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An Overview of the Prediction and Effects of Surface Subsidence

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SUMMARY Papers presented at this conference are reviewed against the background of an overview of ground subsidence management. It is concluded that the papers illustrate the transition from an art to a science, that the prediction of surface subsidence and its effects is undergoing.

1. INTRODUCTION

In recent years conflict has arisen between community and the mining industry over ground subsidence and its effects on the environment, both natural and man-made. The technical aspects of these conflicts are often clouded by strong emotional issues. If these conflicts are to be resolved in a manner which is both economically and socially fair to all parties, it is essential that geotechnical engineers develop reliable techniques for predicting both ground subsidence and its effects on sub-surface and surface features and structures.

Four papers which present comparisons between prediction and performance relating to surface subsidence and its effects have been reviewed in this paper. The subject matter is dealt with in the framework of an overview of ground subsidence management.

2. AN OVERVIEW OF GROUND SUBSIDENCE MANAGEMENT

Figure 1 gives an overview of ground subsidence management and indicates (#) those aspects addressed by papers presented at this conference. The three key elements are:

i. The prediction of the effects of mining on sub-surface and surface behaviour.

ii. The prediction of the effects of sub-surface and surface behaviour on the integrity of structural features.

iii. The selection of appropriate techniques to control the effects of mining on sub-surface and surface features.

Sub-surface behaviour and features have been included in view of the increasing number of mining operations being undertaken under water bodies and the increased concern by agricultural and environmental bodies as to the effects of subsidence on the supply and quality of sub-surface water.

3. THE PREDICTION OF SURFACE SUBSIDENCE

There are three basic approaches to surface subsidence prediction, which may or may not be used in isolation. These are:

i. Empirical.

ii. Numerical.

iii. Geomechanical.

Mathematical analogies illustrate the differences and interactions between these approaches.

3.1 Empirical Approaches

In the empirical approach, field survey observations are used to develop sets of curves which describe the effects of specific parameters on surface behaviour. Empirically derived curves do not take into account all parameters which govern subsidence, and unless all data is collected under the same specific set of conditions, a scatter of data points is to be expected.

This deficiency is overcome usually by constructing the empirical curves to embrace the majority of plotted points, Figure 2. As such, this approach may be conservative and can represent subsidence 'restriction' rather than subsidence 'prediction'.

The following equations provide a mathematical analogy to the approach.

$a_1 \# \ldots \# a_n \# x_1 \# \ldots \# x_n = 7$ A field observation

$a_1 \# \ldots \# a_n \# y_1 \# \ldots \# y_n = 9$ A field observation

$a_1 \# \ldots \# a_n \# z_1 \# \ldots \# z_n = 3$ A field observation

where $a_1 \ldots a_n$ = established site conditions,

$x_1 \ldots x_n, y_1 \ldots y_n, z_1 \ldots z_n$ = unknown site conditions.

\# = an arbitrary relationship between site conditions.

Therefore, empirical subsidence prediction (restriction) is defined by the worst case of $a \# \ldots \# a_n \# k_1 \# \ldots \# k_n = 9$.

where $k_1 \ldots k_n$ encompass unknown conditions at all sites.

An empirical approach to subsidence prediction has been adopted in papers presented at this conference by Holla and by Schumann and Hardman. Holla has utilized empirically derived curves to estimate the magnitude of surface subsidence components in the vicinity of surface structures.

