is thus possible to conclude that the area of influence is approximately 2.5 m in radius. This was confirmed by Ground Penetrating Radar (GPR). Even though there is an increase in gradient and profile length between sockets, the maximum values are still significantly below those recorded for unpreconditioned areas.

Figure 3—Photograph looking away from the face. Note the much smoother hangingwall conditions in the foreground, due to preconditioning

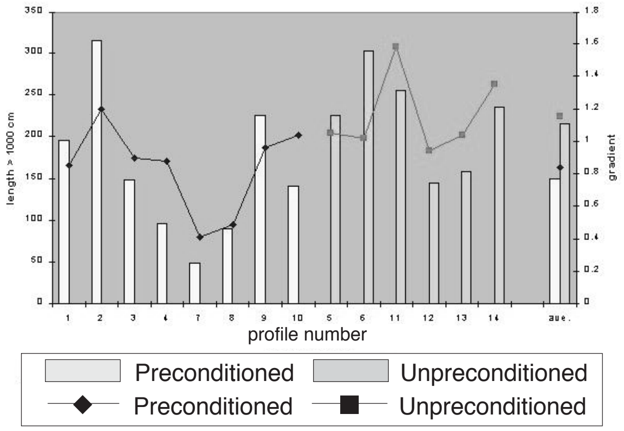

Figure 4—Profile length and average gradient of irregular profiles. Lengths exceeding 1000 cm (i.e. the straight-line length of the profile) are plotted. Preconditioned hangingwall profiles have significantly lower lengths and gradients than those in unpreconditioned areas

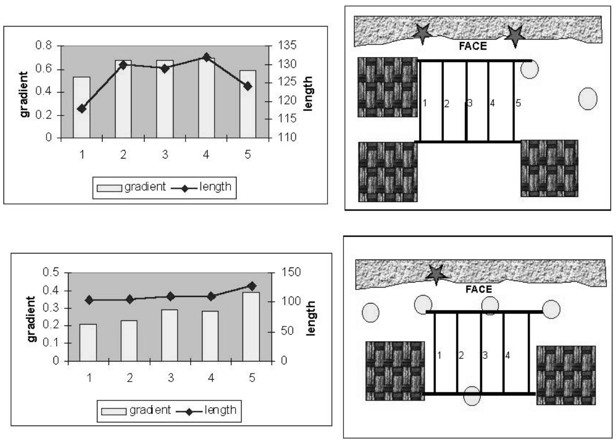

Figure 5—Graphs on the left-hand side are the profile length and average gradients of the profiles measured around a preconditioned hole as shown by block diagrams on the right. The stars indicate the position of the preconditioning sockets from the previous day's blast. The profiles are 1 m long and 0.5 m apart. Note how both the average gradient and the profile length decrease towards the position of the socket, indicating a smoother hangingwall

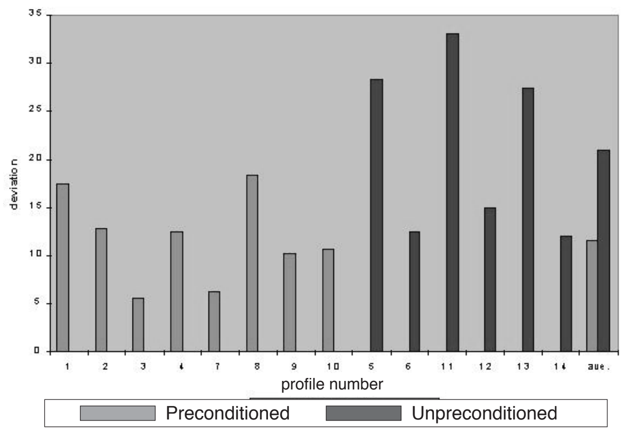

Figure 6—Average absolute deviation from the mean for irregular profiles. The average of these deviations in preconditioned areas is 11.6 compared to an average of 21.0 for profiles measured in unpreconditioned areas, once again indicating a more uneven hangingwall in the latter

The average absolute deviation from the mean of profiles measured in preconditioned areas is roughly half of that recorded for profiles measured in unpreconditioned areas (Figure 6). This confirms that preconditioned areas have a much smoother hangingwall, due to reduced blast damage.

One of the most interesting observations was derived from the spectral analysis of the periodic data. Figure 7 is a plot of the average spectra from the periodic profiles measured in both the preconditioned and unpreconditioned areas.

Several conclusions are drawn from the examination of these spectra: there is a distinct separation of the two sets of data, even though they show the same trend. This common trend indicates that the wavelength (that is, fracture spacing) is similar in the two areas. There is, however, a major difference in the amplitude of the two spectra, with the unpreconditioned areas having a much higher amplitude than preconditioned areas. This indicates that the depth of the (equally spaced) fractures is much greater in unpreconditioned areas, resulting in a rougher hangingwall. The spectral evidence suggests that no new fractures are being produced as a result of preconditioning; rather, the character of pre-existing fractures is modified.

Conclusions

The statistical and spectral techniques allow the 'gut-feel' type of description of hangingwall conditions that are normally used, to be quantified. As distinct values have been used, rather than descriptive terms such as 'good', the time dependent behaviour of the hangingwall can be analysed by re-measuring profiles in the same position over time. This allows the subsequent comparison of similar areas to see how conditions have altered with time.

