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EUROPEAN EMPIRICAL METHODS APPLIED TO
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 DE-AC04-76DP00789.

OCTOBER 1980

Sandia National Laboratories

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Printed in the United States of America

Available from
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EUROPEAN EMPIRICAL METHODS APPLIED TO SUBSIDENCE IN U.S. COAL FIELDS

by

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ABSTRACT

The empirical methods commonly used in Europe to describe the shape of subsidence troughs are tested against the field data of the York Canyon Mine in Northern New Mexico. This mine is in a flat lying seam under rugged terrain. The subsidence data consists of time-correlated measurements of surface displacements above two longwall panels. While the profile fits from the graphical methods (United Kingdom) do not agree with the measured profiles, the profile functions of the error integral type used in Continental Europe fit the data well. The profile function analysis of the development curves also suggests a time-dependent response of the overburden. These results, except for the specific profile function used, are similar to those found previously for longwall subsidence at the Old Ben No. 24 Mine.

Parameter values of the fit, i.e., the effective half range of the function and inflection point offset, were determined for all profiles. These parameters for the development curves and traveling profiles, which fundamentally result from the same raw data, exhibit markedly different apparent "scatter." The rather narrow range of values for the development curves suggest that individual points subside in a well-behaved manner; and hence, the large variation in parameter values for the traveling profiles reflects an inadequacy in the analysis in correlation between points. Consequently, the use of influence functions appears to be a possible method for improving the empirical analysis of longwall subsidence.

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INTRODUCTION

Empirical methods for characterizing surface subsidence caused by longwall techniques of coal extraction have proven very useful in European coal fields. The graphical methods developed by the National Coal Board (NCB)¹ are widely used in the United Kingdom (UK) to describe subsidence, while profile or influence functions are typically used on the Continent.² Successful introduction of longwall technology into the United States (US) has increased the potential for subsidence damage of man-made surface structures, service networks, natural drainage, and groundwater systems in this country. Because of this potential for damage, it is essential that either the European methods be assessed for possible use in the US or that new subsidence prediction methods be developed. The availability of the European experience recommends use of their methods initially, and this assessment was begun in a study of the subsidence over longwall panels of the Old Ben No. 24 Mine in the Illinois Coal Basin.³ The case history typifies a flat lying seam at a depth of 189 m under flat terrain, which is the simplest possible setting. In that study it was found that trigonometric profile functions give adequate representation of the field measurements.

In the work presented here, the evaluation of European methods is extended to include an analysis of a flat lying coal seam under rugged terrain. The case history for this more complicated setting is from longwall panels at the York Canyon Mine in Northern New Mexico.⁴⁻⁶

EMPIRICAL METHODS

In this analysis we make use of an excellent review of empirical methods compiled by Brauner.² European methods consist of essentially (1) the graphical methods of the UK, which are perhaps the best known in the U. S. because of the extensive compilation of case histories by the NCB, and (2) the Continental methods based upon mathematical fits in the form of profile or influence functions. Although the results of our study will suggest otherwise, initially, it did not appear necessary to use the influence functions for analysis of US longwall data. Influence function analysis is too complicated for the simple longwall geometries involved. Consequently, in this study we concentrate upon graphical methods and 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. The most widely used profile functions are 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.

In applying the empirical methods, Munson and Eichfeld³ pointed out that a fundamental difference occurs between those profiles of the subsidence trough that develop at right angles to the mining direction and those that develop parallel to the mining direction. The orientation is classified as a transverse profile if it develops along the rib sides and at right angles to the direction of mining, or as a longitudinal profile if it develops parallel to the direction of mining. Within this framework, other conditions are defined as follows:

- 1) stationary profiles encompass the
  - a) transverse profiles over the rib side,
  - b) longitudinal profiles formed at the beginning of the panel, where rather unique boundary and initial 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 roof failure occurs at the face.
- 2) non-stationary profiles encompass the
  - a) traveling wave profiles which are measured as the face advances; if the subsidence has no time-dependent component, this profile is identical to the stationary end profile, and
  - b) development profiles which 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.