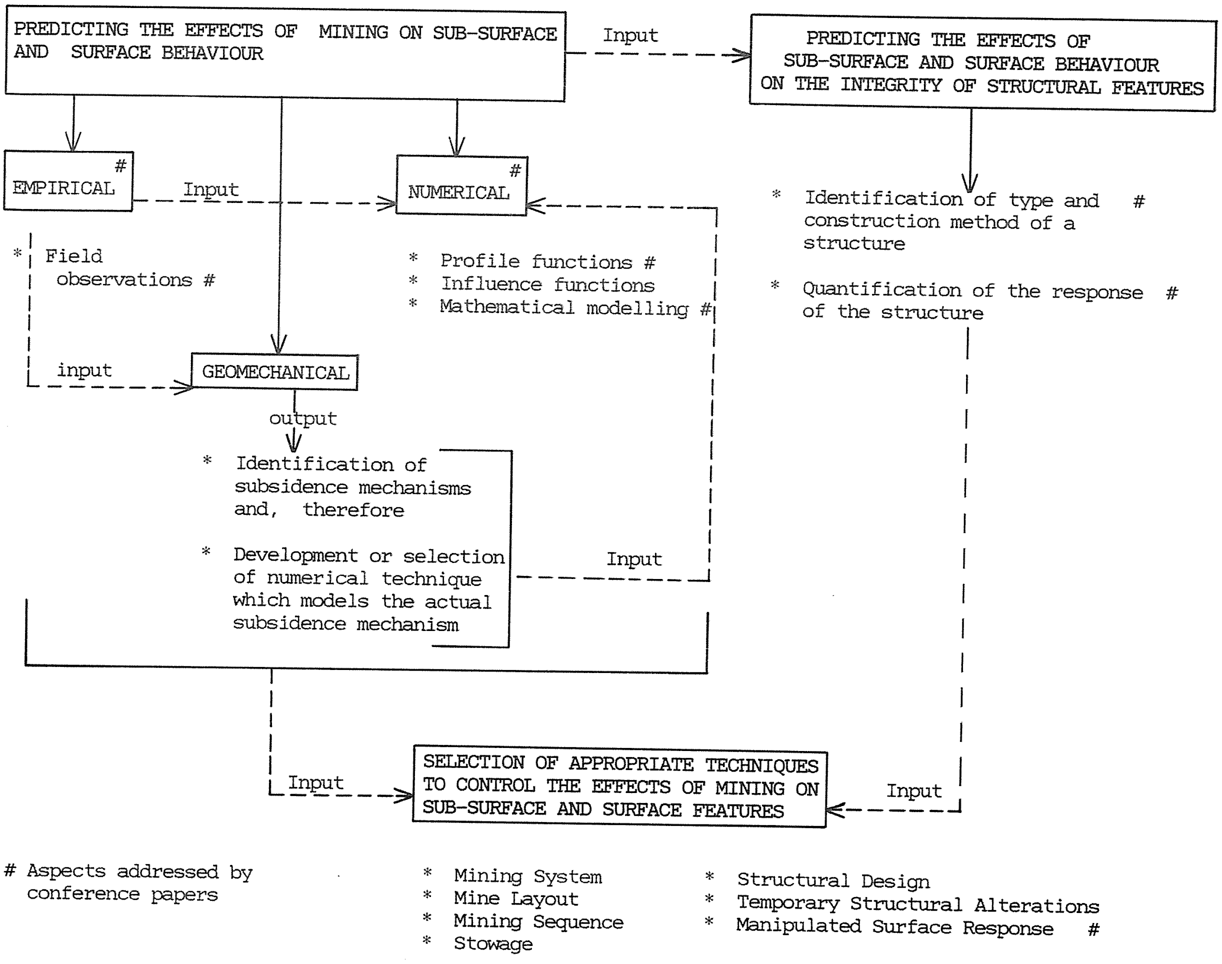


FIGURE 1. An overview of ground subsidence management.

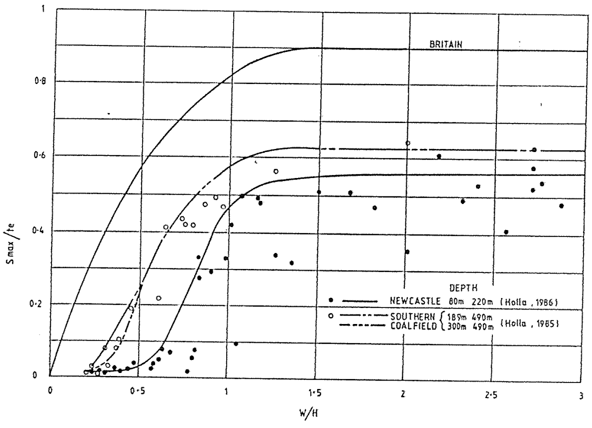


FIGURE 2. Empirical Subsidence Design Curves

Schumann and Hardman have adopted an empirical approach to subsidence prediction due to the complexity of the geology. The scatter of data points presented in Figures (3) to (8) of their paper indicates that all parameters have not been taken into account in the empirical relationships. The site specific nature of empirical prediction curves is illustrated not only by the significant difference reported between the NCB curve and South African curves but also by the different South African curves corresponding to different geological compositions, Figure (6). This latter suite of curves shows very similar trends to those developed for the Southern Coalfield of N.S.W., Figure 3. The scatter of South African data about the Newcastle curve is of a similar magnitude and distribution to the scatter of Newcastle data about the same curve, Figure 2.

