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Surface effects of total coal-seam extraction by underground mining methods*

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SYNOPSIS

The paper gives a detailed overview of the history of subsidence engineering on South African collieries. Surface displacements resulting from total-seam extraction are discussed, and the important role of local geology is highlighted. It is shown that the differences in subsidence behaviour between South African and European collieries can be attributed to the presence of competent strata in the overburden of South African coal seams. Criteria are given for the prediction of the most important subsidence parameters, and a new model for the simulation of surface subsidence above total-extraction panels is introduced.

The final section of the paper deals with the damage to surface structures caused by total-seam extraction. A brief summary of the most important undermining experiments on South African collieries is given, and it is concluded that local experiences of damage compare with those in Europe.

SAMEVATTING

Die referaat gee 'n uitvoerige oorsig oor die geskiedenis van insakkingsingenieurswese by Suid-Afrikaanse steenkoolmyne. Oppervlakverskuiwings as gevolg van die totale uitmyning van 'n laag word bespreek en die belangrike rol van plaaslike geologie word beklemtoon. Daar word getoon daat die verskille tussen die insinkingsgedrag van Suid-Afrikaanse en Europese steenkoolmyne toegeskryf kan word aan die teenwoordigheid van sterk lae in die deklaag van Suid-Afrikaanse steenkoollae. Daar word maatstawwe aangegee vir die voorspelling van die belangrikste insinkingsparameters en 'n nuwe model word voorgestel vir die simulasie van oppervlakinsinking bo totaal uitgemynde panele.

Die laaste deel van die referaat handel oor die skade aan bogrondse strukture as gevolg van die totale uitmyning van steenkoollae. Daar word 'n kort opsomming van die belangrikste ondermyningseksperimente by Suid-Afrikaanse steenkoolmyne gegee en die gevolgtrekking word gemaak dat die plaaslike ondervinding van skade met dié in Europa vergelyk kan word.

INTRODUCTION

It is now generally accepted that South Africa's coal reserves, although enormous by any standards, are limited and that every effort must be made to extract coal seams as completely as is practicable. Apart from strategic and reserve reasons, there are economic and operational reasons that favour total-seam extraction. The trend towards more complete extraction of the country's coal reserves is clearly evident from the changes in mining methods that have taken place over the past twenty years. Much of the growth of the South African coal-mining industry can be attributed to the introduction of total extraction methods, either in the form of opencast surface mining or in the form of pillar extraction and longwall mining. There is every reason to assume that this trend will not only continue, but, in fact, intensify.

A specific feature of total-extraction underground coal-mining methods is that, when the coal seam is extracted, the support to the overlying rock strata is removed and the strata are allowed to subside. The mining-induced ground movements not only change the surface topography but introduce strains in the sub-surface. There can therefore be no question that total seam extraction can have a significant influence on the land surface and its use.

The purpose of this paper is to briefly review the state of the art of subsidence engineering in South Africa and to identify potential problem areas.

SUBSIDENCE ENGINEERING IN SOUTH AFRICAN COLLIERIES

Subsidence engineering can be defined as the prediction of mining-induced surface movements and the assessment of how these movements affect the surface and surface structures. The discipline of subsidence engineering was developed in the coal-mining districts of Great Britain and Europe during the second half of the last century. Methods for the prediction of subsidence were developed[1-3] so that estimates could be made of the degree and extent of ground settlement and damage to structures that were likely to occur as a result of extensive coal-mining operations in built-up areas. One of the main motivations for the development of subsidence engineering in Great Britain and in Europe was a need for the realistic and meaningful allocation of compensation costs for subsidence damage to individual mines. This need was particularly great where mining took place in densely populated areas and where neighbouring mines extracted coal seams.

Subsidence engineering in Great Britain and Europe developed into a highly specialized and recognized discipline, and is seen by many as the forerunner of modern strata control. Today it has reached a very advanced stage

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and is an integral part of coal-mine planning. Major cities, roads, waterways, and harbours have been undermined at greater depth with no danger to the population and with minimal damage to the surface structures.

Subsidence engineering in South Africa is a relatively new discipline. The reasons for this are straightforward. Until fairly recently, bord-and-pillar mining was the almost exclusive method of coal extraction from underground. Provided the pillars are designed to adequate safety factors, the surface movements associated with this method of mining are insignificant and generally much less than the seasonal movements due to the swelling of soils[4,5]. A second, and equally important, reason for the late emergence of subsidence engineering in South Africa is the fact that most coal-mining operations took place in the less populated areas of South Africa and, in the case of the Natal, in mountainous regions. For these reasons very few subsidence measurements were taken. Heslop[6] and Steart[7], reporting subsidence observations above pillar-extraction panels (stooping panels) in Natal, noticed that local coal-mine subsidence did not conform to the European and British subsidence models. In particular, the maximum subsidence above the centre of the pillar-extraction panels was less than that observed overseas, and the limit angle was steeper.

Systematic subsidence observations started with the introduction of longwall mining in South Africa in the 1960s. While much of the earlier work was concerned with the behaviour of dolerite sills above total-extraction panels, Salamon *et al.*[8], Galvin[9], and, more recently, Schümann[10–15], Wagner and Schümann[5], Jack *et al.*[16], Jack[17], and Jack and Schümann[18] were concerned with the effects of subsidence on the surface and on surface structures. Among others, the effects of total seam extraction on farm dwellings, different types of roads, railway lines, and power lines were studied. Most of the present knowledge on mining subsidence is confined to single-seam extraction. Only at Durban Nagivation Collieries in Natal[19,20], and at Sigma Collieries in the Vaal Basin[21–23], have subsidence observations been carried out in connection with single- and double-seam extraction.

The results of all the subsidence work done to date indicate that there are significant differences between the subsidence behaviour of South African coal measures and that of European coal measures. These differences can be attributed to the generally shallower coal seams, and particularly to the more competent rock strata, found in South African coalfields.

As a result of these differences the models for subsidence prediction developed for British and European coal-mining conditions have been found unsuitable for local conditions. Recently, Schümann and Hamenstaedt[24] developed a composite subsidence-prediction model that seems to be well-suited to local conditions.

From the brief history of subsidence work on South African coalfields, it is evident that much progress was made in recent years in the study of coal-mine subsidence, its effect on surface structures, and its prediction. The most important findings of this work are summarized below.

Effects of Mining on the Surface and Surface Structures

The effects of mining on the surface and on surface structures can be divided into two separate but equally important components:

(i) the prediction of mining-induced surface displacements, and
(ii) the response of the surface and surface structures to these displacements.

