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# The extraction safety factor concept in high-extraction coal mining*

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**SYNOPSIS**

It is shown that the safety factor as calculated traditionally by use of the tributary-area theory is not valid for high-extraction methods of coal mining. An alternative approach is suggested in which the pillar loads are calculated more realistically for the period during which pillar extraction is in progress. This safety factor, which is known as the Extraction Safety Factor (ESF), can be used in determining the effects of strong layers in the overburden on pillar sizes.

**SAMEVATTING**

Daar word getoon dat die veiligheidsfaktor soos bereken met gebruik van die deelontginningsgebiedteorie nie vir steenkoolmynboumetodes vir 'n hoë ekstraksie geld nie. 'n Alternatiewe benadering word aan die hand gedoen waarin die pilaarlaste meer realisties bereken word vir wanneer pilaarekstraksie aan die gang is. Hierdie veiligheidsfaktor, wat bekend staan as die Ekstraksieveiligheidsfaktor, kan gebruik word om die uitwerking van sterk lae in die deklaag op pilaargroottes te bepaal.

## Background

The extraction of coal at currently popular mining depths can be increased slightly by use of the more realistic squat-pillar formula for the determination of pillar sizes or, dramatically, by use of high-extraction mining methods.

Pillar extraction, or stooping, is a very popular method in high-extraction mining. In pillar extraction, the Strata Control Engineer is often required to supply answers to two basic questions: what sizes of pillars should be left to facilitate their later extraction, and can existing pillars be extracted safely?

Traditionally, the safety factor determined from the tributary-area theory has been used as the only criterion. When the safety factor was 2 or more, stooping was considered to be viable.

The tributary-area theory rests on the assumption that each pillar is responsible for the support of its overlying strata, between the coal seam and the surface. Therefore, pillar load is merely the unit weight of the overburden, multiplied by the depth below surface, concentrated by the inverse of the extraction ratio:

$$L = 0{,}025\, H \frac{C^2}{W^2} \text{ MPa,} \quad \text{(1)}$$

where $H$ = depth below surface in metres
$C$ = pillar centre distance
$W$ = pillar width.

The pillar strength is then calculated from the well-known formula given by Salamon and Ovarecz (1976) or from the squat-pillar formula, given by Wagner and Madden[1]. The safety factor is the quotient of pillar strength and pillar load.

For bord-and-pillar workings, the procedure outlined above is logical and sound, and has proved successful over many years. However, when high-extraction methods are used, the system of pillar loading is different, and the procedure as normally used is no longer relevant.

## Pillar Loading during Stooping

During stooping, when a pillar is extracted, it can no longer support its share of the overburden, and its neighbours have to bear the additional weight.

From the start of stooping operations, the additional load on the remaining pillars increases continually until the first major break occurs. From then on, the previously unsupported overburden rests on the fractured goaf material, and the only additional loading on pillars is a result of the overhang. Pillar loads are thus reduced. The loading system is shown diagrammatically in Fig. 1.

Fig. 1(b) shows the situation when a strong layer like a massive sandstone or a dolerite sill prevents fracturing of the overburden rock mass through to surface. When that happens, the load decrease described in the previous paragraph does not occur.

The progressive load history of pillars during stooping operations is shown conceptually in Fig. 2, which illustrates the initial load increase with increasing extraction, and then the decrease in load when the first major break occurs. The first major break coincides with the first occurrence of surface subsidence. The diagram also indicates the periodic small increases in load caused by periodic overhangs of the overburden, and the level at which the load stabilizes if a strong layer in the overburden prevents the major break to surface. The pillar load will stabilize when the length of advance is equal to the panel width.

## Extraction Safety Factor

Pillar strengths are not affected by the load sequence described in the previous section. The quotient of the

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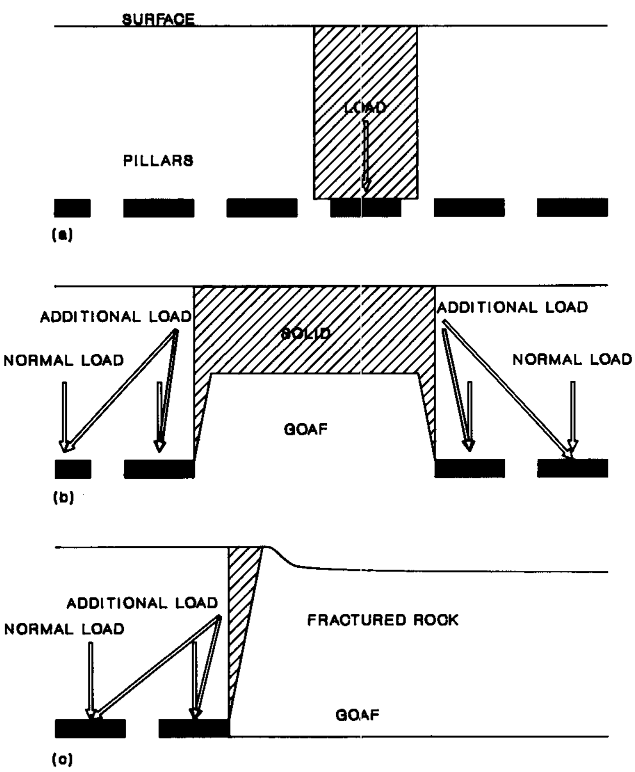


