The risk of encountering 'unexpected geological difficulties' in longwall coalmining—risk assessment, risk insurance and risk reduction

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Introduction

In many countries where deep coal is mined, the longwall method is the usual method of extraction. About half the world's coal is mined in this way. Shallower coal may be extracted by room and pillar methods, or even by opencast methods if the coal is very close to the surface. In the United States there is very little longwall mining because there is an abundance of easily accessible coal at shallower depths, where longwall methods are unnecessary. In many other countries, particularly in Europe, the Soviet Union and the People's Republic of China, most of the available coal is at depths where longwall mining has proved to be essential for extraction.

The longwall method of mining is very inflexible and very sensitive to interruptions in coal seam continuity. Whenever production of coal is stopped by a hitherto unknown break in coal seam continuity, it is usually attributed to 'unexpected geological difficulties'. The extent to which such difficulties could have been anticipated depends on how well the geology of the coal reserves is known. In order to avoid, or minimize, the risk of encountering such difficulties, it is necessary to explore the geology in the target area in sufficient detail before planning the extraction.

This point is so obvious that one might think it need not be made. However, the history of mining shows a great reluctance on the part of mining engineers to carry out the required exploration in advance of mine planning. Some exploration is usually done to prove the reserves, of course, but this is not normally detailed enough to define precisely the geological constraints on mining operations. These have tended to be discovered in the course of mining, and have sometimes caused economic failure of the mine. We can learn from our mistakes.

This paper describes the effects that so-called 'unexpected geological difficulties' can have on longwall mining operations, using examples from British coalfields. It also discusses how insurance is normally made against the risk of encountering such difficulties, how the risk can be calculated to determine how much insurance should be carried, and how both the risk and the insurance may be reduced, in certain geological provinces, by exploration.

The longwall mining method

The main features of a longwall coal face are illustrated in Fig. 1. A rectangular panel of coal is extracted by moving a tunnel sideways between two parallel roads in the coal seam. These roads are linked to the main underground network and, via this, to the surface. The tunnel between the roads is formed between the coal face on one side and the roof supports on the other, as shown in Fig. 2. The supports have cantilevered roof shields which protect the men, coal cutting machinery, and face conveyor system. As the coal is cut away from the face in slices, the coal cutting machinery, face conveyor system and roof supports advance, allowing the overburden to collapse behind into the rectangular worked-out area, to form what is known as the 'goaf'.

Fig. 1. The main features of an advancing longwall coal face.
Figure 3 shows a view down a longwall face. In a typical longwall face of 100 m length the machinery may well weigh as much as 2000 tonnes and cost about £6 million sterling. The face must then advance far enough and fast enough that the value of the coal extracted not only pays for the cost of equipping the face, but also pays a contribution towards the running costs of the mine. These costs include miners' wages and return on the investment made to provide access to the coal. The face must advance uninterrupted at a given average rate in order to pay for itself. Suppose, for example, that this face was one of three such faces in a mine required to produce one million tonnes of coal per year to break even. The density of coal is about 1.3 tonnes m$^{-3}$, therefore the volume of coal to be produced is about 770 000 m$^3$. If the coal is 2 m thick the worked out area must increase by 385 000 m$^2$ per year. That is, each of the three panels must advance approximately 130 m per year or about 2.5 m per week.

**Unexpected geological difficulties and risk insurance**

Suppose one of these faces unexpectedly encounters a discontinuity in the coal seam, such as a sandstone washout or a fault. Normally any fault with a throw of seam thickness or greater will stop a face, while faults with throws less than this will slow down production. Figure 4 shows a sketch of a coal face advancing towards an unknown fault. If this fault were encountered towards the end of the planned life of the fault – near to the position where the face was planned to stop anyway – there would be almost no break in production. Production would continue on a new face all ready to start its life. On the other hand, if the fault were encountered early in the life of the face, there would be no new face ready to replace it, and production on that face would stop for perhaps three or four months, while the face was re-established to mine coal avoiding the fault. In this case it would be necessary to decide whether to turn the face and advance parallel to the fault, whether to drive a new face on the other side of the fault and transfer the equipment, or whether to abandon the face altogether and start a new one somewhere else. In the meantime the loss of three or four months’ production on this face would have to be made.
creasing production on the beginning production on a spare face, it for three shifts. But if the face is already being worked on the face: in principle the face is already being worked face to keep in reserve against the risk at full capacity.

The greater the production of coal from the production faces is stopped by unexpected geological difficulties. The cast of maintaining a spare face is those which can produce faces, and the easier it is to maintain a spare face. It follows that the production faces are those which can produce the most coal, and the spare face is the weakest face in the mine. When production is halted on a production face by some unexpected geological disturbance it is usually impossible for production on the spare face to make up for all production of coal lost while a new face is being set up.

