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Subsidence Caused by Coal Seam Extraction Beneath a Competent Overburden

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SUMMARY Methods of predicting of surface subsidence under varying geological conditions in South Africa are presented. A Subsidence Profile Curve is used to describe subsidence troughs. Results from South Africa are compared to those obtained in the Newcastle Coalfield (NSW). A case study of subsidence and preventive measures at a road affected by shallow longwall mining, is given.

1 INTRODUCTION

Subsidence is caused by caving of the superincumbent strata above longwall or coal pillar extraction panels. Adverse effects of subsidence manifest themselves in differential settlement and horizontal elongation or compression of the ground surface leading to open cracks or thrust failure and to building damage. It is thus important for orderly mine layout planning and efficient recovery of coal reserves as well as for the safety of buildings, structures and the public at large to predict surface subsidence. Measures to prevent or reduce subsidence damage have to be devised.

For comparable mining geometries, maximum subsidence in South Africa is only half of that found in Europe and the UK and subsidence troughs are much narrower. The difference is caused by the presence of competent sandstone layers and massive dolerite sill intrusions in the superincumbent strata, which do not easily cave when being undermined for the first time.

The results of subsidence monitoring and research investigations are summarized in this paper by quantifying surface subsidence and presenting an original approach to the description of a complete subsidence trough in the form of an exponential subsidence profile curve.

It has been discovered that a non-linear parabolic relation between subsidence tilt and horizontal displacements exists for both single seam and multi seam extraction. This new finding is in contrast to conventional belief and assumptions, conveyed by the subject literature.

For the purpose of comparison of maximum subsidence and the K-values of maximum strain and tilt, results from the Newcastle Coalfield in Australia (NSW) have been chosen, since the latter comes closest to South African conditions in respect of mining depth and stratigraphy, except for the local dolerite sills.

The paper gives two typical examples of the local stratigraphy and discusses the caving process and subsequent subsidence. Small maximum subsidence is quantified by using the panel width and the thickness of competent strata (dolerite sill). Maximum trough subsidence above supercritical panels is related to the width/depth ratio of such panels.

The new subsidence profile curve is quoted and strains and tilts are discussed.

Finally, reference is made to subsidence of a provincial road and its deviation. It is shown that a successful implementation of preventive measures can significantly reduce subsidence damage and the time needed for repair as well as the costs incurred.

2 MAJOR COALFIELDS IN SOUTH AFRICA

2.1 Stratigraphy of Coal Measures

Five major coal seams of uneven distribution and varying economic significance are deposited in the Eastern Transvaal Highveld, the northern Orange Free State and Natal. The seams of bituminous coal are found in the Vryheid Formation which belongs to the Ecca Group of Permian paleo age. The superincumbent strata consist of minor siltstone (mudstone), competent sandstone, shale and dolerite sills. The post triassic horizontal sheet-like intrusions of dolerite sills and their associated feeder dykes are a major feature of the overburden cover on many collieries.

Borehole sections illustrating the detailed stratigraphy at two collieries 'D' and 'B', are given in Figure 1. Typical laboratory values of strength and elastic modulus are:

Coal	30 Mpa	2 GPa
Shale	70 MPa	3 GPa
Sandstone	75 MPa	7 GPa
Dolerite	300 MPa	70 GPa

2.2 Mining Methods and Layout

Bord and pillar mining is the dominant method of extraction in South Africa. In 1985 50 per cent of the total coal production came from bord and pillar workings and an additional 8 per cent from subsequent pillar extraction. Longwall extraction produced another 7 per cent while the remaining 35 per cent of coal production was obtained from opencast operations. The surface area affected by longwalling and pillar extraction is estimated at about 600 ha anually. The depth of these underground workings ranges from 30 m to 230 m. Longwall panels are typically 200 - 220 m wide but panels as narrow as 140 m have been extracted. Geological constraints to total extraction are given by the presence of dolerite dykes, dolerite sills and competent sandstone layers. These strata are required to break and cave, in order to reduce the build-up of high rock pressure on the extraction face, on interpanel chain pillars and retreat roads.