**Fig. 1—Loading system on pillars during pillar extraction**
**(a) No pillar extraction—tributary-area theory valid**
**(b) Early stage of pillar extraction—owing to additional load on pillars, the tributary-area theory is not valid**
**(c) Situation after overburden failure—pillar loads have decreased but still exceed the tributary-area load**

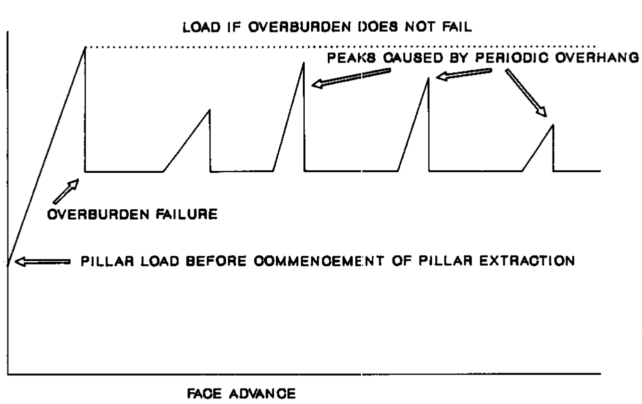


**Fig. 2—Conceptual history of load on front-line pillars during pillar extraction**

strength of a pillar and its actual load, that shown in Fig. 2, is termed the extraction safety factor (ESF).

The ESF thus changes as the mining layout changes, and is influenced by the geological structure. The ESF history with progressive mining stages is shown conceptually in Fig. 3. It is seen to decrease as mining progresses, and then to increase as the first major break occurs. If a major break does not occur, the ESF will stabilize at a low value at the stage when the length of advance is equal to the panel width.

The advantages of the ESF are that it takes cognisance of the actual loading system during stooping, and that the effects of the geological structure are quantifiable.

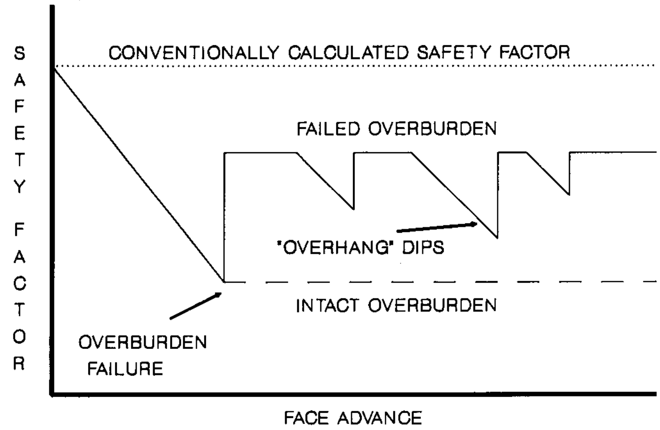


**Fig. 3—Conceptual history of extraction safety factor on front-line pillars during pillar extraction**

In the design of a stooping panel, the ESF for a panel can be calculated and its lowest value can be considered. Limited back analysis to date seems to indicate that a minimum ESF of 1 can be tolerated. If the ESF is less than 1, premature pillar failure occurs and the stooping exercise may have to be abandoned. If necessary, the pillar size can be increased in practical increments to raise the lowest ESF value.

The same procedure can be applied in the evaluation of existing panels for the likely success of stooping. If the ESF will be too low at the minimum level although otherwise reasonable, it indicates that limited stooping may still be done successfully. Every so often pillars may have to be left *in situ* (when the ESF approaches the limiting value) and stooping restarted beyond the critical area. When this is done, the build-up of stress on the abandoned pillars must also be analysed to prevent the occurrence of sudden failure at a later stage. This step is crucial. A sufficient number of pillars must be left to guarantee their stability.

For instance, the application of the ESF procedure has allowed Sigma Colliery, which has a very weak mudstone roof, to safely extract pillars in a panel where the conventionally calculated safety factor was as low as 1,6. This has explained why, at the same mine, stooping failed where the conventional safety factor was in excess of 2,2. In the former case, the ESF dropped to a minimum of 1,2, while in the latter it dropped to 0,8.