3.2 Numerical Approaches

Three of the four papers reviewed present results of numerical modelling, with the paper by Gurtunca and Bhattacharyya providing a concise review of numerical techniques.

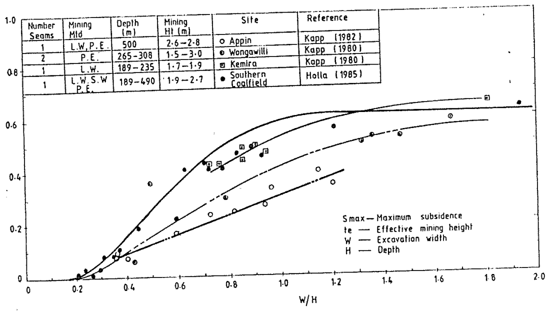


Figure 3. Subsidence design curves for the Southern Coalfield of N.S.W.

In general, the potential of powerful numerical models to predict surface subsidence to the level of accuracy required by surface planners and constructors, remains unfulfilled. More often than not, successful modelling is dependent on the judgements of the modeller, especially in regards to selection of the appropriate model and the quantification of input parameters.

Too often numerical models are being developed on a purely structural engineering approach with little consideration being given to geomechanical principles and strata behaviour mechanisms. Program developers are assuming that their models are correct and therefore, are manipulating input data in order to achieve a known result. Claims to success are often being made in the light of back-analysis and manipulation of input data, with the capability to reproduce the vertical component of subsidence being the only criteria for judging success in many instances.

The mathematical analogy in these cases is;

$$a_1 \# \ldots \# a_n \# x_1 \# \ldots \# x_n = 9$$

where # = some operation ie modelling technique

$a_1 \ldots a_n$ = established input parameters (or site conditions)

$x_1 \ldots x_n$ = input parameters yet to be quantified.

The answer (9) may be arrived at by an infinite number of variations of input parameters and modelling operations, such as;

Model 1: $2 + 6 + 1 = 9$ Input data set 1
$3 + 4 + 2 = 9$ Input data set 2

or

Model 2: $2 \times 3 + 3 = 9$ Input data set 3
$3 \times 1 + 6 = 9$ Input data set 4

Once a model has been refined by back-analysis of site specific results, it can be a valuable tool in accurately predicting performance at that site. However, because both the algorithm and the validity of the input data have never been verified, the model may be completely unreliable outside the set of conditions to which it was artificially adapted.

It is essential therefore, that if numerical subsidence prediction is to be considered as a science and not an art, future subsidence research must concentrate on quantifying:

i. In-situ material properties.

ii. Strata behaviour mechanisms in the field.

Gurtunca and Bhattacharyya have evaluated by back-analysis three displacement discontinuity based models including a model (THREED) which attempts to model strata behaviour as observed in the field. The authors obtained good subsidence profile agreement utilizing the program MSEAMS. However, to achieve this agreement they had to reduce considerably the in-situ Shear Modulus of surrounding rock. The authors report that this is in keeping with the experience of other researchers. It would be valuable to establish to what extent the success of MSEAMS was also dependent on this model having been used to establish by back-analysis, the elastic constants used in all three mathematical models. The reported results are interesting in that subsidence has been modelled relatively accurately over interpanel pillars as well as panels.

Gurtunca and Bhattacharyya have recognised that different subsidence mechanisms, and thus numerical models, may apply for different mine geometries. However, their classification of the Lambton Colliery shortwall panels as supercritical is open to debate since maximum subsidence was only 226mm or less than 11% of extracted height. Thus, the authors suggestion that there is a need to determine a new set of parameters for a single panel in virgin ground would appear unwarranted if the panel was not of supercritical dimension.