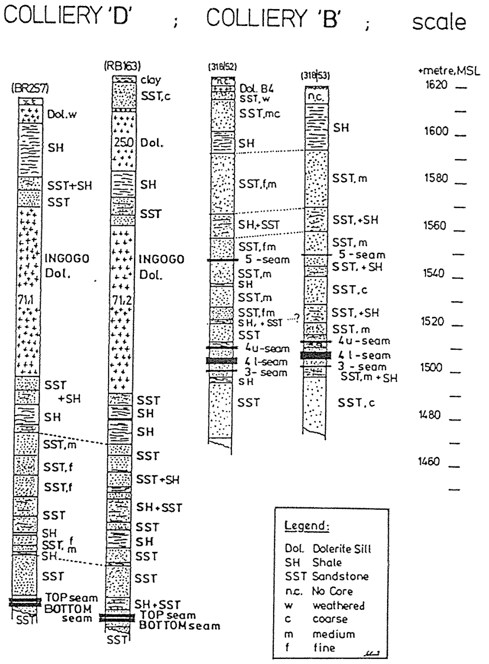


Figure 1 Typical borehole section at Colliery 'D' and 'B'

3 SUBSIDENCE TROUGH CHARACTERISTICS

The subsidence process and the resulting shape and extent of a trough are governed by the deformation behaviour of the superincumbent strata, as well as the level and distribution of stress. The latter depends on the depth and width of the excavation. Dolerite sills play a dominant role.

3.1 Behaviour of a Dolerite Sill

In South Africa total extraction with subsequent caving in the goaf has been confined to single seam operations under intact competent strata in the majority of cases. Caving of the overburden is temporarily arrested at the base of competent strata thus creating lens-shaped narrow cavities of considerable lateral extent. In particular, dolerite sills, due to their superior strength bridge over the goaf and deflect elastically, Salomon et al., (1972). An increase in free span leads eventually to the structural but non-violent failure of such a sill. The effective span necessary to induce failure in a dolerite sill has been quantified by Galvin (1983). The caving angle which develops due to 'First' seam mining under intact competent strata ranges from 110° to 130° reclined over the goaf depending on the strata composition. This angle determines the minimum lateral dimension W_c of the excavation required at the mining horizon.

3.2 Surface Subsidence

Once the competent strata break and caving progresses upwards with an increasing mining span, an initial V-shaped crater-like subsidence trough results, Figure 2. This effect of non-uniform susidence is referred to as 'First Break' and has been observed in South Africa above supercritical panels at extraction height/depth-ratios, h/H, not less than 0,02, that is over a depth of extraction as large as 160 m. Subsidence further on in a given trough is reduced to about 70 to 80 per cent of the initial peak subsidence, Figure 2.

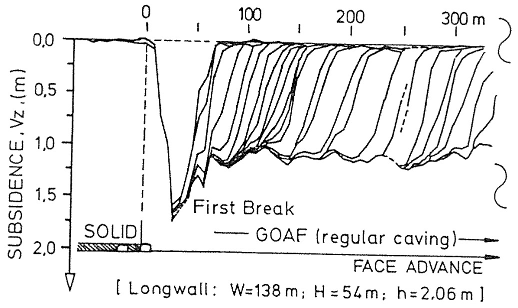


Figure 2 Longitudinal trough section

The presence of dolerite sills and of thick competent sandstones results in subsidence troughs which are much narrower and more shallow than troughs calculated by means of the model proposed by the NCB in the Subsidence Engineers Handbook (1975). In South Africa the cross-sectional area of a subsidence trough is about one third of the product of mining height times panel width, i.e. the excavated cross-sectional area, Schümann (1984). Locally the lateral extent of a subsidence trough is not well defined and a critical panel width is not accurately known due to large variations in the magnitude of maximum subsidence Vz max., Figure 3. This difficulty has been overcome by abandoning the convention of relating the magnitude of subsidence components to maximum subsidence and to the centre of a given trough, and has been replaced by using the mining height h, and the panel edge as references. In order to describe subsidence and trough characteristics, a 'Subsidence Profile Curve' SPC, has been developed analytically for this purpose, Schümann (1986), which is given in 4.2 below.

