Addressing the variability of elongate support performance

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Synopsis

Elongates are commonly used as stope support in South African gold and platinum mines. To evaluate the effect of the inherent strength, stiffness and yield variability associated with elongates, a statistical method is presented which addresses and quantifies the support performance at various levels of certainty. The analysis, which is based on a normal distribution, makes use of force-deformation curves determined from multiple laboratory compression tests on the same support type. The applicability of the method is illustrated making use of actual performance capabilities of various types of elongates.

In order to ensure a high probability that support units installed underground exceed the standard support performance curve established by means of laboratory tests, the statistical mean of a suite of tests based on the same support type is downgraded. The 'correction factor' is a function of the mean and standard deviation of the test data, as well as the sample size of units deemed to control the local rock mass stability. It is shown that downgraded performance curves based on a high probability (90 to 95 per cent) of support units exceeding this performance level are suitable to ensure that the design of support systems will invariably meet the design criteria.

In the highly discontinuous hangingwall rock mass typically associated with intermediate- and deep-level mining operations, the interaction between adjacent support units is comparatively limited (at the support spacings commonly used). Therefore, the appropriate sample size (n) of the support units controlling the *local* rock mass stability should be $n = 1$. In shallow mining conditions, sample sizes of up to $n = 5$ may be warranted, depending on the spacing of joints and other discontinuities in the hangingwall.

Introduction

Elongates, most of which are timber based, are extensively used in the gold and platinum mines for stope support. The elongates are often used in conjunction with rapid yield hydraulic props, but in some cases pre-stressable, yielding types have replaced the latter as face area support in seismically active mines. Support resistance and energy absorption calculations have revealed that the pre-stressable, yielding varieties may be acceptable under seismic conditions, apparently offering both safety and production advantages over an inefficiently organized or resourced hydraulic prop management system.

Some concern has been expressed, however, that the performance characteristics and consistency of elongates have not been fully evaluated.

As part of the work conducted under SIMRAC project GAP 330 (Daehnke *et al.*[1]), a provisional test procedure has been proposed to provide a systematic approach to the performance evaluation of the capabilities of elongates. The test procedure entails various laboratory and underground compression tests of the support units, with emphasis placed on repeated tests using units of the same type to investigate performance variability and obtain a statistical distribution of the load versus deformation curves. The bulk of the tests comprises: (i) ten 'standard' compression tests at a deformation rate of 15 mm/min, (ii) five rapid displacement tests at a rate of 3 m/s, and (iii) five underground tests using load cells and suitable convergence measurement devices. While it is recognised that this number of tests is comparatively small, particularly to facilitate an accurate statistical data analysis and interpretation, the number of tests are nevertheless deemed adequate to give important insights into the performance variability associated with various elongate types, and to establish elongate design curves suitable for use in the mining environment.

The objective of the work reported here is to describe a statistical analysis to interpret the results obtained by the above-mentioned test procedure. The analysis makes use of data from repeated tests using units of the same type, and attempts to quantify the effect of the inherent performance variability. Although the statistical analysis is demonstrated using

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elongate performance data, the statistical method is suitable to quantify the variability of any type of support.

The ultimate output is to enable mine personnel to select units suitable for their particular requirements and engineer support systems, with a high degree of confidence of meeting support resistance and energy absorption criteria. The statistical analysis aims towards ensuring that the variations in support consistency will not compromise rock mass stability, and hence underground safety.

Statistical methods applied to elongate performance data

Variations in material properties and manufacturing tolerances result in individual support units of the same type having different support capabilities. The variation in support performance can be characterized by the mean μ, standard deviation σ, and a probability distribution. The probability distribution is defined by a distribution function, and various functions (e.g. normal, log-normal, gamma, beta and Weibull distributions) have been used to describe and characterize different types of data (Miller and Freund[2]). Among these, the normal probability function is by far the most widely used. It was first studied in the eighteenth century when scientists observed a high degree of regularity in the measurement of errors. They found that the distributions they observed were closely approximated by a continuous distribution, which they referred to as the normal curve of errors, attributed to the laws of chance. The bell-shaped graph of the normal probability distribution is shown in Figure 1.

For the purpose of the statistical evaluation of elongate performance, a normal distribution of support performance is assumed. The validity of this assumption is qualitatively demonstrated in Figure 2, which, as an example, shows the distribution of variability of a Rocprop elongate. The distribution is calculated by considering the load-deformation data of ten laboratory compression tests conducted at a deformation rate of 15 mm/min. The units were compressed over a distance of 450 mm. To obtain the distribution of performance variability, the load generated by the elongate, as measured by the laboratory equipment, was normalized with respect to the mean of the ten compression tests, i.e. at a given deformation, the ratio of the load carried by a particular support unit versus the mean load of the ten support units is calculated. This was repeated for all ten tests at deformation intervals of 0.5 mm. A histogram is drawn (see Figure 2), grouping the normalized load data into one per cent variability intervals. The normal distribution is calculated from the average standard deviation normalized relative to the mean load at 0.5 mm deformation intervals. From Figure 2 it is apparent that a normal distribution approximates the scatter of support performance reasonably well, and is hence a suitable distribution to formulate statistical interpretations, particularly since comparatively little support performance data currently exists. Once the database has been extended, the assumption of a normal distribution can be re-evaluated, and, if necessary, an alternative probability distribution can be used to represent the scatter of support capabilities more accurately.