The sub-division of the problem into two components is of great practical importance since it makes it possible to take full advantage of experiences gained elsewhere. While mining-induced surface displacements are greatly dependent on the local situation (i.e. the local geological conditions, the depth of mining, the thickness and angle of dip of the extracted coal seam, the type of support used, and the length and width of the extraction panel), it should be noted that the response of the surface and surface structures to mining-induced surface displacements depends largely on the type of structure and the nature of the land surface. Since similar structures respond to given surface displacements in a similar manner, it is possible to transfer experiences gained in other mining areas, and even in other countries, to the assessment of local subsidence problems. This aspect is of the greatest practical significance since it means that use can be made of the wealth of experience that has been gained overseas. Accordingly, it is proposed to deal with the topic of subsidence engineering under the above two headings.

Mining-induced Ground Displacements

During an underground excavation, displacements are induced in the rock mass, and their magnitude depends on the excavation geometry, the stress field in which the opening is excavated, and the physical properties of the rock mass. Often the displacements induced by mining excavations are not noticed on the surface, but there are many situations when surface displacements as a result of mining are noticeable or even damaging.

Ground displacements consist of absolute movements such as vertical subsidence, horizontal displacements, and differential movements. The lastnamed are relative displacements of various points of the surface in respect to one another. In the case of relative horizontal displacements, adjacent surface points can either come closer together, resulting in a compressive strain, or can move further apart, resulting in a tensile strain. The horizontal strains in different directions are frequently of different magnitude or even different signs, leading to distortion of the surface. Similarly, the differential vertical movements of adjacent surface points will result in a change in the slope of the surface. Since a change in slope is particularly critical for tall buildings, the term *tilt* is frequently used in subsidence engineering.

Experience has shown that, in most instances, absolute ground displacements do not cause damage to surface structures. However, vertical ground movements, even if they are uniform over considerable distances, can cause inconvenience or give rise to the formation of pans. Relative ground displacements, on the other hand, can seriously affect surface structures, resulting in tension cracks or the buckling of surface structures, which is dependent on the magnitude of the horizontal strains and whether these are tensile or compressive.

In subsidence engineering, it has become accepted practice to refer to absolute and relative surface displacements as follows:

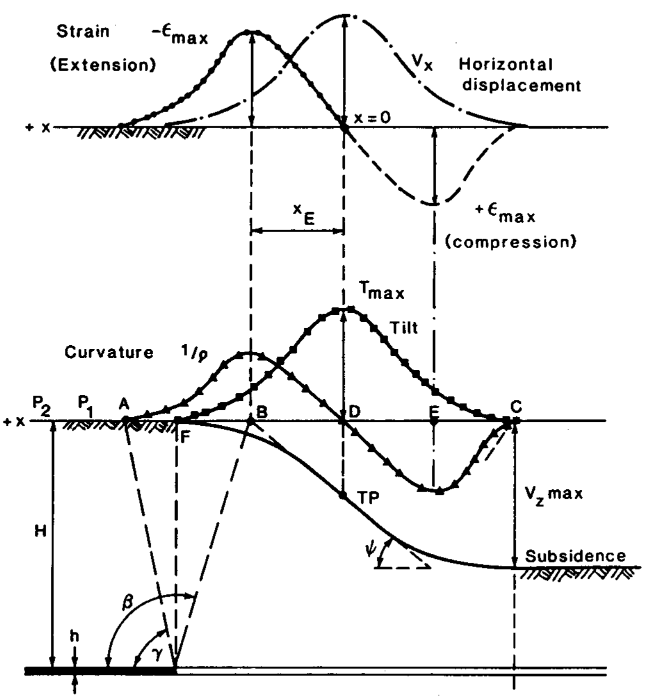
Absolute ground displacements

V_z Vertical subsidence (m)
$V_{z\,max}$ Maximum vertical subsidence (m) ($V_{z\,max}$ usually occurs above the centre of a mined-out area)
$V_x V_y$ Horizontal displacement (m)

Relative ground displacements

ϵ_x, ϵ_y Horizontal strain in the *x* and *y* directions respective (mm/m)
η Ground curvature (1/m)
T Change in slope (mm/m).

Fig. 1 shows a vertical section through the centre line of a very wide total-extraction panel. The face of the extraction panel advances to the left. The various elements of mining-induced ground movements are shown in schematic form. The position and magnitude of the horizontal and vertical ground movements, and the horizontal strain and tilt, depend, among other things, on the local geological conditions, the ratio between the extracted mining height, *h*, and the depth below surface of the seam, *H*, and the ratio between the width of the total-extraction panel, *W*, and its depth below surface, *H*.



Legend:
A Trough limit
B Point of maximum tensile strain
C Subsidence complete
D Transition point TP
E Point of maximum compression
F Face position
γ Influence angle or angle of draw
β Angle of break
ψ Tangent angle

Fig. 1—Schematic model of the various elements of mining-induced ground movements

Effect of Geology

Among the most important factors influencing mining-induced surface displacements are the strength properties of the various rock strata that overlie the coal seams. Since the formation of coal seams is a sedimentary process, the thickness of individual rock strata tends to be fairly uniform over considerable distances. However, the strength of individual strata can vary greatly depending on the rock type and the thickness of the strata. The dominant rock formations in South African coalfields are sandstones, ranging in grain size from more than 1 mm (coarse-grained) to a few micrometres (fine-grained), and shales. The shale bands often contain carbonaceous material and are usually thinly bedded. From the point of view of strata control, relatively massive, fine-grained sandstone layers can bridge spans of many tens of metres without failing, whereas the self-supporting spans of thinly laminated shales are generally much less than 10 m in length.

Apart from the differences in strength properties, there are other significant differences between sandstone and shale formations. When sandstone layers fail, they tend to break up into comparatively large blocks with many voids between the blocks. Sandstone formations have, therefore, good bulking properties, which is an important factor as far as surface subsidence is concerned. In contrast, shale formations tend to fail in thin slabs, resulting in tightly packed caved material with poor bulking properties[25].

A special feature of many South African coalfields is the presence of igneous intrusions that intersect the coal seams as near-vertical dykes or that form massive sills above or below the coal seams. These dolerite dykes and sills have exceptional strength properties when unweathered, but can be very weak in their decomposed state close to the surface. Dolerite sills of 30 or 40 m in thickness can span several hundred metres without failing and, by doing so, prevent surface subsidence. However, the longterm stability of undermined sills can be critical, and the possibility of surface movements taking place many years after the completion of mining cannot be ruled out.

