The geostatistical evaluation of low-ash coal reserves in No. 2 seam, Witbank area

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SYNOPSIS

The geostatistical methods given for the estimation of low-ash coal reserves take into account the geological structure of the seam, and consequently give far more reliable results than have been obtained in the past. Confidence limits are given for all the estimates.

SAMEVATTING

Die geostatiese metodes wat aangegee word vir die raming van laeassteenkoolreserwes hou rekening met die geologiese struktuur van die laag en gee gevolglik baie meer betroubare resultate wat in die verlede verkry is. Daar word vir al die ramings vertroubaarheidsgrense aangegee.

Introduction

The No. 2 seam in the Witbank area has a well-defined geological structure, which Anglo American Corporation have used very effectively in measuring the quality of the coal being mined. The use of their approach seemed a worth-while possibility in the evaluation of reserves.

The seam is composed of four different types of coal in layers, which are referred to as zones, and the main point in the approach mentioned is that fixed average values for all the coal qualities are assigned to each zone. These average values differ considerably, and consequently the proportions mined from each zone play the major role in determining the average quality of mined coal. This means that the quality of the coal in a block, instead of being predicted from borehole values, is estimated according to the quantity of each zone present in the block. The average quality of the coal is then calculated.

Variability of Coal Quality

When coal reserves are evaluated, estimates are required for the tonnage and qualities of the coal contained in the blocks into which a mine has been divided. For a specific quality of coal, an estimate of the average value in a block is made from the values indicated by borehole cores, and, since the degree of regionalization plays a key role in determining the accuracy of the estimate, it is very important that it should be taken into account in the choice of estimation method to be used.

Regionalization is measured by the variogram obtained from an analysis of the quality values found for samples taken from the seam. A large number of samples is usually required to define a variogram, and it is preferable if they are placed on a square grid. The positions of these samples must be co-ordinated, and it is desirable for them to have the same support, i.e. for them to be of identical size.

Such a geostatistical analysis was started on data for No. 2 seam in Greenside Colliery in the Witbank area. The data had been gathered over a number of years, before the low-ash coal contract had been signed, and consequently did not take into account the washing of coal or the zonal structure of the seam. However, the data met all the other requirements. Close on a thousand samples had been taken on a square grid, and had been analysed to give the ash content and calorific value of the unwashed coal. The positions of the samples had been accurately surveyed, and it was reasonable to assume that, being run-of-mine samples, they had the same support.

The variogram for ash content is shown in Fig. 1, and that for calorific value is very similar. To preserve the integrity of the data, this variogram has been normalized; that is, it has been divided by the population variance so that the sill has the value 1. No anisotropy was detected, and this variogram is the average for all directions. On two occasions a grid point had inadvertently been sampled twice, and these two pairs gave the variogram value shown at the origin.

High Nugget Effect

The most noteworthy feature of the variogram in Fig. 1 is a very high nugget effect, which implies that samples from neighbouring sites may have substantially different values. In geostatistical terms, the variability of a regionalized variable can be regarded as having two components: the regionalized component and a random component. Since the nugget effect contributes solely to the latter, Fig. 1 suggests that, in the case of coal quality, the random component predominates. The consequences of a high nugget effect are far reaching.

As pointed out by Royle *et al.*[5], a nugget effect will include not only the inherent randomness in variability but also the errors arising from sampling and laboratory analysis, i.e. human error. Coal-processing technologists have found that, if coal from a borehole core is crushed and mixed thoroughly, the quality values obtained by the analysis of different samples from this mixture are very similar. This implies that the human element of the nugget effect for crushed samples from the same core is small, and that laboratory values are highly reproducible. On the other hand, if the borehole core is split and the two halves are crushed and thoroughly mixed *separately*, the quality values obtained by the analysis of a sample

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from each half can differ considerably, confirming that the inherent nugget effect is high.

For an understanding of the consequences of a high nugget effect, a point made by Krige[2] is worth recalling; namely, that the mining engineer is not interested in the coal (or ore) quality at any specific point. What does concern him is the average quality of a *block of coal*, which could be, for example, a month's production, and the variability that interests him is the variation of this *average block value* from block to block.

In a *block* of coal it is only the regionalized component that will cause variations in actual average block values. Consequently, when the nugget effect is high and the regionalized component small, the average block values will differ very slightly from the average value for the mine.