There is always a risk that production will be halted by unexpected geological difficulties. The mine manager can insure against this risk by operating his production faces at less than full capacity, or by carrying a spare face, or by doing both. The way it is handled in any individual mine depends on many factors including the supply of labour, the availability of spare machinery, and so on. In any case it is clear that the cost of this form of insurance is high: without it the mine could be operated at full capacity to produce more coal for very little increase in operating costs. That is, the coal would cost less to produce. If the risk of encountering geological difficulties can be reduced, the cost of insurance can be reduced and the cost per tonne of coal is reduced.

Conventional risk reduction
In mining, the principal method used to reduce the risk of encountering unexpected geological difficulties is to make exploratory drivages and mine by longwall retreat. Figure 5 shows the main features of a longwall retreat face. The two parallel roadways are driven out from the main road first, and the coal is then extracted by moving the face back between the roadways. The risk of the face encountering unexpected geological hazards is reduced, for only after the geology has been 'proved' by the roadways will the face be set up. Suppose the roadways prove that there is a fault with a throw exceeding seam thickness cutting the planned panel. If the fault cannot be carried on the face, then the face will not be set up. Only this development work will have proved abortive, not the whole face.

In coal deep enough to require longwall mining, it is impossible to obtain sufficient production from the development roadways; faces must also be set up. When development proves abortive, fresh developments must be made underground to find suitable places for retreat panels. If the geological structure is not well known in advance it is likely that underground development drivages will prove abortive in several areas of the mine. This abortive development work makes it impossible for these areas to be mined. The coal reserves in these areas thus become sterilized.

For the longwall method to prove effective, it is necessary to find pieces of coal into which the rectangular panels will fit. Underground drivage is one way to find such places, but it may also sterilize an important fraction of the reserves. If the geological structure can be established before the underground developments are made, using a combination of boreholes and seismic exploration, there are a number of benefits:

1. The risk of encountering unexpected geological difficulties is reduced, and the cost of spare capacity required to insure against this risk can be reduced, thus reducing the cost of the coal production.

2. The amount of abortive underground development work will be reduced, and the ratio of effort spent on
development to effort spent on production will decrease, thus reducing the cost of coal production.

(3) The quantity of coal reserves sterilized by abortive development will be reduced and the percentage extraction in any seam can therefore be increased. Therefore, the coal produced for a given capital investment to obtain access to the coal will be increased, and the need to sink costly new mines to maintain production will be reduced.

These are very important considerations. Longwall mining, and particularly longwall retreat accounts for most of the deep mined coal production in the world.

Assessment of the risk

From the point of view of a mining company, a distinction must be made between coal 'reserves' and 'assets' (Dunham 1976). A coal reserve becomes an asset when economic conditions favour an investment in facilities to extract the coal. The reverse is also true: when economic conditions become unfavourable for extraction of reserves previously regarded as assets, they cease to become assets. The assessment of reserves is the evaluation of the quantities of coal that exist. These reserves may then be classified or ranked as assets in terms of the financial risk involved in their successful extraction, under the economic conditions existing at the time of classification. These conditions change with time; therefore, classification of reserves must be reassessed periodically.

Suppose conditions favour extraction of a certain part of the coal reserves. This coal may be extracted by an extension to an existing mine or by a totally new mine. Suppose a broad programme of exploration by drilling on a 2 km by 2 km grid has taken place to determine the average depth and thickness of every seam in the reserves area, and the approximate lateral extent of each seam. Suppose the known reserves in place are at least 300 million tonnes and that it is planned to begin extraction with a new mine designed to have a production capacity of two million tonnes per year. (It is planned to have a long life).

What will the initial layout of the mine be? This should be such as to provide the easiest access to the coal for the minimum cost, and should be designed such that the output from the mine can be easily transported to the market. The less that is known about the geological structure of the coal, the more freedom there is to design a mine layout, but the greater the risk that any given layout will be inadequate to meet unexpected geological difficulties. How do you assess the risk? And how do you reduce the risk if it is too high? These questions seem obvious, but it is really only since the 1970s that they have been answered in any systematic way.

Failure to assess the risk—the example of Bevercotes

In the United Kingdom the attitude to mine planning changed in the 1970s after the most modern mine in the country, Bevercotes, failed to live up to the expectations of the mining engineers who planned it. Bevercotes was supposed to produce one million tonnes of coal per year, but in its first seven years produced hardly any coal because the new modern highly mechanized longwall faces were always stopped by unexpected geological difficulties. This occurred in the 1960s. By about 1970 it was recognized that the concentration of resources and capital into fewer large longwall faces increased the level of risk over the earlier room and pillar working method, and the risk could only be reduced by obtaining more detailed knowledge of the geology. This realization did not come overnight and even today there is no worldwide agreement among mining engineers that there is any great necessity to spend money on detailed investigation of the geology before planning the mine layout.