Table I summarizes the more important strength and bulking properties of the major rock formations found in South African coalfields.

TABLE I
TYPICAL STRENGTH AND BULKING PROPERTIES OF ROCK FORMATIONS IN SOUTH AFRICAN COALFIELDS

Rock type		Uniaxial compressive strength MPa	Flexural strength MPa	Bulking factor, k_i
	Fine	70–120	5	
Sandstone	Medium	50–70	3	1,3–1,5
	Coarse	30–50	2	
Shale		40–80	2	1,1–1,2
Dolerite		250–390	10	?
Coal		15–40	1,5	1,3

An estimate of the self-supporting spans of different types of rock strata can be obtained from equation (1):

$$(\sigma_x)_{max} = \frac{\rho \cdot g \cdot L^2}{2t}, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where ρ = density of the rock strata (kg/m^3)
g = gravitational acceleration (9,81 m/s^2)
L = unsupported span (m)
t = thickness of strata (m).

Based on the values of flexural strength given in Table I, the relationship between strata thickness and self-supporting spans for the different rock strata found in South African coalfields is shown in Fig. 2. The simple model, equation (1), holds remarkably well, in a comparison of the calculated spans with observed spans at which the strata failed in total-extraction panels[9,10,25].

From the significant differences in the strength properties of various rock strata and their influence on the self-supporting spans of rock beams, it is clear that the local geology plays an important role in the subsidence process. Careful consideration has therefore to be given to the specific geological features of the coal-mining district during the prediction of the surface subsidence caused by total coal-seam extraction.

The role of dolerite sills on surface subsidence above total-extraction areas deserves particular attention. Field observations and theoretical studies have shown that strong dolerite sills behave like elastic plates close to the point of failure[8]. Based on these findings and the analysis of numerous total-extraction panels beneath massive dolerite sills, Galvin[9] developed a semi-empirical model for the prediction of the mining span, S_{crit}, required to induce failure of the sill:

$$S_{crit} = \sqrt{1165\ t_d - 935\ \frac{t_d^2}{D_d}} + 2t_p \tan(\beta - 90), \quad \ldots\ldots (2)$$

where t_d = thickness of dolerite sills (m)
D_d = depth of base of dolerite sill below surface (m)
t_p = thickness of parting between sill and coal seam (m)
β = caving angle of parting measured from the coal seam ahead of the working face (°).

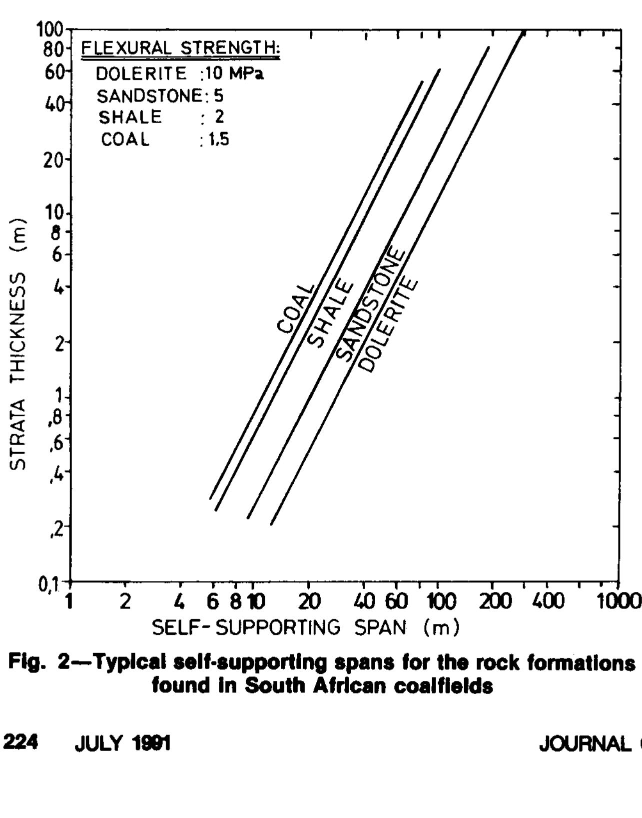


Fig. 2—Typical self-supporting spans for the rock formations found in South African coalfields

Surface subsidence above total-extraction panels whose width is smaller than the critical span given by equation (2) is governed by the elastic deflection of the dolerite sill. A systematic analysis of subsidence above longwall panels of subcritical dimensions in the top seam at Durban Navigation Collieries (DNC) by Schümann[20] has shown that the maximum subsidence in the centre of a total-extraction panel is given by

$$V_{z\ max} = 0{,}04\ (S/D_d)^2 - 0{,}06\ (\mathrm{m}), \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where S is the width of the total-extraction panel.

In cases where S exceeds the critical width, S_{crit}, it was found[12] that the vertical and horizontal surface displacements in the region of the first break of the dolerite sill were larger than anywhere else in the subsidence trough. Furthermore, the presence of dolerite sills resulted in subsidence troughs that were narrower and shallower[13] than troughs calculated by use of the subsidence model developed by the National Coal Board (NCB) in Great Britain. The effect of dolerite sills on the maximum amount of surface subsidence above total-extraction panels is clearly evident from Fig. 3, which compares[14] local subsidence data with the NCB subsidence model. To account for the important influence of the width of extraction panels, the subsidence data were plotted against the ratio of panel width to mining depth (W/H). Two important observations can be made. First, in the presence of dolerite sills, the panel widths have to be much greater than on British coalfields for significant subsidence to occur. Second, the maximum amount of surface subsidence is only about two-thirds of that observed on British coalfields. The reasons for these differences are related entirely to differences in the geological conditions.

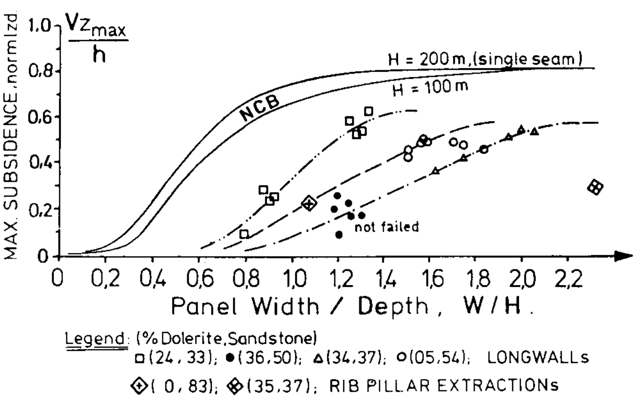


Fig. 3—Maximum subsidence versus ratio of panel width to depth for Sigma, Brandspruit, and Coalbrook Collieries

The presence of massive, strong sandstone beds in the strata overlying coal seams has a similar effect on surface subsidence to that of massive dolerite sills. However, in quantitative terms the differences are less pronounced because of the lower strength of the sandstone beds.