Evaluating data represented by a normal distribution

The equation of the normal probability distribution, the graph of which is shown in Figure 1, is

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad -\infty < x < \infty, \qquad [1]$$

where μ and σ are the population mean and standard deviation, respectively (i.e. the mean and standard deviation of, for example, the reaction force at a given displacement of the tested support units), and x is the sample value (reaction force at a given displacement) of the installed support unit. The *population* mean and standard deviation is used to describe the performance of support units evaluated by means of laboratory and underground compression tests,

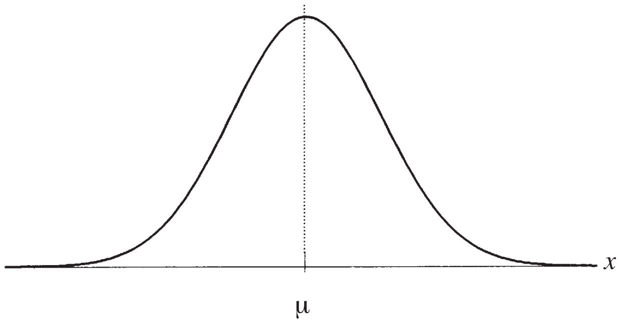

Figure 1—Graph of a normal probability distribution

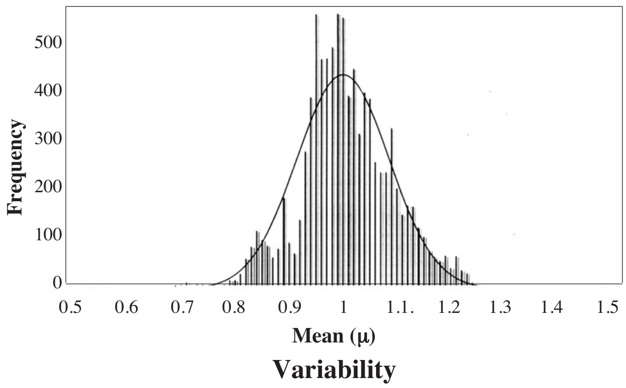

Figure 2—Histogram of the variability of support performance of a Rocprop elongate versus the normal probability distribution

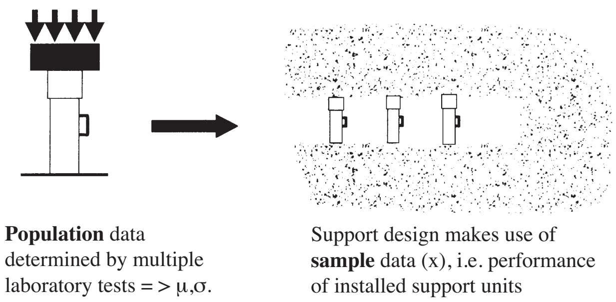

Figure 3—Schematic illustrating the difference between population and sample data

whereas the *sample* data is defined as the actual performance of underground installed support systems (Figure 3).

The total area under the curve represented by Equation [1] is equal to 1.0 or 100 per cent, and is used for probability calculations (see Equation [2], where $F(z)$ is the probability). Since the normal probability distribution cannot be integrated in closed form between every pair of limits a and b, probabilities relating to normal distributions are usually obtained from special tables, such as provided by Miller and Freund[2].

$$F(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{-\frac{1}{2}t^2}\, dt \qquad [2]$$

In order to engineer support systems with a high degree of confidence of meeting support resistance and/or energy absorption requirements, performance curves characterizing the load versus deformation behaviour should be established for each support type used by the mining industry. A performance curve representing some lower limit of the support capability will ensure that a high percentage of units would meet or exceed this prescribed limit. In Figure 4, the shaded area represents the percentage of units exceeding the performance specification, whilst the unshaded area to the left should be minimized, as these units would fall below the specification.

In the work presented here, the lower limit of elongate performance is of relevance. To date, relatively little work has been done on the effect of comparatively high elongate loads on the hangingwall rock mass stability, and hence no upper bound for elongate loads is stipulated. Once further understanding of the support–rock mass interaction is gained, the validity of lower *and* upper performance limits can be re-appraised.

The percentage of units exceeding the performance specification (i.e. the probability of the sample exceeding the performance specification) is a function of the population mean and standard deviation. Furthermore, if multiple support units are installed and the mean performance is of relevance, as opposed to the performance of a single unit, the probability is dependent on the sample number. This relationship can be expressed by the central limit theorem (Miller and Freund[2]):

$$z = \frac{\bar{x} - \mu}{\sigma / \sqrt{n}}, \qquad [3]$$

where the mean $\bar{x}$ of a random sample of size n is taken from a population having the mean μ and the standard deviation σ. It is instructive to re-arrange Equation [3] as follows:

$$\bar{x} = \mu - \alpha\sigma \text{ where } \alpha = \frac{-z}{\sqrt{n}}, \qquad [4]$$

i.e., the mean sample performance $\bar{x}$ is a function of the population mean μ and standard deviation σ, as well as a factor α, which depends on (i) the probability z of exceeding the sample performance and (ii) the sample size n. The probability of exceeding the sample performance for various values of α is given in Figure 5.

