Beyond Coalbrook: what did we really learn?

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Transaction Paper

Synopsis

Rock engineering research and technology development in South Africa received serious attention in reaction to the Coalbrook disaster only in 1960. At the time, a number of gaps in knowledge of rock-related matters were identified and in the ensuing years, these were progressively attended to.

The paper describes the events that led up to the Coalbrook disaster and reviews the developments that took place afterwards. The effectiveness of the research outcomes is tested by referring back to the disaster. It is concluded that tremendous advances were made but that not all the unknowns were attended to at the same level. The strength of nominally square internal pillars is the one issue that received the most attention, but the strength of barrier pillars, overburden behaviour and loading systems is still largely unknown.

Due to the complexity of the remaining unknowns, they can and should be addressed by the application of back calibrated numerical models. There are no readily available simple analytical solutions.

The state of mining rock engineering research in South Africa borders on an emergency. More than a 1 000 years of aggregate research experience has been lost in the last three years and funding is under severe pressure. There are disturbing parallels between the current positioning of the industry as a whole and the Coalbrook mine in the years preceding the disaster.

Introduction

Coal mining in South Africa started with the gathering of coal from outcrops in the Kwa-Zulu-Natal province by the indigenous Zulu people. Later, after the colonization of the Cape by the Dutch, a small deposit was exploited in the Franschoek Valley in the 17th century.

The Talana Hill mine near Dundee in KwaZulu-Natal, which started production in 1860, was the first underground mine. After that, the Molteno coalfield, which commenced production in 1864, could be regarded as the first serious mining of coal.

Following the opening of the gold mines on the Witwatersrand and the diamond mines in Kimberley, coal was also mined in the Vereeniging and East Rand areas for energy supply.

The current mining activity is concentrated in the Witbank coalfield, most of the KwaZulu-Natal mines having closed down. The bulk of the remaining reserves is contained in the Waterberg, where the coal-seams are deep and thick with interlayered stone bands. The infrastructure in that area has not yet been developed to an extent that will allow high production mining and water is scarce. For the time being, there is limited mining activity, but studies to investigate infrastructure requirements are already underway in anticipation of the depletion of the Witbank reserves.

Today, South Africa is the world's fourth largest coal producer at just less than 250 Mtpa and the second largest exporter. More than 40% of the coal produced is used for the generation of electricity. The single most popular mining method is bord and pillar, accounting for more than 50% of production. The most popular high-extraction methods are pillar extraction and longwalling. The frequent occurrence of intrusive dykes is a barrier to more widespread application of longwalling.

Safety is a major concern. While significant improvements have been made over the last years, the fatal accident frequency rate is still above an acceptable level at 0.42 per thousand workers per year—as recently as 1993, the rate was almost four times higher at 1.57 per thousand per year. Rock related accidents still account for more than 30% of all the fatalities and it is the biggest single cause of fatal accidents.

The aim of this paper is to describe the progress that has been made in ground control measures and to give a personal view of the future.

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History of rock engineering technology development

The first rock engineering application to mining, was done not by a researcher but by a mine manager in the 1950s, FG (Pinky) Hill, manager of the ERPM gold mine. He implemented a suggestion by Roux and Denkhaus (1954) to reduce the frequency of rockbursts by destressing stope faces. The success of the method was reported by Hill and Plewman (1957). Gold mine stopes are destressed by controlled blasting in deep holes ahead of the working faces. The technique, although shown to be effective, was discontinued, presumably due to the difficulty at the time with the drilling of the longer holes. The method has lately (after re-introduction) become known as pre-conditioning, see Toper *et al.* (1998).

Development follows need. The major need for coal mine rock engineering safety research in South Africa was identified when the Coalbrook disaster occurred on 21 January 1960. In total, 437 workers lost their lives when pillars over an area of 324 hectares (1.25 sq. miles) collapsed. Following the disaster, the South African government sponsored research into coal mine safety by forming the Coal Mines Research Controlling Council (CMRCC). Research to find a method to determine pillar strength received the highest priority, both from the then state owned Council for Scientific and Industrial Research (CSIR) and the industry funded Chamber of Mines Research Organization (COMRO).

Coalbrook

It is perhaps pertinent to summarize the important aspects of the Coalbrook collapse at this stage. Refer to Figure 1, a copy of the mine plan. Later, the technology that was developed over the intervening 46 years will be tested against Coalbrook, asking the question whether we are still vulnerable to a similar disaster. Note that Coalbrook was not the last pillar collapse in South Africa. A further 23 collapses occurred in areas that were mined after 1969, when the Salamon and Munro (1967) pillar strength formula was widely applied, see van der Merwe (2006). However, there has not been a similar disaster in terms of casualties.

Geology

The coal in the Vaal Basin occurs near the bottom of the Ecca series, of Permian age, of the Karoo system. The Ecca series consists of sandstones, shaly sandstones, sandy shales, carbonaceous shales and subordinate coal-seams.

Three coal-seams occur in the Coalbrook area, the No. 1, No. 2 and No. 3 Seams, named from the bottom up. Initially only the No. 2 Seam was mined (at a depth of 137 m)—this is the seam on which the pillars collapsed. At the time of the disaster there was limited mining on the No. 3 Seam, remote from the collapse area. The coal was deposited on an uneven pre-Karoo floor consisting of lava. The seams are predominantly flat (as is the surface) and pinch out on the edges of the pre-Karoo valleys.

Two major dolerite dykes traverse the area, striking north-east to south-west. There are no major faults. There is a horizontal dolerite sill in the overburden, approximately 40 m thick. The parting between the base of the sill and the No. 2 Seam is approximately 80 m.

Mining history

(Note: the information contained in this and subsequent paragraphs was obtained from Government Mining Engineer (1965), a report on the disaster produced by the Government Mining Engineer, CM Moerdyk, four years after the event. After the formal inquest-enquiry, the state appointed a commission of Enquiry inti safety into mines, headed by a judge of the Supreme Court. In December *1960, the* Commission issued an interim report and recommended that the Government Mining Engineer should complete the investigation, resulting in the quoted report.)