Estimation of Block Quality Values

By its definition, kriging[3] is the best linear unbiased estimator, and consequently will on the average give the most accurate results. However, in cases of a high nugget effect coupled with a small regionalized component, the estimates for blocks of a practical size will be very similar and all close to the arithmetic average of all the sample values; also, since kriging requires fairly heavy computation, its use would not be justified in this case.

Two other frequently used estimators are the Sharapov and polygon methods. In the case of strongly regionalized variables, they could give results that are similar to the kriging estimate. However, in cases where the nugget effect is high, both methods will show variations in the average block values that do not, in fact, exist.

With a high nugget effect and a small regionalized component, the simplest solution is to find the arithmetic average of all the sample values and to use this as an estimate for all the blocks of a practical size. However, there may be long-range trends (over a distance of kilometres) that are not shown up in the variogram. If such trends are found, the mine should be divided into regions, each region being treated as a separate entity.

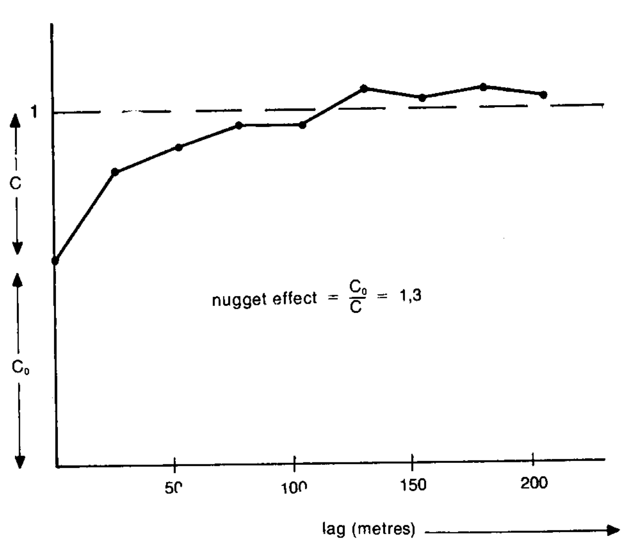


Fig. 1—Normalized variogram of ash content for the whole of seam No. 2

Geological Structure

As mentioned before, No. 2 seam is composed of a number of types or zones of coal of completely different quality and physical appearance. The Geology Department at Anglo American Corporation have used this seam structure very effectively in determining the quality of the coal for their grade-control system at Landau 3 mine[6]. To determine the overall quality, they assign average values to each zone, and the proportions mined from the zones then determine the quality of the mined coal.

Two types of structure have been encountered in the seam.

(1) In the first area, the zones lie in horizontal layers that extend without a break over kilometres and can be clearly seen in the pillars underground. Their identification in borehole cores requires geological expertise but, once this has been done, the boreholes can be correlated without difficulty.

(2) In the second area, the coal seam was originally deposited in layers but has subsequently been eroded so that this layered structure contains erosion channels of poor-quality coal. These channels have a well-defined average direction, which, on a scale of kilometres, changes very slowly. However, the individual channels tend to wander about this average direction, which makes prediction of their occurrence more difficult.

Layered Portions of Seam No. 2

It was in the layered portions that Ortlepp[6] developed the grade-control system for Landau 3 mine. The seam is being mined principally for low-ash coal, and the most important quality of the coal is the yield when it is floated at a relative density of 1,38.

The seam is composed of four horizontal layers labelled zones 1, 2, 3, and 4 from the bottom up, as illustrated in Fig. 2. Since the top layer, zone 4, is of poor-quality coal that is not usually mined, only zones 1, 2, and 3 are considered here. Typical values for the zones are given in Table I.

Distribution of Zone Widths

The distributions of zone widths are roughly normal, and typical values for statistics are given in Table I. If all the low-ash coal is mined (i.e. if the mining channel runs from the floor of zone 1 to the ceiling of zone 3), then for the data of Table I the average yield of mined coal will be

$$\frac{1{,}28\times 72{,}5+1{,}29\times 11{,}5+0{,}87\times 42{,}5}{1{,}28+1{,}29+0{,}87}=42{,}0 \text{ per cent}$$

at an average mining height of 3,44 m. The 90 per cent limits are 36,8 to 48,3 per cent and, as this is a fairly large spread, there appears to be scope for predictions for local areas or blocks.

