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A GENERALISED EMPIRICAL METHOD FOR PREDICTING SURFACE SUBSIDENCE IN DIFFERENT COALFIELDS

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ABSTRACT: In the context of surface subsidence studies, a single index, called a strata parameter (P), is proposed to describe the overall deformation character of the undermined strata in different coalfields. Based on the strata parameter, a generalised empirical method is developed to predict the maximum surface subsidence and the shape of a transverse subsidence profile resulting from a single completely mined kmgwall panel in different coalfields. The validity of this method is tested against field data from other researchers.

1. INTRODUCTION

The approaches for predicting subsidence of strata above extensively mined areas in bedded deposits could be classified, based on the degree of mathematical analysis involved, roughly into three main groups: empirical, theoretical and semi-empirical. The empirical methods are directly based on simplified relationships between subsidence magnitudes and the mining factors derived from the statistical analyses of the data from measurements in a given coalfield. The so-called theoretical methods combine idealised models for the deformation characteristics of materials, e.g. elastic, elastoplastic, etc. with mathematical analysis techniques, e.g. FEM, BEM etc. to simulate the movement of the large undermined rock mass. The deformation characteristics are determined from the testing of small samples from the relevant rock mass. The semi-empirical methods, e.g. the 'profile-' and 'influence-' functions use mathematical expressions derived to directly fit measured subsidence profiles.

The theoretical and semi-empirical methods, which incorporate many simplifications and assumptions regarding the deformability of the undermined strata must be calibrated before they can be used for reliable predictions (Pariseau, 1993). The input values for the parameters in these methods should be derived through the back analyses of measured subsidence data. As different idealised models are applicable to different degrees to the behaviour of the undermined strata encompassing caving, fracturing and bending zones, such derived values for the parameters would be different for different models. Because the process of the surface and strata movement, especially the extent of the caving and fracturing movements, depends on the mining factors, such derived values factors even in the same given model would also be different for different mining factors. Thus, the calibration of a model against measured subsidence must be made for different mining factors (Bhattacharyya and Zhang, 1993; Zhang and Bhattacharyya, 1995).

In view of the wide variations in field conditions with many unknown factors and the complicated nature of the movements of the undermined strata depending on the mining factors, a single randomly chosen field study may not be representative. Therefore, the data in the empirical methods obtained by the statistical analyses of many field measurements should be used for calibrating the other methods. Although most reliable for the two-dimensional predictions of transverse subsidence profiles in a given coalfield, the empirical methods at present cannot consider differences in the characters of the undermined strata (overburdens) and therefore, can not be reliably used for other coalfields. Thus, to develop a generalised empirical method which could be applied to different coalfields, the consideration of the characters of the undermined strata must be included in the analysis. A single index, i.e the strata parameter is proposed here to describe the general character of die undermined strata.

2. STRATA PARAMETER

2.1 Definition

The factors which control the magnitude and extent of ground movements induced by mining can be broadly divided into two categories (Shadbolt, 1978), namely "mining factors' and 'site factors'. The mining factors are the active ones which can be controlled, while the site factors include the ground environment in which the mining factors interact

Mining factors relate to the mining methods and the geometry and dimensions of the excavation, e.g. panel width *(w)* and depth (A), method of support, extracted seam height *(H)*, rate of advance, etc. Site factors refer to the geotechnical conditions influencing mining subsidence, such as type and thickness of strata, soil cover etc., geological discontinuities and hydrology. It is extremely difficult (if not impossible) to investigate the individual influence of each of the aspects on surface subsidence. If a single index, e.g. the 'strata parameter' *(P)* is used to describe the overall character of the undermined strata, it would depend on many aspects such as the deformation behaviour, positions, thicknesses and distributions of all the rock beds in the overburden and the variable geological structures within the undermined strata. Obviously, it would again be almost impossible to study the influence of each aspect on the strata parameter by using any empirical approach. On the other hand, the current theoretical approaches, based on simplified idealised models for describing the deformation behaviours of the rocks included within the undermined strata, cannot reliably simulate the actual strata movements which include caving, fracturing and bending. Therefore, the so called theoretical approaches can not directly be used. for such investigations. Thus, the study of the strata parameter *(P)* has to be simplified for practical use. Accordingly, while the absolute value of the strata parameter could be anything, the relative values of *P* could be useful for practical purposes.