Previously[3], as an initial guideline to evaluate support units, it was suggested that, in order to design support systems conservatively (accounting for the variability of support capabilities), the design force-deformation curve $\bar{x}$ of a support type should be the mean μ less one standard deviation σ, i.e. $\bar{x} = \mu$-1.0σ. Substituting $\bar{x} = \mu$-1.0σ in Equation [4], it is found that $z = -\sqrt{n}$, that is the probability $F(z)$ of exceeding the mean design curve $\bar{x} = \mu$-1.0σ, depends only on the size n of the random sample taken from a population having the mean μ and the standard deviation σ. This is evident from Figure 5, where it is shown that, if n = 1 and $\bar{x} = \mu$-1.0σ, the probability of exceeding the performance specification is 84 per cent. For n = 3 or 30 the probability of exceeding the performance specification increases to $F(z)$ = 95.8 or 99.9 per cent, respectively.

In other words, the probability of a single support unit meeting the performance requirements is 84 per cent, whereas the probability of the mean of 30 support units exceeding the design specification is 99.9 per cent. Thus, by choosing a design curve calculated by $\bar{x} = \mu$-1.0σ, the design specification for a single support unit is probably not conservative enough (84 per cent), whereas the specification for the mean of a system of, for example, 30 units is too conservative (99.9 per cent), as correctly pointed out by Handley[4].

From a support design point of view, it is convenient to design for a constant confidence level (say 90, 95 or 99 per cent), irrespective of the number of units comprising the support system. Hence, the extent to which the mean of a suite of tests is downgraded to give a design force versus displacement curve is variable, depending on the number of support units comprising the system or part of the system

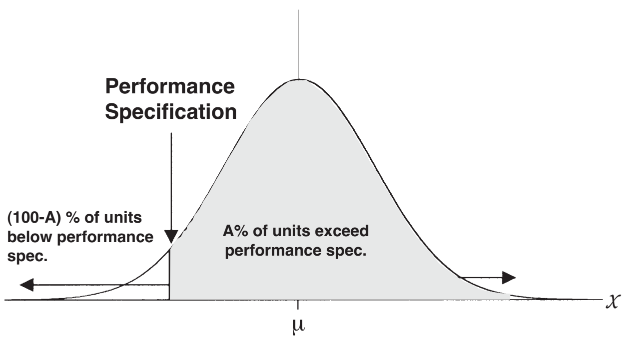

Figure 4—Probability density function sectioned according to performance specification

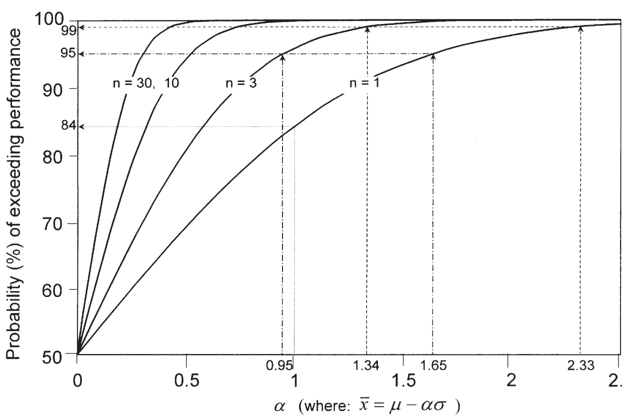

Figure 5—Probability of exceeding sample performance for various values of α and *n*

which is considered relevant. Table I shows relationships between $\bar{x}$, μ and σ for probability levels of 90, 95 and 99 per cent of meeting the performance specification, and for n = 1, 3, 10 and 30. The relationships for n = 1 and 3, and $F(z)$ = 95 and 99 per cent, are indicated graphically in Figure 5.

The sample size (n) is chosen according to ground conditions, which dictate the interaction of multiple units as a system, as opposed to single units acting in isolation. Further details of the parameters influencing sample size, as well as recommendations thereof, are given in the penultimate section of this paper.

Statistical analysis of actual support data

The following examples, using actual support test data, serve as a guide to illustrate the applicability of the statistical method. In all cases, the support data used was obtained by CSIR: Mining Technology's laboratory elongate testing programme. Further details of the elongate testing programme, as well as discussions and analysis of the results thereof, are documented in Daehnke *et al.*[1].

Rocprop: quasi-static loading

As part of the elongate testing programme, ten 1.2 m Rocprop units were compressed at a constant displacement rate of 15 mm/min. The resulting force-deformation curves are shown in Figure 6. The Rocprop is an engineered steel prop, and hence the ten units display comparatively consistent behaviour. After an initial rapid load increase, the load carrying capacity remains between 200 and 300 kN for the main duration of the test.