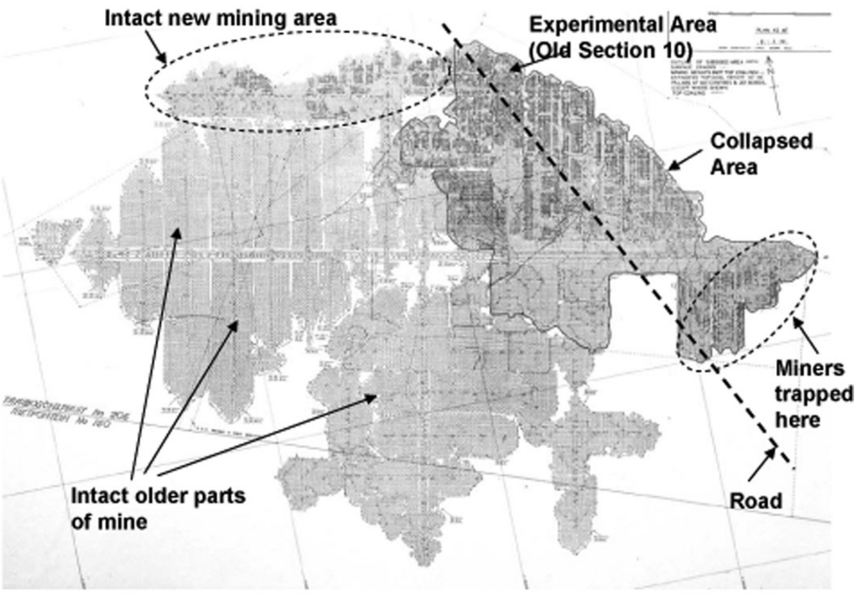

Figure 1—Plan of the mine at the time of collapse. The collapsed area is the outlined area in the eastern part of the mine. Note the orderly mining in the older western part of the mine and the obvious presence of wide barrier pillars between the panels. Later, reference will be made to the narrow strip north-west of the collapsed area, where collapse did not occur. The other important feature is the experimental area in the top left-hand area of the collapsed area. This is a reproduction of a very old copy of the mine plan. The mined area is about 5.6 km east-west and 3.7 km north-south

The first Coalbrook shaft was sunk in 1905. Between then and 1908, 3-road development was done north and south with 6.7 m wide roadways on 24.4 m centres. From this, secondary 3-road development was done west on the same dimensions (development toward the east was limited due to seam undulations and unfavourable mining conditions).

From the east-west development, panels up to 300 m wide and 900 m long were mined with 6.7 to 7.3 m wide roadways on 24.4 m centres at a height of 2.4 m. The panels were separated by 24.4 m wide barriers (i.e. equal to the pillar centre distances).

From 1932 onwards, attention turned to mining south and east of the shaft. Pillar centres were reduced to 19.8 m and bord width to 6.1 to 6.7 m, still at a height of 2.4 m. Barrier width was reduced to 18.3 m and dummies were often cut into in the barriers.

By 1949, pillar centres had been reduced to 18.3 m and barriers to 12.2 m, still with 6.1 to 6.7 m wide roadways. Barriers by then were extensively mined. In 1948 limited top coaling was done, increasing the height to 3.7 m. However, this practice was discontinued due to the inferior quality of the top coal.

In 1950 the planning of a thermal power station in the district started. Coalbrook was awarded the contract for coal supply and in 1954 the first generators came on line. This had a dramatic impact on the mine, as production had to increase from 1 600 tons per day to 10 000 within a period of four years.

The Electricity Supply Commission engaged a prominent mining engineer, F.A. Steart, to report on the mine's ability to supply the required coal. Steart pointed out that '…competent planning, technical equipment and organization would be necessary if the greatly increased output were to be maintained safely…' and, in drawing attention to the 'poor support strength of the No. 2 Seam', recommended that the mining height be limited to 2.9 m with extraction not exceeding 40% (note: with 6.1 m wide roadways, this requires 27.1 m centres). He also recommended that 'adequate barrier pillars' should be left around panels where mining was done on 18.3 m centres and 6.1 m to 6.7 m wide roadways.

The top coaling practice was revived in 1951, again in limited fashion, but by 1957 it had become a major source of output. It was done on the retreat, to a height of 3.7 m. During 1957, the general top coaled height had increased to 4.3 m, reaching 5.5 m in places.

In 1957 the Inspector of Mines, concerned about the number of local roof fall accidents during top coaling operations, required the mine to limit road width to 6.1 m and the mining height to 4.3 m. From then on, top coaling was done on the advance to a height of 4.3 m, and more in places.

During the period 1954 to 1958, the mine's output increased from 134 240 tons per year to 2 260 660 tons, almost a 17-fold increase.

The experiment

In order to meet production requirements, the mine felt the need to do secondary extraction in the form of top coaling and pillar reduction in the old mining areas to the west of the shafts. It was decided to precede this mining by an experiment. However, the experiment was done in the more recently mined areas east of the shafts, due to easier access.

The area that was chosen was the old No 10 Section, an area where mining had been completed in 1952. To the north the area was bounded by solid where the coal pinched out on the Pre-Karoo ridge (the coal also dipped up in the area). To the west there was mostly unmined ground and to the south was a 12.2 m wide partially mined barrier. To the east, there was a working section separated by solid coal in the north and a 12.2 m barrier in the southern area.

The experiment consisted of cutting dummies 4 m wide by 2 m deep into the pillars and top coaling (extracting coal left in the roof following the initial mining) to a height of 4.3 m to 6.1 m in places. Some pillars were cut on all four sides, some on two and most on one side only. It would appear that the experiment was done on 91 pillars, over an area of about 3 ha.

Monitoring consisted of visual and audio observations. No measurements were carried out. After two months, nothing untoward had happened and the experiment was concluded to have been a success. Section 10 then continued top coaling towards the south.

Mining on either side of the experimental area continued —thus removing the support of the unmined areas on either side of the experimental area—with top coaling on the advance to 4.3 m high, with the by then customary 6.1 m wide roads at 18.3 m centres. Barriers were 12.2 m wide. This mining had reached its limits by March 1959.

The collapse

At about 19:00 on 28 December 1959, the Northern part of section 10, including the area where the experiment had been done, collapsed. The accompanying wind blast injured one person some distance away. There were no other casualties, as the top coaling, which was still being done by Section 10, was done on day shift only. It covered an area of approximately 6 ha and had been arrested towards the south by one of the 12.2 m wide barriers.

Top coaling was in progress approximately 300 m south of where the collapse occurred. No roof noises, scaling or any other indication of instability was observed during the day shift. For the next three days, roof noises and pillar scaling were observed around the perimeter of the fall, but then it died down.

Top coaling and other mining operations continued. Two weeks later an Inspector of Mines made a routine visit to the mine and carried out an underground inspection at sections in the vicinity. The collapse was not reported to the inspector, and there is no record of anything abnormal being observed during the inspection.

On 21 January, 24 days after the first collapse, the major event took place.

At about 16:00, the miner in charge of a section, which was then working just west of Section 10, was alarmed by loud shot-like noises coming from the direction of Section 10 and pillar spalling. He withdrew his gang to a safe place and on the way out they were overtaken by a wind blast. He reported the incident to the shift boss, who proceeded in-bye to investigate.