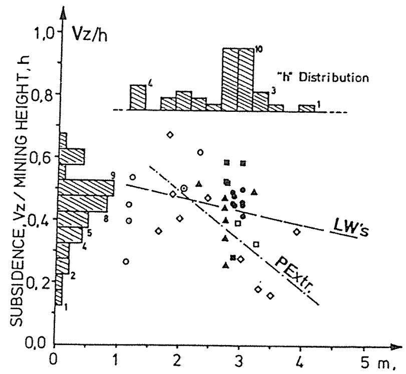


Figure 3 Distribution of mining height versus normalized subsidence

4 SUBSIDENCE PREDICTION IN SOUTH AFRICA

The approach taken and the tools developed for the prediction of subsidence in South Africa are described below.

4.1 Maximum Trough Subsidence

An empirical approach to subsidence prediction has been taken in South Africa due to the complexity of the geology and absence of detailed geotechnical data. Small maximum subsidence above subcritical total extraction panels under superincumbent strata containing a dolerite sill has been monitored at colliery 'D'. The analysis of the results by means of elastic plate theory led to a simplified expression for the prediction of subsidence, Figure 4, which does not strictly conform to theory. Here, maximum surface subsidence is a function of the square of subcritical panel width, W_L, and the depth to the base of the shallow intact dolerite sill, H_D. The extraction height, h, plays no direct role in the expression but, together with the bulking factor of the goaf, governs the height of the cavity at the base of the sill. Failure of the dolerite sill occurs when the Bottom seam - (see Figure 1) - is extracted at colliery 'D', provided the underground panel width equals W_C or larger. The combined effect is shown as normalized subsidence in Figure 5.

Small subsidence above total extraction panels under sandstone and shale strata, having initial subcritical dimensions or a subcritical panel width, has rarely been monitored by the authors.

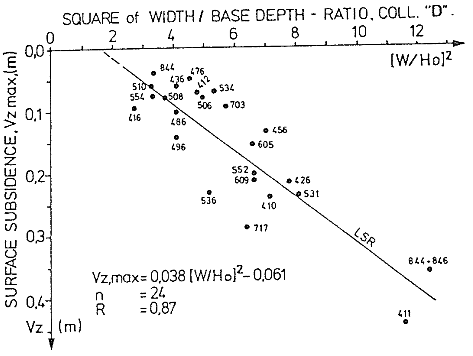


Figure 4 Subsidence due to top seam extraction at colliery 'D'

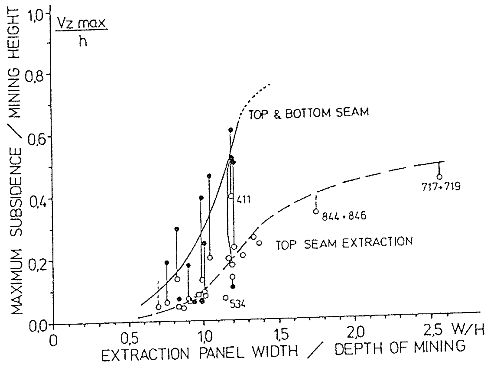


Figure 5 Subsidence due to bottom seam extraction at colliery 'D'

Maximum trough subsidence at other collieries has to be treated individually due to variations in the geological composition of the superincumbent strata. A diagram of normalized maximum subsidence, Vz max, over panel width to depth-ratio, is shown in Figure 6. The large deviation from the NCB model is evident. The Vz max curve has been reduced by the factor f = 0,9 to account for virgin mining as suggested by the Subsidence Engineers' Handbook. Data from the Northern Coal field in the Newcastle district (NSW), (Holla 1986), correlate well with the findings in South Africa when using local peak subsidence in the first-break region above longwalls (Figure 6).