Table I

Relating $\bar{x}$, μ and σ for probability levels of 90, 95 and 99 per cent, and n = 1, 3, 10 and 30

	Probability of exceeding performance specification		
	90%	95%	99%
n = 1	$\bar{x} = \mu - 1.282\ \sigma$	$\bar{x} = \mu - 1.645\ \sigma$	$\bar{x} = \mu - 2.326\ \sigma$
n = 3	$\bar{x} = \mu - 0.740\ \sigma$	$\bar{x} = \mu - 0.950\ \sigma$	$\bar{x} = \mu - 1.343\ \sigma$
n = 10	$\bar{x} = \mu - 0.405\ \sigma$	$\bar{x} = \mu - 0.520\ \sigma$	$\bar{x} = \mu - 0.736\ \sigma$
n = 30	$\bar{x} = \mu - 0.234\ \sigma$	$\bar{x} = \mu - 0.300\ \sigma$	$\bar{x} = \mu - 0.425\ \sigma$

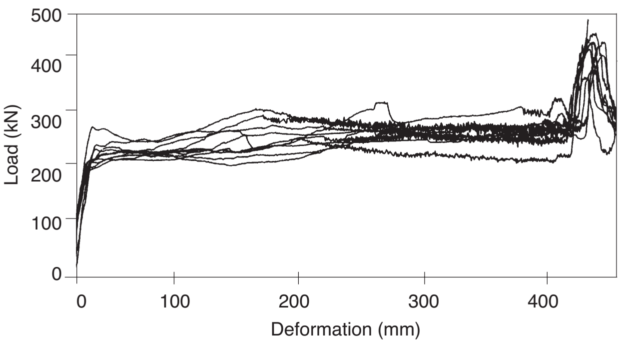

Figure 6—Force-deformation profiles of ten 1.2 m Rocprops; 15 mm/min deformation rate

The statistical analysis described previously is used to establish performance curves for various probabilities of exceeding the support load bearing capabilities. The mean μ and standard deviation σ of the force transmitted by the elongate are calculated for the ten compression tests at various values of deformation (0→450 mm, at deformation intervals of 0.5 mm). Inserting μ and σ in Equation [4], the parameter $\bar{x}$ can be calculated at deformation intervals of 0.5 mm, resulting in a force-deformation curve of reduced amplitude, which is referred to here as the design performance curve.

Figure 7 gives Rocprop performance curves for 90, 95 and 99 per cent probabilities of exceeding the support capabilities. Also shown is the mean μ of the ten Rocprop tests, as well as the performance curve calculated by the mean minus one standard deviation $\bar{x} = \mu - 1.0\sigma$, which previously was shown to represent a probability of 84 per cent. The curves shown in Figure 7 are calculated assuming n = 1, i.e. a single Rocprop unit acting independently of the surrounding support.

The performance curves shown in Figure 7 are applicable if the support capability of a single unit is of importance. In some instances, however, the average support capability of multiple units is of interest. In this case, the performance curves shown in Figure 8 are applicable, which are given for n = 1, 3, 10, 30 and ∞, and a probability of 95 per cent of exceeding the average support capability. As intuitively obvious, in the limit, i.e. $n = \infty$, the performance curve equals the mean μ.

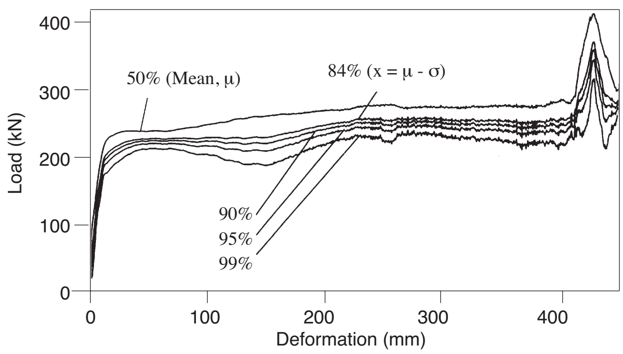

Figure 7—Rocprop performance curves for various probabilities of exceeding the support capacity (n = 1)

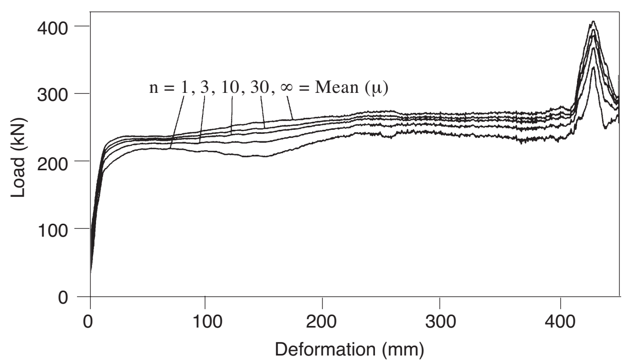

Figure 8—Performance curves for a support system comprising n = 1, 3, 10, 30 and ∞ Rocprop support units (95 per cent probability of exceeding performance curve)

To reiterate, for a fixed probability (of the average support capability of multiple units exceeding the performance curve), the performance curve approaches the mean as the number of units increases. Conversely, for a fixed performance curve, the probability of exceeding the support capability increases with increasing number of support units.