In the context of subsidence study, the simplest aspect is the maximum subsidence, which has been most extensively studied around the world. Thus, whatever approach is used, the prediction of the surface subsidence should at least accurately indicate the maximum surface subsidence. In order to keep the prediction of the maximum subsidence accurate, the strata parameter *(P)* should be directly based on measurements of maximum subsidence. In the absence of anomalous circumstances, the m»™»™ subsidence occurs at the trough centre above a mined panel in a horizontal or near-horizontal seam in a given coalfield. In such circumstances, the ratio of maximum subsidence (5) to an extracted seam height *(ft)* can be defined as a function of the single longwall panel width/depth *(yv/h)* ratios (NCB, 1975; Holla, 1985, 1986, 1991). For différent coalfields, the *S/H* ratio can be simplified in a general formas:

$$\frac{S}{H} = f\left(\frac{w}{h}, P\right) \qquad (1)$$

where *S* = maximum subsidence; *H* • extracted seam height; *w*=panel width; *h* - extraction depth and *P* * the strata parameter.

The function defined in Equation 1 can not be expressed explicitly. But, it would be possible to use a nomogram to describe it For practical purposes, it can be assumed that the character of the undermined strata within a given coalfield is consistent, or the differences in the character can be ignored. Thus, die relative values of *P* in different coalfields can be estimated by comparing the values of the corresponding *S/H* ratios for given *w/h* ratios. If a linear relationship between *P* and *S/H* for various *w/h* ratios (including supercritical panel width) can be assumed, then the relative value of the strata parameters in a new coalfield can be linearly interpolated or extrapolated from two differing values of the strata parameter in two different coalfields.

2.2 Derivation of the strata parameter value

The curves as shown in Figure 1 for determining the *S/H* ratios in the U.K. and the Northern coalfield of NSW are used as references. These (relative) values of the strata parameter in the UK coalfields and the Northern coalfield of NSW are taken to be 0.0 and 0.7, respectively. Those two values are so chosen that the ratio of the total thickness of the strong rock (i.e. sandstones, limestones, conglomerates, dolerites) beds in an overburden to the overall thickness of the overburden, can approximately reflect the value of the strata parameter (Zhang and Bhattacharyya, 1995). The-other contours (dashed lines) in Figure 1 were derived by Zhang and Bhattacharyya (1995). To estimate the values of the strata parameter in other coalfields, the appropriate curves for determining *S/H* ratios should, therefore, be compared with the dashed lines in Figure 1.

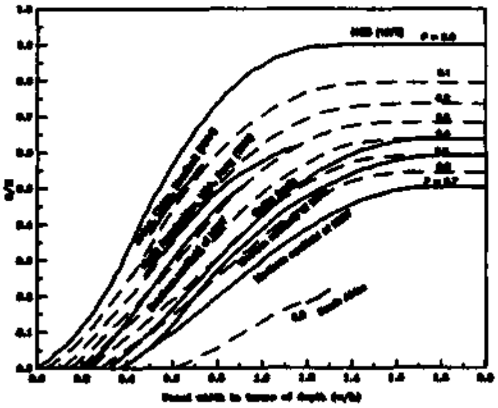


Figure 1 Comparison of the nomogram and the actual data (solid lines) from different coalfields

The general trends of the curves (dashed lines) shown in Figure 1, need to be compared with the data from other coalfields. Such data collected by the authors from past case studies by others, are also shown in Figure 1. In Figure 1, it can be seen that all the curves (dashed lines) maintain trends similar to those (solid lines) based on die field dauby the other investigators. It can be concluded that the nomogram in Figure 1 does provide the general trend between die *S/H* and *w/h* ratios in different coalfields. The (relative) values for die strata parameter *(P)* as shown in Figure 1 are proposed in order to make subsidence study easier. It is likely dut die values of die strata parameter may not be within die range 0.0 and 1.0 for certain coalfields in die world. According to die definition of the strata parameter *(P),* die higher are die values of use strata parameter, the stronger are die undermined strata. Conversely, die lower die values of die strata parameter, die weaker are die undermined strata.