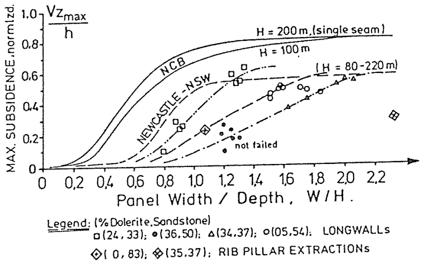


Figure 6 Maximum subsidence related to the W/H ratio

4.2 Subsidence Profile Curve

Investigations into the subsidence process have led to the development of the Subsidence Profile Curve, SPC, mentioned above. Controlled subsidence of a point is said to take place when the growth rate of vertical displacement is proportional to both the size reached and the remaining size, as well as a function of time i.e. face advance x, Schümann (1986). The differential equation describing this growth rate is

$$dy/dx=y(c-y)g(x) \qquad (1)$$

where 'c' is the maximum size, i.e. the asymptote y = Vz max and g(x) is a linear time function. Solving for y leads to the growth curve:

$$y = C / [1 + a \, EXP(-bx)] \qquad (2)$$

which describes a subsidence development curve, (NCB 1975). Parameter 'a' governs the position of the curve in relation to the y - axis, (x = 0, face or ribside position) while 'b' defines the steepness and curvature. Any half-profile, which is symmetric about the inflection point, can easily be fitted to equation (2) by a least square regression. The shifted superposition of two half-profiles result in a complete symmetric or asymmetric trough profile. Derivatives of equation (2) give tilt and curvature profiles.

Principal sections of a subsidence trough are fully described if some relation between vertical and horizontal displacements can be found. Such a relation exists for deflecting beams but not for breaking strata undergoing distinct lateral displacement while being undermined. The basic relation defining horizontal displacement according to Brauner (1973) is a linear function of tilt in the form Vx = d Vz / d x. The correlation between tilt and horizontal displacement from extensive monitoring surveys at seven different sites in South Africa has, however, revealed a clearly defined non-linear parabolic relation, Schümann (1986), as illustrated in Figure 7. All components of subsidence can thus be evaluated analytically, provided the fundamental trough characteristics as functions of geometry and geomechanical parameters have been determined by systematic observations of vertical and horizontal displacement along principal trough sections.

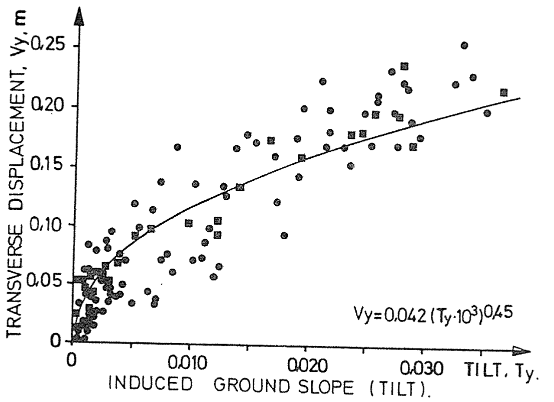


Figure 7 Tilt-displacement relation at colliery 'B'

4.3 Magnitude of Strain and Tilt.

A comparison of spot values, namely the maximum strain-factor in a trough, in relation to the panel width over depth ratio, is presented in Figure 8a. The K1 and K2 multiplier curves apply to the Northern Coal Field (NSW), Holla (1986). Curves for K1 and K2, published by Kapp (1985) for the same district are shifted to larger W/H values and agree better with values found in South Africa. However, a significant difference remains, namely that compressive strain in a given trough in South Africa is generally smaller than extension (Figure 8a). This difference is due to the shallow or absent alluvial cover and higher strength of strata of the overburden which do not permit large compressive strains to develop.