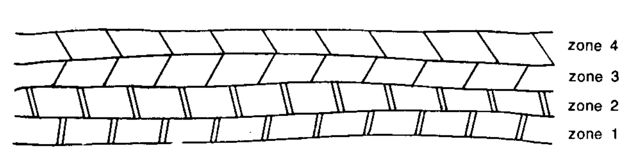


Fig. 2—The four zones of seam No. 2 where it is layered

The zone widths are fairly regionalized, although the variograms show little anisotropy. The Matheron spherical variogram was used, and typical values for the range were from 150 m to 320 m, as shown in Table I. This means that geostatistics could only be of use in estimating from borehole grids up to say 100 m or 200 m.

Evaluation of Reserves

In the evaluation of reserves, the mine is divided into blocks and the tonnage of low-ash coal in each of these blocks is estimated. However, before this can be done, a realistic size must be found for the blocks taking into account the spacing of the borehole grid.

Choice of Block Size

The spacing of the borehole grid imposes limitations on the size of reserve blocks. The variograms are stable and, if the parameters could be roughly estimated from neighbouring mined-out areas, a quantitative method[7] would be available for the determination of a realistic size.

For illustrative purposes, the data of Table I are used. If the three zones are to be mined completely and kriging is to be used in the estimation of average zone widths, then 90 per cent limits for an estimate can be determined as a function of borehole grid and block size (Fig. 3). (An example of how these limits were found is given in Addendum 1.)

As shown in Fig. 3, with a borehole grid of 100 m by 100 m, an estimate of the average yield of a 200 m by 200 m block will have a possible error of 1 per cent at the 90 per cent level. Consequently, for example, an estimated average yield of say 39,4 per cent will have limits from 38,4 per cent to 40,4 per cent. It can therefore be seen that the size of the blocks should not be less than

100 by 100 m for a 50 by 50 m borehole grid,
150 by 150 m for a 100 by 100 m borehole grid, and
500 by 500 m for a 200 by 200 m borehole grid.

For larger grids the use of blocks would not be justified.

Tonnage of Raw Coal

Once the mine has been blocked, estimates are required for the average widths of the zones in each block. The variograms must be known if kriging is to be used. The nugget effect is zero, and the variance will be available from an analysis of borehole values. The variograms are stable and have shown little anisotropy. If, therefore, the ranges do not emerge from borehole values, it would be reasonable to estimate them from experience.

TABLE I

DETAILS OF ZONES 1, 2, AND 3, SEAM NO. 2

Parameter	Zone 1	Zone 2	Zone 3
Average yield, %	72,5	11,5	42,5
Mean width, m	1,28	1,29	0,87
Variance, m²	0,014	0,092	0,067
Standard deviation, m	0,12	0,30	0,26
90% limits, m	1,09 to 1,47	0,79 to 1,79	0,44 to 1,30
Variogram range, m	150	320	240

The nugget effects are zero

The usual policy is to mine zones 1, 2, and 3 completely. If for any reason vertical selective mining is to be practised in a block, the average zone widths must be modified accordingly and the area of the block corrected for pillars, dykes, faults, etc. The tonnage of raw coal from the three zones can then be calculated.

Tonnage of Low-ash Coal

As mentioned above, in all the samples (both borehole and underground) the three zones are identified and analysed separately. If any trends are detected, or if there are geological reasons for doing so, the mine can be divided into regions that are treated independently. The average yield of all the sample values from each zone is assigned to that zone.