At 16:20, the miner in charge of a gang working just south of Section 10 also became aware of problems in Section 10 by a strong wind blast from that direction and sounds like heavy thunder. He also withdrew his gang.

The mine overseer and acting manager (the mine manager was on annual leave at the time) proceeded underground to investigate. They found that some of the ventilation stoppings around No. 10 Section had been blown out and methane was emanating. No carbon monoxide was detected, ruling out the possibility of an explosion. Cracking noises were still coming from No. 10 Section, but from nowhere else. Word was received from surface that a depression with wide cracks had formed over Section 10.

The mine overseer and acting manager concluded that as surface had subsided, the 'weight had come off', and as the problems were confined to Section 10, the remaining areas were safe. They nonetheless withdrew the two sections in the immediate vicinity of Section 10 and made arrangements for the damaged ventilation stoppings to be replaced.

The sections to the east apparently continued working normally, as the haulages continued to operate and no word of problems had been received from those sections.

Some time after 19:00, the men replacing the ventilation stoppings south of Section 10 became aware of increasing thunder-like noises from Section 10 and increasing methane emissions. They withdrew but before they could reach a safe place, were 'overtaken by a hurricane of dust laden air accompanied by crashing like thunder'.

The gale swept through the mine for ten minutes with great force and then at diminished force for a further 45 minutes. Men were blown over, and a general exodus from the mine ensued. It was not realized until much later that not a single one of the 438 persons from the four sections working in the east had come out of the mine.

The general manager and mine overseer proceeded underground to investigate. All the entries to the east had collapsed completely. They found one person from Section 4 who had been working in the haulage and brought him to safety. He was the only survivor from the east.

The rescue operation was covered extensively in daily newspapers and on the radio. Attempts were made to drill rescue holes from the surface, but the strong dolerite sill hampered the operations. After some weeks, the rescue attempts were abandoned. All the boreholes indicated a general scene of collapse, several flooded with water and high concentrations of methane gas. The bodies of the 437 men who died in the collapse were never recovered.

Seismic and surface observations

The following seismic events were recorded that can be connected to the collapses:

- December at 19:16, Richter magnitude 0.5
- January at 16:45, Richter magnitude 0.3
- January at 19:26, Richter magnitude 1.0.

Due to the very wide spacings of seismographs it was not possible to locate these events accurately, but they were roughly located in the general area of the mine.

The events on 28 December and at 16:45 on 21 January exhibited single amplitude peaks while the one at 19:26 on 21 January lasted for 5 minutes, with three distinguishable amplitude peaks during that period. Comparison of the times at which the seismic events were recorded to the times at which wind blasts and other observations indicating collapse underground were made, leads to the conclusion that the seismic events were caused by the collapse and were not minor earthquakes leading to the collapse.

No surface cracks were observed on an inspection by the general manager on 29 December, although a cattle herder did report cracks to the local farmer on 9 January. On 21 January, the first surface cracks were observed on the road traversing the mine at 16:20. By 18:30, the cracks had progressed some 1200 m to the south-east.

Above the area of the experiment, a circular depression of about 1.8 to 2.1 m deep and diameter of 150 m had formed, bounded by cracks approximately 0.5 m wide. The total area of collapse as indicated by the extent of surface cracks, was approximately 324 ha. Over most of the area, the amount of subsidence was approximately 0.6 m, but more in areas where top coaling had been done.

The general conclusion to be reached was that the collapse on 28 December occurred above the experimental area and on 21 January it spread outwards from that area, only stopping where it reached solid ground or pillars that were wider than 12.2 m. The notable exception was in the north-west, where an area that was both mined on the 12.2 m wide pillars and top coaled, bordering on the collapsed area, did not collapse—there the mined span was restricted to approximately 275 to 300 m.

Conclusions of the government Mining Engineer

The Government Mining Engineer came to the following conclusions:

- Safe pillar dimensions, bord width and height of working being interrelated to depth, should be decided upon only after careful study of mining experience under similar conditions.
- Mining should be carried out in panels surrounded by barriers of unmined coal of dimension which will limit subsidence to a single panel in the event of pillar collapse.
- Main travelling roads and ventilation roads to every working section should be securely protected by pillars of substantial dimensions.
- If it is necessary to conduct an experiment up to the point of failure, the experimental area must be, and must remain, isolated from the body of the mine.
- Sufficient pit room should be provided to ensure that an orderly rate and pattern of extraction can be maintained.
- Positive means should be provided to warn persons in every section of the workings underground in case of an emergency.

Unknowns at the time of the disaster

Pillars can fail only if both the overburden and the pillars fail. It has been widely accepted that the collapse occurred because the pillars were too small, but being protected from the full overburden load by the dolerite sill, did not exhibit any sign that they were overloaded. When the sill then failed by virtue of the first collapse, it changed in nature from being a clamped beam to a cantilever. The second collapse then occurred when the dolerite sill failed totally. The sill failure was arrested in areas where the underlying pillars were large enough to bear the full weight or where the mined span was too small to allow failure loads to develop in the sill. Inside the failed area, the barrier pillars were likewise too thin to bear the load of the overburden.

The most important unknowns at the time were thus the following:

- ➤ Strength of square coal pillars
- ➤ Strength of barrier pillars
- ➤ Strength of the overburden
- ➤ Nature of pillar loading.

The rest of the discussion will thus concentrate on the extent to which those unknowns have been addressed in South Africa over the last 46 years.

Pillar strength research

The first important reaction to the Coalbrook disaster was that attempts were made to find ways to determine pillar strength scientifically. To set the scene, the state of the art was described by Denkhaus (1962), who described a number of theoretical approaches to the problem, but concluded that satisfactory methods to determine the strength of mine pillars did not exist at the time.

The attention was focused on pillar strength research, very little attention initially being paid to overburden strength. This is not an unreasonable approach: if the pillars are strong enough to support the overburden, it doesn't matter how weak the overburden is—failure cannot occur. This is especially true if the Tributary Area Theory (TAT) is used to determine pillar load because TAT predicts the maximum load on a pillar.

According to TAT, the load on a pillar σ_l, in a panel with regularly distributed pillars of uniform size, is:

$$\sigma_l = 0.025H\frac{C_1C_2}{w_1w_2}\,MPa \qquad [1]$$

where H = depth to floor of workings (m)
C_1,C_2 = pillar centre distances (m)
w_1,w_2 = pillar widths (m)

The safety factor, S, is then simply the ratio of pillar strength, σ_p, to pillar load, or

$$S\frac{\sigma_p}{\sigma_l}. \qquad [2]$$

Initial developments to determine pillar strength

Initial attempts focused on methods to determine the strength of small coal specimens and then to extrapolate that to full-scale mine pillars. It soon became clear that this was an almost impossible task, due to the wide scatter obtained from the laboratory tests and then because a method to extrapolate the strength to large pillars could not be found. There were simply too many unknowns.