Graphical Methods

The UK graphical analysis represents a large collection of subsidence field data over longwall mines, and therefore must be one of the major comparison points for our analysis. These data were collated and analyzed through a series of non-dimensionalized graphs under the auspices of the NCB. A handbook¹ was published in 1966, revised 1975, as a practical guide for predicting subsidence above mines 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. In most cases, the NCB addressed the transverse

stationary profile. They have, however, in some cases also characterized the development profile.

Profile Functions

On the Continent, 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. There have been a number of mathematical forms proposed.

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

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

where ξ is an integration limit, 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 and x is a horizontal distance measured from the inflection point. A schematic of a profile function and interpretation of the parameters is shown in Figure 1. 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. This empirical form has been applied to the flat coal seams with single workings of Upper Silesia (Poland) with success.⁷ 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.⁸ The stochastic, or void-diffusion, models have also been applied to the upper Silesian fields.

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

$$s/S_m = \frac{1}{2} \left[1 - \frac{x}{B} - \frac{1}{\pi} \sin \left(\pi \frac{x}{B} \right) \right] \quad (3)$$

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

• SUBSIDENCE PROFILE (s / S_m)

• STRAIN PROFILE (ϵ)

Figure 1. Schematic of Subsidence Displacement and Strain Profiles.

fields,² and the profiles of the subsidence over the Old Ben No. 24 Mine of the Illinois Coal Basin.³

The final function, which is of mixed form, describes the field experience for Hungarian coal mines,⁹

$$s/S_m = \exp \left[-\frac{1}{2} \left(\frac{x+B}{B} \right)^2 \right] \quad (4)$$

which asymptotes only at the trough lip; i.e., in the direction of the unsubsided ground.

These 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 . Consequently, no distinction is necessary in application of the fit to a particular profile type. The specific values of the parameter B will of course reflect the different profile classifications. An additional parameter of importance is d , the offset of the inflection point of the profile from the vertical line up from the rib or face.

LONGWALL SUBSIDENCE ANALYSIS

The investigation⁴⁻⁶ of subsidence over two longwall panels mined in a flat lying seam under rugged terrain provides a rather extensive case history for analysis. The site of the investigation is the York Canyon Mine of the Kaiser Steel Corporation in northeastern New Mexico. Panel 4N, mined first, is 167.6 m wide by about 486 m long, as mined. Panel 5N, mined second, is 134.1 m wide by 622 m long, as mined. A schematic of the panel layout is shown in Figure 2. The coal seam in Panel 4N consists of a lower, main seam 2.74 ± 0.30 m thick and an upper, roof seam 0.38 ± 0.07 m thick that are separated by a carbonaceous shale parting varying from 0.21 m to 0.45 m thick. The coal seam in Panel 5N consists of a lower, main seam 2.43 ± 0.30 m thick and an upper, secondary seam about 0.45 m thick that are separated by a carbonaceous shale parting varying from 0.30 m to 1.52 m thick. The nominal extraction height is 3.20 m in Panel 4N and 3.04 m in Panel 5N, although the actual extraction height varied considerably from this value.* The two longwall panels are separated by a chain pillar. Panel 4N is adjacent to a previously mined, conventional room and pillar (robbed) development of Panel 3N and Panel 5N is adjacent to an unmined Panel 6N. Overburden depth over the panels ranges from about 68 m to 180 m, with the

*No detailed records of extraction height are available, however, the height apparently ranged from the lower limit of the main seam, 2.13 m, to well beyond the upper extension limit of the longwall shield, 3.58 m.¹⁰

Figure 2. Plan of the York Canyon Mine Longwall Panels 4N and 5N.

maximum depth over the end of panel 5N and the minimum depth over the start of Panel 4N. The topography that controls the overburden depth results from two major arroyos cutting transversely across the panels with drainage from 5N to 4N.

