Discussion: Support in shallow mines using horizontally reinforced systems*

Contribution by M. D. G. SALAMON†

The first sight of a paper by members of another branch of engineering in the *Journal*, especially when the contribution is in my field of interest, fills me with anticipation. Also, the notion of using horizontally reinforced artificial pillars to support tabular excavations undoubtedly justifies attention. It is disappointing in view of these factors that the arguments and data presented in the paper do not vindicate the conclusions offered.

The authors assert, if I interpret the implications of their statements correctly, that the proposed support system is safe and ready for a full-scale underground trial. However, in my opinion, so much of the mechanism of the system has been left unexplored that no firm conclusion can be drawn at this stage. Furthermore, I do not believe that a field trial can be initiated safely without first obtaining and analysing the results of additional theoretical and laboratory studies.

To substantiate these remarks, I touch upon a number of aspects of the paper.

Rock and Support Deformation

Little attention is devoted in the paper to the deformation of the supports and of the surrounding rock mass. On p. 278 an elementary analysis of the 'equivalent roof beam' is introduced. It is apparent from the Addendum (p. 289) that the authors visualize the depth of the roof beam as approximately 1,5 to 2,0 m. This view of the beam and the relevant analysis are unacceptable over-simplifications. In practice, the support and the strata above and below the seam all participate in the deformation mechanism[1-3]. The simple beam theory is incapable of describing this complex process.

The cost analysis presented by the authors suggests that the use of artificial pillars in the case of complete extraction in one operation would be economic only if the extraction ratio achieved by the conventional bord-and-pillar methods, e_x, is less than 60 per cent (p. 288). According to the procedure currently employed in pillar design[4,5], this requirement is satisfied if the working height *exceeds* the height defined by the curve in Fig. 1. This curve was calculated to exemplify representative mining conditions. It would appear from this illustration that, at shallow depths, say under 60 m, artificial pillars are economic only if the working height is substantial.

Assume that a thick seam of coal exists at a depth of 100 m. According to Fig. 1, the use of artificial pillars at this depth would break even at a working height of about 3 m. To give the artificial pillars a chance of economic success, a working height of 4 m is postulated. If the bord width and safety factor are left unaltered, the procedure of pillar design for this geometry yields a width of coal pillar of 11,9 m, which is equivalent to an extraction of 55,7 per cent. It is estimated on the basis of some detailed theoretical work[1,3] and field observations[1,3] that the surface subsidence over these workings would be in the region of 7 to 8 mm.

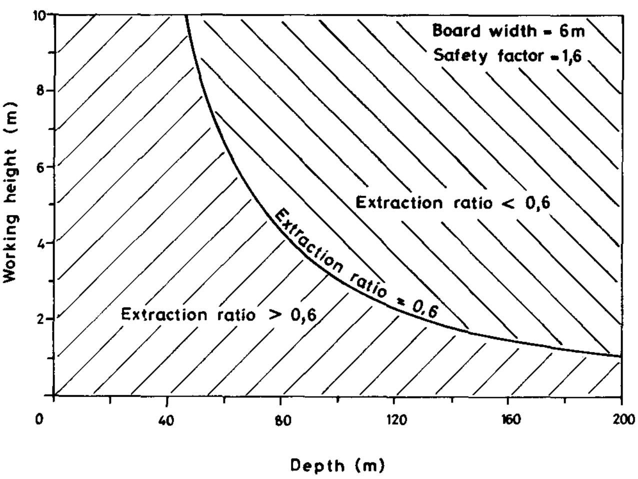

Fig. 1—Relationship between working height and depth for 60 per cent extraction

Postulate that reinforced ash pillars (rib pillars or 'walls') of adequate strength can be designed with a cross-sectional area to ensure that about 25 per cent of the roof and floor is in contact with the new pillars. The use of ash is proposed because this is the material favoured by the authors for the field trial (p. 287). The ultimate load on these artificial pillars would be four times that of the virgin vertical stress, which is about 2,5 MPa at a depth of 100 m. Thus, the average pillar load would be about 10 MPa. As the strength should not be less than the load, it follows from the data in Fig. 13 (p. 283) that the reloading modulus of these ash pillars would be about 900 MPa. In practice, the modulus would be less than this value because of the compaction of the top section of the pillars and imperfections in the underground construction. A realistic estimate of the modulus appears to be about 600 MPa. In these circumstances, the ultimate convergence of the artificial pillars would be about 70 mm and, as the surrounding strata also deform, the surface subsidence, which is a useful measure of the deformation caused by mining, would approach 100 mm. This value is an order of magnitude greater than the subsidence that would occur in conventional pillar mining.

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The effects of a large increase in displacement may be serious, regardless of whether complete extraction in one operation or secondary pillar extraction is practised. The much 'softer' pillars would provide support to the roof only after considerable pillar convergence and rock deformation. Thus, maximum pillar support would develop only at a considerable distance away from the position where the artificial pillars are first called upon to act as supports. Would the roof strata fracture and fail as a result of a long, perhaps inadequately supported, span and large deflection? We do not know the answer to that question.

Strength of Reinforced Cemented Material

On pp. 280 and 281 an attempt is made to derive a strength formula for pillars consisting of horizontally reinforced cemented material. The resulting expression (10a) is fundamentally flawed.

The derivation of the formula is based on Poissons' effect, i.e. on the observation that most materials tend to expand laterally owing to vertical pressure and that the magnitude of this expansion for elastic materials is determined by the Poisson's ratio. Of course, the reinforcement will resist this expansion and in the process will provide some confinement to the cemented material. This thought process leads to (9) on p. 280, which is the expression for the lateral tensile strain in both the cemented material and in the reinforcement. At this point the authors suggest that, as the vertical load on the pillar increases, the tensile strain 'will increase until it reaches a limiting value, at which the cemented material will fail by vertical splitting. For brittle materials such as concrete and brick, the limiting value of [the tensile strain] is about $200 \cdot 10^{-6}$'. No attempt is made to substantiate these statements.

