27
5/8/80
240 NTIS

SAND80-0537

UNLIMITED RELEASE

MASTER

EVALUATION OF EUROPEAN EMPIRICAL METHODS FOR SUBSIDENCE IN U. S. COAL FIELDS

D. E. MUNSON AND W. F. EICHFELD

Prepared by Sandia Laboratories, Albuquerque,
New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy under
Contract Number DE-AC04-76DP00789.

PRINTED APRIL 1980

Sandia Laboratories
energy report

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia Laboratories, operated for the United States
Department of Energy by Sandia Corporation.

NOTICE

This report was prepared as an account of work sponsored by
the United States Government. Neither the United States nor
the Department of Energy, nor any of their employees, nor
any of their contractors, subcontractors, or their employees,
makes any warranty, express or implied, or assumes any legal
liability or responsibility for the accuracy, completeness or
usefulness of any information, apparatus, product or process
disclosed, or represents that its use would not infringe
privately owned rights.

Printed in the United States of America

Available from

National Technical Information Service

U. S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161 6-62

Price: Printed Copy \$3.50; Microfiche \$3.00 50

Add \$2.50 per copy for foreign price.

SAND80-0537
UNLIMITED RELEASE

Evaluation of European Empirical Methods

for

Subsidence in U. S. Coal Fields

by

D. E. Munson

Geotechnology Research Division, 4732 ✓

951 1100 Sandia National Laboratories, Albuquerque, NM 87185

W. F. Eichfeld

Carbondale Mining Research Center

Department of Energy, Carbondale, IL 62901

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Abstract

The purpose of this study was to assess the applicability of European subsidence methods for the emerging U. S. longwall practice. Subsidence prediction in Europe has typically used either graphical methods (United Kingdom) or mathematical methods. The mathematical methods utilize either profile or influence functions. The graphical methods were developed in the United Kingdom (UK) by the National Coal Board (NCB) from the subsidence data obtained from numerous mines. Although a large data base in the United States (US) is not available, the methods can be tested against some recent measurements of subsidence of an essentially flat deposit mined at a depth of 189 m in the Illinois Coal Basin. While the total predicted subsidence by the NCB

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

method is approximately correct, the profile shapes are not well matched. On the other hand, the profile functions, which are fundamentally independent of orientation with respect to mining, give quite accurate representation of the measured profiles. Of the antisymmetric forms tried, a trigonometric form was slightly preferable because it predicted strains that were conservative, i.e., always somewhat greater than the measured values. These results suggest that much of the European subsidence experience is applicable to US practice. Consistent values of the parameters were found for profiles with similar initial conditions or similar orientations for two longwall panel results.

It should be noted that the actual profiles were always somewhat more complex than the profile functions could adequately handle and that the development curves showed time-dependent effects as well. The magnitude of these time-dependent effects, while possibly small compared to the time-independent or instantaneous subsidence, are of importance and must be eventually incorporated into a proper analysis.

Introduction

For several decades, the European coal mining industry has been forced by extensive surface utilization to deal realistically with subsidence. This has resulted in several techniques that are more or less routinely applied. Because of the nature of the development, these techniques center about empirical methods and simple analytic procedures for describing the subsidence trough. Typical of these methods are the graphical empirical methods used in the United Kingdom and the mathematical profile functions or influence functions used on the Continent. Several circumstances, principally the slow introduction of longwall mining practice and sparse population in active mining areas, have deemphasized the need for such subsidence studies in the United States (US). However, increased reliance on coal as a prime energy source, progressive surface development over critical coal basins, and new laws regulating surface effects of underground mining operations suggest that a closer look at US practice is warranted. A first step is to evaluate the well-established foreign methods relative to US practice. It is the intent of this report to test these methods through application to those domestic longwall mines where the subsidence process is documented.