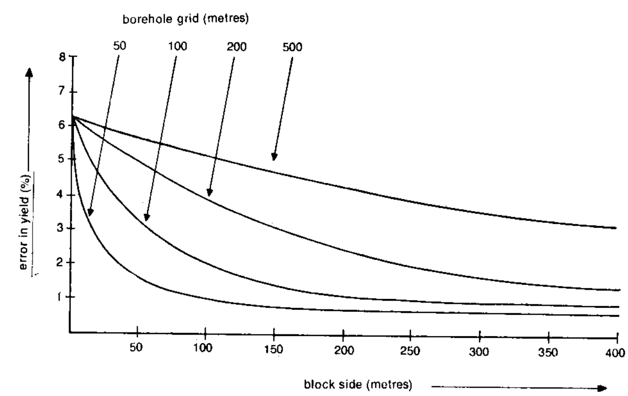


Fig. 3—90 per cent limits for the error in the estimated yield

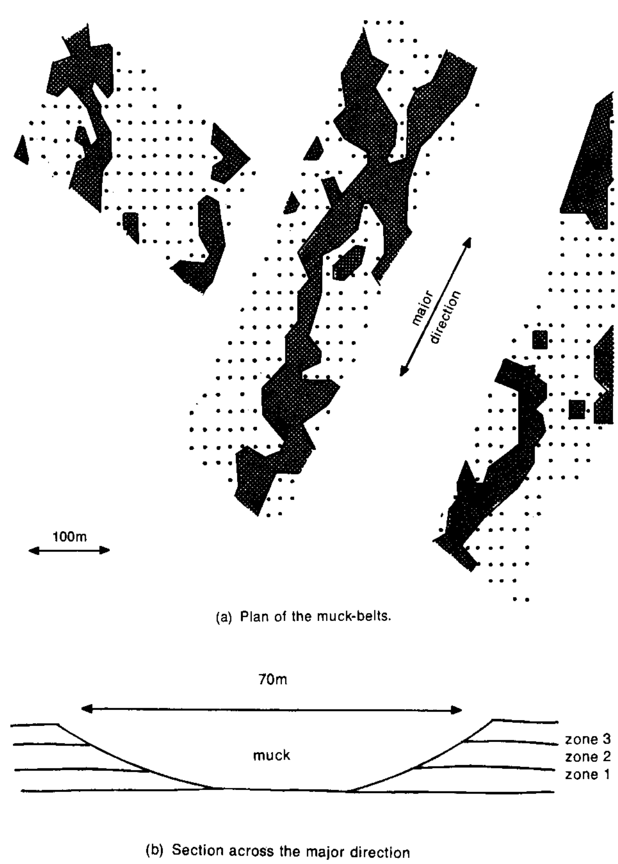


Fig. 4—Muck-belts

If, when mining has commenced, the zone widths are monitored, an alternative method of estimating the yields of the three zones (Addendum 2) can be used.

Once the yield and tonnage of raw coal from each of the zones is known, the tonnage of low-ash coal can be calculated and confidence limits can be placed on it.

Eroded Portions of Seam No. 2

In the layered portions of No. 2 seam, the variograms of zone widths showed little anisotropy. However, in another region of the seam, the variogram of zone 1 width showed very strong anisotropy in a NE–SW direction, and it was Irish who associated this with muck-belts, which had been previously encountered at Greenside Colliery. This was followed up by Slade[8]. The theory is that the seam was originally deposited in layers but had subsequently been seriously eroded and the erosion channels had filled with poor-quality coal, mainly from the upper layer, zone 4 in Fig. 2.

A typical plan of the muck-belts is given in Fig. 4(a). They lie along a well-defined major direction, but this direction changes slowly over a distance of kilometres. A typical section of a muck-belt across the major direction is shown in Fig. 4(b). The average width is in the region of 70 m, and the variogram had a periodicity of about 160 m across the major direction.

Effect of Muck-belts on Yield

As already mentioned, the muck-free coal has a yield of about 42,0 per cent. Typically, 40 per cent of the total coal is muck with a yield of 14,5 per cent, which gives an average yield for the entire seam of

$0,6 \times 42,0 + 0,4 \times 14,5 = 31,0$ per cent.

Thus, it can be seen that the effect of the muck is considerable.

The yield can be increased by selective mining, i.e. leaving blocks unmined or reducing the mining height in muck. Fig. 5, which shows the yield as a function of the percentage of muck left unmined, illustrates the effect of selective mining.

A second disadvantage of the presence of muck is that it can cause fluctuations in the yield. For example, if all the panels strike muck simultaneously, the yield will drop to 14,5 per cent. Some control is required over mining operations to avoid this.

