Coal mine subsidence prediction using a boundary-element program

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Abstract

This paper presents several case studies in which a mechanics-based boundary-element program is used to back-calculate the surface subsidence associated with various panels at several northern Appalachian coal mines. The program used in this case study is called LAMODEL, which incorporates a frictionless, laminated overburden into a general-purpose displacement-discontinuity code primarily designed for calculating the stresses and displacements in coal mines or other thin-seam or vein-type deposits. In this paper, the program is used to calculate both the underground convergence and the resulting surface subsidence at five longwall panels and a room-and-pillar section. The fitted subsidence from the model is compared with the field measurements and analyzed. The results from this work show that the LAMODEL program is not as accurate as available empirical subsidence-predictive methods; the expected correlation between the geology and the optimum input parameters is not evident. However, for a mechanics-based program, LAMODEL does provide moderately accurate subsidence calculations, and it is one of a few programs that can even attempt to practically calculate both underground stress and convergence and the resulting surface subsidence.

Introduction

Historically, the surface subsidence above underground coal mines has been predicted using profile or influence functions that use little or no mechanics to calculate the ground movement (Kratzch, 1983; Adamek et al., 1987; Heasley, 1988). Without a mechanistic input, establishing the exact seam convergence and function parameters to use in these empirical methods has typically required extensive and expensive field measurements to calibrate the function parameters to a specific mining area. A practical subsidence-predictive method based on mechanics has the appealing capability of allowing the determination of site-specific parameters from fundamental properties of the overburden with minimal field calibration work.

Recently, a laminated overburden model derived from plate mechanics was used to predict surface subsidence with fairly good results (Salamon, 1989a, 1989b, 1991; Yang, 1992). The model has shown the capability of fitting a generic, empirically derived subsidence curve for northern Appalachia (Heasley and Salamon, 1996). The combination of both of these capabilities in a single mathematical model gives it the potential to accurately calculate both underground stresses and displacement and the associated surface subsidence with the same mechanical basis. This laminated overburden model has now been coded into a full-featured displacement-discontinuity program, LAMODEL, for analyzing coal mine stresses and displacements, as well as surface subsidence (Heasley, 1998). In this program, the various properties of the seam and gob materials are mechanically combined with the laminated overburden properties to realistically calculate seam stresses and convergence. This calculated seam convergence can then be projected to surface subsidence using the laminated overburden mechanics.

This paper relates the application of the laminated overburden in LAMODEL to subsidence prediction at several longwall panels and a room-and-pillar section in northern Appalachia and provides an initial evaluation of the program's accuracy and utility for subsidence prediction.

The LAMODEL program

LAMODEL is a PC-based program for calculating the stresses and displacements in coal mines or other thin-seam or vein-type deposits. It is primarily designed to be utilized by mining engineers for investigating and optimizing pillar sizes and layouts in relation to overburden, abutment and multiple-seam stresses (Heasley, 1998). The program uses a displacement-discontinuity variation of the boundary-element method for determining and solving the elastic equations of equilibrium around the mine openings. LAMODEL simulates the overburden as a stack of homogeneous isotropic layers with frictionless interfaces and with each layer having the identical elastic modulus, Poisson's Ratio and thickness. This "homogeneous stratification" formulation does not require (or allow) specific material properties for each individual layer. Yet it still provides a realistic suppleness to the overburden that is not possible with the classic, homogeneous isotropic elastic overburden.

The two primary factors that influence the shape and magnitude of the subsidence (particularly in LAMODEL) are the gob compaction stiffness and the overburden flexural stiffness. Therefore, the primary parameters that are adjusted in LAMODEL for fitting the measured subsidence are the final gob modulus (E_f), which is used to control the gob stiffness, and the lamination thickness (t), which is used to control the overburden stiffness. In the process of analyzing the potential of LAMODEL for surface subsidence calcula-