Subsidence measurements consist of periodic surveys of surface monuments. As shown in Figure 2, the measurements involve a longitudinal survey along the center line of each panel, a common transverse survey across both panels at about midlength (South) and a separate transverse survey (North) across only Panel 5N.

The North and South transverse profiles, and seam depths, are given in Figure 3. Both Panel 5N profiles appear to be subcritical; although the North profile may be just at the critical. The Panel 4N profiles appear to be supercritical. Because of the sequence of mining, both left and right* transverse profiles were available for Panel 4N; apparently the right profile was not appreciably affected by the room and pillar workings which are unsubsidized. Profiles resulting from mining Panel 5N were unaffected only on the left; on the right they showed the influence of the chain pillar, as well as the previous subsidence of Panel 4N.

Graphical Analysis

The large variation in overburden depth causes some difficulty in applying the NCB graphical method; as a result, analysis is based on average depths and extremes of depth. Average depths are used for the transverse maximum subsidence values; as shown in Table I, the NCB predictions are consistently larger than the field measurements. Moreover, the NCB profiles are rather poor descriptions of the actual transverse profiles, as demonstrated in Figure 3. Extremes in maximum subsidence are quite large as can be seen in the final longitudinal measurements, Figures 4 and 5. The appropriate extreme field values, compared to NCB prediction, are given in Table I. Here again, little consistency is found between the observed and predicted values. One traveling profile as determined from an NCB development curve, unnormalized to the predicted maximum subsidence, is shown in Figure 4. Again, agreement between the measured and predicted profile is not very good. Normalization of the NCB profile to the measured maximum subsidence (not shown) improves the agreement to the profile shape; however, as previously noted by Munson and Eichfeld,³ the UK experience gives a larger trough extent and a less steep slope; i.e. smaller strains throughout the profile. In summary, our comparisons suggest that the UK graphical methods are not adequate representations of the subsidence characteristics of this mine.

*In a convention to be established, left and right are with respect to the direction of mining.

Figure 3. Comparison of Empirical Functions and Measured Transverse Subsidence Profiles.

Table I - Maximum Subsidence - NCB

Profile	Depth (m)	Nominal Extraction (m)	Maximum Subsidence		Prediction Error		Remarks	
			NCB Prediction* (m) (s/S _m)	Measured (m) (s/S _m)		(%)		
Transverse								
4N-South	48**	3.20	2.50	(.78)	2.03	(.63)	19	Super-critical
5N-South	103**	3.02	2.23	(.74)	1.98	(.66)	11	Sub-critical
5N-North	152**	3.02	1.96	(.65)	1.73	(.57)	12	Subcritical to critical
Longi-tudinal								
4N	80***	3.20	2.50	(.78)	1.53	(.48)	41	Arroyo
	125***	3.20	2.46	(.77)	2.15	(.67)	13	Ridge
5N	115***	3.02	2.17	(.72)	1.63	(.54)	25	Arroyo
	132***	3.02	2.05	(.68)	2.20	(.73)	-7	Ridge

*Corrected for virgin ground.¹ Since the NCB results were obtained for seams in previously worked ground, they must be multiplied by 0.9 to conform to the virgin ground conditions typical of US mines.

**Average values.

***Extreme values.

Figure 4. Comparison of Empirical Functions and Measured Longitudinal Subsidence Profiles, Panel 4N.

Figure 5. Comparison of Empirical Functions and Measured Longitudinal Subsidence Profiles, Panel 5N.

Profile Function Analysis

Application of the empirical profile functions to the York Canyon subsidence data is a straight-forward process in which several functions were tested against the various types of profiles. It was determined through this process that the error function gives the best overall fit, while remaining conservative with respect to the field data in the calculated maximum strain. This is illustrated in the profile function fits of the transverse profiles of Figure 3, where the function matches exactly the toe of the subsidence trough but has a smaller radius of curvature in the lip of the trough. The cause of the greater measured subsidence in the lip of the trough is unknown. Clearly, rate effects, deformation of entry systems, or ground slumps of the steep terrain could all be potential contributors to the cause. Interestingly, this discrepancy between the profile function and measured subsidence is not observed in the longitudinal stationary and traveling profiles of Figures 4 and 5, here the error function is an acceptable representation throughout the trough.