However, it is necessary dut die differences in die character of die undermined strata within a given coalfield can be ignored. Otherwise, further division of die coalfield would be necessary. It should be noted dut die correlations between die maximum subsidence and the extracted seam height are different for different *w/h* ratios. For very small *w/h* ratios witirout substantial roof caving, die maximum subsidence (5) is independent of die extracted seam height *(H)* because die subsidence is mainly due to elastic deformation of die abutment pillars and die undermined strata for a given depth of mining. Thus, die use of *S/H* would cause some errors for die small *w/h* ratios if die extracted seam heights (W) are not equal. However, as die interaction of die mining factors (tf, A an w) are too complicated, there is no other way to overcome die problem at least at present On die other hand, die usually extracted seam height of around 1.0m to 3.0m in kmgwall mining around die world may not cause significant error. It should be remembered dut, strictly speaking, die derived values of die strata parameter, to some extent, also includes die influence of die mining factors.

3. METHOD FOR PREDICTING MAXIMUM SURFACE SUBSIDENCE

The prediction of a complete transverse subsidence profile requires die prédictions of its maximum subsidence and shape. These predictions can be made separately because die shape of a transverse subsidence profile is independent of die magnitude of die maximum subsidence (NCB, 1975). It should be noted dut, strictly speaking, this is not die case (Whittaker and Reddish, 1989). Again, there is no other way around die problem and die influence would not be significant if *H/h* ratios are not significantly different.

3.1 Nomogram based on strata parameter *(P)*

In die instances of a horizontal or near-horizontal seam, die ratio of-maximum subsidence *(S)* to an extracted seam height (H) can be determined from Figure 1 if die value of die strata parameter *(P)* is known.

Table 1 Predictions of *S/H* ratios from die Queensland, Australia by die nomogram shown in Figure *

w/h	Measured *S/H*	Predicted *S/H* 1 error *(%)*
0.67	0.17	Used for estimating the srata parameter
1.65	0.51	0.52 I 2

The nomogram shown in Figure 1 was tested against field data from an additional coalfield as shown in Table 1. From Table 1, die value of *P* was first estimated for a given case with *S/H* and *w/h* ratios known. Next, die estimated value of *P* was used to determine *S/H* ratios for other *w/h* ratios in the same coalfield. Table 1 suggests that the predictions in the given instances for these cases are quite good.

In Figure 1, just considering the many solid curves available, linear interpolation certainly can be used for estimating *S/H* ratios in other coalfields without defining the values of the strata parameter as above. For example, for a given *w/h* ratio, if the value of *S/H* ratio is between two adjacent curves, then for all other *w/h* ratios in the same coalfield the values of *S/H* ratios may be assumed to be between the two curves. Therefore, Figure 1 could serve as a useful guide for creating a prediction curve for estimating the *S/H* ratios for a new coalfield when very few data are available.

3.2 Nomogram based on simplified strata parameter *(Ps)*

The value of the strata parameter *(P)* in a given coalfield must be determined from back analyses of empirical data linking *S/H* and *w/h* ratios and even one typical case (for any *w/h* ratio) is sufficient for estimating the value of the strata parameter in a new coalfield. However, before such measurements of the maximum subsidence become available for a new coalfield, a simplified strata parameter *(Ps)*, i.e. the ratio of the total thickness of all the strong rock beds in an overburden to the overall thickness of the overburden can be used as an approximate estimate of the value of the strata parameter. The strong rocks are such as sandstone, limestone, conglomerate and dolente. In this paper, that ratio is called the simplified strata parameter *(Ps)* to distinguish from the strata parameter *(P)* discussed earlier. If the field measurements on the maximum subsidence are not available for estimating the strata parameter in a new coalfield, a nomogram for predicting the maximum subsidence based on the simplified strata parameter *(Ps)* (Zhang and Bhattacharyya, 1994a, 1994c) may be used

4. PREDICTION OF SHAPES OF COMPLETE TRANSVERSE SUBSIDENCE PROFILES

4.1 Methodology

The strata parameter *(P)* was defined according to the maximum subsidence. If the strata parameter can be used for studying other subsidence trough features, say angle of draw, inflection point and the shape of a transverse subsidence profile, it can be treated as a reasonable index for describing the general deformation character of undermined strata. According to Zhang and Bhattacharyya (1994c, 199S), the strata parameter can be used for studying the angle of draw and the positions of the inflection points.