Reddy and Dhar have utilized an electrolytic analogue to model surface subsidence. Predicted subsidence values tend to agree with measured field values over about one half of each subsidence profile presented, Figure (4) to (7). Unfortunately, over the remaining section of the profiles the field values range from one half to double the predicted values. The greatest differences between predicted and measured values occur in the general area of panel abutments, where permanent strains and tilts induced by mining subsidence are often of maximum value. Thus, the model requires further development before it could be applied to assessing the risk of mining induced damage to surface structures. The authors have noted a number of extraneous factors which could have contributed to the differences between prediction and performance. It may be worthwhile to also investigate the strata behaviour mechanism at such shallow depth (<50m) to determine how closely linear elasticity theory models field behaviour.

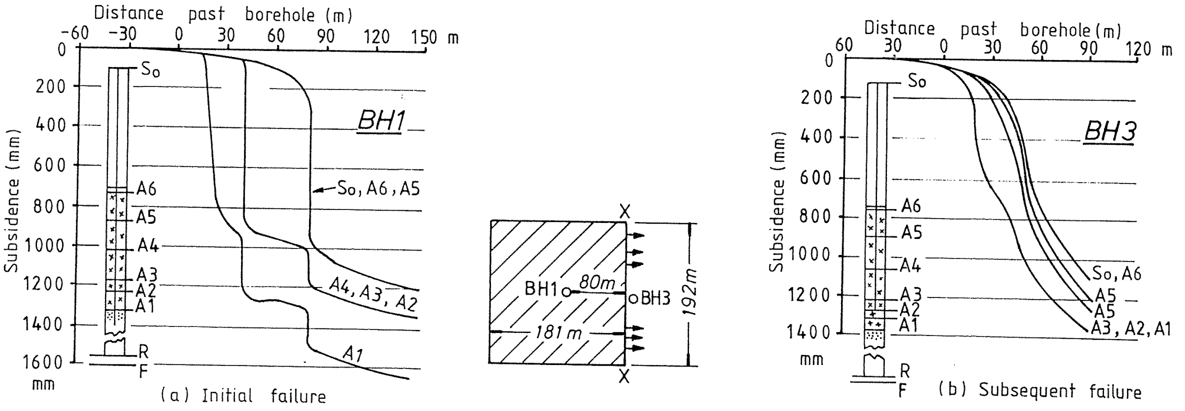
3.3 GEOMECHANICAL APPROACHES

Geomechanical observations usually do not stand alone as a subsidence prediction technique but are an essential element in identifying the subsidence mechanism in operation and therefore, in developing or selecting the appropriate mathematical model. In the mathematical analogy of subsidence prediction, geomechanical observations serve to;

i. Identify the algorithm which describes the subsidence mechanism (#).

ii. Quantify the geomechanical input data, $(a_1 \ldots a_n, k_1 \ldots k_n)$.

Whilst perfect definition of both these factors will probably never be achieved, even basic geomechanical observations can assist significantly in the selection of the appropriate mathematical model. This is illustrated in Figures 4 & 5 which show examples of the development of surface subsidence due to caving of a 40m thick dolerite sill in the superincumbent strata of a South African longwall panel (Salamon et al, 1972, Galvin, 1982). Borehole extensiometer measurements and underground observations and measurements highlighted that different mechanisms are associated with the development of initial surface subsidence and that which subsequently occurs.



(a) Initial failure

(b) Subsequent failure

FIGURE 4. Borehole extensometer measurements highlighting different subsidence mechanisms.

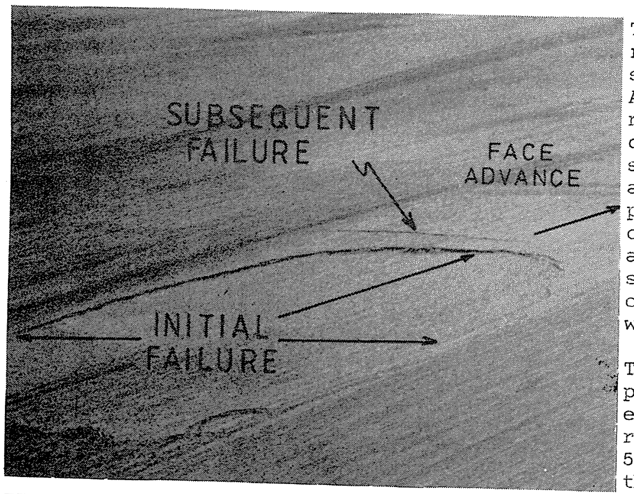


FIGURE 5. Aerial photograph illustrating different subsidence mechanisms.