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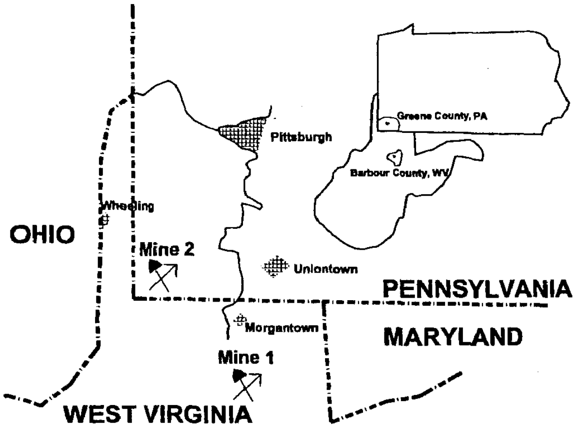

Figure 1 — Location map of the case study mines.

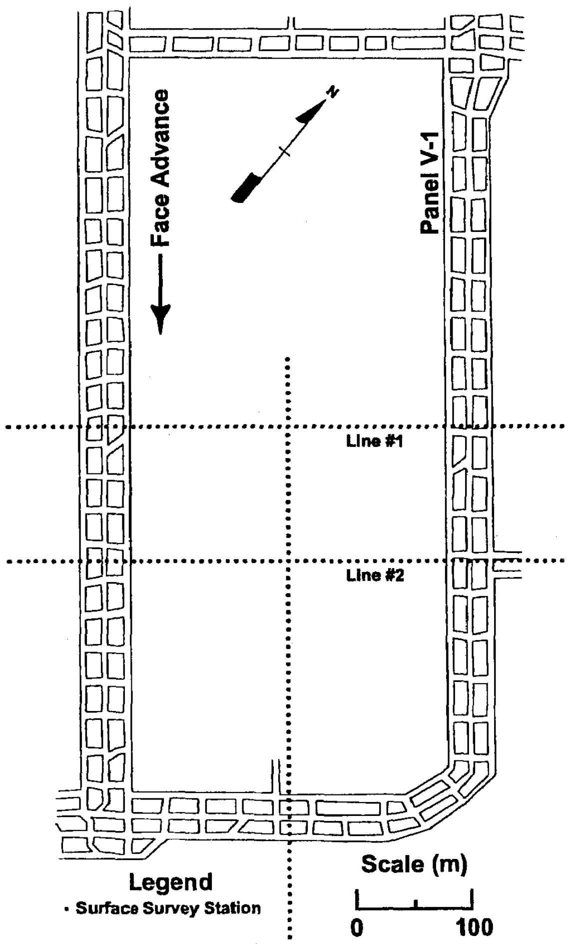

Figure 2 — Map of the V-1 panel.

tion presented in this paper, the measured subsidence is used to "calibrate" the model. This calibration process consists of an interactive trial-and-error process where the critical model parameters (in this case the lamination thickness and the final gob modulus) are initially estimated. The program is run to calculate the surface subsidence, the calculated subsidence is compared to the measured subsidence, the model parameters are adjusted to improve the fit and, then, the program is run again. This cycle continues until the calculated subsidence fits the measured subsidence as close as desired. The resulting values of the critical model parameters are considered to be "calibrated" to the given site conditions.

Table 1 — Panel dimensions used in the calibration models.

Panel	Length, m	Width, m	Seam thickness, m	Depth, m
V-1	640	285	1.8	120
D-3	1,250	180	1.8	230
D-5	1,050	168	1.8	230
C-3	256	168	1.7	180
E-1	1,430	194	1.8	277
E-2	1,730	194	1.8	247

Mine 1

The location of the first subsidence-prediction case study in this paper is a longwall mine in Barbour County in the northwest corner of West Virginia (see Fig. 1). This mine started production in 1975 with continuous miners in room-and-pillar sections. In 1982, the first longwall was installed and, by the time of the final subsidence monitoring in this study (1985), the mine had successfully completed five longwall panels (Jeran and Barton, 1985; Heasley, 1988). The mine operates in the Lower Kittanning seam that averages 1.8 m (5.9 ft) in thickness and has an overburden between 120 and 420 m (390 and 1,380 ft) across the property. The immediate roof of the seam consists of a thinly laminated sandy-shale overlain with a main roof of interbedded sandstones, shales and limestones. The mine area is also noted for high horizontal in situ stresses.