An empirical method for predicting the shapes of transverse subsidence profiles has been proposed by Zhang and Bhattacharyya (1994c). That method modifies the profile shape predicted by the NCB (1975) method according to the respective angles of draw for the other coalfields. As the limit angle, Le. angle of draw is used as the only model parameter, that method is named as the limit Angle Method (LAM). Although that method is quite suitable, it can not be reliably used if values of the limit angle are less than around 20° or the extraction is super-critical. Thus, another method is proposed next for predicting the shapes of transverse subsidence profiles, which can be used for various *w/h* ratios.

In general, distance *x* of a point on a transverse subsidence profile from the centre of a panel in terms of depth *(x/h)* for different coalfields can be expressed as:

$$\frac{x}{h} = f\left(\frac{s}{S}, \frac{w}{h}, P\right) \qquad (2)$$

where *s* = subsidence at the point at distance x from the centre of the panel; *S* = maximum subsidence; *w* = panel width; *h* = extraction depth; *P* = strata parameter.

Similar to Equation 1, the function defined in Equation 2 can not be expressed explicitly. But, it would be relatively easy to describe it using the nomograms based on different values of the strata parameter P.

If nomograms in many different coalfields with different values of the strata characters *(P)* are available, the ratio *x/h* in a new coalfield could be determined from Equation 2 by using the Linear Interpolation Method (LIM):

$$\frac{x}{h} = r = r_i \frac{P_{i+1} - P}{P_{i+1} - P_i} + r_{i+1} \frac{P - P_i}{P_{i+1} - P_i} \qquad (3)$$

$$(i = 1, 2, \ldots, n)$$

where *n* = number of nomograms established; r = distance of a point from centre of panel in terms of depth *(x/h)* in the new coalfield; r, = distance of a point from centre of panel in terms of depth *(xjh)* in

the t-th coalfield for which a nomogram has been established, for example in the UK coalfields; r_{i+1} = distance of a point from centre of panel in terms of depth *{x_{i+l}lh)* in the (j"+l)-th coalfield for which a nomogram has been established; *P* = the strata parameter in the new coalfield; P, = the strata parameter in the i-th coalfield; P_M = the strata parameter in the (i+ l)-th coalfield.

According to Equation 3, two nomograms are used each time for predicting the shapes of subsidence profiles in the new coalfield. The value of the strata parameter *P* should be close to those of P_t and P_{i+l}; and *P(* £ *P* £ P_{i+1} to improve accuracy. Therefore, the more nomograms are available, the closer are *P* and *Pj+i* and the better is the prediction accuracy. Such calculations by hand are quite time-consuming, then a computer program called E-METHOD has been developed by Zhang (1994).

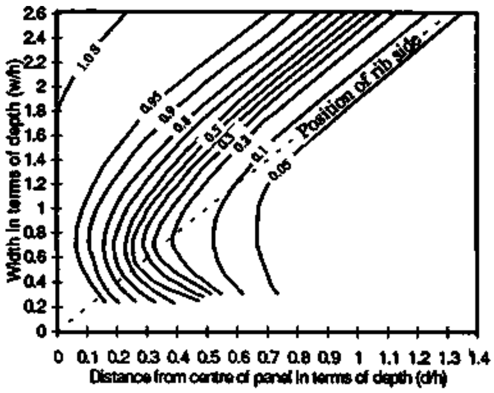


Figure 3 Nomogram for predicting shapes of transverse subsidence profiles for different *w/h* ratios in the Southern coalfield of NSW