The geomechanical information minimises conjecture in explaining the shape of the surface subsidence profile presented in Figure (2) of the paper by Schumann and Hardman. It serves as a basis for developing numerical techniques which will model the actual subsidence mechanism and so enable subsidence to be predicted. The need to have to manipulate input data into models which do not mirror actual strata behaviour in order to achieve acceptable results should therefore be eliminated. Development of the appropriate numerical model depends upon a knowledge of basic geomechanical properties such as caving angles and goaf recompaction behaviour (noted in the Schumann and Hardman paper) and caving mechanisms (incorporated in the THREED programm, Gurtunca and Bhattacharyya paper).

4. THE EFFECTS OF SUBSIDENCE ON STRUCTURES

Predicting the performance of a structure subjected to subsidence is a difficult problem since the performance is dependent not only on the accuracy of the surface subsidence prediction but also on the method of construction of the structure. This is illustrated by the range of damage classification systems in use throughout the world, Table 1. (Schumann 1979)

The paper presented by Holla is one of the few recorded attempts to predict the effects of subsidence components on the integrity of Australian residential structures. Unfortunately, no measurements were made of the actual tensile and compressive strains and the tilts to which the structures were subjected, and damage has had to be assessed in the light of empirically based predictions of the maximum value of these components. Care must be adopted with such an approach to ensure that the use of maximum subsidence component values does not result in an over-estimation of the amount of ground movement which actually caused the structural damage.

The results indicate that technically there is potential for conducting 'unrestricted' pillar extraction and longwall mining operations under residential areas in Australia at depths of 265m to 500m. However, future studies may need to assess the impact of permanent residual surface strains and tilts.

One major deficiency in most empirical strain prediction techniques is that no consideration is given to the nature of the surface material. The composition, strength and thickness of the surface material significantly influences the magnitude and distribution of surface strains. Schumann and Hardman for example, attribute the difference in

TABLE 1 - CATEGORIES AND LIMITS OF SURFACE SUBSIDENCE DAMAGE
(Schumann, 1979)

CLASS OF DAMAGE	GREAT BRITAIN (NCB 1975 Subs Eng p49) For a 60m long building	POLAND (S Knothe 1952) (Rimant 1958)	SOVIET UNION Donetsk District (VNIMI 1958)
I Very slight or Negligible	Haircracks in plaster, isolated slight fracture in building, not visible outside E = 0.5 mm/m	Haircracks, no damage T < 2.5 mm/m E < 1.5 mm/m	T < 4 mm/m E < 2 mm/m
II Slight	Several slight fractures inside, doors and windows stick E = 0.5 - 1 mm/m	Damage easy to repair T < 5 mm/m E < 3 mm/m	Limit for 5 storey building T < 4.5 mm/m E < 2.5 mm/m
III Appreciable	Slight fracture outside or one main fracture. Doors and windows stick E = 1 - 2 mm/m	Appreciable damage, building still useable T < 10 mm/m E < 6 mm/m	Three and four storey buildings T < 5 mm/m E < 3.5 mm/m
IV Severe	Severe open cracks, floors sloping, walls leaning. Anchoring required E = 2 - 3 mm/m	Severe damage, anchoring required T < 15 mm/m E < 9 mm/m	Two storey buildings T < 8 mm/m E < 6 mm/m
V Very severe	Part or complete rebuilding E > 3 mm/m	Destruction of building	One storey only T < 10 mm/m E < 7.5 mm/m

T - Tilt

E - Strain

compressive strain behaviour between South Africa and Australia to the shallow or absent alluvial cover and higher strength of strata in the overburden in South Africa.

The variable nature of the surface material is one factor which accounts for the scatter of empirical strain factors when plotted against panel width to depth ratio, W/H eg Figure (8a) of Schumann and Hardman. In quantifying accurately the effects of subsidence on structures, it is important that the nature of the surface material is assessed and the surface subsidence components are monitored in the vicinity of the structure.