In essence, the ESF is a method by which the effects of geological structure on the success of stooping can be quantified.

## Calculation of ESF

By definition, ESF is the ratio between the strength of a pillar and the actual load imposed upon it:

$$\mathrm{ESF} = \frac{\text{Strength}}{\text{Actual load}} \qquad (2)$$

The determination of the two variables, strength and actual load, will be discussed separately.

### *Calculation of Pillar Strength*

Pillar strength is a function of pillar geometry and the strength of the material comprising the pillar. It is not affected by the overall geological structure or the mining method.

Therefore, use can be made of generally accepted methods of calculation. For squat pillars, the strength, $S$, as given by Wagner and Madden[1] is

$$S = k\,\frac{R_o^b}{V^a}\left\{\frac{b}{\epsilon}\left[\left(\frac{R}{R_o}\right)^{\epsilon} - 1\right] + 1\right\} \qquad (3)$$

where $k$ = strength of pillar material
$R_o$ = ratio of critical pillar width to height (= 5)
$V$ = pillar volume
$R$ = ratio of pillar width to height
a, b, and $\epsilon$ are constants.

For slender pillars, with a width-to-height ratio of less than 5, equation (3) reduces to the well-known formula after Salamon and Munro[2]:

$$S = 7{,}2\,\frac{W^{0,46}}{H^{0,66}} \qquad (4)$$

*Calculation of Actual Pillar Load*

The calculation of actual pillar load is more complex than the determination of pillar strength, and an easily applicable method of hand calculation does not exist. However, a number of computer programs that will yield the required answers are available commercially. The procedure outlined here relates to a popular two-dimensional boundary-element code.

This procedure describes the steps to be taken when a decision is to be made as to whether an existing panel should be stooped.

The computer model is based on the possible loading systems shown in Fig. 1. The transformation of these systems into computer models is shown in Fig. 4.

The models in Fig. 4 have the following features.

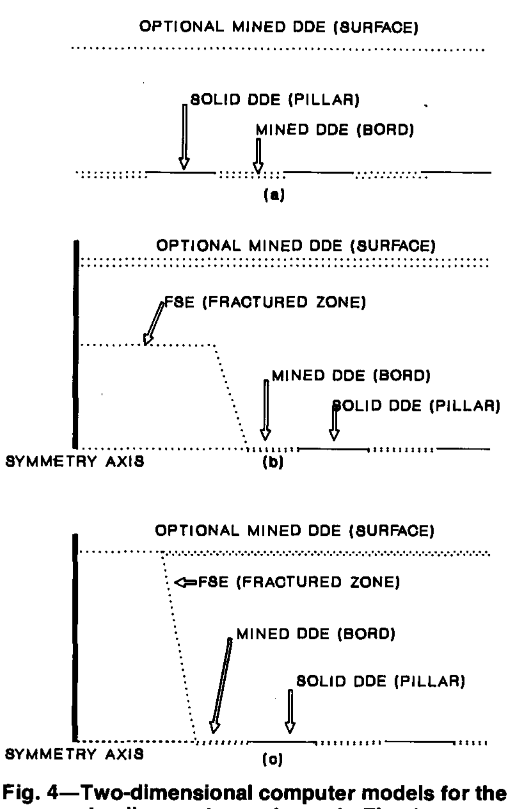


**Fig. 4—Two-dimensional computer models for the loading systems shown in Fig. 1**

(a) The zone of fractured rock overlying the high-extraction panels are constructed by the use of Fictitious Stress Elements (FSEs). This is valid since cracks in the rock mass have been seen to extend to surface. Where an unfailed dolerite is present, that zone is modelled as extending to the base of the sill, as shown in Fig. 4(b). The FSEs forming the bottom of the fractured zone are loaded by a vertical pressure equal to the weight of rock within the FSE zone. Horizontal forces are zero. All the other FSEs are free of stress.
(b) The coal seam is simulated by Displacement Discontinuity Elements (DDEs). The pillars are represented by 'solid' DDEs, and the bords by 'mined-out' DDEs.
(c) It has been found that the provision of a line of mined elements representing surface has only a negligible effect on the stress on the pillars, and may be omitted.
(d) Care should be taken that the first DDE next to an FSE must be a mined element to avoid anomalous results.

The dimensions of the various elements need careful consideration in view of the two-dimensional modelling of a three-dimensional problem. The following rules have been found to apply.

(i) The maximum model span underneath an unfailed dolerite is equal to the panel width. Exceeding this limit will lead to unrealistically high pillar stresses.
(ii) Road widths must not be reduced.
(iii) Pillar sizes are reduced from their actual sizes, so that the two-dimensional extraction ratio is equal to the three-dimensional one. The pillar widths for the model are then calculated as follows:

$$P_m = \frac{RP_a^2}{(P_a + R)^2 - P_a^2}, \qquad (5)$$

where $P_m$ = model pillar width
$R$ = road width
$P_a$ = actual pillar width.