As previously noted by Munson and Eichfeld,³ development profiles appear to be very well-behaved and reproduceable. This is true also for the York Canyon data, as shown in Figure 6 which is a composite of the five reported profiles. The correction of the Panel 5N data essentially normalizes the profiles to the same offset as the Panel 4N data. As in the case of Old Ben No. 24 profiles,³ a change in the character of the curves at large positive values of x/h is indicative of the time-dependent compaction response typically referred to as the "residual subsidence." The residual subsidence is roughly 6 percent of the total. If the residual subsidence portion of the development curve is subtracted from the total subsidence, the remainder of the curve is accurately described by the error function. The rather large discrepancies between the error function fit and the field data occurs in the toe of the trough, if the residual subsidence is included in the analysis, as shown in Figure 7. It should be noted that the development profiles were obtained at various overburden depths, yet the half range and offset parameters are identical fractions of the depth. Since B/h for finite functions can normally be taken as measure of limit angle through the relation

$$B/h = \cot \gamma,$$

a constant value of γ of 69° , independent of overburden depth, is implied. Comparison of the measured limit angle ($\sim 70^\circ$) as determined from the first detectable displacement, to the above value is quite good. A constant value of the limit angle for a given mine or geologic setting is often observed. This value, while thought

Figure 6. Representative Raw Development Curve Fit to an Empirical Function.

Figure 7. Development Curves Showing Rate Effects.

to be representative of US mines, is considerably larger than the 55-65° typical of the UK or the somewhat smaller values of 45-60° in continental Europe.^{2,11,12}

In order to investigate the profile function range parameter, B , more completely, this parameter and the offset parameter, d , were determined for all reported profiles. The values are tabulated in Table II. Results for the stationary profiles show considerable variation; moreover, no higher order trends can be established on the basis of these data. The results for the non-stationary profiles are more interesting. The results for the longitudinal traveling and development profiles, after the trough becomes supercritical, are plotted against depth of overburden in Figure 8. The important observation is the large amount of apparent scatter in the values of B/h and d/h for the traveling profiles as compared to the small amount of scatter in these values for the development profiles. This suggests that the subsidence of individual points (development profiles) on the ground surface is well-behaved and that the apparent scatter for profiles involving more than one surface point (traveling profiles) is a real effect. This effect is possibly caused by rate dependent response, changes in extraction heights, or overburden geology differences between the surface points (which are not a part of the analysis). It is evident from these remarks that the development profiles yield the best resolution of the subsidence process and that greater insight is necessary to analyze the stationary and traveling profiles. These arguments also suggest that the use of influence functions is perhaps the preferred analysis procedure even for longwall panels in order to obtain the point by point contributions to subsidence.

CONCLUSIONS

The European empirical methods for describing subsidence troughs have been evaluated for longwall panels at the York Canyon Mine. In general, graphical methods typically used in the UK by the NCB were not good representatives of the US results because they over predict the total subsidence. The best representation is found to be a profile function of the error integral type commonly used on the Continent. Analysis of the development curves suggest a rate dependent subsidence effect typically described as "residual" subsidence. The fit of the error function to the development profile is impaired when the residual subsidence is included.