The V-1 panel. The first panel at which the subsidence was investigated using LAMODEL is called the V-1 panel. It is actually the fifth longwall panel to be extracted at the mine (see Fig. 2 and Table 1.). The panel advanced from the northwest towards the southeast, and, as shown in Fig. 2, there were two transverse lines and one longitudinal line of subsidence monitoring stations over the later half of the panel. For this initial subsidence-fitting exercise, the entire panel was discretized into LAMODEL. The overburden was set at a constant 120 m (390 ft), the elastic modulus of the rock mass was set at 20 GPa, the modulus of the coal was set at 2 GPa and the coal thickness was set at a constant 1.8 m (5.9 ft).

For this first calibration process on the V-1 panel, it was found that a wide range of lamination thicknesses and final gob moduli combinations could be fit equally well to the measured subsidence. A distributed sample of these parameter combinations is listed in Table 2 and shown in Fig. 3. The range of parameters shown in Table 2 covers the complete spectrum of reasonable behavior for this panel. For the thinnest laminations (1.5 m), the peak gob load is essentially equal to the overburden load (see Table 2). Therefore, at this lamination thickness, the gob is supporting the total overburden load at the middle of the panel and the flexural stiffness of the laminations is not effectively supporting any overburden load. On the other end of the spectrum, for the thickest lamination (7.5 m), the peak gob load is only about one-sixth of the overburden load, and the flexural stiffness of the

Table 2 — Calibrated LAMODEL parameters.

Lamination thickness, m	Final gob modulus, MPa	Peak gob stress, MPa	Average gob stress, MPa	Coal strength, percent of Bieniawski strength
Panel V-1				
1.5	124	3.0	2.0	100
4.5	100	2.5	1.6	100
7.5	1.38	0.5	0.4	100
Panel D-3				
1.5	383	5.7	4.5	100
4.5	372	5.4	3.6	100
7.5	324	4.3	2.3	100
Panel D-5				
1.5	383	5.7	4.5	60
4.5	372	5.4	3.6	60
7.5	324	4.3	2.3	60
Panel C-3				
3.0	340	4.2	–	100
4.5	293	3.3	–	100
6.0	212	1.8	–	100
Panel E-1				
3.0	203	6.7	–	100
6.0	179	5.1	–	100
9.0	141	3.2	–	100
Panel E-2				
3.0	170	5.9	–	55
6.0	149	4.2	–	75
9.0	84	1.7	–	95

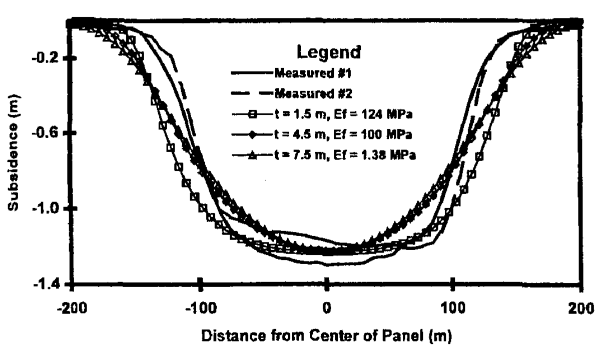

Figure 3 — The measured and fitted subsidence for the V-1 Panel.