Background

Perhaps the best, although not the most recent, review of the empirical methods is that given by Brauner;¹ we make extensive use of his work in this report. European methods consist essentially of (1) the graphical methods of the United Kingdom (UK), which are perhaps the best known here because of the extensive compilation of case histories by the National Coal Board (NCB),² and (2) the Continental methods based upon mathematical fits in the form of profile or influence functions.¹ Initial phases of this study concentrate upon the graphical methods and the profile functions. NCB practice pertains to the longwall mining of flat lying deposits in the UK, frequently in areas of previous intensive mining of adjacent coal or mineral seams. Profile functions center about two antisymmetric forms, the error integral form found successful in the coal fields of Upper Silesia (Poland) and the trigonometric form found successful in the Donets (USSR) coal fields. Each of the empirical types will be discussed separately in some detail, but first it is necessary to clarify our nomenclature somewhat.

In using the empirical methods, it is essential that we recognize certain details of the subsidence trough and distinguish them. A fundamental difference occurs between those profiles which develop at right angles to the mining direction and those that develop parallel to the mining direction. Thus, these orientations are classified as transverse profiles which develop along the rib sides and at right angles to the direction of mining, and longitudinal profiles which develop parallel to the direction of mining. Within this framework, other refinements are necessary* to describe the conditions under which the profile was obtained as follows:

- 1) stationary profiles encompass the
 - a) transverse profiles over the rib side, and
 - b) longitudinal profiles formed at the beginning of the panel, where unique initial and boundary conditions occur due to the failure and collapse of a free roof span, and
 - c) longitudinal profiles formed at the end of the panel, where immediate roof failure occurs.
- 2) non-stationary profiles encompass the
 - a) traveling wave profiles measured in the panel interior as the face advances; if the subsidence has no time-dependent component, this profile is identical to the stationary end profile;
 - b) development profiles describe the subsidence motion of a surface point over the panel as a function of face position; if there is no time-dependent component and the beds are transversely isotropic, this profile is identical to the traveling wave; a special form of this curve is the time-correlated development profile that describes the motion of a surface point with time.

In the definition of the various non-stationary profiles, the influence of time becomes a prominent feature. We need to recognize that two types of time effects occur. One of these is a pseudo time-dependent response which arises because the mine face advance rate is finite, and normally discontinuous. The other time effect is a true time-dependent response directly related to material constitutive response.

*These straight forward definitions mainly follow previous practice except for some slightly broadened scope of the stationary waves and a change of name for the time-correlated development profile.

The ensuing background discussions will cover not only the types of empirical subsidence descriptions, but also pseudo and true time-dependent responses.

Graphical Methods

Nationalization of the coal mines in the UK established the mechanism for systematic evaluation of subsidence. As a result, more than 165 subsidence case histories over numerous collieries are available. These data were collated and analyzed through a series of non-dimensionalized graphs under the auspices of the NCB. A handbook² was published in 1966 and revised in 1975 as a practical work for predicting subsidence and categorizing structural damage. In a systematic way, one can work through the graphs to determine subsidence for mines with similar design and geological features to those summarized in the handbook. The parameters include seam thickness, seam depth, seam inclination, topography, and panel geometry parameters for longwall mines. The results reflect the fact that typically the UK mines are in previously worked ground. Although time-related effects are discussed, these are reduced to simple estimates of the residual subsidence.

The UK graphical analysis represents the largest collection of subsidence field data over longwall mines, and therefore must be one of the major comparison points for our analysis. The NCB addressed the transverse stationary profile since its extent normally dominates the final trough periphery. They have, however, characterized the development profile as well.

Profile Functions

On the Continent, a different approach emerged for characterizing subsidence. Here individual investigators attempted to find mathematical functions which matched the measured subsidence profiles. These functions then pertain to a given district or geological setting and can be used to determine surface strain and to plan mining practice to minimize surface effects. As a consequence of the approach, there have been a number of mathematical forms proposed. The functions typically have the form of

$$s/S_m = f(B, x, c) \quad (1)$$

where s/S_m is the local subsidence normalized to the maximum subsidence, B is a parameter related to the maximum slope of the profile which governs the horizontal extent or range of the function, c is either a function or constant and x is a horizontal distance. An expression for B is

$$B = S_m/S_i \quad (2)$$

where S_i is the profile slope at the inflection point of the curve. In practice B corresponds to the horizontal base of a right triangle formed by the maximum slope line and the vertical subsidence depth; it is normally expressed in a dimensionless ratio with the seam depth. These features are shown schematically in Figure 1. When the function is finite rather than asymptotic, B is related to the limit angle through

$$B = h \cot \gamma \quad (3)$$

Figure 1. Schematic of the Subsidence Displacement as Described by a Profile Function.