In the interests of accuracy, a balance must be found between the various dimensions, the sizes of the elements, and the number of elements the computer can handle.

It has been found that element sizes in multiples of 3 metres work well. If the required sizes of mined and unmined zones of elements are difficult to balance with element sizes, it has been found useful to reduce the element sizes. More elements are then required, and one must often be imaginative to avoid exceeding the legitimate number of elements, which is a function of the version of the program that is being used.

If it proves impossible to balance the sizes of the elements (remembering that large and sudden changes in size must be avoided) with the available number of elements, the best strategy is to go ahead with the most reasonable simulation that the rules pertaining to sizes will allow. After the solution has been obtained, stresses must be adjusted in the ratio of the modelled to the actual percentage extraction.

The need for great care in setting up the model cannot be over-emphasized. It is worth while to remember that one must attempt to model, as precisely as possible, not necessarily the actual situation, but the transformation of a three-dimensional situation into a two-dimensional model so that the effects of the model correspond as closely as possible to the effects of the real situation. This is what numerical modelling is all about.

*Calculation of ESF*

Once the actual pillar loads for various stages in the mining process are known and the pillar strengths have been calculated, the ESF for the various stages of mining can be determined from equation (2).

The limiting value of ESF is best determined by back-analysing previous pillar-extraction exercises. This technique is especially handy if an unsuccessful pillar-extraction attempt can be included in the study. Either way, the back-analysis technique can be relied on only if the theoretical analysis can be coupled to physical observations.

If back-analysis cannot be used owing to the absence of suitable historical cases, an ESF limit of 1 can be assumed.

To reduce the probability of errors and the time taken in setting up the model, the modelling procedure and the post-processing calculations have been computerized. The three components (pre-processor, main processor, and post-processor) are run as a single program. From the basic input (depth, pillar size, etc.) the pre-processor sets up data files corresponding to the models in Fig. 4 for the main processor, which is run automatically. After that, the post-processor takes over. It reads the output file from the main processor, adjusts the stresses if necessary, and then uses the relevant expressions for the calculation of ESF. The ESF values are then stored in the final output file. To aid the design process, ESF values are calculated for a range of pillar sizes.

## Conclusions

The Extraction Safety Factor has been shown to provide a realistic norm for the extraction of pillars. While it can be used to show whether existing pillars can be safely extracted, its most significant use lies in showing whether planned pillars that are intended for extraction at a later stage can be extracted safely. The concept incorporates the effects of the geological structure on the mining method. Of vital importance for a successful ESF analysis is the interpretation of the effects of the geological structure, since the model from which actual pillar loads are obtained is based on this interpretation.

The procedure is also valid for the design of inter-panel pillars between high-extraction panels.

## Acknowledgement

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# Formation of Eurominerals

At the annual meeting of the Société de l'Industrie Minérale, held in Strasbourg from 6th to 9th June, 1990, Benelux Metallurgie, the Consejo Superior de Colegios de Ingenieros de Minas, GDMB (Gesellschaft Deutscher Metallhütten- und Bergleute), The Institution of Mining and Metallurgy, and the Société de l'Industrie Minérale announced the formation of Eurominerals—The Confederation of Learned/Engineering Societies in the Mineral Industry.

Dr Barry Scott, President of The Institution of Mining and Metallurgy, has been elected President of Eurominerals, and Claude Beaumont, Vice-President of the Société de l'Industrie Minérale, has been elected Vice-President. The Institution of Mining and Metallurgy has been appointed to act as the Secretariat (Secretary: Michael J. Jones, from whom further information can be obtained).

Eurominerals seeks to bring together national learned/engineering societies from the present-day EC countries. Eligible for membership are learned/engineering societies within EC countries—at present or in the future—whose area of activity covers mineral exploration, development and extraction, and/or the treatment and processing of metals, industrial minerals, solid energy minerals, and quarry products in general. Specialized related fields are included: mining technology for civil use (tunnelling, underground storage caverns, etc.), drilling, geotechnical engineering and engineering geology, financial services, and environmental industry.

The object of Eurominerals is to promote and facilitate communication, information exchange, collaboration, and joint action among its members. In particular, this object shall relate to

- communication with the EC authorities
- assessment of the most significant technical/scientific and professional matters
- technical meetings and conferences organized by the individual member bodies, in which participation by the representatives and members of other bodies would be encouraged; attention should be paid to the best possible coordination of meeting/conference dates and topics
- the publications, both regular and occasional, of the various member bodies, as well as, to the extent possible and appropriate, joint publication of articles and papers.