At this stage, efforts diverged into two main directions. Bieniawski and van Heerden, with the CSIR, concentrated on testing large coal specimens underground by creating small pillars and then loading them internally, *in situ*. Their work gave rise to two important conclusions: firstly, beyond a size of approximately 1.5 m, the size effect disappeared and secondly, the post failure modulus of a coal specimen is a function of its witdh-to-height (w/h) ratio while the pre-failure modulus is a constant.

Bieniawski (1968) found a linear relationship between pillar w/h and strength for pillars with w/h>1 and w>1.5 m , as follows:

$$\sigma_p = 2.76 + 1.52\frac{w}{h},\ MPa \qquad [3]$$

where σ_p = pillar strength
w = pillar width
h = pillar height.

Van Heerden (1975) published his results on the post-failure characteristics of large specimens. Based on his data Van der Merwe (1998) found the following linear relationship between post peak stiffness, E_p, and w/h:

$$E_p = \frac{0.56w}{h} - 2.293\ GPa \qquad [4]$$

Salamon preferred to overcome the problem posed by the large number of unknowns in pillar strength by using empirical methods. He collected a database of 27 failed pillar cases and 92 intact pillar cases. With the help of A.H. Munro, they determined a power formula for coal pillar strength (see the landmark publication: Salamon and Munro, 1967):

$$\sigma_p = 7.176\frac{w^{0.46}}{h^{0.66}}\,MPa \qquad [5]$$

The 7.176 constant in Equation [5] is no more than a statistical number related to coal strength. It is not the strength of a cube metre of coal.

In fact, it is that number that results in failure of 50% of the cases in the database of failed pillars at a safety factor of 1.0. This implies that in order to achieve stability, a much higher safety factor should be used. Salamon advised that for normal panel mining, a safety factor of 1.6 should be used, as that was the most frequent value of safety factor of cases in the database of stable pillars. Salamon and Oravecz (1976) also recommended a safety factor of 2.0 for main development.

The Salamon-Munro formula gained wide acceptance in the South African coal mining industry, almost to the level of a statutory requirement.

Later refinements and additions

Equations [3] and [5] are valid only for square pillars. The first refinement occurred with the handling of rectangular pillars, by Wagner (1974), who recommended using an equivalent width, w_e, in the equation for strength of a pillar with cross-sectional area A and circumference c, calculated as follows:

$$w_e = \frac{4A}{c} \qquad [6]$$

Equation [6] indicates that the maximum equivalent width for a pillar with infinite length, is twice the physical width of the pillar. The same publication contains unique information on the shifting zones of high load on a pillar when tested to destruction, indicating that the maximum load shifts from the pillar edge towards to centre as the edges fail progressively.

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Salamon (1982) realized that for very wide pillars, Equation [5] underestimates the strength as the formula indicates a decreasing rate of pillar strength increase for increasing *w/h*. He then extended the strength formula for wide pillars, as follows:

$$\sigma_s = k\frac{R_0^b}{V^a}\left\{\frac{b}{\varepsilon}\left[\left(\frac{R}{R_0}\right)^{\varepsilon}-1\right]+1\right\} \quad [7]$$

where V = pillar volume
R = width-to-height ratio of pillars
R_0 = critical width-to-height ratio at which the formula becomes valid,
ε = rate of strength increase
a, b = material constants

According to Madden (1991), the following values can be used for the constants in Equation [7]:

R0 = 5
ε = 2.5
a = 0.0667
b = 0.5933

For ease of use in practice, Van der Merwe (1998) algebraically simplified Equation [7] to

$$\sigma_s = \frac{0.0786}{V^{0.0667}}\left\{R^{2.5}+181.6\right\} \quad [8]$$

The major advantage of using empirical methods to solve problems, is that the difficulty of quantifying a large number of unknowns is overcome by finding often undefined 'constants'. Perhaps for this reason, an astute analyst like Denkhaus (1962) could not resist referring to 'factor of safety' as 'factor of ignorance' in a light vein.

The major disadvantage is that one is in the hands of a database, which is often incomplete and which may change over time. During the period 1965, when the Salamon and Munro database was created, and 1991, a further 17 collapses had occurred. Madden (1991) re-analysed the data in the Salamon and Munro database with the addition of the 17 new cases, and found new constants for the formula, which then took the form:

$$\sigma_s = 5.24\frac{w^{0.63}}{h^{0.78}} \quad [9]$$

However, it was felt at the time that this was not sufficiently different from the original Salamon and Munro (1967) formula to warrant changing the formula.

By 1994 it became clear that the three coal mines in the Vaal Basin, namely Sigma, Cornelia and Coalbrook, experienced a disproportionate number of pillar failures at high safety factors. When the failures there were analysed as a group, it was found by Van der Merwe (1993) that the distribution of failures as a function of safety factor could match the original Salamon and Munro (1967) distribution only if the so-called k-factor was reduced from 7.176 to 4.5 MPa. The coal in that area was distinguishably weaker that the rest of the country's coal. The strength formula for that coalfield was then adapted to:

$$\sigma_s = 4.5\frac{w^{0.46}}{h^{0.66}} \quad [10]$$

It is ironical that the original Salamon and Munro (1967) formula, developed as a result of a disaster in the Vaal Basin, was not strictly valid for that area.

Esterhuizen (1995) studied the effect of discontinuities on pillar strength. He suggested that considerable variations in the strength of full-scale pillars are likely to exist due to variations in the intensity and orientation of discontinuities. He used numerical model studies to show that the impact of discontinuities is not constant, but that it diminishes with increasing *w/h.*

By 2003, even more new collapses had been recorded, to bring the total number of new collapses in the database to 45. Knowing by now that the Vaal Basin and Klip River coal was significantly weaker than the other coal, those failures were not taken into account when the data was re-analysed by Van der Merwe (2003). This still left a database containing 54 failures for the 'normal coal', double the size of the original one.