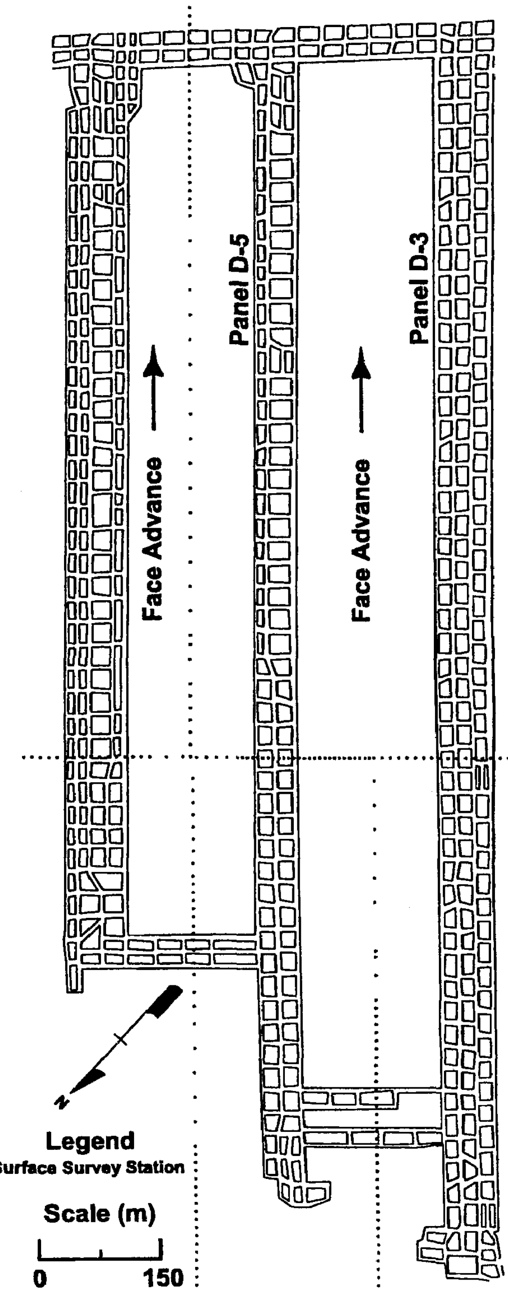

Figure 4 — Map of the D-3 and D-5 panels.

laminations is supporting the other five-sixths of the overburden load. Thus, for fitting LAMODEL to a given maximum subsidence, the thinnest, most flexible laminations require the stiffest gob, while the thickest, stiffest laminations mandate a softer gob.

The D-3 and D-5 panels. The next two panels at which the subsidence was investigated using LAMODEL are known as the D-3 and D-5 panels, and they are the first and second panels to be extracted at Mine 1 (see Fig. 4 and Table 1). Both of these panels advanced from the northwest towards the southeast, and each panel had its own longitudinal line of subsidence monitoring stations and a shared transverse line that extends over both the panels and the intervening gate road (see Fig. 4). Because these panels are considerably narrower (≤180 m) and deeper (≥230 m) than the V-1 panel, the surface subsidence is expected to be subcritical.

For the subsidence calculation at these two panels, a single LAMODEL grid was created that covered the initial half of both panels. The elastic modulus of the overburden and coal were set to the same values as used for the V-1 panel. However, the input coal strength was varied to fit the subsidence over the intervening gate roads. Essentially, both the convergence in the gate road and the associated overlying

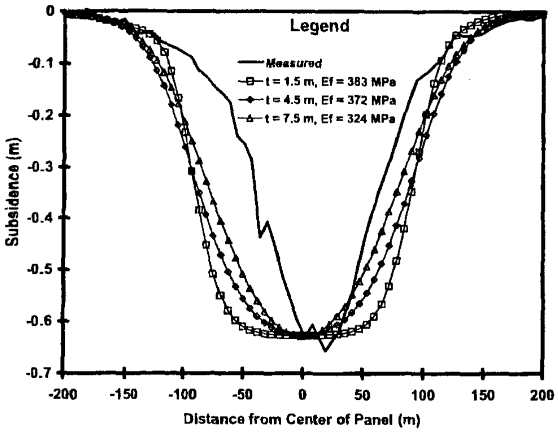

Figure 5 — The measured and fitted subsidence for the D-3 Panel.