The main motive behind Bevercotes was the modernization of British coal production in the face of falling oil prices, and the reduction of production costs by replacing men with machines. According to Ironman (1974):

“At one time, in the 1960s, it was the dream of senior management within the National Coal Board that the mine (Bevercotes) should become the first fully automated mine in the world. Faulted coal seams, 3000 feet deep in virgin territory, prevented this dream from becoming a reality.” (p. 64).

“Since it first started production, Bevercotes has experienced seven years of serious problems, each new difficulty following closely upon the heels of the previous one. There has followed three years of extensive roadway drivage and investigations and 18 months of high productivity coal mining.” (p. 70).

The proving roadways referred to by Ironman are shown in Fig. 6. Bevercotes was sunk in a southerly extension of the Nottinghamshire coalfield. The reserves were established with seven boreholes. For many years the only methods of exploration available to the management of Bevercotes were boreholes from the surface and underground exploration in the form of tunnel drivages and mining. Two decades after the mine was opened Bevercotes is now producing more than enough coal to cover the running costs.

One advantage that Bevercotes has – in common with many other mines – is that there are several workable seams. The large normal faults which halted production in the first few years of production cut through all the seams, the throw tending to increase slightly with depth. Once the position and throw of the fault is known in one seam, it can be projected into seams above and below (see Fig. 7). In this way it is possible to prove the structure in one seam and to adjust the mine layout in the seam above and below to ensure that the longwall panels fit into the proven structure. If there are several recoverable seams in the sequence it is possible to make a loss in the first seam, but to make such a profit in the
subsequent seams that overall the mine gives a reasonable return on investment eventually. Normally, of course, it is not possible to wait 20 years for the mine to make a profit; the decision to invest is based on the expectation of a more rapid return.

**Seismic surveying to reduce the risk — the example of Selby**

The level of investment risk clearly increases when only one seam is to be mined. This is the case at Selby in Yorkshire, England, planned to be the largest deep mine in the world.

The Selby Coalfield lying between York and Selby was discovered early in the 1970s and is a northeastern extension of the East Pennine Coalfield of Yorkshire, Derbyshire and Nottinghamshire (Fig. 8). The surface of the coalfield is a low-lying farming area drained by the slowly flowing Yorkshire Ouse. The average level of the land is 6 m above sea level. The coal lies at depths from 600 to 1200 m, dipping from west to east. There are four workable seams in the area, the thickest being the Barnsley Seam with an average thickness of about 2.7 m. If the Barnsley Seam alone were extracted using the longwall mining method, the collapse of the overburden would cause subsidence amounting to about 1 m, reducing the level of the area to 5 m above sea level. Since no subsidence in excess of 1 m can be tolerated in this low-lying area, this imposes the constraint that not more than one seam can be mined. Nevertheless, the mining conditions and the quality of the coal were believed to be so attractive that a new mine with a capacity of ten million tonnes per year was planned (Mills 1975), based on extraction of only the Barnsley Seam.

The exploration of the reserves was planned on a grid of boreholes at 2 km intervals in both the north–south and east–west directions, to cover an area of about 250 km². This amounts to about 60 boreholes, which is a large number for the determination of the reserves of a new mine. Nevertheless it was not sufficient to establish the best layout of the mine and the retreat panels. Panels have dimensions of the order of 200 m and are affected by structure on a scale at least an order of magnitude smaller than can be inferred from interpolation between boreholes spaces at 2 km intervals. After the experience at Bevercotes it was clear that there would be an unacceptable level of risk to the Selby plan unless the main structural trends were determined before any financial commitment to a particular layout was made.
These structural trends were determined by seismic methods at the instigation of the Chief Geologist of the National Coal Board (NCB), A.M. Clarke, who was solely responsible for apprising the NCB management of the nature of the risk and the consequent necessity to determine the structural trends in the area. The Selby seismic survey of 1973–74 was the first ever major seismic survey designed to reduce the level of investment risk in a coal mine. It permitted the NCB to make the necessary financial commitment to a mine plan which took the determined structure very much into account, without an unacceptable level of risk (Clarke 1976).