The approach that was used for this analysis, was not the maximum likelihood method used by Salamon and Munro (1967). Rather, a statistical procedure aimed at minimizing the area of overlap between the databases of failed and stable cases, was used. This is based on the argument that the optimum formula is the one that will best distinguish between failed and stable pillar cases. The outcome was a linear formula with regard to *w*/*h*, as follows:

$$\sigma_s = 3.5\frac{w}{h}\ MPa \quad [11]$$

For the weaker coal areas, a lower strength was predicted, although this was not investigated in great detail:

$$\sigma_s = 1.5\frac{w}{h}\ MPa \quad [11a]$$

Also in 2003, Van der Merwe (2003a) published a method to predict the time of failure of coal pillars. The time of failure, T, based on progressive scaling as the mechanism of failure, is given as

$$T = \left[\frac{d}{mh^x}\right]^{\frac{1}{1-x}}, \quad [12]$$

where h = mining height
m, x = dimensionless, seam specific constants, quantified in the reference for different areas in South Africa

The parameter 'd' is the distance of scaling required for the pillar to fail, given as:

$$d = w - \left[0{,}00714S_mHhC^2\right]^{0{,}333} \quad [13]$$

where S_m = safety factor at time of failure (0.4)
H = depth of mining
h = mining height
C = pillar centre distance
w = pillar width

In 2004, SIMRAC (Safety In Mines Research Advisory Committee) funded a project to create a standardized database for failed and intact pillar cases in South Africa. Van der Merwe (2006) reported on the results. The new database contains 75 cases of failed pillars (all seams and areas) and 270 cases of intact pillars. The project also provided an opportunity to review the impact of the application of the Salamon and Munro (1967) pillar strength formula.

It was shown that although pillar failures continued to occur, the frequency was less than would have been expected had pillar sizing methods not changed. Pillars had become larger, at a cost of 600 million tons of coal, but out of an expected 114 collapses if the pre-1967 practices had been continued with, only 23 did occur in areas that were mined post 1967.

Two rather disturbing facts emerged from the comparison between failures that occurred before 1967 and those that occurred later. Firstly, the average age of pillars at failure increased from 8.2 years to 21.3 years-note that the data base itself is now older. This illustrates the danger of making simplistic statements about the expected lifespans of pillars and of coming to conclusions about stability too soon. Secondly, the average safety factors of the failed pillars increased from 0.9 to 1.8, using Equation [11] to estimate strength. This is not a function of the formula, as using Equation [3] to estimate the strength results in similar numbers, an increase from 1.0 to 1.7. Both observations strengthen the argument in favour of evaluating stability in terms of time rather than a number.

Barrier pillar strength

Very little has been done to determine the strength of barrier pillars in coal mining in South Africa. There was Wagner's (1974) suggestion to use the equivalent width as an estimate of the strength of rectangular pillars, but Wagner did not particularly have very long pillars in mind even though the approach may be valid.

The only formal investigation was done by Esterhuizen (1992). He suggested using the confined core approach of Wilson (1983) as a realistic estimate. He stated that simple two-dimensional numerical methods could also be used. Roberts and van der Merwe (2005) used the 3-D hybrid code ELFEN to develop a Mohr-Coulomb strain-softening model for coal, which can also be used for long pillars.

In the early stages of mining at Coalbrook, the norm was that the width of a barrier pillar should be equal to the pillar centre distance. This was later reduced to the width of the pillars in the adjacent panel, and this is still the case in South Africa. However, wider pillars are now left, and consequently they are much stronger than the ones at Coalbrook at the time of the collapse.

Using the Wagner (1974) notion of equivalent width, Equation [3] predicts a 74% increase in strength of a very long barrier pillar compared to a square pillar of the same width, Equation [5] predicts a 38% increase in strength and Equation [11] predicts a 100% increase. The only commonality is that all three predict greater strength.

Strength of the overburden

Mainly due to the fact that attempts were made to design pillars that would not fail, the strength of the overburden was not regarded as a serious issue for bord and pillar mining. It became important only with the advent of high extraction mining methods, in particular longwall mining at Sigma Colliery, where the possibility existed that failure of the overburden to cave could result in very high abutment loads on the adjoining pillars.

Under the influence of Coalbrook where the dolerite sill was believed to have bridged over the small pillars, the attention was focused on methods to determine span widths which would result in failure of the sill. No other potentially strong layers were considered.

The first formula to predict a failure span was by Galvin (1983) who used elastic plate theory and empirical observations to develop a formula for sill failure. This formula was found to be ineffective in situations where the sill occurred close to the surface. Van der Merwe (1995) used a different approach, based on the fact that the sill is vertically jointed and viewed the problem from the point of view of the dislocation of discrete blocks of dolerite. He found the following:

$$L_c = 2T\sqrt{k + \frac{\beta}{D} + 2(H - D)\tan\phi}, \qquad [14]$$

and

$$\beta = \frac{c - b\gamma_d}{\gamma_m \tan\theta} - \frac{k\lambda}{2} \qquad [15]$$

where T = dolerite sill thickness
k = ratio of horizontal to vertical stress
D = depth of base of dolerite sill
H = mining depth
ϕ = goaf angle
c = cohesion of joints in dolerite
γ_d = unit weight of dolerite
γ_m = average unit weight of overburden rock
_ = angle of friction of dolerite joints
_ = height of keyblock

Substitution of reasonable values for the constants in Equation [15] allows it to be used in the simplified form:

$$\beta = \frac{1.53}{\gamma_m} - 0.8 \qquad [16]$$

Apart from this, very little has been done about learning more about the strength of the overburden rocks. The reason for this is possibly that dolerite, being of igneous origin, is significantly stronger than the surrounding sedimentary rocks—UCS is in the range 180 to 500 MPa, as compared to 40 to 90 MPa for the other rock types. However, the material strength is not the issue, as the dolerite sill is known to be densely jointed and the real issue is the behaviour of the sill as a unit.

Van der Merwe (1998) developed a fundamental procedure to evaluate system stability in terms of both pillar and overburden stability. Pillar stability is evaluated using the conventional procedure, while the overburden stability is based on the tensile stresses generated in overburden beams, where the resistance to deflection caused by the presence of pillars is taken into account; the maximum deflection of overburden beams is equal to the maximum compression of the pillars.

This aspect clearly needs to be addressed in more detail. With the increasing application of high extraction methods, not only the strength but also the stiffness of the overburden needs to be quantified.

Pillar loading

The only method commonly used to determine pillar loading is the TAT (Tributary Area Theory). As previously explained, this is a conservative and therefore safe approach as the TAT predicts the maximum load on a pillar. However, there are limits to its application: the pillars have to be uniformly sized, they must be regularly spaced and the panel width must be at least equal to the depth of mining.

What is not always appreciated, is that in the presence of barrier pillars, it is also only valid at low rates of extraction. The reason for this is that the barriers bear load that is disregarded by TAT and the higher the percentage extraction inside the panel, the greater the proportion of load carried by the barriers. At extraction rates of 70% or greater, the deviation becomes significant. While TAT overestimates the load on the internal pillars, it underestimates the load on the barriers.