Rocprop: dynamic loading

According to the elongate test procedure, support units used in seismically active areas are evaluated by means of rapid compression tests. Load versus deformation laboratory test data for 1.2 m long Rocprops is given in Figure 9. The Rocprops are initially loaded at a low deformation rate of 15 mm/minute up to 50 mm deformation, then rapidly at 3 m/s up to 300 mm total deformation, followed by a 15 mm/minute loading rate for the remainder of the test. The Rocprop yielding mechanism is based on frictional resistance and hence, due to lower dynamic compared to static friction coefficients, the load decreases during dynamic loading. The statistical evaluation for these data is given in Figure 10, which shows Rocprop performance curves for seismic conditions at various probability levels.

Loadmaster: quasi-static loading

As a further example of the elongate data analysis, the load versus deformation curves of the Loadmaster support unit are investigated. Figure 11 shows the ten curves of the slow (15 mm/minute) compression tests. It is evident that the behaviour of the timber-based Loadmaster is not as consistent as the Rocprop, and the scatter of the load-deformation data is increased. The statistical analysis of the Loadmaster data is shown in Figure 12, giving performance curves for various probability values.

Loadmaster: dynamic loading

Results of high loading rate compression tests are shown in Figure 13, whilst Figure 14 shows performance curves for various probabilities of exceeding the seismic performance curves.

Consequence of the statistical analysis on support spacing

The proposed statistical analysis aims to improve support

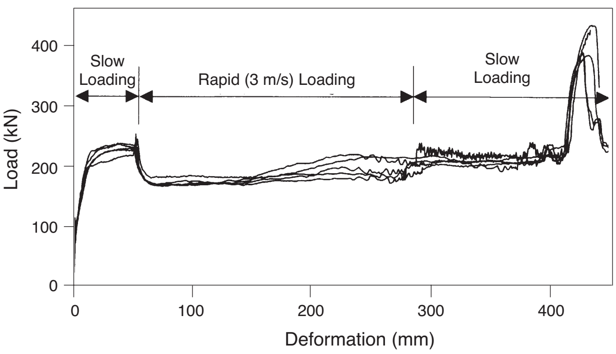

Figure 9—Force-deformation curves of five 1.2 m Rocprop; 3 m/s deformation rate

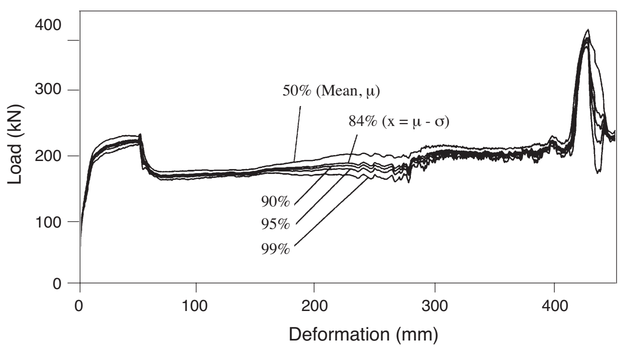

Figure 10—Rocprop performance curves for various probabilities of exceeding the seismic support capacity (n = 1)

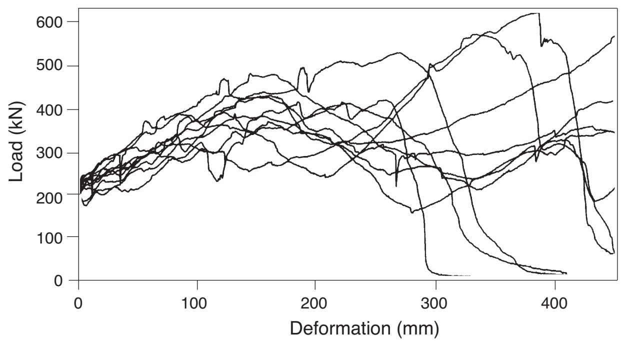

Figure 11—Force-deformation profiles of ten 1.6 m Loadmaster units; 15 mm/min deformation rate

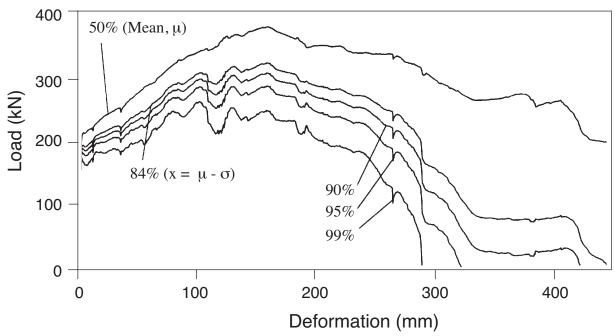

Figure 12—Loadmaster performance curves for various probabilities of exceeding the support capacity (n = 1)

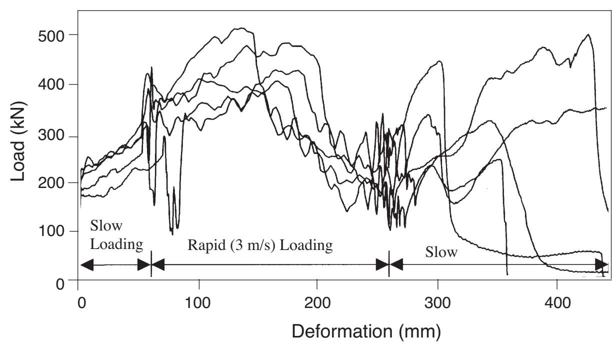

Figure 13—Force-deformation profiles of five 1.6 m Loadmaster units; 3 m/s deformation rate