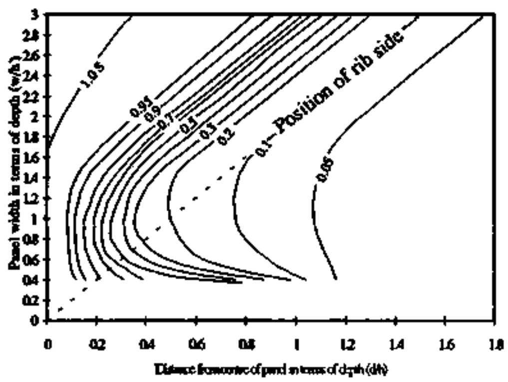


Figure 2 Nomogram for predicting the shapes of transverse subsidence profiles for various *w/h* ratios in the Northern coalfield of NSW

The nomogram from NCB (1975) was based on a **large amount of data.** Therefore, that nomogram **should be the first to** be used for predictions by **Equation 3. Two nomograms** for predicting the **shapes of subsidence profiles for** various *w/h* ratios in **the Northern coalfield of NSW** and Southern **coalfield of NSW were developed** by Zhang (1994) **as shown in Figure 2 and 3, respectively.** According **to these nomograms and the corresponding nomogram from NCB (1975), the shapes** of **transverse subsidence profiles are sharper for the stronger strata when *w/h* ratios are higher, while the shapes are flatter for the weaker strata when *w/h* ratios are lower.**

4.2 Influence of undermined strata on the shapes of transverse subsidence profiles

The influences of the undermined strata on the shapes of transverse subsidence profiles for different *w/h* ratios are discussed next. According to the strata parameter as discussed earlier, the overburdens in the Northern coalfield of NSW are stronger than those in the UK coalfields.

i) When *w/h* ratios are smaller than, say less than 0.75, unlike the weaker strata in the UK coalfields, the strong strata over the caving zone in the Northern coalfield of NSW still have higher **bridging** effects, causing relatively smaller expanse of caving zones. The upper non-caving strata still dominate in controlling the surface subsidence compared to the caved strata. Thus, the overall undermined strata could behave rather elastically, causing the shapes of subsidence profiles in the Northern coalfield of NSW to be flatter than those in the UK coalfields. Such elastically behaving undermined strata could also cause larger angle of draw magnitude at zero subsidence cut-off.

ii) When *w/h* ratios increase, say above 0.75, the greater bridging effect in the undermined strata in the Northern coalfield of NSW also vanish like those in the **UK** coalfields. **The** caving zone **would then** extend **further** in both **the vertical** and **lateral directions. As the** strata **within the overburdens in the Northern coalfield of NSW are thickness, they would break and cave in** larger blocks **around the centre of the panel. The bulking factor is smaller due to the** uniform distributions of the caved blocks, which may cause higher caving and fracturing height (Holla, 1989). Thus, the overall undermined strata can no longer be treated elastically. However, the non-caved parts of the strong and thick rock beds immediately above the caving or fracturing zone near the rib may still act as cantilevers. Therefore, strong 'edge effects' would be created, causing less subsidence to occur at the surface over the ribs. This may cause the sharper shapes of subsidence profiles and smaller angle of draw for higher *wlh* ratios in the Northern coalfields. In addition, the strong rocks e.g. sandstones or limestones in the Northern coalfield of NSW are much more sensitive to the effects of tensile strain (Whittaker and Reddish, 1989). When the *wlh* ratios are high, the presence of the fissures at the surface in strong rocks like sandstone or limestone results in a relatively small influence on the surface from a panel extraction. This type of rock characteristic reduces the influence of mining on the surface outwards from the fissures so that less subsidence is produced towards the extremities of the profile. Therefore, this may be another reason that the sharper shapes of subsidence profiles and smaller angle of draw for higher *wlh* ratios would happen in the Northern coalfield of NSW.