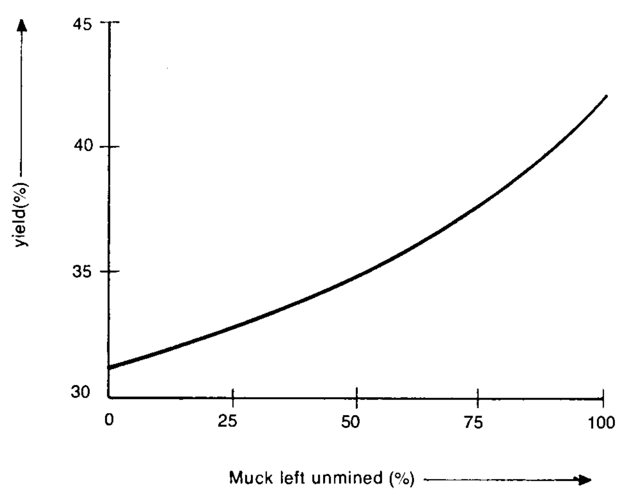
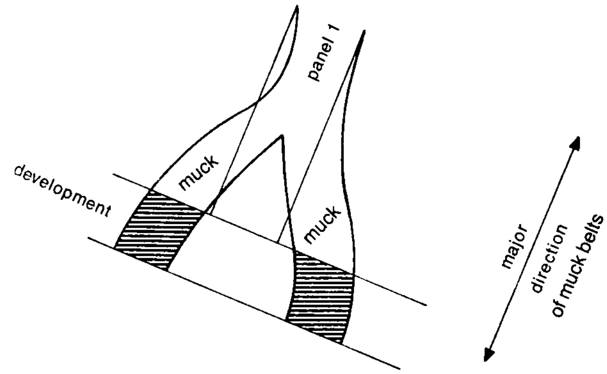
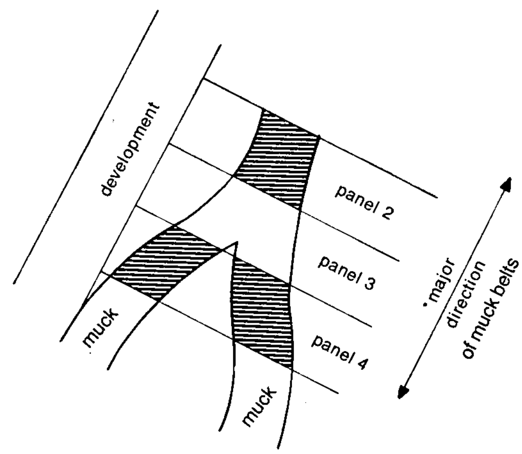


Fig. 5—Effect of selective mining



(a) Developing across the major direction of muck belts



(b) Developing parallel to the major direction of muck belts

Fig. 6—Mine layout in muck-belts

Attempts have been made to develop mines across the major direction of muck belts and to mine panels selectively between muck. However, the muck belts tend to wander and, as illustrated in Fig. 6(a), panel 1, which starts between two muck belts, can end in muck only. Surface drilling could, to a certain extent, avoid this.

An alternative is to develop in the major direction and mine the panels across it as illustrated in Fig. 6(b). If, in addition, alternate panels are mined, then, as the mine develops, a considerable amount of information concerning the intermediate unmined panels becomes available. For example, when panels 2 and 4 in Fig. 6(b) have been mined, panel 3 will be well understood and can be used as a buffer to control the mining operations and hence to stabilize the yield.

Evaluation of Reserves

The muck belts can be regarded as a fourth zone, and, as for the layered portions of the seam, estimates have to be made of the tonnage of raw coal that will be mined from each of the four zones. The difference in the estimate of muck is that it is an estimate of horizontal area as opposed to vertical width. This is a much more difficult problem, and it is therefore essential that as much information as possible concerning the muck-belts should be available. It is, therefore, worth trying to find a suitable borehole grid for this purpose.

Choice of Borehole Grid

Three important parameters for the muck-belts are major direction, average width, and periodicity across the major direction. These do change on a scale of kilometres but very slowly, and it appears feasible to estimate their values from neighbouring mined-out areas. If this can be done, the information obtained will assist considerably in the choice of an appropriate borehole grid.

For illustrative purposes, an average width of 70 m and a periodicity of 160 m are assumed. For the muck-belts to be detectable, the sampling interval across the major direction should be less than 70 m and should also avoid a periodicity of 160 m. A reasonable interval satisfying these conditions would be one of 50 m.

If a square borehole grid is put down parallel to the major direction of the muck-belts as in Fig. 7(a), it will have to be a 50 by 50 m grid if sampling is to be done at an interval of 50 m across the major direction. This could not be justified for deep boreholes, which are fully analysed, although it may be feasible in the case of a surface mine where boreholes are drilled purely to indicate whether muck is or is not present.

However, if the grid is at an angle of 45° to the major direction as in Fig. 7(b), a 70 by 70 m grid would sample at a 50 m interval across the major direction; and, if it is at an angle of 26° as in Fig. 7(c), a 110 by 110 m grid would suffice. Rectangular grids with rotation, as shown in Fig. 8, would give still larger grids. The 103 by 206 m borehole grid inclined at an angle of 14° to the major direction of the muck-belts given in Fig. 8(c) is approaching the size of the 200 by 200 m grids currently being used for underground mines, and also samples at 50 m intervals across the major direction.