where h is the seam depth and γ is the limit angle. In these functions, no distinction is possible between longitudinal and transverse subsidence profiles, or between traveling and boundary subsidence profiles. Since the functions are actually curve fits that require normalization in both subsidence magnitude through measured values of S_m and horizontal range through measured values of B , no distinction is necessary in application of the fit to a particular profile type. Subcritical subsidence is handled through modifying the functions to reduce the total subsidence.

An asymptotic profile function* which reoccurs frequently is the error integral or its complement,

$$s/S_m = 1/2 \left[1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{\pi x}{B}} e^{-\xi^2} d\xi \right] \quad (4)$$

where ξ is an integration limit. This empirical form has been applied to the flat coal seams with single workings of Upper Silesia (Poland) with success.³ The error integral also results from the integration of some influence functions and is the natural form which results from the Gaussian distribution functions of the Litwiniszyn stochastic models.⁴ The stochastic, or void-diffusion, models have also been applied to the Upper Silesian fields with success.

A profile function of the non-asymptotic, trigonometric type,

$$s/S_m = 1/2 \left[1 - \frac{x}{B} - \frac{1}{\pi} \sin \left(\pi \frac{x}{B} \right) \right] \quad (5)$$

has been found to accurately match the subsidence profiles of the Donets (USSR) fields.¹

The final function, which apparently describes the field experience of Hungarian coal mines,⁵ is of mixed form,

$$s/S_m = \exp \left[-1/2 \left(\frac{x+B}{B} \right)^2 \right] \quad (6)$$

*These forms and the asymptotic or non-asymptotic nomenclature are as given by Brauner.¹

which asymptotes only at the trough lip; i.e., toward the unsubsided ground.

Brauner¹ also summarizes other forms based on the results of laboratory stress tests of physical models. Because it is difficult to establish the correlation between the physical models and field results, we will not use profile functions obtained in this manner for our analysis.

Influence Functions

The use of influence functions developed from the need to treat irregular mine areas. These functions describe the response of an incremental area of the mine and how it influences the region around it. Proper selection of the influence function gives upon integration over the mined area the observed subsidence profile. The form is

$$S_m = 2\pi \int_0^{\zeta} r p(r) dr \quad (7)$$

where ζ is the half range of the influence function $p(r)$ and r is a radial distance. Numerous schemes to generate $p(r)$ and the zone sizes for calculating the subsidence have been advanced; notably among the schemes are those of Bals⁶ and Knothe.⁷ A detailed comparison of the latter two methods has been given by Zenc.⁸ Some of the influence functions lead to integrals of the same form as the error integral, with the obvious implications.

At this point, we do not need to use the influence functions for comparative analysis of US longwall data. Such an analysis is too complicated to be warranted for the simple longwall geometries involved. It is adequate to note that the influence functions can lead to forms analogous to the profile functions being tested here. As our comparisons evolve, indeed to the point of describing the interaction of adjacent longwall panels and entry systems, it may be necessary to explore then the applicability of influence functions.

Longwall Subsidence Analysis

We have focused the evaluation of European empirical methods on the flat lying deposits in flat terrain, in this case the Illinois Coal Basin. There exists a large body of data^{9,10} from two longwall panels of the Old Ben No. 24 Mine in the Illinois (Herrin) No. 6 seam. Here a nominal 2.1 m thickness of coal was extracted from an approximately 2.7 m thick seam at a depth of 189 m. No previous workings existed either above or below the current mine. Panel 1 was 140 m wide by 529 m long and Panel 2 was 140 m wide by 536 m long. Adjacent to Panel 1 was a conventional room and pillar extraction with retreat pillar robbing. A chain pillar was left between the room and pillar area and longwall Panel 1; a similar chain pillar also was left between Panel 1 and Panel 2. A schematic of the study area is shown in Figure 2.