An interesting point presented in the paper by Schumann and Hardman is the magnitude of horizontal displacements (+240mm to -130mm, = 370mm). Depending upon the orientation of the structures relative to the direction of mining, such displacements can impact significantly on the function of structures such as overland conveyors. Future systems for classifying structural tolerance to surface subsidence may need to take into account the magnitude of lateral surface displacements.

5. TECHNIQUES TO CONTROL THE EFFECTS OF SUBSIDENCE

Various techniques to control the effects of mining on sub-surface and surface features are noted in Figure 1. None of the papers reviewed specifically addressed mining based techniques. Of the remaining techniques, Holla has noted that differential horizontal movement of soil particles causes friction at the soil-structure interface and stresses in the structure. Whilst not developed further in the paper, it should be noted that modification of the soil-structure interface is a construction technique used to restrict strain damage to dwellings in expansive soil environments in Australia. Such strains often exceed those associated with many total extraction mining operations.

Schumann and Hardman have reported on the protection provided to a structure against strain damage by the use of strategically located slots of up to 300mm width and 800mm depth. The authors note that although subsidence damage was reduced, extension slots failed to attract extension cracks in their vicinity. Similar behaviour has been observed at Angus Place Colliery in N.S.W. (Mong, 1986). Despite the existance of well developed natural fracture systems, tension cracks associated with the undermining of escarpments have tended to develop in fresh rock, often immediately adjacent to natural joints.

6. CONCLUSIONS

Research into the geotechnical aspects of surface subsidence covers a very broad field as illustrated in Figure 1. Papers presented at this conference have touched on a number of the elements which make up the field.

The papers highlight the number of significantly different approaches that are currently being applied to the prediction of surface subsidence components and their effects. In general, the papers are not concerned with justifying the approach selected but, in keeping with the theme of the conference, with comparing predicted results with performance.

Overall, it could be concluded that subsidence prediction techniques have developed to the stage where on the basis of pre-existing subsidence field data, the vertical component of surface movement can be predicted reasonably accurately by both empirical and numerical prediction techniques. Further research needs to be undertaken into quantifying the in-situ geotechnical properties of strata and sub-surface behaviour mechanisms if acceptably accurate predictions of subsidence components are to be made without the assistance of pre-existing field data, back analysis and manipulation of input data.

Much of the subsidence research undertaken in the past has been concerned with measuring and predicting the vertical component of surface subsidence. However, due to rapid encroachment of urban development into coal mining areas and increasing environmental pressures, it is very important that future research addresses the prediction and effects of the strain and tilt components of surface subsidence.

The papers illustrate the transition that the prediction of surface subsidence, and its effects, is currently going through. That is, from an art, based on judgements, to a science, based on the laws of physics. Completion of this transition should enable acceptably accurate subsidence predictions at existing and greenfield sites.

7. REFERENCES

GALVIN, J.M. (1982)
Total extraction of coal seams - the significance and behaviour of massive dolerite sills. Chamber of Mines of South Africa Research Organisation. Research Report No. 19/82.

HOLLA, L. (1985)
Mining subsidence in New South Wales. Surface subsidence prediction in the Southern Coalfield Department of Mineral Resources, N.S.W.

HOLLA, L. (1986)
Evaluation of surface subsidence characteristics in the Newcastle Coalfield of New South Wales. The Coal Journal, No.11

KAPP, W.A. (1980)
A study of mine subsidence at two collieries in the Southern Coalfield, New South Wales. Proceedings Aus. Inst. Mining Metall. No. 276, December 1980

KAPP, W.A. (1982)
Subsidence from deep longwall mining of coal overlain by massive sandstone strata. Proceedings Aus. Inst. Mining Metall. No. 281, March 1982.

MONG, J. (1986) Geotechnical report on the surface effects of mining longwall No. 9 panel at Angus Place Colliery. Internal Report - Electricity Commission of N.S.W.

SALAMON, M.D.G., ORAVECZ, K.I. and HARDMAN, D.R. (1972)
Rock mechanics proplems associated with longwall trials in South Africa. 5th International Strata Control Conference. London, August 1972

SCHUMANN, E.H.R. (1979)
Surface subsidence over longwalls at Durban Navigation Colliery. Chamber of Mines of South Africa Research Organisation. Research Report No. 19/79