Choice of Block Size

In this case, there is no quantitative method for the choice of block size, which therefore has to be made intuitively. The mine should be blocked parallel to the major direction, and each block should contain a reasonable number of boreholes, say twenty[9]. This means that, for the 200 by 200 m borehole grids currently being used on underground mines, the blocks should be very large.

Tonnage of Raw Coal

Once the mine has been blocked, the proportion of muck in each block is determined. The proportion of boreholes in the block that struck muck is the estimate used, and Matheron[10] has indicated a method for placing confidence limits on this estimate. His method is illustrated in Addendum 3.

The tonnage of muck-coal that will be mined from a block is determined by the mining policy. For example, it may be decided that certain sub-blocks will be left unmined, in which case the area of muck must be reduced accordingly. The mining height in muck must be specified, and the area to be mined will have to be corrected for pillars, etc.

The area of muck-free coal will be known and should be corrected for pillars, dykes, faults, etc. Estimates for the widths of zones 1, 2, and 3 can be found as described above by the use of the muck-free boreholes. However, if the blocks are very large, average values will probably suffice. The tonnages that will be mined from zones 1, 2, and 3 can then be calculated.

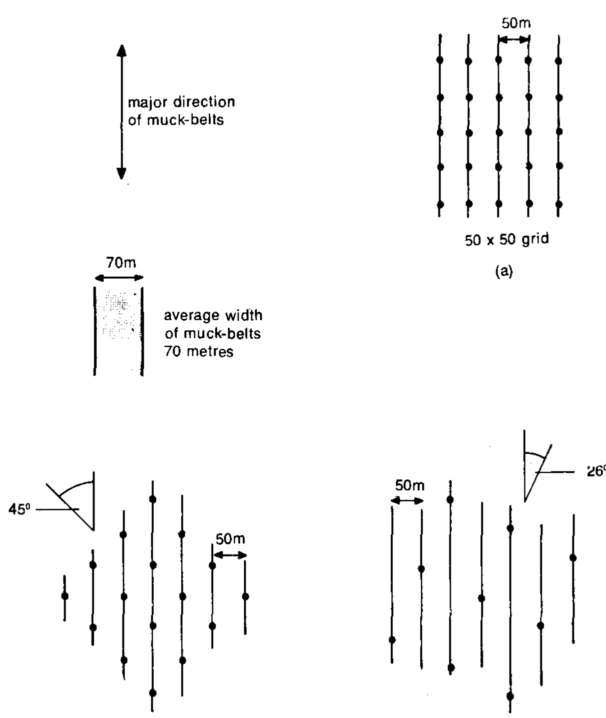


Fig. 7—Square borehole grids

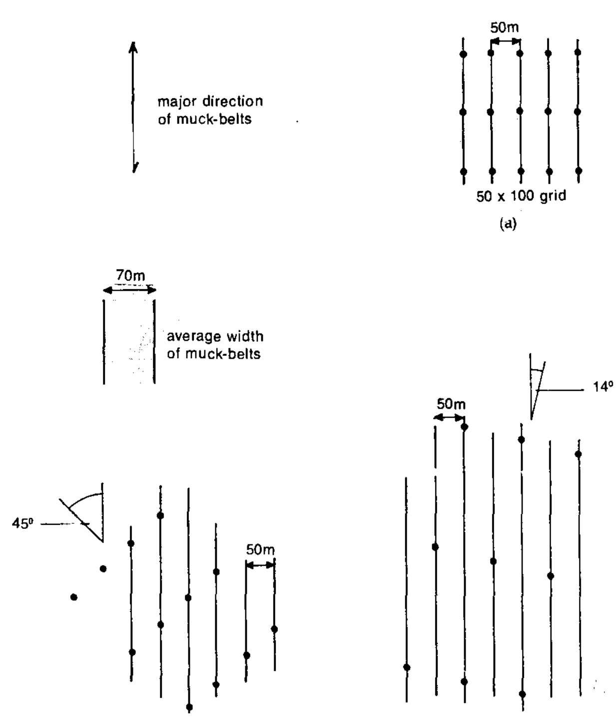


Fig. 8—Rectangular borehole grids

Tonnage of Low-ash Coal

An estimate for the tonnage of low-ash coal that will be mined from a block can be found as described for the layered portion of the seam, the only difference being that there are now four zones instead of three. Again, confidence limits can be placed on this estimate.