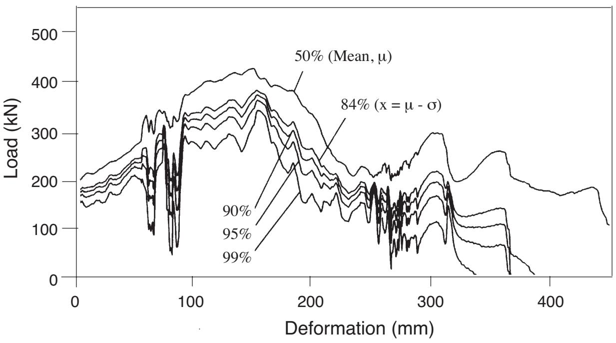

Figure 14—Loadmaster performance curves for various probabilities of exceeding the seismic support capacity (n = 1)

design and reduce rock-related hazards by taking into account and quantifying the inherent variability associated with elongate performance. To this end, force-deformation curves are downgraded to ensure a high probability of installed units exceeding the design performance curve. The aim of this section is to investigate the consequences of the modified load-deformation curve on support system design and support spacing.

For purposes of illustrating the average effect of load-deformation curve downgrading, the average load carrying capability of the support unit is calculated up to a deformation of 300 mm (Figure 15a). The energy, which can be absorbed by the unit, is calculated during dynamic deformation between 50 mm and 250 mm compression (Figure 15b).

Table II lists the average support load (of relevance in non-seismic applications, i.e. rockfalls), as well as energy absorption capabilities (seismic applications, i.e. rockbursts), of various support types. The data are given for the mean of the laboratory tests, as well as for downgraded curves, representing the 90, 95 and 99 per cent performance specifications.

To demonstrate the effect of curve downgrading on support spacing, the maximum tributary area per support unit, versus fallout height, is determined. The curves are calculated by equating the load carrying and energy absorption capability, to the weight and total energy (Wagner[6]) of the rock mass for rockfall and rockburst conditions, respectively:

$$\text{Rockfall}: \; F = \rho\, b\, A\, g \qquad \text{Rockburst}: \; E = \rho\, b\, A\left(\frac{v^2}{2} + gh\right)$$

where: F = average support unit load (N)
E = energy absorbed by support (J)
ρ = rock density (2700 kg/m^3)
v = max. hangingwall velocity (3 m/s)
b = fallout height (m)
h = hangingwall displacement (0.2 m)
A = tributary area (m^2)
g = 9.8 m/s^2

The tributary area (A) is solved as a function of fallout height (b) and plotted in Figures 16a) to 16d) for four elongate types at various probabilities of exceeding the design curve. When designing support systems and the spacing thereof, it is essential to consider additional parameters influencing the rock mass stability that are not considered here. Examples of these are local geological features and discontinuities, mining induced fracturing, mining depth, rockfall and seismic history, support unit interaction with the rock mass and each other, and areal support coverage. These parameters significantly influence the stable hangingwall span between support units, and need to be considered in addition to tributary area rockfall and rockburst criteria.

From Figures 16a) to 16d), the influence of curve downgrading on support spacing can be estimated. For example, when designing for rockburst conditions on the Vaal Reef using Rocprops, the tributary area is 1.72 m^2, 1.62 m^2, 1.58 m^2 and 1.53 m^2 when using the mean (μ), 90, 95 and 99 per cent probability curves, respectively. In the case of the Loadmaster, the tributary areas are 3.20 m^2, 2.48 m^2, 2.25 m^2 and 1.86 m^2, respectively. The tributary areas associated with the comparatively consistent Rocprop are reduced by 11 per cent when using the 99 per cent probability curve as opposed to the mean; similarly, in the case of the more variable Loadmaster, the tributary areas are reduced by 42 per cent. A comparatively high level of adjustment does not necessarily imply poor support performance, as the resulting performance curve might be high enough to ensure the elongate meets the required support resistance or energy absorption criteria. Table III

Table II

Average support load and energy absorption capability of four elongate types (*n* = 1, probability *F*(*z*) = 90, 95 and 99 per cent)

	Mean (μ)	90%	95%	99%
1.2 m Rocprop				
Average support load	250 kN	224 kN	217 kN	203 kN
Energy absorption capability	36 kJ	34 kJ	33 kJ	32 kJ
1.6 m Loadmaster				
Average support load	322 kN	250 kN	230 kN	192 kN
Energy absorption capability	67 kJ	52 kJ	47 kJ	39 kJ
1.6 m Ebenhaeser				
Average support load	332 kN	257 kN	236 kN	197 kN
Energy absorption capability	55 kJ	46 kJ	44 kJ	39 kJ
1.6 m Cone Prop				
Average support load	242 kN	190 kN	175 kN	148 kN
Energy absorption capability	29 kJ	24 kJ	22 kJ	19 kJ