Assessment of the risk of encountering unexpected geological difficulties: Geosimplan

The determination of the risk of encountering unexpected geological difficulties is a non-trivial task. The simplest way to think about it is in terms of money. First, the mine requires a certain capital investment to obtain access to the coal reserves, and there has to be an agreed rate of return on that investment. Secondly, in extracting the coal there are operating costs in the form of salaries and wages, cost of electricity, maintenance and replacement of equipment, and so on. The return on investment and operating costs must be paid for by the sale of the coal. The operating costs can be minimized by carrying no spare capacity and no other insurance in the form of spare faces or development drivages. If any of the production faces is stopped or slowed down unexpectedly by geological difficulties, the coal output suddenly drops and production is insufficient to cover the return on investment and operating costs: the mine is making a loss.

Spare capacity and underground development drivages are forms of insurance essential to maintain production. However, they increase the operating costs. The higher the costs of these forms of insurance, the greater the volume of coal production necessary to break even.

The question of the risk can be posed as follows: How much additional coal must be produced to cover the cost of insurance necessary to maintain production? This question is easy to pose, but it can be answered only when it is known how much insurance is necessary and how that insurance is to be split between spare shifts, spare faces and underground development work. This of course is a problem for the mine manager, who will attempt to mine the coal as efficiently as possible. Without constraining the freedom of the manager, it is still necessary to determine whether the overall plan to extract the coal is likely to succeed.

In the NCB in the United Kingdom any proposal for a major investment in a new mine plan, or a new extension of an existing mine, must demonstrate that the plan is likely to succeed before the proposal can be financed. One of the crucial elements in this demonstration is the testing of the mine plan against a number of possible geological models. (This test is known as Geosimplan in the NCB and is the invention of A.M. Clarke.) The mine plan has to be robust in the face of geological difficulties.

In each area the mining conditions are different. Elliott (1974) analysed 29 instances where geological factors reduced coal face performance in the East Midlands Region of England. In each case the problem was small enough to be overcome on the face without halting production entirely, but the loss of production was nevertheless significant. In fact, the total loss of output for the 29 faces considered amounted to 56% of the normal shift production.

In a given coalfield there is usually a huge volume of information, gathered over years, of the kind of difficulties likely to be experienced. As the coal is worked, a map of the geological structure and sedimentary setting can be made, more details being added with the advance of every coal face and every underground roadway. Statistics of the geology can be assembled to determine, for example, the number of faults per square kilometre, the strike directions of the fault systems, the percentage of faults which have a throw in excess of seam thickness, and so on. In a hitherto unmined area of the coalfield it is possible to
postulate an infinite number of different models which can be made to fit to known information within the area. These hypothetical geological models will have different structures and sedimentary features, but will also have geological statistics consistent with those of the coalfield. The robustness of a given mine plan may be tested against a number of these hypothetical models.

The test is performed as follows. The mining engineer and his team are armed with a certain amount of information about the geological structure, both from exploration (usually boreholes from the surface and mineworkings underground) and from regional geological considerations. A basic mine plan is drawn up together with a mining strategy including some insurance in the form of spare shifts, spare faces and underground drivage. This plan is now put into action on paper on a week-by-week basis to see how much coal is produced. At the end of each week the expected face advance and coal production are checked against the geological model, which is not disclosed to the mining engineer’s team. They find, for example, that one face advances as planned, another meets a fault on the left hand side with a throw equal to three times seam thickness, and one of the development drivages finds that the seam is splitting. With this information they plan the following week’s production. At the end of the following week, they find a little more about the geological model and adjust the plan again. This continues for the equivalent of, say, five years. At the end of this test the mining engineer and his team find how the mine plan and mine strategy have performed in one geological model. The exercise must then be repeated for a number of geological models.

It may emerge that the mine plan is particularly sensitive to geological structure. For example, if the main roadways of the mine are planned to be north-
south and east–west, and the main structural trend happens to be northeast–southwest, then the basic layout of the mine will not fit into the structure of the geology, and every main roadway will encounter difficulties until the underground plan is rotated by 45°. In such a case the test would show that it would pay to spend some calculable sum of money on exploration to determine the structure first in order to avoid enormous probable costs in production. It was exactly such a consideration that led to the Selby seismic survey of 1973–74.

The Geosimplan method can be used to test various mining strategies. For example, the mine manager may wonder whether it pays to do more development drivage and have fewer spare faces; whether to have a larger number of shorter faces; whether to carry more spare faces; or whatever. In an anthracite mine in South Wales which had been making an enormous loss every year for many years, Geosimplan was used in the late 1970s to determine which of a number of mining strategies would be the best for the mine. Each strategy was tested against a number of models. It was found that none of the strategies could make the mine avoid losses. The problem was the geology. The anthracite seam was known from previous workings to contain numerous faults with throws of about seam thickness and with strike lengths of the order of 100 m. There was no general trend to the strike direction. The intensity of this faulting was such that there were not enough unfaulted pieces of coal into which rectangular panels could be made to fit. The loss of production on nearly every face as faults were encountered, could never be made up on other faces which always encountered similar problems.