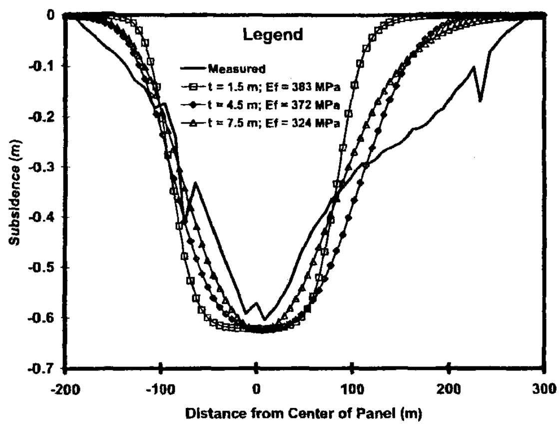

Figure 6 — The measured and fitted subsidence for the D-5 Panel.

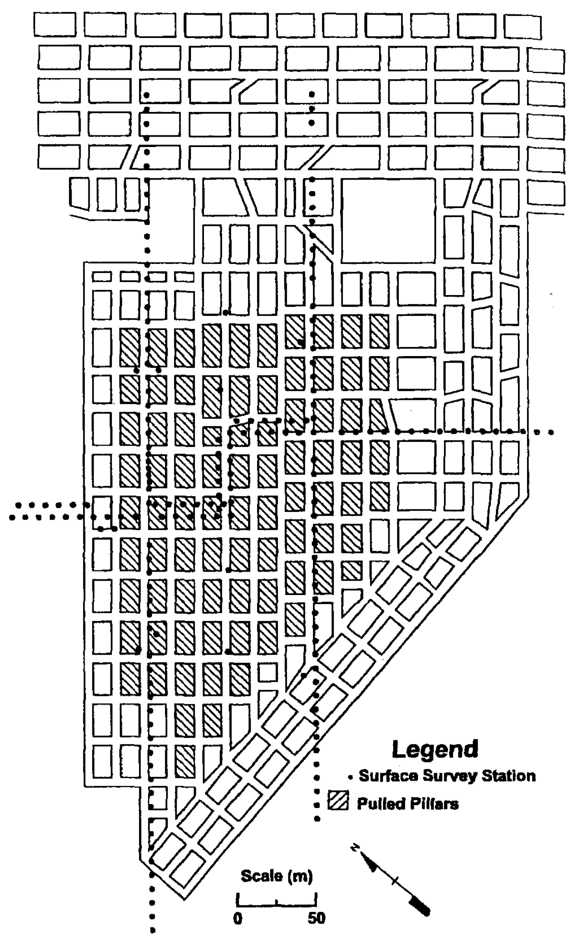

Figure 7 — Map of the C-3 panel.

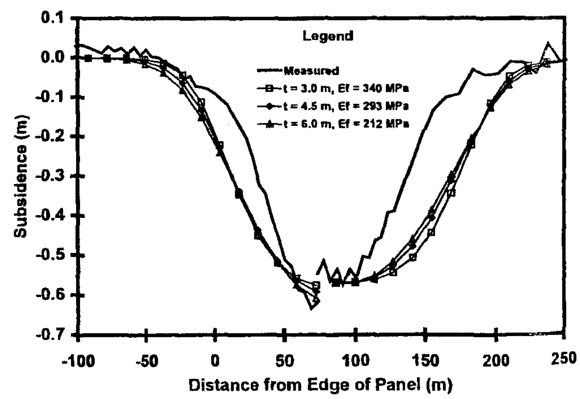

Figure 8 — The measured and fitted subsidence for the C-3 Panel.

subsidence were increased by decreasing the gate road coal strength. Typically, the coal strength is initially set at 100% of the strength determined by the Bieniawski pillar formula (Heasley, 1998). When more subsidence is needed over the gate roads for better calibration, the coal strength is lowered to some percentage of the recommended Bieniawski pillar strength (see Table 2). The calibrated subsidence for the D-3 and D-5 panels is shown in Figs. 5 and 6, respectively.