Although the measurement and subsequent analysis of irregular data through techniques such as the determination of the length, average gradient and average absolute deviation from the mean is meaningful, the measurement of continuous profiles provides a much more complete description of the hangingwall. This more complete data-set can be examined using all the suitable techniques that are applied to the irregular data, as well as more sophisticated techniques such as spectral analysis. The downside of continuous profile measurement is that it is slightly more

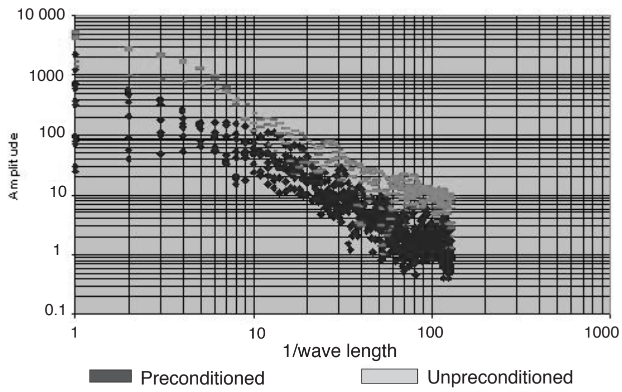

Figure 7—Averaged spectral data from periodic profiles. Note the wavelength (or distance along profile) varies from 0.02 m to 5 m

time-consuming and, as such, smaller areas are covered during a typical underground shift. Continuous profile measurements are thus more suited to technical investigations (such as described in the example) or for the comparison of different support types in similar geotechnical areas. When different geotechnical areas need to be broadly defined (as per the Codes of Practice) it may be sufficient to measure several irregular profiles within each potentially different area to determine if hangingwall conditions vary on a broad scale.

As a tool, hangingwall profile measurements can be used in a variety of ways including assessing the effects of changing explosives, various support units or even changing the mining strategy. It is also very important to note that assessment of what type of hangingwall conditions are more dangerous than others cannot be made unless these differences in hangingwall conditions are actually quantified. In addition, the techniques described allow one to quantitatively determine whether a certain support type or mining strategy is more appropriate and thus represents a useful decision-making tool for the engineer.

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Appendix

The following is a step by step procedure for the analysis of hangingwall profiles.

Profile measurement

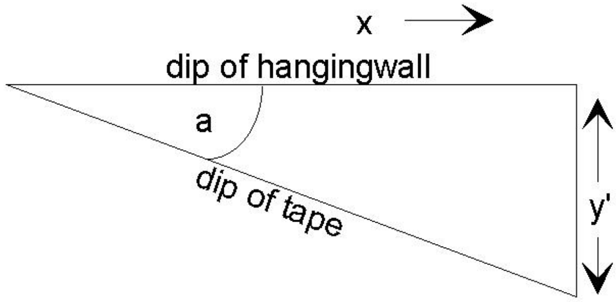
a) Anchor tape between two points, ensuring that it is taut, with no sag in the middle.
b) Record position and orientation of tape.
c) Measure dip of tape and average dip of hangingwall.
d) Proceed with measurements of the distance between the hangingwall and tape.

Data analysis

a) Enter data into spread-sheet as a set of x (distance along tape) and y (distance between hangingwall and tape).
b) Correct for differences in dip of tape and hangingwall as shown below. Subtract y' from the y value of each point,

where
$y' = x/\tan(a)$
x = distance along profile,
a = difference in dip of tape and dip of hangingwall.

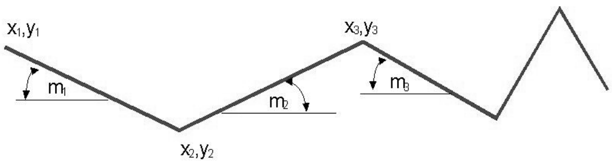
c) If the data are periodic, determine if the profile measured is long enough by comparing the moving average of the heights at various window lengths. Once there is no longer a major increase in the average height then a representation of all the sizes of the steps has been included.
d) Calculate height of steps in profile from the absolute differences in the heights (y-values) of successive points along the profile.



e) Calculate profile length and average gradient. Profile length is calculated using the distance from $(x1, y1)$ to $(x2, y2)$ to $(x3, y3)$ etc. (as shown in the diagram below). Each distance is in fact the hypotenuse of a triangle and so the following equation can be used:

$$Length = \sum_{\substack{i=1 \\ j=i+1}}^{n-1} \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2},$$

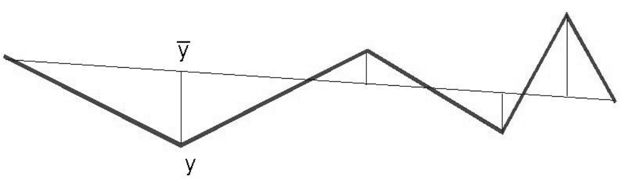
Gradient is calculated by dividing the absolute differences in the x coordinates of successive points and dividing it by the absolute differences in the y coordinates of these points. An average of these gradients (m) is then taken for each profile.



f) Calculate the average absolute deviation from the mean using the equation.

$$D_{average} = \frac{1}{n}\sum\left(y - \bar{y}\right)$$

where y is the y value at each point, and $\bar{y}$ is the mean y -value at that distance along the profile.



g) If the profile measured was periodic (i.e. at regular intervals) the spectra can be determined by converting the data (which may be considered to be in the time domain) into the frequency domain using a Fast Fourier Transformation.

h) With periodic data it is also possible to determine the fractal dimension of the profile. The fractal dimension can be calculated relatively easily by modifying the method described above for the calculation of the profile length. In this case the lengths of the profile are calculated using a 'measuring-stick' (r) of various fixed lengths, the longest of which is the length of the profile and the shortest is the minimum spacing of the measurements. Each point is determined where the end-points of the 'measuring stick' and the profile intersect (see next diagram). These points define another profile, whose length can be measured. This length (L_r) can be substituted into the equation and the fractal dimension (D) calculated. ◆

The equation is $L_r = F_r^{(1-D)}$.