The hidden flaw in the argument is that the empirical methods used to derive pillar strength formulae all used the TAT to estimate pillar loads at the point of failure. As TAT is known to overestimate pillar loads, it follows that the derived pillar strength, being equal to the load at failure, is likewise overestimated. To make matters worse, the pillars that were included in the databases of failed pillars were not situated in panels of the same width or at the same extraction ratio.

The pillar loading was investigated by Roberts *et al.* (2001), using different numerical methods. They found that the models predicted loading to a reasonable degree of uniformity and that the loading was less sensitive to the ratio of panel width to mining depth than previously believed. There was significant sensitivity to the stiffness of the overburden and the extraction ratio.

Due to insufficient funding, however, field trials consisting of *in situ* stress measurements could not be done. For this reason, and based on the fact that pillars can only fail if the overburden loses continuity (i.e. the overburden layers have to fail first) because the elastic deflection of the overburden layers is insufficient to compress the pillars to failure, it was recommended to continue using TAT.

In the end, as long as the same loading assumption is used for both the strength determination and the pillar sizing on the mines, it does not matter. What is important, though, is that using empirically derived pillar strength in conjunction with numerical methods to determine load to evaluate stability, is not correct.

Other developments

For reasons explained previously, the emphasis in this review is on research that may have had an impact on the Coalbrook disaster, had the knowledge been available in the years leading up to 1960. However, these are by far not the only developments that took place.

For instance, considerable effort went into developments to handle surface subsidence, see Wagner and Schümann (1985), Van der Merwe (1991), and several others. These resulted in methods to predict the amounts of subsidence and to handle the effects on a variety of surface structures.

Roof support also received substantial attention. Van der Merwe *et al.* (2001) investigated the causes of over a hundred roof falls; Frith (2002) investigated the magnitude and impact of horizontal stress on roof stability, finding that while horizontal stress was evident in the areas he investigated, it was of low impact; Canbulat and Van der Merwe (2000) investigated the impact of the distance mined prior to installing roof support on roof stability, finding that while there was ample evidence that the low magnitudes of roof deflection could be seen as justification to extend that distance to more than the statutory 12 m, the unexpected occurrence of joints mitigated against the practice.

This is by no means a comprehensive list of either topics or projects—interested parties are advised to visit the SIMRAC website at <simrac.co.za>. Research reports can be downloaded from the site.

Evaluation of research results at the hand of the Coalbrook disaster

Pillar stability

The first and obvious topic to be addressed is pillar stability. It was shown earlier that pillars were progressively made smaller as time went by and no instability occurred. With the benefit of hindsight, the sequence of events can now be seen as shown in Table I. The first column identifies the situation, the second shows pillar dimensions by height (h), bord width (**B**) and centre distance (C) while the last three columns

Table I

Coalbrook pillar safety factors for different situations

Case	*h* x *B* x *C*	SF (Equation [5])	SF (Equation [10])	SF (Equation [11a])
1905–1932 Main development	2.4 x 6.7 x 24.4	2.3	1.4	1.7
1905–1932 Panels	2.4 x 7.3 x 24.4	2.1	1.3	1.5
1932– 1948 Panels	2.4 x 6.7 x 19.8	1.7	1.0	1.0
1948–1957 Panels	*3.7 x 6.7 x 18.3*	*1.1*	*0.7*	*0.6*
1948–1957 top coaling	*5.5 x 6.7 x 18.3*	*0.8*	*0.5*	*0.4*
North-west of Section 10	4.9 x 6.1 x 18.3	1.0	0.6	0.5
West of Section 10	2.4 x 6.1 x 18.3	1.6	1.0	1.0
South-west of Section 10	2.4 x 6.7 x 22.9	2.1	1.3	1.4
South of collapse	2.4 x 6.1 x 21.3	2.1	1.3	1.4
Inspector of Mines requirement	4.3 x 6.1 x 18.3	1.1	0.7	0.6
Steart (1) with substantial barriers	2.9 x 6.1 x 18.3	1.5	0.9	0.8
Steart (2)	2.9 x 6.1 x 27.1	2.5	1.6	1.9
Section 10 Experiment	*4.9 x 6.1 x 18.3*	*1.0*	*0.6*	*0.5*
Section 10 Experiment (2)	*6.1 x 6.1 x 18.3*	*0.9*	*0.6*	*0.4*
Section 10 South	*2.4 x 6.1 x 18.3*	*1.6*	*1.0*	*1.0*

Note: the mining depth was taken as 137 m for all cases contain safety factors for the pillars, using the strength estimates obtained with Equations [5], [10] and [11a] respectively. The rows shown in italics, are from the areas that had collapsed while the others describe areas that did not collapse.

The three the equations that were used, resulted in safety factors that differ in magnitude, but the magnitudes vary in harmony. All three indicate low safety factors for the area that had collapsed, with the exception of Salamon and Munro (1967)—Equation [5]—that indicates a high safety factor for the southern collapse area where top coaling had not been done. The other two equations give better results for the collapsed areas.

Also, and again in retrospect, had the requirements of the Inspector of Mines been adhered to, the safety factors would still have been low and the collapse would probably have occurred anyhow. It appears that Steart's recommendation would have been closer to the target. His basic requirement would have resulted in high safety factors (2.5 to 1.6), while the alternative to mine at lower pillar centres would have resulted in low safety factors, hence his additional requirement for 'substantial barrier pillars'.

The most significant observation is that there are areas that did not collapse where the safety factors are as low as in the collapsed area, indicated in Figure 2. Geographically, these areas are all located to the north-west of the collapsed area. Inspection of the mine plan indicates that the main difference between those areas and the collapsed area, is that while the collapse occurred in an area where extensive mining was done (the diameter is in the region of 1 200 m), the mining span in the intact area was restricted to 300 m to 500 m.

The conclusion to be drawn from this is that while the safety factor concept can explain the collapse, it is not on its own sufficient to explain the total stability situation including the non-collapsed areas. It is not, in its present form, a stand-alone differentiator of stability and instability. More is needed. Current understanding indicates that the missing component is most likely to be the overburden stability consideration.

Barrier pillar stability

Very little can be quantified regarding the barrier stability. If one assumes that the equivalent width of a barrier is twice its minimum dimension for the purpose of calculating its strength, and that the load can be calculated as if the internal pillars made no contribution to the overburden support, it follows that the 'safety factors' of the barriers are as given in Table II for different situations.

Under these assumptions, it is shown that the only barriers that may have survived, would have been the 24 m wide barriers that were left in the 'old' mine in the very beginning, but then only if no top coaling had been done. This example, with all the unknowns about the load bearing contribution by the failed pillars (both Van Heerden (1975) and Wagner (1974) showed that pillars offered resistance even after failure), the height of strata that had to be supported by the barriers, the strength of barriers, etc, merely serves to indicate that we simply do not know enough about barrier pillar design.