4.3 Case studies

Three nomograms are available for predicting the shapes of complete transverse subsidence profiles, namely for the UK coalfields, the Northern coalfield of NSW, and the Southern coalfield of NSW. According to Zhang and Bhattacharyya (1995), the values of the strata parameter in the UK coalfields, the Northern coalfield of NSW and the Southern coalfield of NSW were 0.0,0.7 and 0.3, respectively. The predictions here are based on the corresponding three nomograms: one from NCB (1975) and the other two in Figures 2 and 3. The use of any two of the three nomograms depends on the value of the strata parameter in the prediction area. The predictions were carried out by Program E-METHOD developed by Zhang (1994).

It is checked here how well these nomograms can be used to predict the shapes of transverse subsidence profiles for some case studies in the U.S.A. by using Equation 3. Several cases were used for testing this method (LIM) by the authors. Then-relevant mining factors are shown in Table 2. As the values of the actual strata parameter for these cases were not available, the simplified strata parameter, i.e. the ratios of the total thickness of all the strong rock beds in the overburdens had to be used instead. The measured and predicted subsidence profiles are compared in Figures 4 to 9. The predictions by LAM are also shown in these figures for comparison. It can be seen that the predictions by LAM and LIM are quite close. In order to compare the shapes of die measured and predicted subsidence profiles, the maximum subsidences are taken to be equal to the measured ones. From these figures, it seems mat the predictions of the shapes of transverse subsidence profiles are fairly good, although not perfect The difference could have been caused by the following:

Table 2 Mining factors and the simplified strata parameter (*Ps*) for longwall subsidence case studies

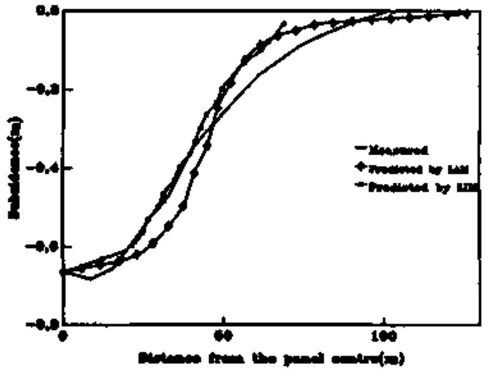
Case studies Begley and Khair (1989)	*H* (m)	*h* (m)	*w* (m)	*Ps*
Case 1	1.10	122	143	0.37
Case 2	1.83	229	183	0.30
Case 3	1.87	195	154	0.39
Case 4	1.98	229	148	0.23
Case 5	1.89	122	132	0.24
Case 6	1.31	235	154	0.20

i) The simplified strata parameter *(Ps)* was used for the predictions in all these cases. As discussed, the simplified strata parameter *(Ps)*, namely the ratio of the thickness of all the strong rock beds in an overburden to the overall thickness of the overburden does not consider many other important factors, e.g. the differences in deformation behaviours between the strong rocks, even with the same name; the influence of weak rocks; number of strong rock beds; distributions and positions of particular rock beds in the overburden relative to the seam; structural discontinuities such as fault» and dykes. AU those factors could influence the accuracy of the predictions.

ii) In all the cases, the predictions were based on the assumptions of uniform seam thickness and horizontal seams and ground surfaces, which may not be true. Also, multiple extractions may not have been acknowledged.

iii) The measured subsidence profiles may also have been influenced by unknown or un-reported abnormal geological factors, time-subsidence effects and inaccuracy of measurement, especially in the case of small subsidence magnitudes.

iv) In all the cases, the so-called measured subsidence profiles were obtained by the authors by using adigitiser on the subsidence profiles given in the relevant references. Thus, some errors were unavoidable, especially when the diagrams were very small in size.



Rgure4 Comparisonof me shapes of measured and predicted transverse subsidence profiles for case 1

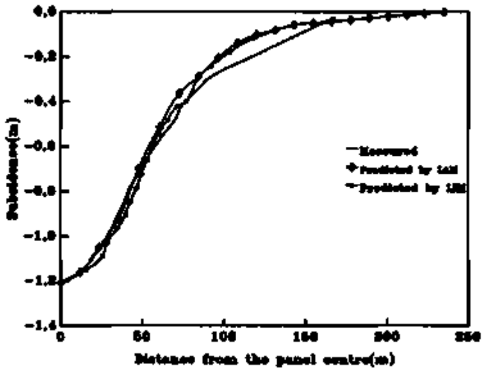


Figure 8 Comparison of the shapes of measured and predicted transverse subsidence profiles for case **4**