Conclusion

A consideration of the geological structure of a coal seam provides deeper insight into the problems that can be expected when it is mined, and makes possible a far more realistic evaluation of the low-ash coal reserves. Geostatistics gives the most accurate estimates for the reserves, and places confidence limits on all the estimates.

Addendum 1: Calculation of Estimation Errors

A method is available[7] for the calculation of the order of magnitude to be expected in estimation errors, and this was used in the derivation of the graphs in Fig. 3. An example is given, using the notation in reference 7, of how these graphs were calculated.

Consider a 50 by 50 m borehole grid so that $G=50$, and a 50 by 50 m panel so that $P=50$. Then, for zone 1 (data given in the second column of Table I), the range $R=150$, which means that the relative grid size $g=G/R=0{,}33$ and the relative panel size $p=P/R=0{,}33$. From graph 3 in reference 8, the relative estimation variance $V=0{,}08$, which means that the estimation variance $\sigma^2=0{,}014\times0{,}08=0{,}0011$, and 90 per cent limits are $\pm1{,}65\times\sigma=0{,}056$.

Hence zone 1 has limits 1,22 m to 1,34 m. Similarly, zone 2 has limits 1,19 m to 1,39 m, and zone 3 has limits 0,77 m to 0,97 m.

If these are combined, the limits for yield of the complete seam are

$$\frac{72{,}5\times1{,}22+11{,}5\times1{,}39+42{,}5\times0{,}77}{1{,}22+1{,}39+0{,}77}=40{,}58$$

and

$$\frac{72{,}5\times1{,}34+11{,}5\times1{,}19+42{,}5\times0{,}97}{1{,}34+1{,}19+0{,}97}=43{,}45.$$

This means that, for $G=50$ m and $P=50$ m, the error in the estimated yield is

$$\pm\frac{43{,}45-40{,}58}{2}=\pm1{,}44$$

as shown in Fig. 3.

The correlation between the zone widths will determine at what exact level this error applies but will not affect the shape of the graphs in Fig. 3.

Addendum 2: Improved Estimates of Coal Quality

Once mining is established, it is customary for underground samples to be analysed in the laboratory periodically so that the estimates of coal quality in the zones can be improved. This has two disadvantages:

(1) it is time-consuming and costly, and
(2) the conditions under which coal is floated in a laboratory are very different from those in a washing plant.

It would be preferable if the plant could do its own sampling.

If y_1, y_2, and y_3 are the yields of three zones and p_1, p_2, and p_3 are the proportions mined from each of them, then the yield of coal entering the plant is

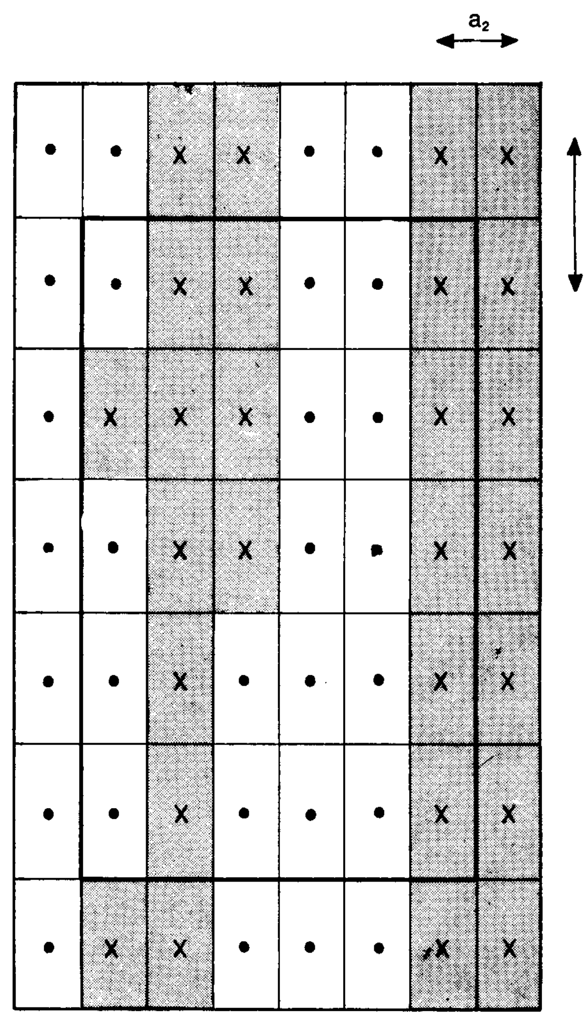
$$y=\frac{p_1\times y_1+p_2\times y_2+p_3\times y_3}{p_1+p_2+p_3}.$$

If it is possible to monitor p_1, p_2, p_3, and y during a specific period so that their values are known, a linear equation in the unknowns y_1, y_2, and y_3 will be obtained.