Overburden stability

There is insufficient geological information available to test the applicability of the Van der Merwe (1998a) method to evaluate the combination of pillar and overburden stability in this case. The early Coalbrook borehole logs (dating to the early 1900s) merely distinguished between soil, rock and coal.

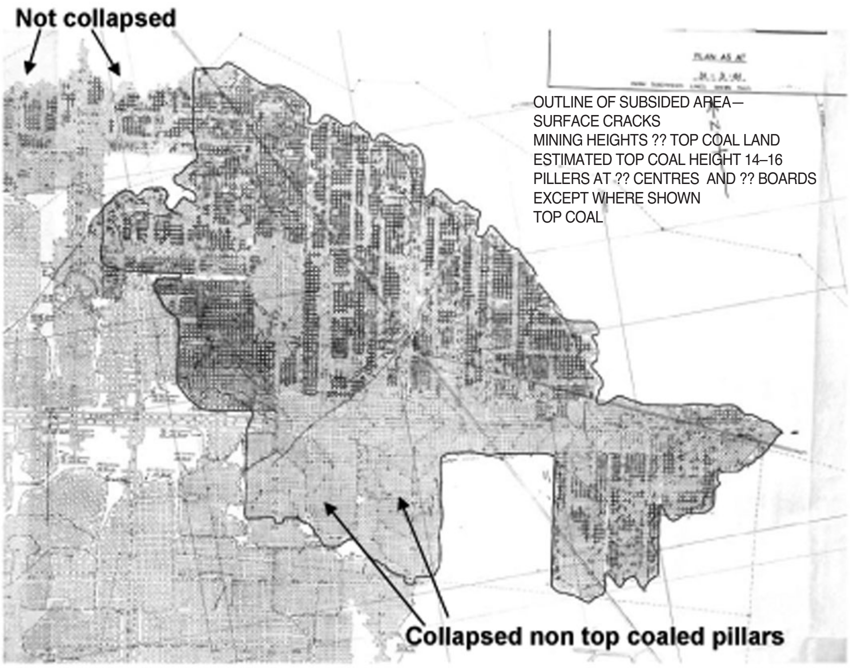

Figure 2. Detail of the collapsed area. The pillars in the area indicated as 'Not collapsed' had the same dimensions as those in the 'Collapsed non top coaled pillars' area but were in a worse situation as top coaling had been done there. The only important difference is that the mining span of the 'Not collapsed' area is smaller

Table II

'Safety factors' of the barriers

Width	Height	SF Equation [5]	SF Equation [10]	SF Equation (11a)
12.2 m	2.4 m	0.4	0.2	0.3
12.2 m	3.7 m	0.3	0.2	0.2
12.2 m	5.5 m	0.2	0.1	0.1
18.3 m	2.4 m	0.7	0.4	0.7
18.3 m	3.7 m	0.5	0.3	0.5
18.3 m	5.5 m	0.4	0.2	0.3
24 m	2.4 m	1.0	0.6	1.2
24 m	3.7 m	0.7	0.5	0.8
24 m	5.5 m	0.6	0.4	0.5

In the table, the load was calculated for each case with the assumption that the overburden failed up to the base of the sill and the only load on the barriers would then come from the sill and the strata above the sill.

The dolerite data, however, is available. Under the conditions of a 38 m thick sill occurring with a base depth of 58 m and mining depth of 137 m, the critical span for dolerite failure, obtained with Equations [14] and [16] is 170 m. This result is confirmed by practical experience of longwalling at the new Coalbrook, where mining spans of 150 m were found to be insufficient to result in sill failure while spans of 200 m were sufficient.

However, the formula that was used is not valid for this situation, as the premise for using the formula is that high extraction mining was done—in other words, there is no support contribution from the pillars.

Therefore, the fact that those pillars did not also fail, cannot be explained by either the pillar safety factors or the presence of the dolerite sill based on current understanding. Clearly, a better understanding of the overburden stability is required. Had the overburden failed, then the pillars could not have survived, but current knowledge does not offer a method to evaluate the role of the overburden.

For the time being, this question cannot be answered.

Pillar loading

Over an area as wide as was mined at Coalbrook, the TAT is certainly considered to be valid using the traditional norm that the mining span has to at least equal the mining depth. Strictly speaking, however, the relative distribution of load between the internal barriers, small as they were, the other small unmined areas and the internal pillars, cannot be evaluated using TAT. The fact that the barriers were also mined into in several places, may negate this objection to a large extent. Under these conditions, it is fair to assume that the TAT was valid, at least up until the point when the overburden failed.

The only real problem arises with the lack of knowledge about overburden behaviour. Again, using TAT for the areas to the north-west where the span was also sufficient to permit its use according to the traditional norm, indicated that those pillars had the same safety factors as the ones inside the collapsed area, yet the fact remains that they did not fail.

The only difference between the two situations is that the unfailed area was mined on a smaller span. Until there is a reasonable and quantified explanation for this observation, we cannot claim to understand the interrelationship between overburden behaviour and pillar loading.

Nature of the experiment

The Government Mining Engineer (1965) criticized the way in which the experiment to reduce pillar sizes and mine top coal was conducted. He criticized the fact that no scientific measurement was done, but visual and audio observations only were made. When nothing untoward was then noticed by human sensory observations, the experiment was concluded to have been a success and observations ceased.

The current concern is that this is still, in certain cases, being done under the guise of 'practical trials'. There is still a lack of long-term scientific measurement in mining methods that are developed, or where measurement is done, it is not always scientifically planned and the correct parameters are not always measured.

At the time of the enquiry, this was seen as the most important cause of the collapse: the experiment was not conducted scientifically and the results were applied too soon. Rock failure is time dependant, and mining under dangerous conditions continued for a long time—11 years—before the collapse occurred. Note that the time should not be taken from the time of the experiment, as the 'experiment' was little more than a repetition of common mining practice during the period before the Inspector of Mines insisted on certain restrictions.

The collapse geometry was in increasing use from 1949 onwards, eleven years before the collapse. The experiment may well have been the final trigger, but if it had not been done, there is a good probability that something else, at some or other time, may have been the trigger. This could have been merely an increase in the mined area, thinning of a crucial strata layer in the overburden, etc.

Discussion of post Coalbrook developments

The safety factor concept successfully explains why the collapse at Coalbrook occurred: the pillars were simply too small. There are indications that the newly developed strength formulae fit the observations better than the original formula, so some incremental progress has been made in this field since the original work was done 40 years ago.