The substitution of the so-called limiting value of tensile strain into (9) leads to the erroneous formula in (10a), where the pillar strength, σ_{max}, is *inversely* proportional to the Poisson's ratio. If this formula were correct, a pillar built from a material that has a Poisson's ratio of zero would have infinite strength. This is, of course, impossible: a zero Poisson's ratio would imply the absence of lateral confinement, and hence no strength enhancement would occur. In such a situation, the strength of the pillar would be equal to the uniaxial compressive strength of the cemented material.

It is simple to derive a strength formula that avoids this inconsistency and that is still based on Poisson's effect and on the assumption of elastic behaviour by both the cemented material and the reinforcement. This model would have to satisfy the following criteria.

(i) The tensile force exerted on the reinforcement must be in equilibrium with the compressive forces of constraint to which the cemented material is subjected.

(ii) The horizontal strain in the reinforcement must be equal to that in the cemented material.

(iii) The strength of the pillar must satisfy the Mohr–Coulomb criterion for failure of brittle materials[6]:

$$\sigma_{max} = k\sigma_h + \sigma_c, \qquad (1)$$

where σ_h and σ_c are the horizontal constraining stress and uniaxial compressive strength of the brittle material respectively, and k is a dimensionless parameter in the region of 6 for a variety of brittle rocks.

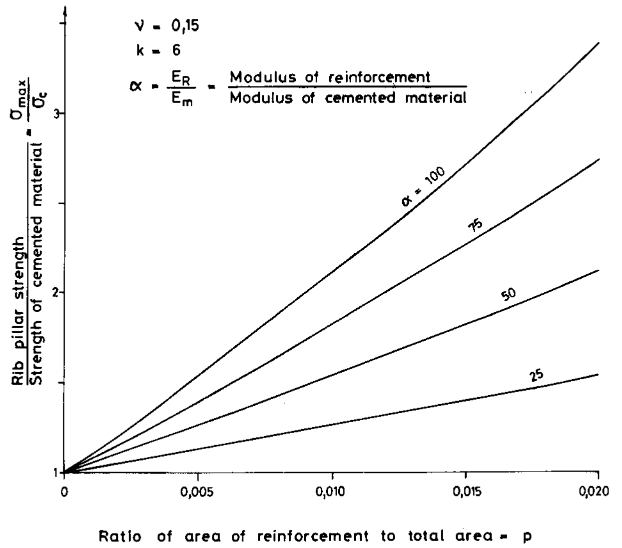

Fig. 2—Strength enhancement due to lateral reinforcement

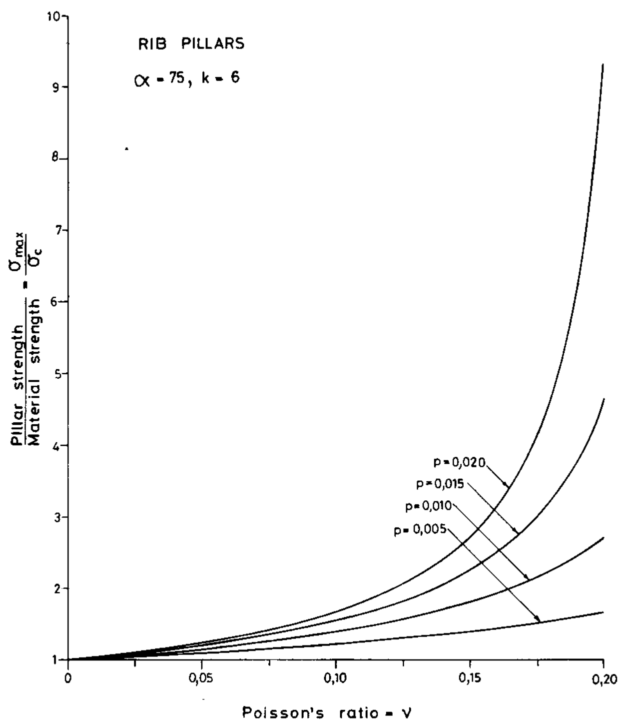

Fig. 3—Influence of Poisson's ratio on the strength of reinforced pillars

These criteria, together with Hooke's law, lead to the following results for artificial pillars having a square cross-section:

$$\frac{\sigma_{max}}{\sigma_c} = \frac{(1-p)+(1-\nu)\alpha p}{(1-p)+(1-\nu)\alpha p - k\nu\alpha p} \quad . \ . \ . \ . \ (2)$$

and

$$\frac{\sigma_r}{\sigma_c} = -\frac{\nu(1-\nu)\alpha}{(1-p)+(1-\nu)\alpha p - k\nu\alpha p}, \quad . \ . \ . \ (3)$$

where σ_r is the tensile stress in the reinforcement. The other notations are those used in the paper. The expressions in (2) and (3) are valid as long as

$$k < k_0 = \frac{(1-p)+(1-\nu)\alpha p}{\nu\alpha p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The results corresponding to long rib pillars can be obtained from those in (2) to (4) by the multiplication of factors $(1-\nu)$ and ν wherever they occur by $(1+\nu)$. To derive these latter results, plane-strain conditions were postulated. In Fig. 2 the strength of a rib pillar is plotted as a function of the reinforcement area for various values of the ratio of moduli. These results do not appear to differ greatly from those depicted in Fig. 8 of the paper (p. 281). However, it is important to note that the strength is strongly dependent on the value of the Poisson's ratio and that it *increases* as the Poisson's ratio is *increased* (Fig. 3).

There are two criteria that must be satisfied if the integrity of the artificial pillars is to be assured: it is necessary for the pillar strength in (2) and the yield strength of the reinforcement material to exceed the pillar load and the tensile stress in (3), respectively. The latter criterion is not mentioned in the paper in respect of pillars constructed from cemented material. This is a serious omission. It is clear from Fig. 4 that the tensile stress in the reinforcement may well become a critical condition for pillar soundness.