Mention must be made of the effects of vertical or near-vertical dolerite dykes on the process of subsidence. The contact of a dolerite dyke with the surrounding strata often constitutes a zone of weakness. Consequently, the strata, as a result of total coal-seam extraction, will tend to move along the contact area. The probability for this is greater in cases where the dyke runs parallel or at very acute angles to the panel abutment. Localized departures from otherwise normal subsidence behaviour can be expected in these instances, and have to be taken into consideration in the evaluation of the effects of total-seam extraction on surface structures. Fortunately, many dolerite dykes tend to weather when exposed to water and the atmosphere, and lose much of their strength close to the surface. As a result, the changes in surface subsidence due to the presence of these dykes are not as abrupt as with strong, unweathered dykes.

From this discussion of the effects of local geology on surface subsidence above total-extraction panels, it is clear that this aspect requires careful attention. An integral part of subsidence engineering is therefore the evaluation of local geological conditions and their assessment from a subsidence point of view. Where total-extraction coal mining has already taken place, this assessment is relatively simple and can often be confined to a comparison of borehole logs from panels that had been extracted previously with panels that have been planned and are due for total extraction. The main purpose of this comparison is to ensure that there are no sudden or significant changes in the composition of the overburden strata nor in the thickness of the overlying dolerite sills.

The assessment of the effects of local strata conditions on surface subsidence is more difficult for areas where there is no local experience of total extraction. However, over the years much experience has been gained and much information collected concerning total coal-seam extraction under a variety of geological conditions. This makes it possible for the information gained in other areas to be used for the purpose of subsidence prediction in coal-mining areas where no total-extraction experience exists. A critical examination of Fig. 3 shows a remarkable consistency in subsidence behaviour as a result of strata composition. It should be noted that longwall panels with similar strata composition, as indicated by the proportion of dolerite and sandstone in the overburden strata, show similar subsidence values when allowance is made for the important influence of the ratio of panel width to mining depth.

Fig. 4 gives an overview of the typical stratigraphy of the major South African coalfields. Detailed subsidence information is available for the mines marked with an asterisk.

Effect of Depth of Mining on Surface Subsidence

The depth of mining affects surface subsidence in several ways.

Firstly, as total-extraction mining starts, the mining span increases until a point is reached where the self-supporting span of the immediate roof beam is exceeded and the beam fails. With further increases in mining span, this process continues, and more and more roof strata participate in the caving process. An important aspect of the caving process is that the caved material bulks and gradually fills the void created by the seam extraction. Once this point has been reached, the caved material starts exerting some resistance to further strata movement. The resistance is initially low, but increases rapidly as the caved material becomes more and more compressed by the weight of the overlying strata. Ultimately a point of

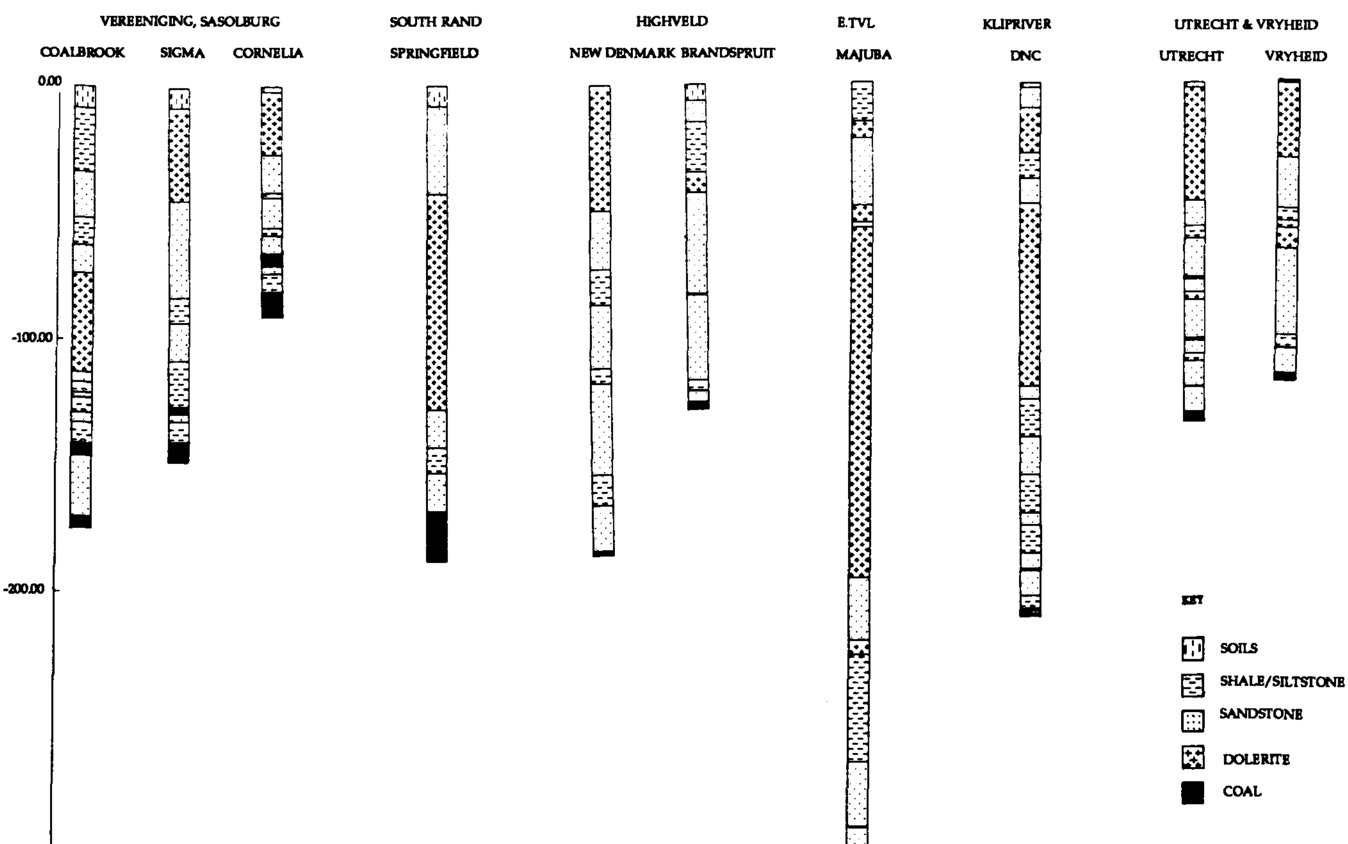


Fig. 4—Typical stratigraphy at collieries conducting total extraction

equilibrium is reached where the resistance of the caved but compressed roof strata equals the weight of the overburden strata. Obviously, the greater the depth of mining, the more compressed will the caved material become and the greater will be the surface subsidence.