The conclusion which one independent observer could reach, was that longwall mining could not pay in this environment.

The cost-effectiveness of exploration

Seismic reflection surveys have been applied successfully to reduce mining risk since the 1970s in the United Kingdom (Goulty and Ziołkowski 1985; Ziołkowski 1981). More recently, Allen (1986) has looked into the cost-effectiveness of exploration – including both seismic reflection and boreholes – to reduce the level of mining risk in the South Wales Coalfield. Because of the steep hills and valleys in South Wales, this coalfield is particularly difficult to explore and exploration costs are high in this region. Nevertheless it can be deduced that exploration has paid for itself handsomely. Allen has made several deductions from his analysis that are worth quoting:

“... On average, two out of every three mining investments in new reserves in South Wales will fail financially, unless the projects are based on detailed exploration. There are no data to quantify the reduction of risk made by modern exploration programmes, owing to the long lead times between prospecting and mining. However the first part of this paper demonstrates that most geological features which seriously affect mining can now be detected and evaluated through surface exploration; and it is considered very unlikely that serious geological difficulties causing heavy consistent losses would be undetectable by current exploration methods, so major financial failures due to geology are avoidable in the future.” (p. 565, my emphasis).

On the level of expenditure, Allen deduces that “the data presented suggest that an average of £0.50 sterling per tonne (about 1% of break-even mining costs) would be appropriate in South Wales” (p. 565). This is about three times the 1985 level of expenditure on exploration. The appropriate level of expenditure in South Wales would then be about £3.5 million per year and boreholes and seismic lines would be so close together that “most of the unforeseen geological problems that have caused financial failure of many South Wales projects in the past would be avoided.” (pp. 565).

South Wales produces somewhat less than ten million tonnes of coal per year. Worldwide deep mined coal production is about 1200 million tonnes of coal per year. There is clearly an enormous potential for reducing the risk – and therefore the cost – of future deep coal mining projects by doing detailed exploration first.

Conclusions

Not all the causes of lost coal production can be attributed to major geological structure, as Elliott (1974) demonstrated. Nevertheless it is possible to estimate the likely cost of not knowing the geology in more detail. The cost can be quantified, using the Geosimplan method, in terms of lost production and coal reserves likely to be sterilized if the mine plan is not a good fit to the geology. Once this cost is known, it is possible to determine what price can be paid to obtain more detailed information about the geology.

The resolution from seismic surveying has been steadily improving since the 1960s, and it is now possible to detect washouts, seam splits and faults with throws on the order of 1% of the target depth (that is, a fault with a throw of 5 m is detectable at a depth of 500 m). In good data areas the resolution may be even better than this; in a poor data area it will be worse. The quality of the seismic data that can be obtained in a given area can only be determined by experiment.

The quality of the data determines the scale of geological features that can be resolved. In some geological provinces a careful combination of seismic surveying and boreholes has paid for itself many times over by providing crucial information on the geology of the coal reserves in advance of mine planning. Indeed, such exploration can make the difference between
probable success or probable failure of a mining project—as in South Wales (Allen 1986). From the results of the exploration the mine plans can be made to fit the known geology, and mining strategies can be developed, with the aid of Geosimplan, to build in the minimum insurance, or spare capacity, to handle the remaining anticipated “unexpected geological difficulties” below the resolution of the survey.

In such geological situations the benefits of this approach are as follows:

1. The risk of encountering unexpected geological difficulties is reduced; the cost of spare capacity to insure against this risk can therefore be reduced, and thus the cost of production is reduced.

2. The amount of abortive development work is reduced, and the ratio of effort spent on development to effort spent on production is reduced, thus further reducing the cost of production.

3. The quantity of coal reserves sterilized by abortive development is reduced and the percentage extraction is therefore increased. Therefore, the coal produced for a given capital investment to obtain access to the coal is increased, and the need to sink costly new mines to maintain production is reduced.

Exploration costs in coal mining are normally much less than the 1% of total costs that Allen (1986) regards as appropriate in South Wales. It is extremely likely that both the coal industry (worldwide) and the exploration industry (worldwide) would benefit if intensive exploration before mine planning were more widely practised. Ultimately, the consumer of energy would also benefit, as the costs of encountering “unexpected geological difficulties” would then become very much reduced. Currently, these costs simply make the coal unnecessarily expensive.

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