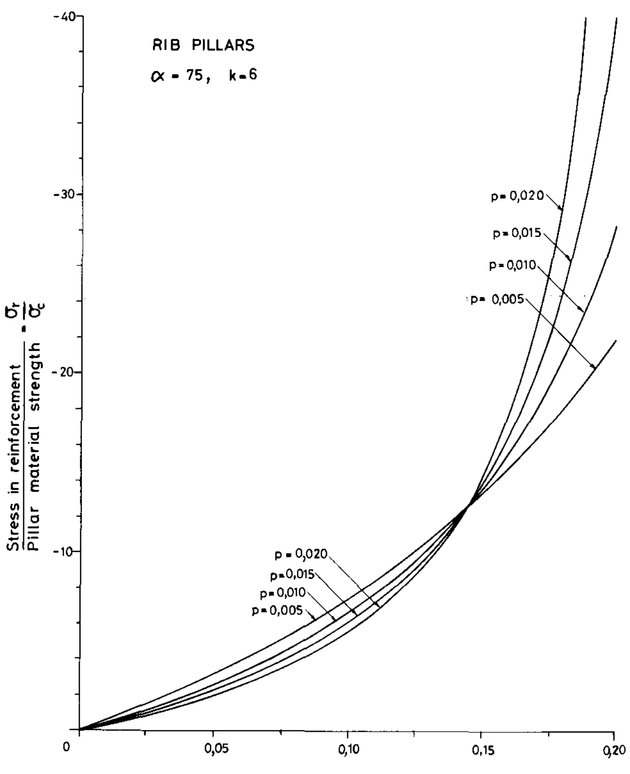

Fig. 4—Tensile stress in the reinforcement

Economic Feasibility

The authors concede on p. 288 that 'it is not possible to predict the total costs of wall building very accurately'. That is understandable at this stage. It is of greater concern to me that no attempt is made in the paper to describe how the construction of the artificial supports is to be integrated with the mining process. Is it possible to achieve the integration without the slowing down of mining operations? If not, which seems to me a strong possibility, the cost analysis as presented is invalid. Increased mining costs, in addition to the cost of the new supports, will have to be covered by the extra revenue earned.

General Comment

It is to be regretted that the authors ventured beyond the presentation of their ideas concerning the theoretical strength of horizontally reinforced artificial supports. In such a paper, the statement that the 'technical contents of this paper are believed to be completely original, and there are no references to related work' (p. 289) would perhaps be acceptable.

As it is, the paper goes far beyond this point. It claims that (i) artificial support systems can be designed rationally; (ii) the theory gives accurate predictions of support strength; (iii) the proposed support systems are flexible and can be varied to suit different working heights and loads; (iv) preloading by jacking ensures that the supports are stiff (relative to what?) and proof-tested; and (v) it can be used profitably provided the cost of construction lies within definable limits, etc.

I submit that these claims are not justified by the material presented, and that the paper would have benefited from a close study of the related literature.

References

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Contribution by H. WAGNER* and B. MADDEN*

The use of artificial pillars to extract mineral deposits as completely as is feasible is not new, and has taxed the minds of many generations of mining engineers. Three factors have prevented the application of this attractive concept on any significant scale: it was found to be extremely difficult, if not impossible, to design a system of artificial pillars of sufficient *strength* and *stiffness* that would (i) carry the weight of the overburden, (ii) ensure *stable* mining layouts, and (iii) be *economic*. It was, therefore, with considerable interest that we followed the development outlined in the paper on support in shallow mines using horizontally reinforced systems.

Close scrutiny of the concepts proposed in the paper and the data presented casts considerable doubt on some of the conclusions reached by the authors. In particular, the conclusions that the system can be designed rationally to support a predetermined overburden load, and that the system can be used profitably provided the cost of wall building lies within definable limits, are misleading since they are based on simplistic assumptions. Because of the far-reaching consequences of these statements, we consider it necessary to elaborate on some of the aspects of horizontally reinforced systems.

Load Transfer

In deriving the conclusion that the system can be designed rationally to support a predetermined overburden load, the authors consider the simplified but unrealistic case that the behaviour of the strata surrounding bord-and-pillar workings can be resembled by the modelling of the behaviour of a thin roof beam. In the examples given in the Addendum of p. 289, the thickness of the roof beam varied between 1,5 and 2,5 m. A detailed analysis of strata movements in bord-and-pillar workings shows that the support, the strata above the seam, and the strata below the seam participate in the deformation mechanism[1]. Furthermore, because of the compressibility of the supports, the critical dimension from the point of view of overall strata control is the minimum lateral dimension of the mining panel, and not the width as determined by the distance between the support pillars, s, and the pillar width, b, as suggested by the authors in equation (2) on p. 278. The main shortcoming of the simplified approach is that it ignores the load transfer from the mined-out area to the panel abutments. It will be shown that it is this load transfer that can lead to dangerous conditions in the working areas and regional instabilities.

The load transfer from the mined-out area to the panel abutments and the working face is a function of the amount of elastic strata deflection that is allowed to take place in the mined-out area. The strata deflection is a function of the panel dimensions and geometry, the thickness and elastic properties of the overlying strata, and the load-deformation characteristics of the support in the mined-out area. In the case of total extraction panels, that is panels with no internal support, the load acting on the panel abutments is limited by the strength properties of the roof strata, which, in turn, govern the amount of strata deflection that can take place before failure of the roof strata occurs. Once the roof strata have caved, only the weight of the overhanging strata has to be supported by the panel abutments and working face. Early caving of the roof strata is therefore a desirable feature of total extraction systems. In the case of mining systems employing internal support in the mined-out area, either in the form of natural pillars or artificial support, the magnitude of the abutment stresses is controlled by the compressibility of the pillars or supports. As a rule, the stiffer the support elements, the lower will be the abutment stresses.

To illustrate the above concepts, two situations envisaged by the authors will be considered in detail. First, the effects of artificial supports of different stiffness on the stress distribution around a 200 m-wide extraction panel situated at a depth of 100 m are examined. The second example concerns the stress distribution in a conventional bord-and-pillar panel in which coal pillars are being extracted under the protection of artificial support pillars.