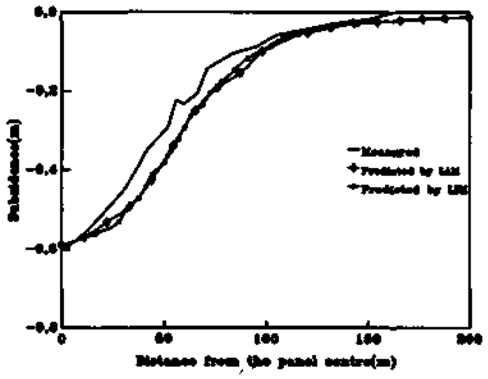


Figure 5 Comparison of the shapes of measured and predicted transverse subsidence profiles for case 2

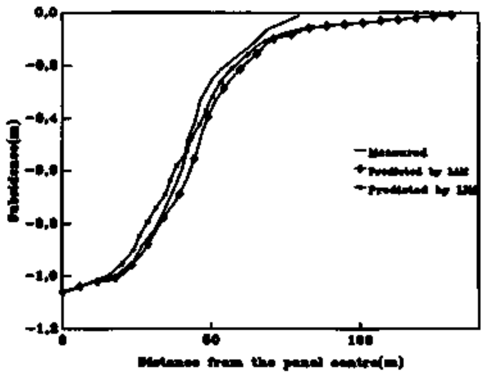


Figure 9 Comparison of the shapes of measured and predicted transverse subsidence profiles for case *5*

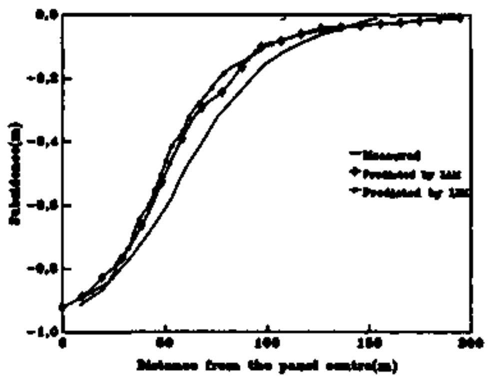


Figure 7 Comparison of the shapes of measured and predicted transverse subsidence profiles for case 3

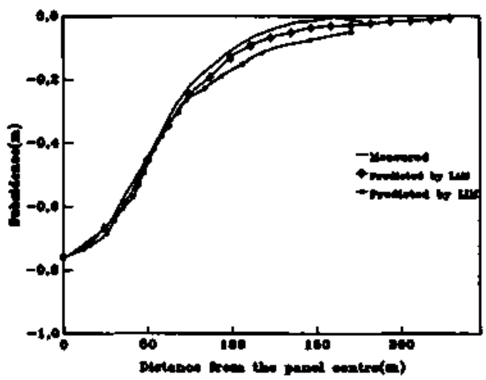


Figure 10 Comparison of the shapes of measured and predicted transverse subsidence profiles for case 6

5. CONCLUSIONS

Based on the strata parameter *(P),* a generalised empirical method has been developed, which can be used for predicting the maximum surface subsidence and the shapes of a transverse subsidence profile due to a single completely mined longwall panel in different coalfields.

Based on this generalised empirical method, it seems that the shape of the complete subsidence profile would be greatly influenced by the character of the undermined strata in addition to the *w/h* ratio. The shapes of complete transverse subsidence profiles appear to be similar for different coalfields when the *w/h* ratios are approximately around 0.7S. However, for other *w/h* ratios, the influences of the characters of the undermined strata are different for low and high *w/h* ratios. For low *w/k* ratios, the stronger an overburden is, the flatter is the shape of the subsidence profile. For high *w/h* ratios, the stronger an overburden is, the sharper is the shape of the subsidence profile.

It is likely that the strata parameter could be used for studying the horizontal displacements and strains in different coalfields. This generalised empirical method can also be used for calibrating the other methods in the future.

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