The relevant field measurements consisted of periodic level surveys of three lines of surface monuments, one line transverse across both panels and one longitudinal line for each panel.⁹ A short base length automated system (ADAS) was also emplaced over the interior of the Panel 2 surface area,¹⁰ as seen in Figure 2. The reported measurements, which were quite extensive, give transverse stationary, longitudinal stationary, traveling wave, development, and time-correlated development profiles. Peripheral information on face advance rates complete the information. Such a complete study over any mine is almost without precedence. In addition, the surface measurements are precise and unencumbered with manmade surface construction features common in European results.

In Figure 3 the transverse profile for Panel 1 is given. Clearly, we can treat only the right side profile since the ground motion on the left has been modified by previous room and pillar workings. After correction for the influence of virgin rather than previously worked ground, the NCB predicts for this subcritical situation a maximum subsidence of 0.60 of the extraction height; this agrees quite well with the observations of about 0.59 for Panel 1 and about 0.62 for Panel 2. However, the NCB transverse profile is a rather poor match to the field data, as shown. The UK experience suggests a profile slope much too

Figure 2. Panels 1 and 2 of the Old Ben No. 24 Mine and the Location of Survey Lines and the Automatic Data Acquisition System (ADAS).

Figure 3. Comparison of the Measured Transverse Profile for Panel 1 and the Empirical Results.

shallow, with a much larger trough extent compared to the measured profile.* Also, the UK results show a much larger radius of curvature and smaller strains in the upper or lip portion of the trough. In fact, typical limit angles in the UK¹¹ are 25 to 35°, where this US mine shows limit angles of 10 or 20° depending upon profile type. Thus, while one can obtain a reasonably accurate measure of maximum subsidence using the UK experience, their strain values would be considerably less than actually experienced over this Illinois mine and in general the profile shapes do not match. The reason for the differences is unknown; however, it may reflect either differences in geologic structure or more probably, the influence of the previous multiple seam mining in the UK results. Logically prior disruption of the ground through subsidence induced fractures would lead to changes in profile shape for subsequent mining events.

The antisymmetric profile functions, Eqs. 4 and 5, were plotted against the measured transverse profile in Figure 3. In general, the profile functions are quite good fits to the data, especially in the bottom of the trough. The measured profile has less curvature, i.e., smaller peak strain, in the lip of the trough than the profile function. As we shall see, this non-antisymmetric behavior of the field data occurs in all the stationary and traveling wave profiles for this mine. Although the reason for the greater subsidence over the solid material is not clear, we suspect this effect is related to true time-dependent material response or partial failure of the solid ribs (or pillars) enhanced by mine workings such as entry systems and deployment or recovery rooms. While it appears that both profile functions are adequate representations of the field results, we select the trigonometric function because it leads to conservative predictions of the peak strain, i.e., the peak strain predicted is greater than that observed. This is illustrated also in the comparisons on the traveling longitudinal wave in Figure 4. Consequently, only the trigonometric function is shown consistently in the figures.

In Figures 4 and 5 the longitudinal profiles for Panels 1 and 2, respectively, are shown; these include beginning and end stationary profiles and representative traveling wave profiles. Here the NCB profile is their development profile,² which for the conditions of

*This conclusion was reached earlier with respect to Panel 1 and the transverse stationary profile by O'Rourke and Turner.¹² They did not, however, show comparison plots of the NCB profile and field data.

Figure 4. Comparison of Measured Longitudinal Profiles for Panel 1 and the Empirical Results.

Figure 5. Comparison of Measured Longitudinal Profiles for Panel 2 and the Empirical Results.

time-independent and transverse isotropic material behavior, should correspond to the measured traveling and end stationary profiles. Because of lack of field data for the face position, the NCB curve was arbitrarily forced to agree with the experimental traveling wave at the 50% subsidence level. As in the case of the transverse profiles, the UK experience does not agree well with the measured profiles for this mine. The profile functions, on the other hand, reproduce the field data (with the exception of the beginning stationary profile of Panel 1) quite closely, i.e., the discrepancy between the measured and function values are always less than 6%.