Artificial Supports of Different Stiffness

Fig. 1 shows the distribution of vertical stresses acting on the abutments and internal support pillars. For convenience, the stress values have been normalized with respect to the value of the vertical component of primitive stress. In the example, continuous artificial rib pillars 1,2 m wide and 1,8 m high, which are separated by 6,3 m wide bords, have been modelled. The compressive modulus of the pillar material in Fig. 1 is 1 GPa.

In Fig. 2 the maximum stress concentration on the artificial support pillars and the panel abutments is plotted as a function of the modulus of compression of the pillar material. The upper value of 3 GPa corresponds to the *in situ* modulus of elasticity of coal. Two important observations can be made from the trends shown in Fig. 2. First, the artificial support pillars in the centre of the panel carry a significant proportion of the overburden load only if the modulus of compression of the pillar material exceeds a value of 1 GPa. In terms of the tributary-area concept, the vertical stress concentration, C, in the artificial support ribs of width, b, which are separated by bords of width s, is

$$C = 1 + \frac{s}{b}.$$

With the appropriate values for s=6,3 m and b=1,2 m, a stress concentration of 6,25 results. Second, in the case of support pillars having a modulus of compression of less than 1 GPa, most of the weight of the overburden in the mined-out area has to be carried by the panel abutments and the working face. The rapid increase in

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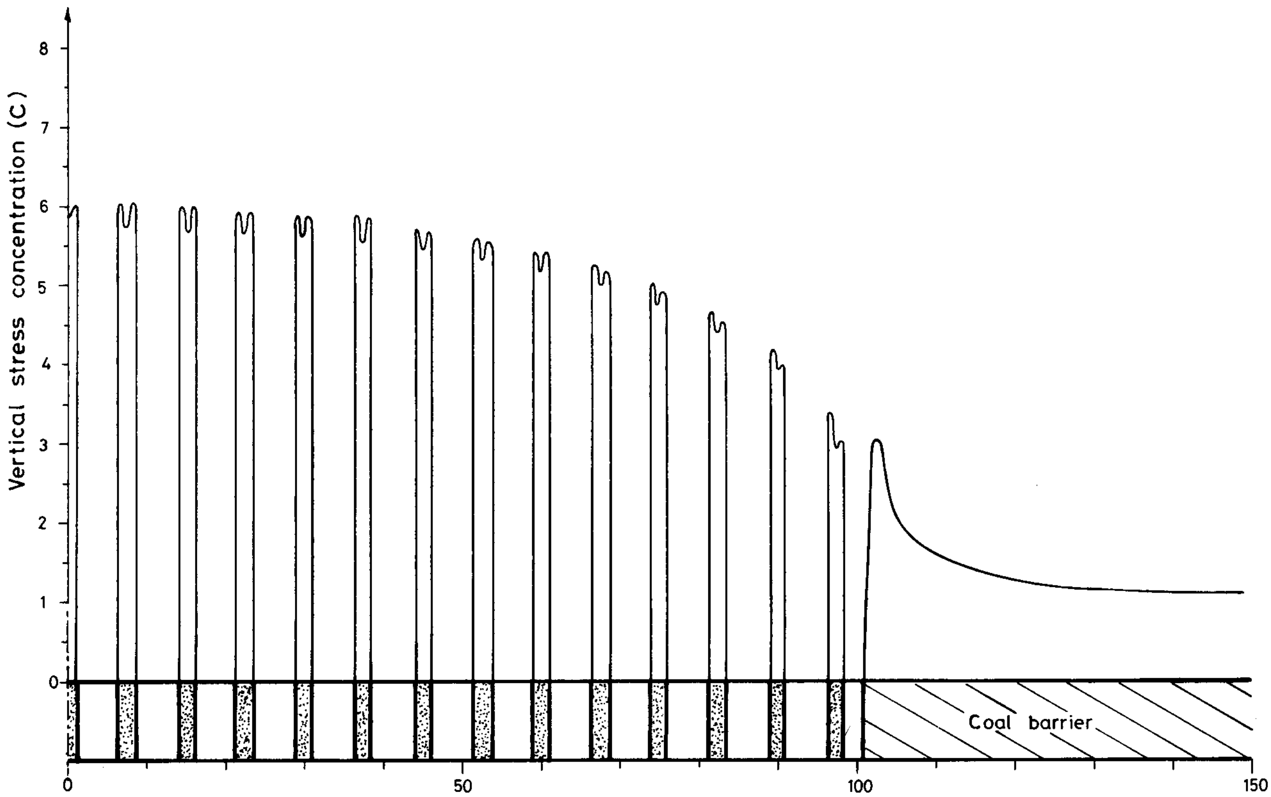

Fig. 1—Stress distribution around a 200 m-wide total extraction panel situated at a depth of 100 m. The panel is supported by artificial pillars that are constructed from a material with a modulus of compression of 1 GPa. Because the panel is symmetrical, only the right-hand side is shown.

the stress concentration at the panel abutments and working face for low values of pillar modulus of compression is evident from Fig. 2. High stress concentrations at the working faces can give rise to serious strata-control problems, and often require special support measures. In this connection, mention must be made of the difficult ground conditions encountered in total extraction panels when mining occurs under a thick sandstone roof or massive dolerite sills. An important feature of mining systems employing relatively soft support ribs is that the condition of high stress concentrations at the working face is maintained throughout most of the life of the panel, since it is the function of these ribs to prevent failure of the roof strata in the mined-out area.