The maximum tilt-factor K3 is shown in Figure 8b, where the broken line represents the Northern Coalfield (NSW) after Holla (1986). The data pairs indicate the left and right flank of a single but non-symmetric subsidence trough which is isolated or separated by a substantial inter-panel chain pillar.

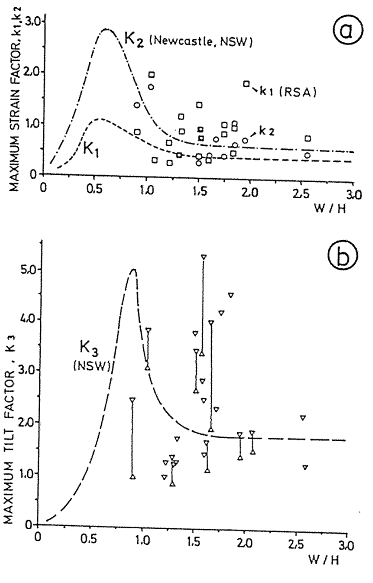


Figure 8a Maximum strain-factors, K_1,K_2 versus W/H ratio

8b Maximum tilt-factor K_3 versus W/H ratio

5 SUBSIDENCE DAMAGE PREVENTION AT A PROVINCIAL ROAD

The knowledge of maximum values of subsidence components, as discussed above, is not sufficient when a structure traverses the whole subsidence through. Detailed experimental work, concerning ground subsidence and the response of a structure, is required for the prediction and the reduction of subsidence damage. The case study below illustrates results, which can be achieved following such an approach. Detailed surface monitoring was conducted along a provincial road with bitumen surfacing at colliery 'B', for which the overburden strata are illustrated in Figure 1 . The road was undermined by a longwall face of 182 m width, 3,0 m height and at a depth of 120 m. The orientation of the faceline was 44° to the centre line of the road. This was the first occasion in South Africa that a provincial road was monitored during undermining by the longwall method. It was anticipated prior to undermining that severe damage would occur. For this reason the colliery was required to construct a deviation to take the flow of traffic during undermining of the road.

It was predicted that subsidence would not exceed 1,5 m, maximum tilt would be about 20 mm/m and ground strain 10 mm/m. The results of a Radial Precision Survey, of 192 monitoring beacons at 7,5 m bay length using a T2 Universal Theodolite and DI4-distomat, were as follows:

Maximum vertical displacement 1,30 m
Max. Hor. displacement + 0,24/-0,13 m
Max. induced tilt + 33/-20 mm/m
Max. vert. curvature 1/+417 & 1/-556 m
Max. hor. strain + 7 mm/m elongation
- 8 mm/m compression

The lateral displacement amounted to +0,12/-0,22 m, the lateral strain of the road structure was + 6/-2 mm/m.

The road had a 'granular base' -pavement structure (125 mm), topped by 25 mm of bitumenous double surface treatment and was underlain by a stabilized subbase consisting of cement treated dolerite gravel (125 mm) and selected subgrade layers (400 mm). Horizontal strain along the centre line of the road after undermining is illustrated in Figure 9.

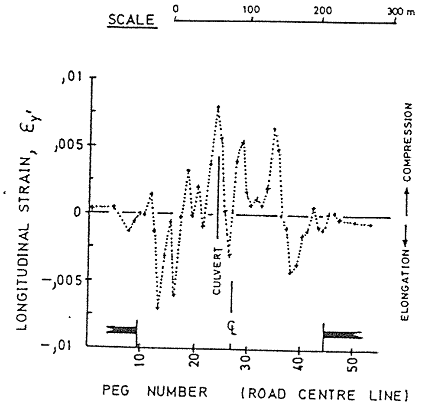
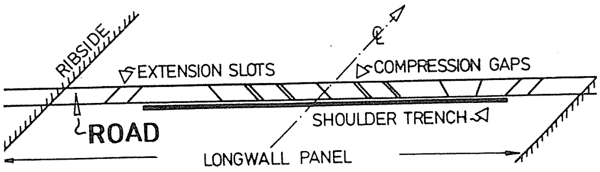