Comparing the situation before the disaster to the current, the progress in the first few years has been tremendous and the contribution made by Salamon, as the main driver behind the development, has been of immeasurable value. The benefit has been extended to the rest of the industry, and it was shown that while all collapses have not been prevented, at least the frequency of collapse has been reduced substantially.

Yet, of the four main unknowns at the time of the collapse, only pillar strength can be said to be understood satisfactorily, if not completely. We have made very little progress in the understanding of barrier pillar strength, overburden behaviour and pillar loading conditions.

The concepts are understood and valid qualitative or descriptive statements can be made, but these matters cannot yet be analysed in a quantified (or engineering) manner using simple equations.

The answer lies in the use of numerical models, a variety of which are available and simple to use. At the moment, numerical modelling is not done on coal mines in South

Africa on a routine basis. The most common argument against modelling is that precise knowledge of the input is not available, but this amounts to no more than an excuse as the speed at which solutions can be obtained, makes refining input through back analyses an almost trivial matter.

Modelling is reserved for special cases like large underground storage bunkers and multiple seam situations. It is also, strangely enough, used to explain unexpected failures of pillars after the event. In those cases, the assistance of specialists is often obtained.

Overburden behaviour is indeed a complex issue, as it is governed by the mechanical properties of individual rock layers of varying thickness, unknown *in situ* stiffness, presence and characteristics of discontinuities, etc. But, as Salamon overcame the problem of complexity of pillar strength by adopting the pragmatic empirical approach, all of these unknowns can be overcome by doing sensible back analyses. Not using every means at our disposal and substituting calculation by guessing and looking, puts us back to 1949.

Coal rock engineering research in South Africa

To illustrate the disturbing parallels between the current positioning of the industry and the Coalbrook mine before the disaster, it is necessary to describe the current situation in the industry and the factors that led to this unfavourable position in some detail.

The golden period

Before 1960, there were very few rock engineering specialists in South Africa. It is only after the Coalbrook disaster that the urgency for more knowledge resulted in the availability of funds, which in turn allowed the influx of experts from Europe.

At that time the science of rock mechanics was still in its infancy. The International Society for Rock Mechanics (ISRM) was formed only in 1962, two years after the disaster.

Names like Salamon, Bieniawski, Denkhaus, Kovari, Oravecz, etc. appeared in South Africa. This tremendous pool of expertise resulted in a number of major developments and perhaps more importantly, in the development of local talent. Researchers who have since departed like Cook, Deist, Laubscher, Wagner, etc. all at one time or another worked under the supervision of the imported scientists and continued to make even more contributions. They in turn trained the next generation, eventually resulting in 5 Rocha Medal winners: Brummer, Daehnke, Malan, Linzer and Hildyard.

After Coalbrook, the Chamber of Mines created their own well funded and supported research organization, COMRO. In 1993, with the downturn in gold production, the Chamber of Mines concluded that research was not their core business and reached an agreement with the CSIR to take over the research organization. The CSIR Division of Mining Technology, Miningtek, was born.

The time of change

At about the same time, the funding mechanism changed. Previously, COMRO was funded by industry on a voluntary basis. From 1995 a statutory safety research levy was charged to the mines. Voluntary research funding dried up and the control over research changed hands from industry appointed experts to representative tri-partite committees consisting of representatives of the Mine Owners, Labour and the State, in the SIMRAC (Safety In Mines Research Advisory Committee) organization. The Coal Mines Research Controlling Council was disbanded. Decisions in SIMRAC could be reached only by consensus, which meant that expert input was substantially diluted. World-renowned researchers were in the hands of people who had little understanding of the research process or the need for fundamental research.

Funding for long-term projects was sacrificed for short-term, quick return problem solving projects. Miningtek had to be financially viable as a unit and invoicing became a more important consideration than it had been before.

The collapse

Due to disillusionment and internal problems in the CSIR, there was an exodus of qualified and experienced researchers from 2003 onwards. It is estimated that in the period 2003 to 2005, an aggregate of over 1 000 years of research experience was lost. This represents substantially more than half of the combined expertise in the organization before the exodus. Respected and acknowledged scientists like Napier, Jaeger, Gürtünca, Ryder, etc., while still contributing to science, are no longer with the CSIR. Of the five Rocha Medal winners, only Linzer remains. In retrospect, the collapse of Miningtek could well in future be seen as having a more severe impact than the collapse of Coalbrook.

In 2004, SIMRAC realized that the research strategy was sub optimal and the decision was reached to revert to longer-term projects with short-term interim targets. But it was too late. A more appropriate research strategy is now in place, but the core research capability has been lost. Miningtek no longer exists. The remaining researchers were merged into a new unit at the CSIR, called the Division for Natural Resources and the Environment (NRE). The mining identity no longer exists.

The future

Currently the organization is in a rebuilding phase. This will last at least a decade. Research expertise can be developed only through experience and the core members are no longer there in sufficient numbers to guide the new generation. The CSIR has embarked on a campaign to appoint experienced associates on a part time basis, but how successful this venture will be, remains to be seen.

When the research funding was channelled through SIMRAC, there was no funding available for productivity-related matters. Miningtek responded by creating the Coaltech 2020 initiative, which was funded in equal parts by the state through the National Research Foundation, the CSIR and the coal mining industry. The management of Coaltech 2020 is in the hands of industry. The programme has an exceptionally high implementation rate of research results, in the region of 70%.

However, the latest developments in Coaltech 2020 are that the CSIR cut its contribution to 1/6 of what it was. The NRF changed their funding rules without prior discussion and the net result is that a number of projects have had to be terminated. At the time of writing, this was still in a state of flux, with the situation for the future not known.

Is it conceivable that the most important lesson from Coalbrook, namely that in order to be effective at all, knowledge has to be generated before it is needed, was not learnt? Coalbrook had to resort to mining methods with unknown consequence in order to meet the demand for coal from the power station. The industry now is facing the end of usable reserves in the Witbank coalfield and the remaining main reserve area, the Waterberg, is not yet ready for exploitation. The Government's plan to rely on electricity generation to support the economic growth by the creation of small, independent companies, failed. The national electricity supplier, ESKOM, could not supply the additional energy required, resulting in the present strain on the electricity supply network. Mothballed power stations are being re-opened and the mining industry is under pressure to provide sufficient coal. Some mines are now producing coal beyond their original design capacity.

The only way out is to mine reserves in the Witbank field that were not intended for secondary mining, like the old, small pillars that contain the last tons of coal, and to stretch current mining methods to the absolute limit. This is similar to what happened at Coalbrook. At this crucial time, we are facing a dramatic decline in research capacity and funding.

Coalbrook was more about a way of doing things than the strength of coal pillars. The next few years will tell whether we learnt the real lessons from Coalbrook.

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