It should be noted that the authors propose to compress the lower portion of the support rib to the design load so that advantage can be taken of the very much higher reloading modulus. To do this effectively, a space of at least 300 mm is required for the insertion of the jacking system. This space will have to be filled after the lower half of the pillar has been compressed. The authors envisage the use of precast slabs or wedges, and final grouting if wedges are not used. Because of the unavoidable roof irregularities and the variations in the width of the jacking space, it appears unlikely that efficient use can be made of precast elements and that extensive use will have to be made of either guniting or grouting. Because of the time required for the grout material to develop its strength properties, it will not be

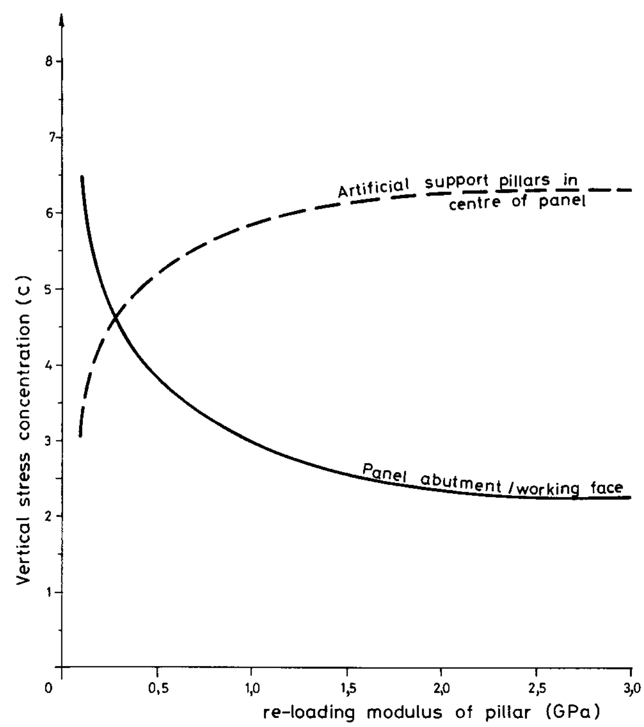

Fig. 2—Effect of the reloading modulus of the pillar material on the stress concentration at the internal support pillars and the panel abutments.

able to resist any initial strata movement effectively, nor will it be able to prevent any strata separation that may have taken place in the roof close to the working face.

Fig. 3 gives an estimate of the effects of unsupported gaps on the reloading modulus of the artificial support pillars. The trends shown in the diagram are for a pillar material that has a reloading modulus of 1 GPa, and are valid for stress levels of 10 MPa. The effective reloading modulus of the pillar will be lower than shown in the diagram for stress levels below 10 MPa, but higher for pillar stress levels above 10 MPa. The influence of even very small gaps on the effective reloading modulus of pillars is very marked, and highlights the sensitivity of the artificial pillar system to operator abuse. If normal mining conditions and the operational environment are taken into account, it is difficult to visualize that values of pillar reloading modulus in excess of 0,5 GPa can be achieved consistently and reliably. It follows therefore that, under most conditions, the artificial pillars will carry only a relatively small portion of the weight of the overburden, while the panel abutments and working faces will be highly stressed. The need for prestressed support pillars has been recognized by the authors, but its importance on the working conditions in total extraction panels has not been fully appreciated.

So far only the effect of the pillar material on the stress conditions around total extraction panels has been discussed. However, this is only one of the design parameters. Other parameters are the extracted seam height and the cross-sectional area of the pillars. These two factors, together with the pillar material, determine the stiffness, k, of the support system. The latter is directly proportional to the cross-sectional area of the pillar and the compression modulus of the pillar material, but inversely proportional to the pillar height.

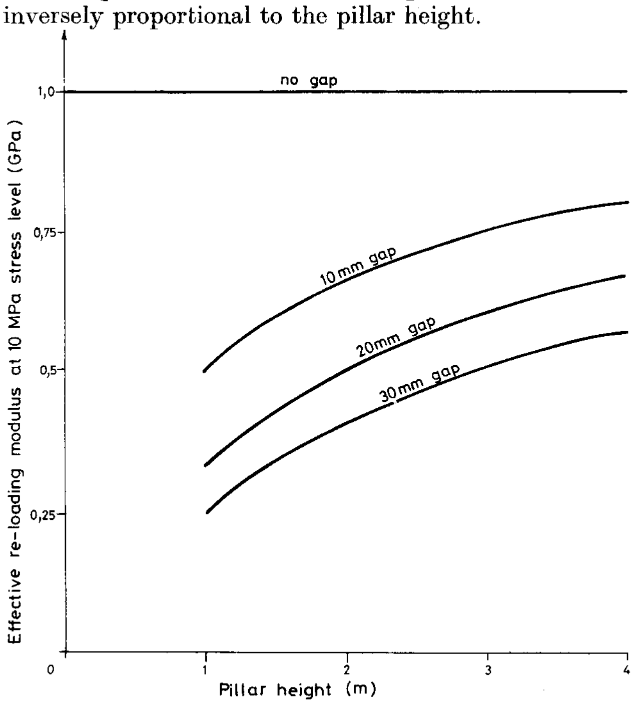

Fig. 3—Effects of unsupported gaps between tops of support pillars and immediate roof contact or strata separation on the effective reloading modulus of the pillar material.

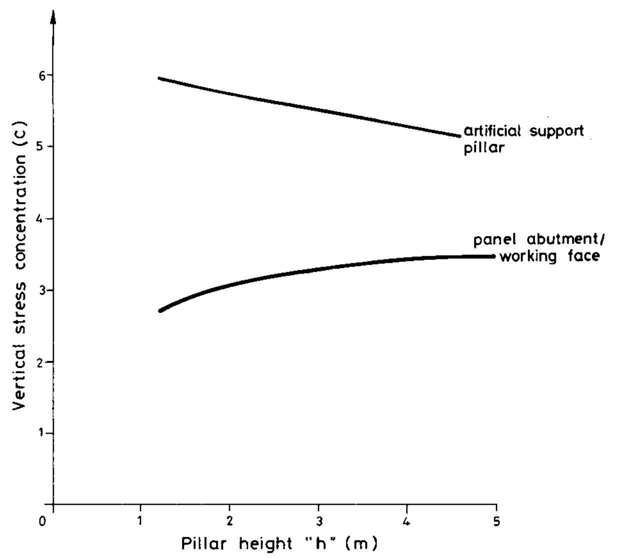

Fig. 4—Effect of pillar height, h, on the stress concentration at the internal support pillars and the panel abutment. The depth of mining is 100 m, the panel width 200 m, and the reloading modulus of the material 1 GPa.