Figure 9 Horizontal strain along road centre line

The deviation, of similar construction to the provincial road, had been built parallel to the existing road. This deviation was undermined ahead of the road by a second longwall extraction panel. Prior to the undermining of the deviation, preventive measures were proposed by the authors in order to reduce the effects of induced strain and to dissipate lateral earth pressure. The preventive measures consisted of extension slots and compression relief gaps across the pavement and of trenching parallel to the deviation. The design was guided by evaluating the differential horizontal displacements which had wreaked havoc with the road by producing differential displacements between subbase and subgrade layers and by peaking of the surfacing and granular base-pavement. Slots and gaps were proposed to a depth of 300 mm, i.e. below the depth of the stabilized subbase. The minimum width of gaps was specified as 100-125 mm, and trenching as 300 mm wide and to a depth of about 800 mm with an uncompacted non-cementing backfill. At the time of implementation of the preventive measures only a backhoe of 300 mm width was available; the cuttings were not filled but were covered with polyethylene plastic sheeting in order to prevent ingress of rainwater and to facilitate periodic visual inspection and measurements. Figure 10 shows the position of slots and gaps, together with the acutal trench, in relation to the ribsides of the longwalls and to the deviation.



SLOT CONVERGENCE: 14 18 40 31 43 81 38 46 90 -14 -6 2 mm
LATERAL SHIFT : 5 0 44 50 23 77 23 33 32 -40 11 4 mm
TOTAL DIFF. MOVEMENT: 15 18 60 59 49 112 39 57 96 42 12 4 mm
TRENCH CONVERGENCE: 18 50 86 (60)45 (30)20 -13 mm
$\sum$SC. = 383mm, $\sum$LS. = 262 mm DIFFERENTIAL MOVEMENT DISSIPATION
LENGTH = 180m, $\varepsilon_{SC.} \geq 2{,}5$ mm/m STRAIN REDUCTION

Figure 10 Road-deviation with slots, listing slot convergence

Results of the displacement survey are included in Figure 10. The table in Figure 10, which combines slots and gaps, shows a total convergence of 383 mm over an active length of deviation of 180 m. This means that some dynamic extension cracks across the pavement did not close. The resultant dissipation of differential movement (262 mm), has been diverted from intact pavement and is significant. The survey showed that subsidence damage caused to the deviation by undermining was much less than that suffered by the road, but the extension slots failed to attract extension cracks in their vicinity. However, extension cracks do not loosen the granular subbase and are easy to repair by means of infilling. The preventive measures considerably shortened the time needed for temporary repair and led to a repair cost reduction by 70 per cent. Similar preventive measures have since been employed at subsequent sites.

6 CONCLUSIONS

It has been shown that surface subsidence is a site specific phenomenon and that the empirical model for the prediction of subsidence proposed by the NCB in the Subsidence Engineers Handbook is at great variance with the findings in South Africa and Australia. The cause for this variance is a different composition of superincumbent strata. Strong sedimentary layers in the overburden restrict the initiation as well as the propagation of caving. When caved, the broken strata bulk but do not recompact fully. The degree of recompaction of the rock aggregate is a function of material strength and applied load, i.e. cover load. It is concluded that a global subsidence prediction formula does not exist and that site specific parameters such as the composition, complex structure and strength parameters of the superincumbent strata have to be taken into account. This can best be done by empirical methods, developed by using results from local in situ measurements, as has been demonstrated above.

7 ACKNOWLEDGEMENT

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