The above process has been described in detail in Salamon's model of strata reconsolidation[26]. According to Salamon, the initial height of caving, h_c, is given by

$$h_c = \frac{P_c}{k_i \cdot \gamma} \cdot [\exp \frac{k_i\gamma \cdot h}{P_c(k_i - 1)} - 1], \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where P_c = a factor describing the compressibility of the caved material,
k_i = bulking factor,
γ = specific weight of the caved material, and
h = height of the extracted seam.

For cases where the depth of mining, H, exceeds the caving height, h_c, the normalized surface subsidence, $\frac{V_z}{h}$, is given by

$$\frac{V_z}{h} = 1 - \frac{(k_i - 1)\cdot P_c}{k_i\gamma \cdot h} \cdot \log_e \frac{k_i\gamma \cdot H + P_c}{k_i\gamma(H - h_c) + P_c}. \quad \ldots\ldots\ldots \quad (5)$$

Wagner and Schümann[5] have shown that this model describes surface subsidence above wide total-extraction panels. As far as the parameters k_i and P_c are concerned, the following typical values have been found for South African coalfields:

P_c	3–5 MPa
k_{shale}	1,2
$k_{\text{sandstone}}$	1,4–1,5.

Secondly, the ratio of the extracted seam height, h, to the depth of mining, H, is critical as far as the mode of surface subsidence is concerned. Salamon and Oravecz[27] have defined three distinctly different modes of subsidence depending on the value of the ratio, h/H, namely:

(1) discontinuous subsidence ($h/H > 0{,}1$),
(2) subsidence with surface cracks ($0{,}1 > h/H > 0{,}01$), and
(3) smooth subsidence ($h/H < 0{,}01$).

Since most South African coal seams have a thickness of more than 2 m and are situated at depths of less than 300 m, it follows that subsidence with surface cracks is the dominant mode of subsidence in South African coalfields. In the case of thick, shallow coal seams, discontinuous subsidence with major surface cracks occurs; also, at instances pronounced surface steps occur above the edge of extraction panels.

This mode of surface subsidence is likely to become more important for the total extraction of more than one coal seam. In this instance, the combined extraction height of all the extracted seams is the critical parameter. Smooth surface subsidence will gain in importance as the depth of coal mining increases. First examples of this mode of surface subsidence were seen at Durban Navigation Colliery and at New Denmark Colliery near Standerton.

From the point of view of surface damage, the effects of total-seam extraction become less and less significant as the ratio h/H decreases. In deep South African gold mines, this ratio is less than 0,001, and damage to surface structures as a result of subsidence is virtually unknown.

Thirdly, the width of total-extraction panels, W, relative to the depth of mining, H, is a critical parameter from the point of view of surface subsidence. When the width of total extraction panels is small compared with their depth, $W/H < 0{,}1$, then most of the effects of total extraction are confined to the immediate vicinity of the extraction panel. However, as W/H increases, more and more of the strata overlying total-extraction panels come into tension (Fig. 5).

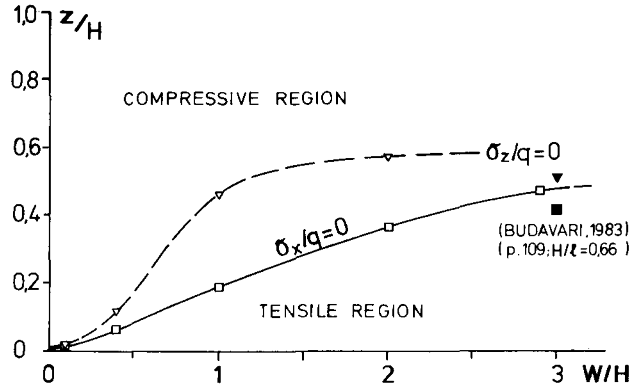


Fig. 5—Increase in height of the tensile zone above the panel centre as a function of the width-to-depth ratio of shallow panels

Since the strength of rock in tension is very much lower than that in compression, strata caving is facilitated. The results of theoretical studies reported by Salamon[28] are in support of subsidence observations. In subsidence engineering, it is well known that the lateral dimensions of total-extraction panels have to meet a certain *critical* value to allow for the full development of surface subsidence in the centre of the panels. Panel dimensions smaller than the critical dimensions are referred to as *subcritical*, while panels that exceed the critical dimensions are referred to as *super-critical*. Fig. 3 provides some useful information on the relationship between W/H and the maximum surface subsidence in the centre of total-extraction panels. The value of W/H at which the vertical subsidence reaches its maximum value corresponds to the critical value, W_c. From Fig. 3 it can be seen that W_c is about 1,4 H for British coal mines, while the value for South African collieries ranges from 1,7 H to 3 H, depending on the composition of the superincumbent strata. As pointed out earlier, the presence of very massive dolerite sills could result in even greater critical panel widths.

Relationship between Vertical Subsidence and Other Subsidence Parameters

So far, the discussion of subsidence phenomena has been largely concerned with the maximum surface subsidence that can be expected as a result of total coal-seam extraction. The reason for this is that vertical surface subsidence is the best understood and most readily measured subsidence parameter. However, from the viewpoints of subsidence and, in particular, surface damage, some of the other subsidence parameters are more important.

Maximum Horizontal Displacements

As shown in Fig. 1, the maximum horizontal displacement, $V_{x\ max}$, occurs above the mined-out area some distance from the edge of the extraction panel. Local experience indicates that horizontal displacements due to the total extraction of the first seam are somewhat smaller than those found over areas of multi-seam total extraction. The relative magnitude of horizontal surface displacement compared with the maximum vertical displacement, $V_{z\ max}$, is

$$V_{x\ max} \approx 0{,}2\ V_{z\ max}.$$

Maximum Horizontal Strain

Ground strains above total-extraction panels on South African coal mines show large variations due to the blocky nature of the caved overburden strata and the absence of a thick soil cover.