The influence of the latter on the stress concentration around a total extraction panel is examined in Fig. 4. The reduced efficiency of the artificial support pillars at higher seam thicknesses is evident. As was pointed out above, the stiffness of the support system, and consequently its effectiveness, can be improved by an increase in the pillar area. As attractive as this approach is from the point of view of strata control it results in unfavourable economics since the cost of the support system and the time required to install it increase more or less proportionally with pillar size.

Stress Distribution in Bord-and-pillar Workings

In their paper the authors mention a second application of the artificial pillar-support system, namely that in connection with the extraction of pillars from existing bord-and-pillar workings. In this instance it is envisaged that the coal pillars are extracted under the protection of the artificial support pillars. The authors give no details as to how this could be done in practice.

A possible approach is to first install the artificial support pillars in the bords that are parallel to the line of pillar extraction, and then to split the coal pillars and install artificial pillars in the splits before the remainder of the pillar is extracted. A close examination of this, as well as of several other possibilities of extracting the coal pillars, reveals a number of logistic problems as far as the basic mining operations are concerned. By far the most serious of these are the transportation of the coal from the working place, and of the support material to the working place. Another problem area is the interaction between the extraction of the coal on the one hand and the installation of the supports on the other. For reasons of ground control, safety, and section productivity, support installation has to be concurrent with the extraction of coal. Since the building of support pillars is time-consuming and interferes with the mining of coal, the two activities have to be separated

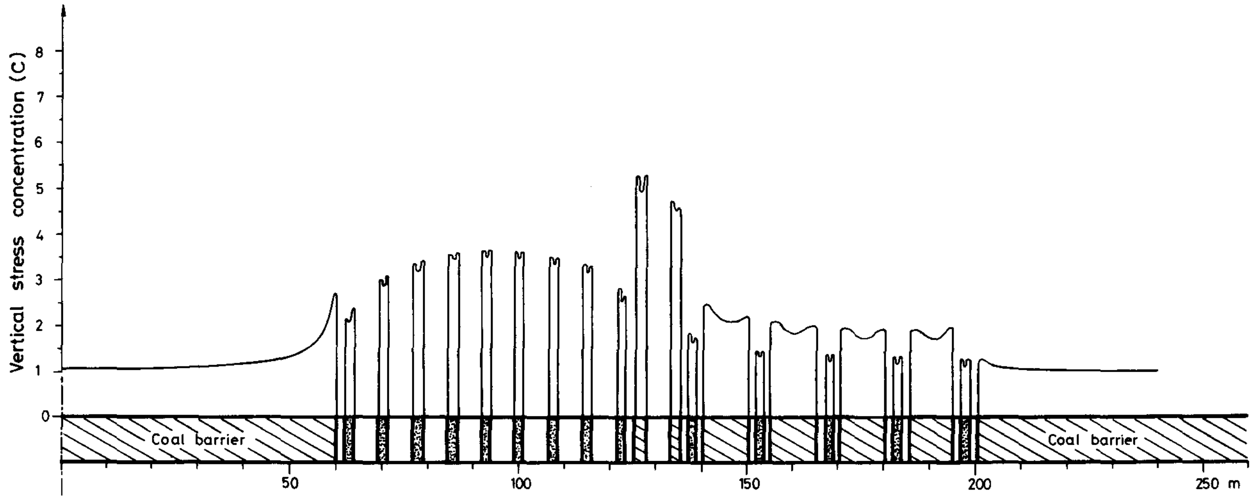

Fig. 5—Vertical stress concentration around an existing bord-and-pillar panel in which pillars are extracted according to the concept of artificial support pillars. The depth of mining is 100 m, the seam thickness 1,8 m, and the modulus of compression of the pillar material 1 GPa.

geographically. To reconcile these conflicting requirements, the mining operations have to be split into support operations in one half of the pillar extraction line, and pillar removal in the other half. Although this is organizationally feasible, it means that the number of available working places is greatly reduced. This has serious implications as far as the productivity and section output are concerned when conventional mechanized equipment is used, but is likely to be of less importance in the case of continuous-miner operations. From this discussion it follows that the economics of the artificial pillar support depend not only on the cost of the support but, even more so, on the effects of the concurrent support and mining activities on productivity, equipment utilization, and section output.

More serious than the economic aspects of the use of artificial support pillars in existing bord-and-pillar workings are some of the strata-control aspects. As an illustration of these, the extraction of coal pillars from existing workings situated at a depth of 100 m was examined. Fig. 5 shows the stress concentrations on the solid abutments, the intact coal pillars, the pillars under extraction, and the artificial support pillars. Despite the relatively small mining span of 60 m, the vertical stress concentration on the pillars that are being extracted is extremely high. Considering that the original pillars are designed with a safety factor that ranges typically from 1,6 to 2,5, it is immediately apparent that the pillars in the extraction line and its vicinity cannot withstand the very high stress concentrations without severe fracturing. The possibility of sudden failure of coal ribs in the extraction line cannot be denied. The implications of this become apparent if it is considered that most mining operations, including the installation of artificial support pillars, take place in this area. In conventional pillar-extraction operations, this danger is overcome largely by encouraging the roof strata to cave as soon after pillar removal as possible. To achieve this, a minimum amount of support is left in the mined-out area, and one of the golden rules of successful pillar extraction is to leave no pillar remnants and so provide as little support as possible to the roof strata and prevent extensive strata overhangs. The concept of artificial support pillars, on the other hand, is designed to maintain the integrity of the roof strata and to prevent roof failure as far as possible.