An unmistakable feature of the measured subsidence shown in Figures 4 and 5 is the considerable variation of its magnitude along the length of the panels. One might initially suppose this variation to be scatter due to geological conditions. However, we believe that it is directly related to the rather large variation in the extraction thickness that invariably occurs during mining. In the case of Panel 2, rather detailed records of the extraction thicknesses throughout the panel were kept.¹³ These show that the range of extraction thicknesses were actually from 2.9 to 2.1 m for a mine in which the nominal extraction thickness is quoted as 2.1 m. Moreover, the trend of the actual thicknesses corresponds to the trend of the subsidence measurements; i.e., the maximum measured subsidence in Figure 5 at $x \approx 1.1 h$ corresponds to an increase of extraction to a value over 2.5 m from the more typical 2.3 m. This is about the correct magnitude to account for the variation of measured maximum subsidence. This appears to be the first recognition that the nominal extraction thickness can be inadequate for use in subsidence analysis. A significant consequence of our simple correlation is that in all probability the variation in subsidence magnitude normally observed is related to variations in mined height rather than geological factors.

Profile functions contain no inherent parameters which distinguish the various types of profiles; rather the differences in the values of the parameter B reflect the various profile types. Another important parameter that we must consider, which is not included in the profile function, is the separation, d, of the inflection point from the vertical to the rib side. A tabulation of B and d for these longwall panels, according to wave type is given in Table I. Even though the range of B for ostensibly the same profile type, in this case the traveling waves which include eleven separate profiles, is large; some

TABLE I - PROFILE PARAMETERS

Parameter	Stationary Profiles						Non-Stationary Profiles			
	Transverse		Longitudinal				Traveling**		Development	
	=*		Start		End				=	
Panel No.	1	2	1	2	1	2	1	2	1	2
B (a)	0.17h	-----	0.14 h	0.13h	0.34h	-----	0.28h	0.23h	-----	0.28h
(b)								0.31h		
d (a)	0.22h	-----	0.34h	0.21h	0.20h	-----	-----	-----	-----	0.24h
(b)								0.18h		

*Under conditions of homogeneous, transversely isotropic, rate independent overburden properties, one might expect the profiles linked by the = sign to be the same.

**These represent the B values for Panel 1 and Panel 2 traveling waves shown in Figures 4 and 5. If we take all the traveling waves shown in the original references,^{7,8} the five Panel 1 waves have a range of 0.28h - 0.53h and the six Panel 2 waves have a range of 0.23h - 0.34h.

simple trends can be established. It appears that the stationary transverse and beginning profiles are appreciably steeper than the other profiles. This, of course, means that the limit angle also differs for these conditions since it is simply related to B. Interestingly, d, the location of the inflection point with respect to the void/coal boundary, is nearly the same for all profile types.

We turn now to analysis of the development profiles. These profiles are less common than traveling wave profiles, an unfortunate situation because they can be very informative. Schmechel et al¹⁰ determined a number of precisely measured development profiles over a relatively short base in Panel 2. These data and the profile function curves are compared in Figure 6. Basically these data confirm our earlier observations except for some important differences. Here, the development curves are nearly antisymmetric and conform much more closely to the profile functions in the lip of the trough. Clearly the development curves differ from the stationary and traveling profiles in the region of the trough lip. Tentatively, we suggest this difference is caused by time-dependent material response. The manner in which the time-dependent material response interacts with the measurement scheme is quite complicated and will be discussed separately in the following section.

Figure 6. Analysis of Empirical Methods for Development Curves of Panel 2 (After Schemechel et al.¹⁰).

Pseudo and True Time-Dependent Behavior

It has been long recognized that subsidence is in some way a time-dependent phenomenon. A very complete study demonstrating time-dependent response in subsidence was made by Orchard and Allen¹⁴ which improved the earlier observations of Corden and King.¹⁵ Regardless of these observations, the dominant tendency in subsidence analysis is to assume an active subsidence phase that occurs instantaneously* with mining and a time-dependent residual** subsidence that occurs after the active phase is over. Typically these two processes have been decoupled in the sense of active subsidence occurring during the mining operation and residual subsidence occurring after the mining operation has ceased. One can then basically ignore the residual as being a small fraction of the total subsidence. An example given by the NCB Handbook² seems to have adopted this viewpoint. In the work of Orchard and Allen¹⁴ there appears to be a tendency to compartmentalize the time-dependent behavior into intermediate and long-time effects and to minimize the contribution of time-dependent subsidence. Since, in some cases, the time-dependent and instantaneous displacements were of nearly the same magnitude, we believe decoupling of this type is probably misleading.