Comparison of the effective half-ranges and offset parameter values of the fits to the traveling profile and development curves has produced a fundamental observation of some significance. The consistent behavior of these values for the development

TABLE II. SUBSIDENCE FIT PARAMETERS

Location	Stationary						Non Stationary				Depth	Remarks
	Transverse		Begin		End		Traveling		Development		h	
	B	d	B	d	B	d	B	d	B	d	(m)	
York Canyon												
4N-Final	0.36h	0.24h									74.7(-)*	Right -1
	0.34h	0.25h									120.4(+)	Left -1
			0.49h	0.24h							115.0(-)	
					0.30h	0.18h					100.0(+)	
5N-Final	0.30h	0.20h									179.8(+)	Left -1
	0.40h	0.18h									128.0(+)	Left -2
			0.36h	0.28h							115.0(-)	
					0.33h	0.28h					140.0(+)	
4N- 6/2/75			∞	?			∞	?			118.9(+)**	Span = 38.1m (elastic)
6/14/75			0.10h	0.18h			0.22h	0.05h			121.9(T)	= 48.8m (elastic)***
6/22/75			0.10h	0.14h			0.18h	0.05h			118.9(-)	= 76.2m (elastic?)
7/8/75			0.23h	0.16h			0.21h	0.14h	0.36h	0.26h	117.6(-)	STN. 12N
8/28/75			0.45h	0.21h			0.62h	0.35h			115.8(-)	= 85.3m
9/29/75							0.39h	0.48h			88.4(-)	= 147.8m
10/29/75							0.39h	0.43h			88.0(B)	
									0.38h	0.26h	88.4(+)	
11/24/75							0.34h	0.20h			96.0(+)	STN. 2N
12/16/75							0.45h	0.20h			102.1(T)	
1/13/76							0.56h	0.22h			105.2(T)	
									0.39h	0.25h	100.0(-)	STN. 3S
2/26/76							0.50h	0.36h			96.9(-)	
											82.3(b)	
Final - Average			0.49h	0.24h	0.30h	0.18h	0.44h	0.31h	0.38h	0.26h		
5 -												
8/10/76			∞	?			∞	?			117.3(+)	Span = 12.2 m (elastic)****
8/20/76			0.32h	0.05h			0.31h	0.05h			125.0(+)	= 48.8 m (elastic)
9/10/76			0.28h	0.17h			0.34h	0.14h			128.0(T)	= 97.5 m
9/20/76			0.34h	0.21h			0.38h	0.17h			128.0(T)	= 117.3 m
10/20/76							0.51h	0.21h			128.0(T)	
									0.38h	0.22h	121.6(+)	STN. 9
11/20/76							0.58h	0.30h			123.0(+)	
12/15/76							0.41h	0.20h			132.0(+)	
1/31/77							0.49h	0.21h			143.0(T)	
2/24/77							0.56h	0.21h			140.0(T)	
									0.38h	0.30h	145.1(T)	STN. 20
3/23/77							0.52h	0.29h			137.0(-)	
4/25/77							0.38h	0.32h			125.0(+)	
Final-Average			0.36h	0.28h	0.32h	0.28h	0.49h	0.25h				

*Terrain slope indicators are: - (falling way), + (rising), B (array bottom), and T (ridge top).

**Depth applies only to traveling profile.

***Profile very asymmetric.

****Some random ground motion was measured but could not be quantified.

Figure 8. Empirical Fit Parameters for Traveling and Development Profiles.

curves is in marked contrast to the wide range of values obtained from the traveling profiles. Because both profiles are generated from the same data, the range of values for the traveling profiles is not due to scatter. Rather, it suggests that individual points are well behaved; and the significant details of geology, extraction height, overburden depth, and perhaps of rate effects necessary to relate adequately one point to another point have been omitted in the analysis of the traveling wave. In practice, the use of properly formulated influence functions, rather than profile functions, should produce a tractable analysis of the traveling profiles.

ACKNOWLEDGEMENTS

The data used in this report were obtained in the Demonstration of Shieldtype Longwall Supports initiated by the U. S. Bureau of Mines (SO-144066) and later transferred to the U. S. Department of Energy (ET-74-C-01-9067). The Subsidence Research 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. The authors wish to express their appreciation to D. A. Northrop for his continued support and numerous contributions during the course of this work.

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