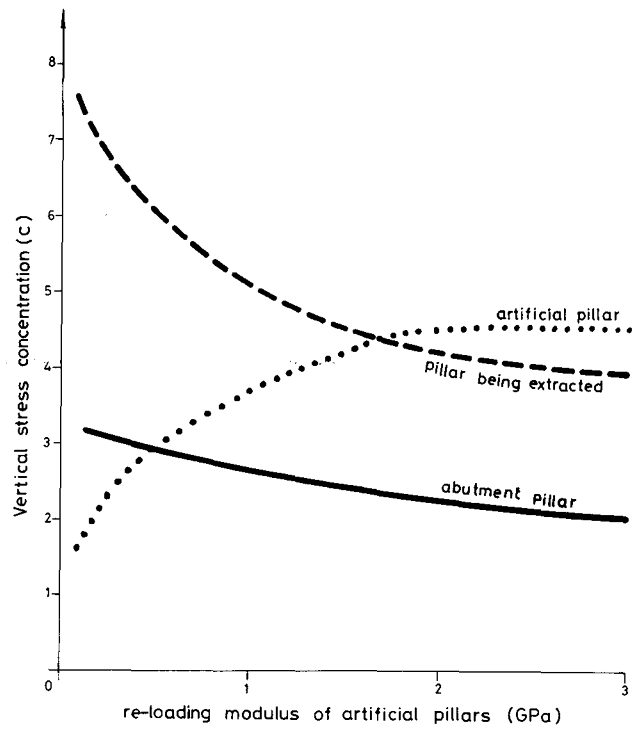

Fig. 6—Effect of the modulus of compression on the stress conditions in pillar-extraction panels employing artificial support pillars. The depth of mining is 100 m, the extracted span 60 m, and the mining height 1,8 m.

As in the previous case, the modulus of compression of the artificial support pillars is a critical design parameter. Fig. 6 shows how the stress conditions in the extraction panel depend on the modulus of compression of the artificial pillar material. Unlike the previous case, a significant deterioration of the situation is observed at moduli of compression of as high as 2 GPa.

Conclusion

We hope that our contribution has helped to clarify some of the inherent problems of artificial support-pillar systems.

Reference

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Authors' reply to Dr Salamon

We thank Dr Salamon for the time and trouble he has put into his discussion. We shall answer his points *seriatim*.

System of Horizontally Reinforced Support

Firstly, we accept that, when one attempts to apply expertise and knowledge developed in one field to another, the attempt will draw criticism and will, perhaps because of differences in terminology and experience, not even be fully understood.

We certainly do not regard the system of horizontally reinforced support to be completely developed. Indeed, we believe that development is only starting. However, we also believe that no engineering development can be finalized on the basis of theory and laboratory experiment alone. It is essential to proceed with underground trials on a limited basis in order to probe some of the queries concerning cost, the possibility of integrating wall building with mining operations, etc., that have rightly been raised by Dr Salamon (as well as by Drs Wagner and Madden).

We regard the system as described in the paper to represent a presentation of fundamental principles and ideas relating to reinforced supports. Any field trial would have to be designed specifically for the chosen site, and the entire system including supports and supported rock mass would have to be considered. We do not regard ourselves as capable of performing the necessary rock mechanics study, and the design of a field trial would necessarily be undertaken on a multi-disciplinary basis. The beam analysis contained in the paper demonstrates our awareness and concern for the interaction between the support system and the supported rock mass. It gives results that we recognize as being not entirely favourable to the proposed system. We also state quite plainly in the paper that the analysis is simplified and not claimed to represent the deformation process accurately.

Compression of Artificial Pillar

We do not agree with Dr Salamon's analysis of the compression of a 4 m high artificial pillar under a stress of 10 MPa. If the pillar has a modulus of compression of 600 MPa, the strain in the pillar will be 1/60 and the pillar convergence 4000/60 = 67 mm. Hence, we presume from Dr Salamon's figures that the surface subsidence would be about 10 mm, and not 100 mm as he states.

Dr Salamon has completely missed the point of our analysis of the strength of a reinforced cemented material. Equation (9) is perfectly general but, as soon as we insert a numerical value for the failure strain of the cemented material, it becomes material-specific; $200 \cdot 10^{-6}$ is so well accepted a value for the failure strain in tension of concrete, brickwork, and similar materials that we did not think it necessary to substantiate the value. For substantiation, Dr Salamon is referred to any textbook on concrete technology. The analysis leads to equation (10a), which, true enough, has Poisson's ratio in the denominator. However, as Poisson's ratio for the type of material under consideration lies in the range 0,1 to 0,15, we are saved the embarrassment of a predicted infinite strength.

We also point out that the tensile failure strain of a material is related to its Poisson's ratio. Thus, rubber has a Poisson's ratio of 0,5 and a tensile failure strain of several hundred per cent. Mild steel has a Poisson's ratio of 0,35 and a failure strain of 20 per cent. The corresponding values for glass are 0,2 and 0,05 per cent (depending on the state of the glass surface). We know of no real materials having a Poisson's ratio of zero, but predict that such a material would have a tensile failure strain of zero. Hence, equation (10a) would predict an indeterminate strength for this hypothetical reinforced material. This is just as sensible as the conclusion from Dr Salamon's equation (2) that the reinforcing would not affect the strength of the material.

Another point missed by Dr Salamon is that the reinforced material is deemed by equation (10a) to have failed when the strain in the reinforcing is $200 \cdot 10^{-6}$. As the yield strain of mild steel is $1000 \cdot 10^{-6}$ (again no substantiation is deemed necessary) and its failure strain 20 per cent, there is absolutely no chance that the tensile stress in the reinforcing will become a critical condition.

Fig. 19 in our paper shows that a reinforced cemented material reverts, after failure, to a granular reinforced material, and its resistance to compression is greatly reduced. This, together with the fact that the reinforcing is very inefficiently utilized, has led us to abandon the idea of reinforcing cemented material.

Reiteration of Conclusions

Finally, we reiterate our conclusions, which we have not been persuaded to change.

(i) Figs. 9 and 11 of our paper show that artificial support systems can be designed rationally.

(ii) The theory predicts support strength remarkably accurately.