In order to investigate coupled response fully, we must have clearly in mind the actual sequence of events during the mining operation. In one scenario, an observer standing on the surface will see a longwall face approach and then pass him by in a manner that depends upon the face advance rate. He will experience a vertical displacement as a result. (We ignore the horizontal displacements and tilts for now.) This displacement is composed of the sum of the instantaneous and the time-dependent displacements. The fact that these displacements begin simultaneously during the active phase but only one occurs at late times is what confuses the issue. One important feature is that time-dependent subsidence can not occur in the absence of some initial active process. Interestingly, because the face advance is under normal mining practice discontinuous, the observer can in some circumstances separate the two subsidence processes. In the following developments we show this separation in a crude manner.

* Theoretically, this is not truly instantaneous because there is a time characteristic typical of rock fall and stress redistribution; however, this time characteristic is much smaller than the material recompaction time characteristic important for our current subsidence analysis.

**Because of the common association of the word residual with late time subsidence effects, we will in the later discussions use time-dependent response to imply a broader sense.

In our analyses, we can treat the two processes independently, a luxury not possible in the field data. Thus, let us first treat the instantaneous process. Because of the finite and often discontinuous face advance rate, the time-independent instantaneous response acting alone will yield a time-correlated development curve. We call this response pseudo time-dependent behavior. Its simple relation can be shown through the profile functions since they are, by definition, time-independent. If we assume that a profile function, for example the trigonometric form, describes the instantaneous part of the subsidence, then a straight forward transformation is possible. The horizontal measure of the face position is given by

$$x = \int_0^{\infty} v(t) dt = \bar{v}t \quad (8)$$

where $v(t)$ is the face velocity history and the real time integration range is for that time where the face is within $+Bh$ to $-Bh$ of the observation point for a non-asymptotic function. Equation 5 becomes

$$s/S_{III} = 1/2 \left[1 - \frac{\bar{v}t}{R} - \frac{1}{\pi} \sin \left(\pi \frac{\bar{v}t}{B} \right) \right]. \quad (9)$$

We can plot this result for the time-correlated development curves obtained by Schmechel et al¹⁰ on the Illinois mine, as shown in Figure 7. Face advance rates have been smoothed. Surprisingly, the instantaneous response component when properly analyzed for the face advance history gives very good agreement with the time-correlated development profile. In fact, this agreement would be more than satisfactory for many practical applications; and thus the analysis based on rate-independent response can be a useful engineering tool.

If one compares the time-independent calculation with the measured profiles in Figure 7 in greater detail, one notices significant differences. This is most clearly illustrated at the point where the face advance was first temporarily stopped. Here the field data show that subsidence continues even though the face has stopped. An analogous behavior was noted on the time scale of individual cutting and non-cutting shifts at the Bardon Mill and the Blaenavon collieries.¹⁴ Further, the continued trough deepening subsidence at late times, which demonstrates the same

Figure 7. Analysis of Pseudo Time-Dependent Effects on the Time-Related Development Curves for Panel 2.

rate effect, can be seen in Figure 5. Such observations of a time-dependent component of subsidence are well recognized; yet this behavior is not treated in current analyses. While fundamentally it is a reasonably simple process, an analysis is not always practical except through numerical techniques. We shall not analyze it either, but we will set out a framework for possible future effort.