Based on numerous field observations, Wagner and Schümann[5] established a relationship between the ratio of the extracted mining height, h, and the depth of mining, H, and the maximum surface strain, ϵ_{max}:

$$\epsilon_{max} = 0{,}43\ (h/H).$$

The corresponding relationship for British coal-mining areas is

$$\epsilon_{t\ max} = 0{,}65\ (h/H) \text{ and}$$

$$\epsilon_{c\ max} = 0{,}51\ (h/H).$$

When the average maximum subsidence of 55 per cent of the extracted mining height replaces h, the strain factor is 0,8 for critical panels, which is larger than the average strain factor of 0,6 used by the NCB[3], but it is similar to the theoretical value of 0,75 derived by Salamon[28].

Maximum Tilt

The position of the point of maximum tilt, T, in the subsidence trough coincides with the position of maximum horizontal displacement. Wagner and Schümann[5] found that the average value of maximum tilt, T can be expressed as a function of (h/H):

$$T = 1{,}5\ (h/H).$$

The local tilt factor of 1,5 compares with a theoretical value of 3,02 derived by Salamon[28] and a value of 2,75 found in Great Britain. When h is replaced by the average maximum subsidence of 55 per cent of the extracted mining height, a tilt factor of 2,73 is obtained, which compares well with the theoretical value and practical experiences in Great Britain.

Subsidence Profiles

So far, only the maximum values of the various subsidence parameters have been considered. However, it is well known that surface subsidence varies across and along total-extraction panels. Numerous observations have shown that subsidence profiles above total-extraction panels in South Africa are remarkably similar (Fig. 6), and can be expressed by the following formula describing a half-profile[5]:

$$V_{z/h} = \frac{c}{1 + ae^{-bx}}. \quad \text{(6)}$$

Parameter c describes the maximum subsidence that can be expected, a is a measure of the distance from the abutment at which significant subsidence can be expected, and b is a measure of the steepness of the subsidence curve. Table II summarizes the values of the various parameters for a number of South African collieries and the standardized British subsidence profile. The latter has been adjusted to allow for the smaller magnitude of vertical subsidence found in South Africa.

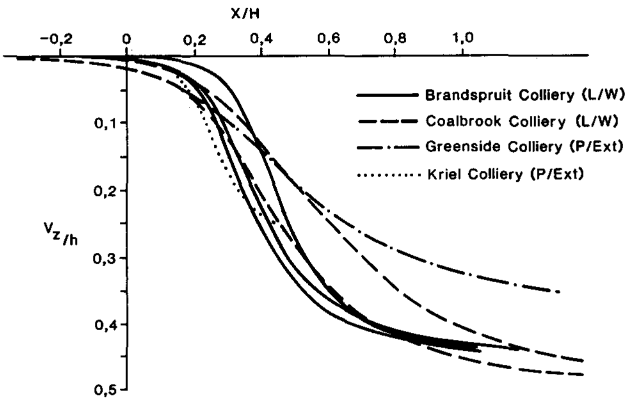


Fig. 6—Dynamic subsidence profiles measured in the centre line of total-extraction panels on different collieries

Modelling of Surface Subsidence

Up to now the discussion has been concerned with idealized situations and the prediction of subsidence parameters using simple semi-empirical relationships. Until recently this was the only practical means of predicting surface subsidence above total-extraction panels. Attempts to develop numerical models for subsidence engineering met with limited success. In particular, it was found that the presence of competent beds in the overburden strata could not be handled by subsidence models developed overseas. This difficulty was overcome recently

TABLE II
PARAMETER VALUES FOR TRANSVERSE (t) AND DYNAMIC (d) SUBSIDENCE CURVES

Colliery	h m	H m	c t	c d	a t	a d	b t	b d
N C B				0,43		6,1		7,6
Brandspruit	2,9	130	0,43	0,43	65	57	11,8	10,2
Coalbrook	2,7	160	0,49	0,49	12	22,5	7,3	5,6
Sigma	2,6	110	0,46	0,46	7,9	25,4	5,7	3,8

by Schümann and Hamenstädt[24], who adopted a two-step approach to simulate surface subsidence above local total-extraction panels. The two-step approach consists, first, of modelling the effects of strong, competent beds, which tend to overhang the total-extraction area, thereby preventing or minimizing strata caving along the edges of the total-extraction panel. The second step consists of modelling subsidence in the inner part of the extraction panel, that is the central area, which is no longer affected by the overhanging competent beds. Finally, the effects of the two simulations are added, resulting in a composite subsidence trough. The principles of the two-step approach are depicted in Fig. 7, which clearly shows the edge zone and the central zone.

A total of seventeen case studies have been conducted to evaluate the applicability of this simulation method to real situations. The results obtained so far have been most encouraging.

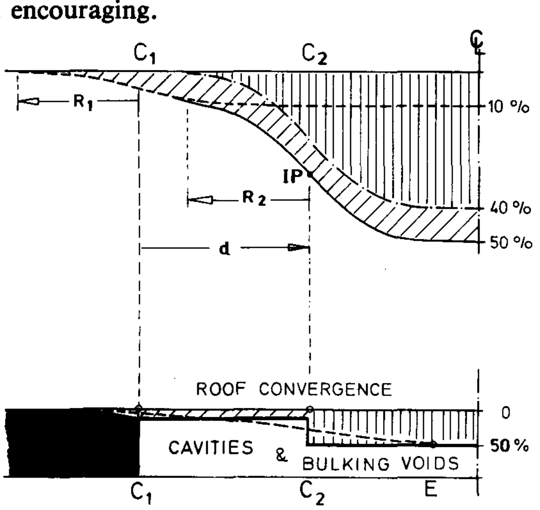


Fig. 7—Simulation of two-step subsidence due to incomplete closure in the edge zone and larger closure in the central zone

Summary of Mining-induced Surface Displacements

The results of field observations, theoretical studies, and numerical simulations of surface subsidence due to total coal-seam extraction can be summarized as follows.

(1) Surface subsidence above local total-extraction panels differs significantly from that observed in European coal-mining districts. The main reasons for these differences is the presence of competent dolerite sills and massive sandstone layers in most local coal-mining areas. As a result of these competent strata, the magnitude of surface subsidence tends to be much less than that observed in Europe, and the extent of significant surface displacements is confined to the mined-out area.

(2) Surface displacements follow a well-defined pattern and can be predicted with a fair degree of reliability and accuracy. Semi-empirical relationships have been derived for all the important subsidence parameters.

(3) The modelling of surface subsidence by advanced numerical techniques has been achieved successfully for a number of situations.