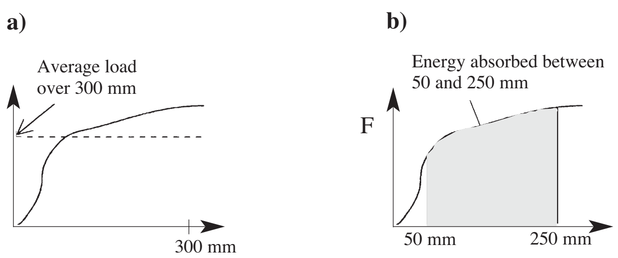

Figure 15a—Average load carrying capability up to a deformation of 300 mm, and (b) energy absorption between 50 mm and 250 mm deformation

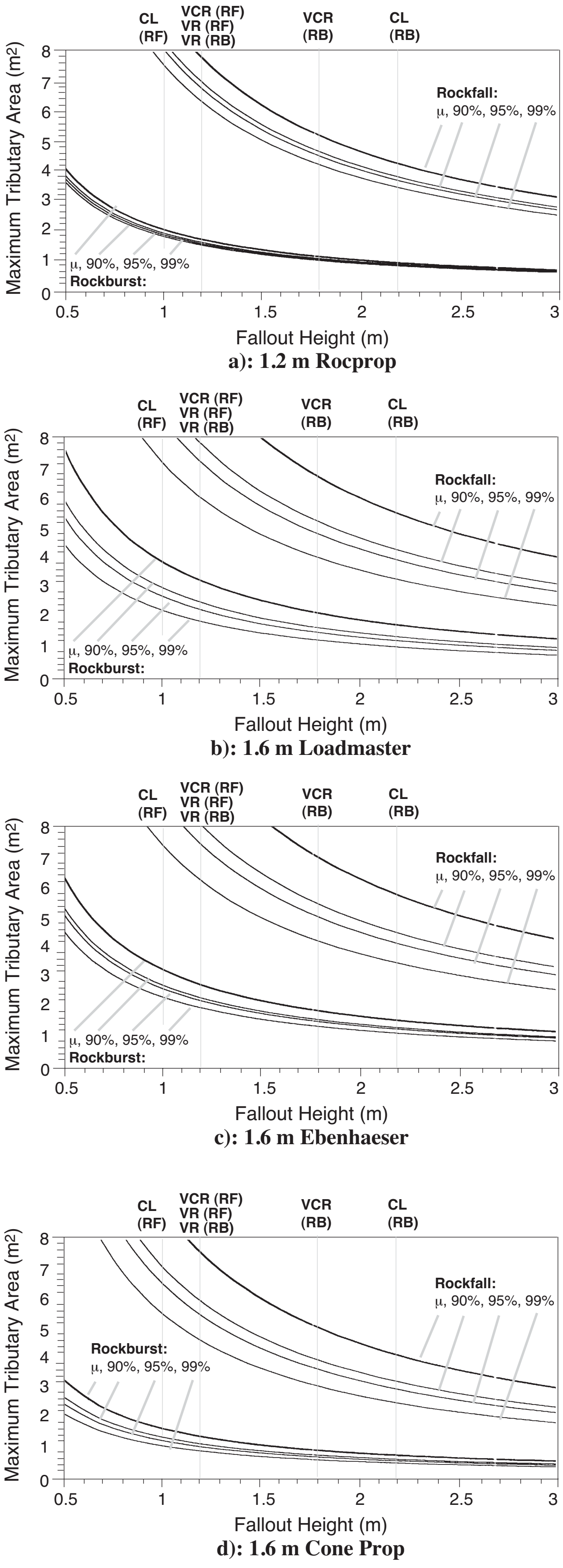

Figure 16—Maximum tributary area for various elongate types in rockfall (RF) and rockburst (RB) conditions. Also shown are the fallout height criteria (Roberts[5]; Daehnke *et al.*[1]) as determined from accident back analyses for the whole of the VCR, Vaal Reef (VR) and Carbon Leader Reef (CL)

lists the maximum tributary area according to the rockfall and rockburst criteria of the four elongate types, as well as the percentage reduction of tributary area for the 90, 95 and 99 per cent probability curves.

From the percentage reductions shown in Table III, it can be shown that the average decrease in tributary area associated with the four elongate types considered here, when designing for rockfall conditions, is 19.2, 24.6 and 34.7 per cent for 90, 95 and 99 per cent probability design curves, respectively. This implies that the support spacing has to be decreased by 10.1, 13.2 and 19.2 per cent for 90, 95 and 99 per cent probability design curves, respectively. For rockburst conditions the average decrease in tributary area is 15.2, 20.6 and 29.0 per cent and in support spacing 7.9, 10.9 and 15.7 per cent, for 90, 95 and 99 per cent probability design curves, respectively.