The rate process is visualized as the recompaction of fractured and bulked overburden. Constitutive behavior of the rock is invoked because the compaction occurs through deformation of contact points of the fragments under the action of the contact stresses. Continued deformation decreases the effective contact stresses and the rate of recompaction thus diminishes with time. The stress relaxation or compaction can be expected to approximate a Maxwell rate equation in which the driving stress (or equivalent) depends upon the depth into the overburden and the magnitude of the instantaneous displacement rate that initiates the process. This suggests the treatment of the history of an element can be handled using linear viscoelasticity concepts as an initial approximation. Potentially a model of this type has the features to simulate the behavior during face advance interruptions, the gradual subsidence (residual) behavior in the trough bottom after the face has passed well beyond the location and the apparent gradual subsidence in the lip of the trough. A model of this type is well within the capabilities of current numerical methods, with the only major problem being the fact that the instantaneous and rate-dependent components can not be separated distinctly in experimental data.

Conclusions

Several conclusions of practical significance and of potential theoretical interest have resulted from our comparisons of European empirical subsidence analyses with field measurements of longwall panels in a mine of the Illinois Coal Basin. As a part of the preparation for analysis, it was necessary to distinguish between profiles of unique initial conditions. This led to a classification of transverse and longitudinal profiles, and also classification of several types of stationary and traveling or development wave profiles.

Although the National Coal Board methods developed in the UK were capable of giving very nearly the correct total subsidence for the sub-critical trough investigated, it was found that this graphical method

did not adequately predict the trough shape. The NCB experience predicted larger limit angles, hence a broader trough extent and a much smaller maximum strain, than observed in the Illinois mine. We suspect the extensive prior working of seams above and below the active mines in the UK causes their experience to be considerably different than the single seam US mine. Thus it appears the current form of UK graphical methods are not adequate for US practices.

A more satisfactory comparison for the Illinois mine was obtained between the antisymmetric subsidence profile functions commonly used in Europe. In fact, these functions predict the subsidence displacements to within about 6%. Both the asymptotic and non-asymptotic profile functions were nearly equally accurate, but on the basis of the most conservative, i.e., over prediction of peak strain, we used a trigonometric form for most of our comparisons. This form has proven successful in the coal fields of Upper Silesia (Poland). The fact that European profile functions can predict US field results in the Illinois Coal Basin, even though the geology is reasonably diverse is, we believe, a significant practical result of this analysis.

There were, however, observable features in the accurately measured development profiles which suggest that appreciable time-dependent effects occur during and after the mining operation. These effects, while they do not diminish the value of the rate-independent empirical analysis through the profile functions, do have considerable importance. The rate effects manifest themselves as non-antisymmetric displacements, late time trough deepening and an inability of the profile functions to accurately treat the subsidence behavior during mining stoppages. A correct simulation of subsidence must eventually incorporate such features.

In summary, it was found the certain forms of European empirical subsidence prediction practice matched the measured results from long-wall panels of an Illinois mine. This result has practical significance for the mining industry because it provides a useful, yet simple, tool for evaluating subsidence effects.

Acknowledgements

The data used in this report were obtained from a study conducted in the Demonstration of Longwall Mining Program (ET-75-C-01-9023) initiated by the U. S. Bureau of Mines and later transferred to the U. S. Department of Energy. The Subsidence Research and Development Program at Sandia Laboratories is supported by the Office of Mining, U. S. Department of Energy and administered through the Pittsburgh and Carbondale Mining Technology Centers.

References

1. G. Brauner, "Subsidence Due to Underground Mining, Part 1," I. C. 8571, U. S. Bureau of Mines, Washington, DC (1973).
2. National Coal Board, Subsidence Engineer's Handbook, (Hobart House, Grosvenor Square, London) 1975, 1111 pp.
3. S. Knothe, "Rate of Advance and Ground Deformation" Bergakademie, 5, 513 (1953) (in German).
S. Knothe, "Observations of Surface Movements and their Theoretical Interpretation," Colliery Eng., 36, 24 (1958).
4. J. Litwiniszyn, "The Theories and Models Research of Movements of Ground Masses," Proc. European Congress on Ground Movement, Leeds, England, 1957, p. 202.
5. F. Martos, "Concerning an Approximate Equation of the Subsidence and Its Time Factor," Proc. Inter. Strata Control Congress, Leipzig, Germany, 1958, p. 191.
6. R. Bals, "A Contribution to the Problem of Precalculating Mining Subsidences," Mitteilungen aus dem Markscheidewesen, 42/43, 98 (1931/1932).
7. S. Knothe, "Observations of Surface Movements Under Influence of Mining and Their Theoretical Interpretation," Proc. European Congress on Ground Movement, (University of Leeds, Leeds, England, 1957) p. 49.
8. M. Zenc, "Comparison of Bal's and Knothe's Methods of Calculating Surface Movements due to Underground Mining," Int. J. Rock Mech. Mine Sci., 6, 159 (1969).
9. J. N. Edl, Jr., and W. F. Eichfeld, "Subsidence Related Data from Four Representative United States Coal Mines," S & SE 78-2, Joint Research Project 14-01-0001-1451, Carbondale Mining Technology Center, DOE (1978).