(4) There is a wealth of subsidence information covering more than two decades of total-extraction mining in South Africa.

Response of Surface Structures to Total-seam Extraction

In recent years considerable local knowledge has been gained concerning the behaviour of a variety of surface structures that were undermined by either longwall faces or pillar-extraction panels. Most of the investigations were sponsored by the Strata Control Advisory Committee of the Coal Mining Research Controlling Committee (CMRCC).

In view of the importance of these investigations for the future of total-extraction coal mining in South Africa, some of the more significant investigations are described briefly.

Railway Lines

At Greenside Collieries, a railway siding was undermined by a pillar-extraction panel situated at a depth of 55 m. The surface subsidence resulting from the extraction of the 2,0 m thick coal seam was 0,9 m. Throughout the six-week period of undermining, rail transport was not interrupted. Ballast was introduced for concurrent lifting of the railway tracks to maintain acceptable gradients and to compensate for any lateral tilt. This experiment showed that railway lines can be undermined by relatively shallow total-extraction panels provided adequate precautions are taken and close contact is maintained between the mining personnel and the operators of the railway line.

Roads

At Secunda Collieries, a provincial road has been undermined several times by longwall panels situated at depths ranging from 120 to 130 m. Surface subsidence resulting from the extraction of the 3 m thick coal seam ranged from 1,3 to 1,5 m. Tensile cracks and buckling of the upper layer of the road structure were observed in regions of tensile and compressive strains. Some damage was done to the sub-base of the road. The overall damage was within acceptable limits, and the roads were repaired. In order to minimize compressive damage, vertical slots were cut at regular intervals into the road surface at two of the roads in the Secunda area. The 0,5 m deep slots, which were cut prior to undermining, virtually eliminated compressive damage and significantly reduced the costs of road repair.

At New Denmark Colliery, a provincial road was undermined by several 212 m wide longwall panels situated at a depth of about 200 m. The effects on the road of the extraction of the 2 m thick coal seam were minimal. The maximum subsidence in this instance did not exceed 0,4 m.

At Matla Collieries, several district gravel roads were undermined by longwall faces situated at a depth of about 60 m. The extracted seam thickness in this instance was 1,8 m. The roads were kept fully operational throughout the period of undermining, and the maximum subsidence to which they were subjected was 1,0 m.

Numerous farm roads have been undermined by longwall and pillar-extraction panels at Usutu, Sigma, Coalbrook, and Durban Navigation Collieries without any subsidence damage and without being rendered unserviceable.

Transmission Towers

Four experimental 400 kV transmission towers were undermined by a 212 m wide longwall panel at Secunda Collieries. The surface subsidence resulting from the extraction of the 2,9 m thick coal seam situated at a depth of 121 m was 1,3 m. A maximum tilt of 35 mm/m and maximum strains of 8 mm/m in tension and 7 mm/m in compression were observed at the position of the towers. There was no damage to the towers, and only one of sixteen footings showed hairline cracks in the concrete collar[11].

Buildings

The most comprehensive subsidence investigation in South Africa was conducted at Brandspruit Colliery in Secunda, where a whole farm complex was undermined by a 212 m wide longwall panel situated at a depth of 130 m. The buildings that were undermined included a brick farm house, a sandstone building, two long steel-framed brick structures, and a number of small structures such as a circular water reservoir. The conditions of the various structures were carefully recorded prior to the extraction of the 3 m thick coal seam, and the structures were monitored on a virtually continuous basis throughout the undermining process. Damage to the structures was very limited—a maximum subsidence of 1,3 m. Subsequent to undermining, most of the buildings were restored at moderate cost to a condition equal to or better than before total-seam extraction took place, and they now form the basis of the Secunda Mines Centre for Ground Conservation.

Recently, a club complex consisting of two buildings and a swimming pool was undermined by a 212 m wide longwall face at New Denmark Colliery, near Standerton. The maximum subsidence resulting from the extraction of the 2 m thick coal seam at a depth of 185 m was 0,36 m. The induced tilt in the vicinity of the club house was 1 mm/m, and the tensile strain was 0,2 mm/m. The Division of Building Technology of the CSIR found that the crack pattern in the club house had changed little, except for a small extension of a few existing cracks, and a slight widening of some of these cracks or a slight compression of others. The overall rating of damage to the building before and after undermining remained unchanged. Furthermore, it was concluded that the damage could be regarded as negligible, particularly when compared with that due to heaving clay. The swimming pool, consisting of a glass-fibre shell set in sand, remained undamaged after approximately 30 mm of subsidence[18].

Summary of Observations

The most important finding of all the undermining studies is that local experiences of the damage to surface structures due to mining-induced surface displacements is similar to that in other mining countries. Consequently, overseas experience can be applied with a fair degree of confidence in South Africa.

The findings of numerous undermining experiments in South Africa can be summarized as follows.

(1) Damage to surface structures is closely related to the magnitude of the mining-induced surface strains and tilts.
(2) No single incidence of catastrophic and unexpected structural failure was observed.
(3) In most instances, structural damage was well within the range of repairs.
(4) Damage to buildings was generally less than that observed overseas owing to the very shallow foundations of local structures (no basements).

Classification of Damage

Based on observations of local and overseas damage, various categories of damage can be established. Examples of damage criteria for buildings are given in Figs. 8 and 9 and in Table III. An important aspect is the influence of the length of a building on the value of surface strain that leads to a certain degree of structural damage. Fig. 8 shows that small buildings can tolerate very much greater surface strains without being damaged than very long buildings.

Conclusions

Based on more than twenty years of detailed studies into the effects of total coal-seam extraction on the surface and surface structures, the following conclusions have been reached.

(1) The magnitude and extent of the surface displacements resulting from total coal-seam extraction can be predicted with a fair degree of accuracy for most geological conditions.
(2) The magnitude of the vertical subsidence above total-extraction panels in South Africa is generally smaller than observed on European coal mines. This is due to the presence of competent beds in the overburden strata.

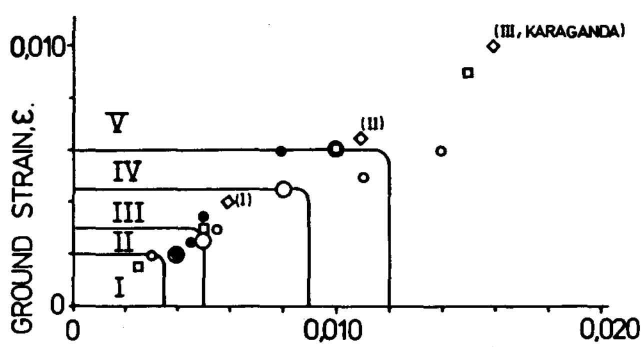


Fig. 8—Classes of damage in terms of ground strain and slope.