Current gold and platinum mining support practice is to install a system of multiple elongates in the mining excavation. In most cases, however, falls of ground occur in a local area only, and individual support units can be highly stressed and deformed, and in such situations are likely to fail. Thus, from a conservative design point of view, the statistical analysis should only consider the probability of failure of a single support unit, i.e. $n = 1$. This is particularly the case in intermediate- and deep-level mining operations, where the zone of support influence in a highly discontinuous rock mass has been shown to be confined to the immediate vicinity of the support unit, and comparatively little support interaction between adjacent support units at typical support spacings takes place (Daehnke *et al.*[7]). In shallow mining operations, the rock mass is less highly fractured, and, in many cases, multiple units support comparatively competent large blocks of rock. In this case the average support performance of multiple units is of relevance, and a value of $n > 1$ could be chosen.

Table III

Maximum tributary area and percentage reduction (in brackets) due to downgrading of performance curves from the mean value to 90, 95 and 99 per cent probability curves. The tributary area is given as a function of fallout height (*b*) for rockfall (RF) and rockburst (RB)

Elongate Type		Mean	90%	95%	99%
Roc prop:	RF	9.45/b m^2	8.47/b m^2 (-10.4%)	8.20/b m^2 (-13.2%)	7.67/b m^2 (-18.8%)
	RB	2.06/b m^2	1.95/b m^2 (-5.3%)	1.89/b m^2 (-8.3%)	1.83/b m^2 (-11.2%)
Loadmaster:	RF	12.17/b m^2	9.45/b m^2 (-22.4%)	8.69/b m^2 (-28.6%)	7.26/b m^2 (-40.3%)
	RB	3.84/b m^2	2.98/b m^2 (-22.4%)	2.69/b m^2 (-29.9%)	2.24/b m^2 (-41.7%)
Ebenhaeser	RF	12.55/b m^2	9.71/b m^2 (-22.6%)	8.92/b m^2 (-28.9%)	7.45/b m^2 (-40.6%)
	RB	3.15/b m^2	2.64/b m^2 (-16.2%)	2.52/b m^2 (-20.0%)	2.24/b m^2 (-28.9%)
Cone Prop:	RF	9.15/b m^2	7.18/b m^2 (-21.5%)	6.61/b m^2 (-27.8%)	5.59/b m^2 (-38.9%)
	RB	1.66/b m^2	1.38/b m^2 (-16.9%)	1.26/b m^2 (-24.1%)	1.09/b m^2 (-34.3%)

Future support systems incorporating, for example, bar links between individual elongate units, will provide integrated areal coverage. This will reduce the dependence on individual units and the design specification will be calculated according to the average support capability of multiple units. This would result in the use of less conservative performance curve, whilst maintaining a similar probability of exceeding the performance specification.

Conclusions and recommendations

The work presented here has demonstrated a statistical methodology to address the variability of elongate support performance. The analysis is based on a normal distribution, taking into account probabilities of exceeding statistically downgraded performance curves, as well as the influence of multiple support units on the average support load bearing capability. As an example of the applicability of the statistical methodology, the quasi-static and dynamic performance of various elongate types is investigated. By means of example evaluations based on the performance of actual elongates, it is shown that, in order to meet the 90 or 95 per cent probability curve, the design curve is adjusted within acceptable limits. Based upon these findings, the following conclusions and recommendations are reached:

- It is recommended that support performance curves be used that ensure a high probability, i.e. 90 per cent (if $n = 1$: $x = \mu - 1.282\sigma$) or 95 per cent (if $n = 1$: $x = \mu - 1.645\sigma$), of units exceeding the support capability. This specification will provide higher levels of safety, whilst rationalizing the support costs and practical difficulties associated with installing high-density support systems.
- The rock engineer needs to assess the degree of interaction between adjacent support units, and choose the appropriate sample size (n). In deep and intermediate mines $n = 1$ should be used in most cases, whereas in shallow mines the sample size can typically range from $n = 2$ to $n = 5$. Until further expertise is developed in quantifying zones of support influence, it is not recommended to use $n > 5$.
- It is recommended that the appropriate performance curves be used when designing support systems for seismic and non-seismic applications. In some cases the support bearing capacity of elongates increases during dynamic loading, whilst in certain cases the loading capacity decreases. Thus, a single correction factor for various elongate types loaded under quasi-static and dynamic loading conditions is not applicable, and separate performance curves, based on laboratory and *in situ* tests, are required.
- Additional safety factors should be incorporated when calculating the performance curves. These factors take into account underground considerations, such as poor support installation, slow convergence rates and high humidity/temperature, which have been shown to significantly influence support performance (Roberts *et al.*[8]) and have not been included in this evaluation. Currently, underground field tests are conducted to establish appropriate correction factors to laboratory data, and these will be incorporated in the performance curve calculation as soon as sufficient underground data are available.

To advance support system design and continue mining at ever-increasing depths with reduced rock-related risk, design methodologies need to be based upon sound engineering principles. A probabilistic approach is particularly suited to quantitatively assess rock mass behaviour and support performance. Although many aspects of the interaction of support with the hanging- and footwall rock mass are poorly defined and understood (e.g. the ubiquitous use of the 3 m/s hangingwall velocity criterion[5] across the various geotechnical areas), it is nevertheless necessary to quantify comparatively straightforward design parameters, such as the inherent variability of support systems.

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