10. F. W. Schmechel, W. F. Eichfeld, and W. P. Santy, "Automated Data Acquisition for Subsidence Characterization," Proc. AIME Annual Meeting, New Orleans, LA (1978).
11. B. Voight and W. Pariseau, "State of Predictive Art in Subsidence Engineering," J. Soil Mech. Found., Proc. ASLE, 96, 721 (1970).
12. T. D. O'Rourke and S. M. Turner, "A Critical Evaluation of Coal Mining Subsidence Patterns," Proc. AIME Annual Meeting, New Orleans, 1979. (preprint)
13. R. A. Bauer, Illinois State Geological Survey, Urbana, IL, (private communication).
14. R. J. Orchard and W. S. Allen, "Time-Dependence in Mining Subsidence," Proc. Inter. Symp. on Minerals and the Environment, London, England, 1974, p. 643.
15. C. H. H. Corden and H. J. King, "A Field Study of the Development of Surface Subsidence," Int. J. Rock Mech. Min. Sci., 2, 471 (1954).

Distribution:

U. S. Department of Energy
Fossil Energy
Mail Stop B-126 (Germantown)
Washington, DC 20545
Attn: G. Fumich

U. S. Department of Energy (2)
Office of Mining
Mail Stop D-107 (Germantown)
Washington, DC 20545
Attn: W. B. Schmidt
D. B. Uthus

U. S. Department of Energy (13)
Carbondale Mining Technology Center
P. O. Box 2587
Carbondale, IL 62901
Attn: A. Van Beisen
R. J. Wenzel
W. F. Eichfeld (10)

The Aerospace Corporation (2)
P. O. Box 92957
El Segundo, CA 90009
Attn: G. F. Kuncir
D. A. Lewis

Los Alamos Scientific Laboratory (2)
Los Alamos, NM 87545
Attn: W. J. Carter, G-7,
Mail Stop 329
Attn: P. L. Smith, G-7
Mail Stop 329

Lawrence Livermore Laboratory
Livermore, CA 94550
Attn: R. T. Langland
Mail Stop L-90

Department of Materials Science
and Materials Engineering
University of California
Berkeley, CA 94720
Attn: Prof. N. G. W. Cook

Department of Geosciences
Texas A&M University
College Station, TX 77843
Attn: Prof. E. Hoskins

Department of Engineering Mechanics
Ohio State University
Columbus, OH 43201
Attn: Prof. S. H. Advani

1500 W. A. Gardner
1530 W. E. Caldes
1531 P. D. Adams
Attn: D. L. Fulton, 1531

1535 H. L. Rarick
5500 O. E. Jones
5520 T. B. Lane
5522 T. G. Priddy
5522 K. W. Schuler
5522 S. E. Benzley
5522 R. Johnson (UNM)
5530 W. Herrman
Attn: B. M. Butcher, 5532
4512 T. O. Hunter
4541 L. W. Scully
4700 J. H. Scott
4730 H. M. Stoller
4731 B. Granoff
4732 D. A. Northrop
4732 H. J. Sutherland
4732 D. E. Munson (25)
4733 C. L. Schuster
4732 A. L. Stevens
4737 B. E. Bader
4738 R. L. Fox
4740 R. K. Traeger
4744 H. M. Dodd
3141 T. L. Werner (5)
3151 W. L. Garner (3)
For: DOE/TIC (Unlimited Release)
8266 E. A. Aas (2)
3154-3R. P. Campbell (25)
For: DOE/TIC