(iii) Supports can be designed to suit various loads. Provided the support is not too slender (i.e. has a height-to-width ratio of less than 3 to 4), the strength is independent of the working height.

(iv) Preloading by jacking ensures that the modulus of compression is of the same order of magnitude as that of a coal pillar, although the compression modulus of coal cannot be matched.

Our final conclusion, concerning the economics of horizontally reinforced systems, will be tested as development proceeds.

Authors' reply to Drs Wagner and Madden

We find Drs Wagner and Madden's discussion very interesting and useful. It answers many of the questions that we, as civil engineers not versed in the technology of mining and rock mechanics, have been unable to answer.

Rational Design of Supports

We have already answered the criticism of our statement that, for a predetermined overburden load, suitable supports can be designed rationally. Drs Wagner and Madden's contribution goes a long way to demonstrating how the loads can be predetermined. Our statement was not, however, based on any assumptions, simplistic or otherwise, but on the solid evidence of the agreement between test results and predictive theory.

It is interesting to follow through the example illustrated by their Figs. 1 and 2 by looking at the actual stresses represented by the stress concentration factor C. Taking the unit weight of the overburden strata as 25 kN/m^3, the overburden stress is 2,5 MPa and the stress on the abutment 7,5 MPa. According to reference 5 of Dr Salamon's discussion, the abutment, if treated as a wide pillar, would fail at a stress considerably in excess of this. Hence, the factor of safety against failure of the abutment appears to be well above 2. The design strength for the artificial pillars would be $1{,}6 \cdot 2{,}5 \cdot 6{,}25 = 25$ MPa. Reference to our Fig. 13 shows that, even if ash were used as backfill, a reloading modulus of 2 GPa would be possible and, with sand backfill, easily attainable. This would reduce the abutment stress to $2{,}3 \cdot 2 \cdot 5 = 5{,}75$ MPa, which gives a factor of safety of more than 3 against failure according to reference 5. This encourages us to think that, with some further design and tailoring of the properties of the rib pillars, the hypothetical layout illustrated in Fig. 1 of the discussion would be feasible.

The discussors rightly point out the difficulty of providing artificial supports that are installed hard against the roof and are therefore as stiff as they are designed to be. We fully appreciate this difficulty and are giving it a lot of attention in our current research. We appreciate their treatment of the effect of pillar height on abutment stresses, and are relieved to find the effect so small. In our numerical example above, it appears possible to go to a pillar height of 5 m without causing the abutment stress to rise above 6,5 MPa if the pillar reloading modulus is 2 GPa. This, once again, indicates that a feasible situation should be possible with careful design of artificial pillars. We would point out, in passing, that the stiffness of a horizontally reinforced pillar depends only on the height and compression modulus of the pillar, and not on its cross-sectional area.

Figs. 5 and 6.

The situation represented by Figs. 5 and 6 certainly appears alarming. However, let us follow it through in terms of the dimensions used elsewhere in the discussion. The width of the unsplit coal ribs is not given, but let us assume that it is 6,3 m with 6,3 m bords. These sizes would fit in with the vertical stress concentration C of 2 shown in Fig. 5 for the unsplit coal ribs, and are the same as those used in Fig. 1. It would not be possible to split a pillar of this width and leave remnants of a sensible size in place. Therefore, we would suggest the building of two artificial ribs in each bord, each artificial rib being hard against the adjacent coal rib. For a vertical stress concentration of 4,5, these ribs could each be 1,5 m wide, leaving a 3,3 m bord between them. The coal rib could then be removed completely, leaving no remnants and resulting in a new bord between the artificial ribs of 6,3 m. Hence, again, we consider that a feasible system is possible by careful design.

Conclusion

We thank Drs Wagner and Madden for the effort they put into their most useful and constructive discussion.

Silver — the dangers of over-optimism

The world mining industry is in danger of having to suffer the consequences of inadvisable business decisions in both precious- and base-metal mining, taken on the basis of an over-optimistic assessment of the future price of silver. Many mining companies at present seem to be calculating on the basis of long-term silver prices in the region of US $10–15 an ounce. In the view of Commodities Research Unit (CRU) Ltd, the price of silver, in constant money terms, will be substantially below this range. This is one of the main conclusions of a new study 'Silver — The Next Five Years' published by the independent London-based research organization.

The study presents strong evidence that, in the final analysis, silver prices react to the level of above-ground stocks of bullion. After estimating the present and future levels of unreported silver stocks, CRU concludes that total stocks in private hands have reached, and are likely to remain at, higher levels than at any time in modern history. The study's analysis of investor behaviour patterns suggests that these will ultimately reflect the deteriorating fundamentals in the metal.

Since 1980, when world consumption of silver in industrial uses and coinage fell by over 20 per cent, there has been no improvement in total demand. Nor does CRU expect very much in the future. Meanwhile, world mine production grew by over 10 per cent in 1980–1981 and is likely to grow by almost as much again by the mid-1980s.

The study also contains detailed analyses of present and future trends in East–West trade, government stockholding practices, supplies from India and the Far East, and scrap.

Further information is available from

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Copper production

Pincock, Allen and Holt, Inc., an international mining and metallurgical consulting and engineering firm, has announced the release of its annual analysis of copper production costs in the non-Communist world.

The study is based on an evaluation of published data, on-site analysis, and discussions with mine personnel. The costs are broken down where possible into mining, milling, smelting, refining and freight, general byproducts and depreciation, depletion, and amortization. Also included are tables on mill recoveries, the metallurgical accounting at major mines, ore production and reserves, statistics on stripping ratios, and breakdowns of mill operating costs, copper-smelting energy costs, block-caving costs, and capital costs.

By mid 1982, the production costs of mines in Chile, Peru, and South Africa had experienced the beneficial impact of currency devaluations, which in some cases resulted in a decrease from mid 1981 costs (measured in U.S. cents per pound).

For more information, contact Randall J. Scott, Pincock, Allen and Holt, Inc., 1750 East Benson Highway, Tucson, Arizona, U.S.A. (85714-1798, U.S.).