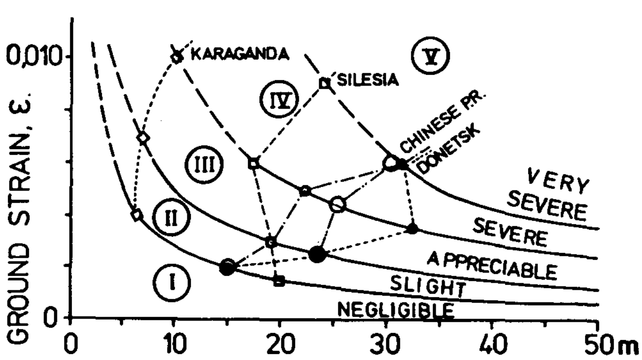


Fig. 9—Classes of damage in terms of ground strain and length of structure.

TABLE III
CATEGORIES AND LIMITS OF DAMAGE

Class of damage	Great Britain (ref. 3, p. 49)	Poland (S. Knothe, 1952; Rimant, 1958)	USSR Donetsk district (VNIMI 1958)
I Very slight	Haircracks in plaster, isolated slight fracture in building, not visible outside $\Delta l = 30\,\text{mm}/60\,\text{m}$ $\epsilon = 0{,}5\,\text{mm/m}$	Haircracks, no damage $T < 2{,}5$ mm/m $\eta < 20 \cdot 10^{-6}$/m $\epsilon < 1{,}5$ mm/m	$T < 4$ mm/m $\rho > 20$ km $\epsilon < 2$ mm/m
II Slight	Several slight fractures inside, doors and windows stick $\Delta l = 30\text{–}60$ mm/60 m $\epsilon = 0{,}5\text{–}1$ mm/m	Damage easy to repair $T < 5$ mm/m $\eta < 50 \cdot 10^{-6}$/m $\epsilon < 3$ mm/m	Limit for five-storey buildings $T < 4{,}5$ mm/m $\rho > 18$ km $\epsilon < 2{,}5$ mm/m
III Appreciable	Slight fracture outside or one main fracture, doors and windows stick $\Delta l = 60\text{–}120$ mm/60 m $\epsilon = 1\text{–}2$ mm/m	Appreciable damage, building still useable $T < 10$ mm/m $\eta < 90 \cdot 10^{-6}$/m $\epsilon < 6$ mm/m	Three- and four-storey buildings $T < 5$ mm/m $\rho > 12$ km $\epsilon < 3{,}5$ mm/m
IV Severe	Severe open cracks, floors sloping, walls leaning, anchoring required $\Delta l = 0{,}12\text{–}0{,}2$ m/60 m $\epsilon = 2\text{–}3$ mm/m	Severe damage, anchoring required $T < 15$ mm/m $\eta < 120 \cdot 10^{-6}$/m $\epsilon < 9$ mm/m	Two-storey buildings $T < 8$ mm/m $\rho > 5{,}5$ km $\epsilon < 6$ mm/m
V Very severe	Part or complete rebuilding required $\Delta l > 0{,}2$ m/60 m $\epsilon > 3$ mm/m	Destruction of building $\eta > 160 \cdot 10^{-6}$/m	One-storey only $T < 10$ mm/m $\rho > 3$ km $\epsilon < 7{,}5$ mm/m

Note: The radius of curvature $\rho = \frac{1}{\eta}$

(3) Most of the mining-induced surface displacements, particularly damage to structures, is localized and confined to mined-out areas.
(4) Surface subsidence due to total-seam extraction is a gradual and controlled process, and results in the gradual development of damage.
(5) In the majority of cases, more than 90 per cent of the surface displacement occurs within a period of less than three months of undermining.
(6) Residual surface movements are generally very small and do not give rise to damage.
(7) Most surface structures can be maintained in an operational condition during undermining provided proper precautions are taken.
(8) The cost of subsidence monitoring is small compared with the longterm benefits that can be gained from the improved local knowledge.
(9) Most of the subsidence investigations have been confined to evaluations of the effects of single-seam extraction on the surface. Much work needs to be done to improve the knowledge on the effects of multi-seam extraction on the surface.

Outlook

The coal locked up in underground coal seams, the land surface, and the ground water are important natural resources that are essential for the future development of the country. Optimal utilization of these resources is therefore of national importance.

In an effort to improve the utilization of the country's limited coal reserves, the coal industry is moving towards the wider application of total-extraction mining methods in the form of opencast mining and underground longwall mining and pillar extraction. At present, about one half of the country's annual coal production is mined by total-extraction methods—a proportion that is likely to increase in the future.

Questions related to the effects of total coal-seam extraction on the land surface and its use will therefore be raised more frequently. As far as the agricultural sector is concerned, it is hoped that the work of the Van Niekerk Commission will provide the basis for a harmonious co-existence between that sector and mining, which are both vitally important pillars of South Africa's economy. As for the interaction between coal mining and other users of the surface, it is hoped that the rigid attitude that exists in some quarters will give way to a more flexible approach based on sound engineering and economics principles. Only on this basis will it be possible to lift unnecessary restrictions or to avoid unnecessary duplication of costly surface infrastructures.

A mechanism will have to be found to pool all knowledge on the effects of total coal-seam extraction on the environment, and to promote improved communication between all parties who have a vested interest in this important area.

Acknowledgements

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above coal-mine workings that is being sponsored by the Coal Mining Research Controlling Committee (CMRCC) and conducted under the auspices of its Strata Control Advisory Committee. The Coal Mining Division of the Chamber of Mines' Research Organization (COMRO) has carried out most of the subsidence research programme under contract to the CMRCC.

The coal-mining industry, particularly Sasol Corporation, the Trans Natal Collieries Ltd, Amcoal, Iscor, and Gold Fields, have supported these research efforts over a long period of time. In recent years, the Road Research and Building Research Divisions of the CSIR have made valuable contributions to the evaluation of subsidence-related damage to roads and buildings. The collaboration of Eskom in the work on power-line pylons is greatly appreciated.

Finally, the substantial progress of subsidence engineering in South Africa was made possible only through the enthusiastic support given to the research teams by the various mines that participated in the investigations, and through the understanding and continuing support provided by the various inspectorates under the Government Mining Engineer.

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