If the monitoring is continued over several months, a large number of such equations will accumulate, and they can be solved by minimization of the squared error. Once this error is small enough, the values found for y_1, y_2, and y_3 can be accepted as reliable.

Addendum 3: Variance in Surface Estimation

Matheron[10] has given a method of placing confidence



Borehole grid size is a_1 x a_2
Block is bounded by the heavy line
Boreholes X struck muck
Shaded area is the estimated muck

In the panel (that is within the heavy line)

Total no of boreholes	=	30
No. which struck muck	=	15
No. of boundaries$\|\|a_1$	=	15
No. of boundaries$\|\|a_2$	=	6

Fig. 9—Example of surface-estimation variance

limits on the estimation of a surface area, and this method is illustrated by use of the example shown in Fig. 9. Boreholes have been drilled on a grid of a_1 by a_2, and those indicated by X have struck muck. It is required to estimate the proportion of muck in the block bounded by the heavy line and to place confidence limits on this estimate.

The total area of the block is

$T=30\times a_1\times a_2$.

The number of boreholes in the block that struck muck is 15, so that the estimated area of muck (the shaded area in the block) is

$S=15\times a_1\times a_2$.

Hence, the estimated proportion of muck is

$$\frac{S}{T}=0{,}5.$$

The relative estimation variance of this estimate is given by Matheron's formula

$$\left(\frac{\sigma}{S}\right)^2=\frac{1}{n^2}\left(\frac{N_2}{6}+0{,}061\times\frac{N_1{}^2}{N_2}\right),$$

where

n=no. of positive boreholes=15

$N_1=\frac{1}{2}\times$(no. of boundaries $\parallel$ a_1)=15/2=7,5

$N_2=\frac{1}{2}\times$(no. of boundaries $\parallel$ a_2)= 6/2=3.

Substitution gives

$$\left(\frac{\sigma}{S}\right)^2=\frac{1}{15^2}\left(\frac{3}{6}+0{,}061\times\frac{(7{,}5)^2}{3}\right)=0{,}0073.$$

Therefore,

$$\left(\frac{\sigma}{S}\right)=0{,}085 \text{ and}$$

$$\left(\frac{\sigma}{T}\right)=\left(\frac{\sigma}{S}\right)\times\left(\frac{S}{T}\right)=0{,}085\times0{,}5=0{,}042,$$

which gives 90 per cent limits of $1{,}65\times0{,}042=0{,}071$, i.e., the estimated proportion of muck is $0{,}5\pm0{,}071$.

Acknowledgements

This investigation was based on the ideas developed by the Geology Department (Coal Division) of Anglo American Corporation Ltd and used the excellent data supplied by them. The interesting idea of muck-belts was initiated by the Geology Department of Gold Fields of South Africa Ltd.

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Mining exhibition

An International Mining Exhibition, the first ever staged in Istanbul, is to be held in that city from 15th to 22nd September, 1979, in conjunction with the Tenth World Mining Congress.

Suppliers are invited to exhibit machinery and services used in every type of underground and surface operation in coal, metalliferous, and other types of mining.

Further details are obtainable from Brintex Exhibitions Limited, International Mining Exhibitions, 178-202 Great Portland Street, London W1N 6NH, England.

Mine surveying

The IVth International Symposium on Mine Surveying is to be held in Aachen from 24th to 29th September, 1979. The main theme is 'Mine surveying and extraction of raw materials today and tomorrow.'

The programme is divided into the following topics:

1. Mine Surveying — History of Development, Education, Organization, Legal Regulations
2. Exploration and Mapping of Mineral Deposits, Evaluation and Use of Resources
3. Surveying Instruments and Equipment, Mensuration and Evaluation Methods
4. Strata Control, Ground Subsidence, Subsidence Damage
5. Mining Industry and Regional Planning.

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