The C-3 panel. The next panel where the measured subsidence was calibrated using LAMODEL is called the C-3 panel, which is a room-and-pillar retreat section at Mine 1 (see Fig. 7 and Table 1). The chain pillars in the section were typically driven 13-m (43-ft) wide by 22-m (72-ft) long, with 5-m- (16-ft-) wide rooms and crosscuts. The overall retreat line moved from the southwest towards the northeast, with pillars being extracted systematically row by row, west to east using the split-and-fender cut sequence on a single pair of pillars at one time. On the surface above this section, the subsidence was monitored with two longitudinal survey lines and one doglegged transverse survey line of subsidence monitoring stations (see Fig. 7). For the subsidence calibration of this panel, the elastic modulus of the overburden and coal were set to the same values as previous LAMODEL runs at this mine. The calibrated subsidence for this panel is shown in Fig. 8 and the associated LAMODEL parameters are given in Table 2.

Mine 2

The second case study mine in this paper is a longwall mine in Greene County in the southwest corner of Pennsylvania (see Fig. 1). The mine operates in the Pittsburgh seam, which averages 1.8-m (6-ft) in thickness and which has an overburden between 230 and 300 m (750 and 1,000 ft) across the property. In the study area, the immediate roof of the

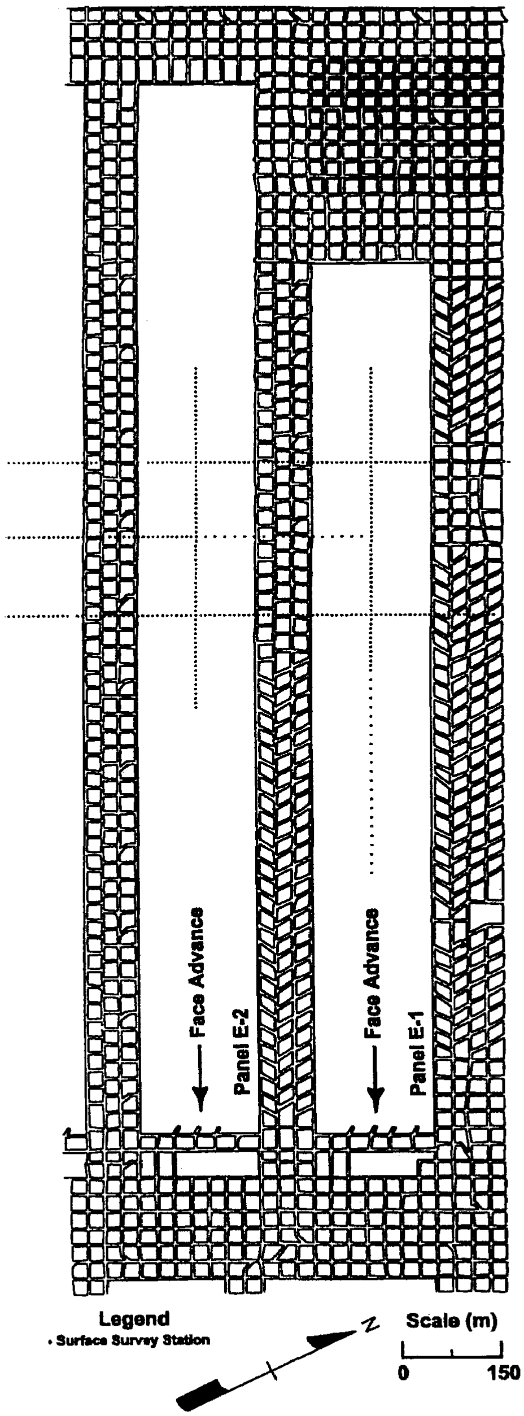

Figure 9 — Map of the E-1 and E-2 panels.

seam consists of limestone overlain with a main roof of interbedded shales, sandstones, limestones and coal (Moebs and Barton, 1985).

The E-1 and E-2 panels. The two panels at Mine 2, where LAMODEL was used to investigate the subsidence, are known as the E-1 and E-2 panels. These are the first and second panels to be extracted at the mine (see Fig. 9 and Table 1). Both of these panels advanced from the northwest towards the southeast, and each panel had its own longitudinal line of subsidence-monitoring stations and shared three transverse lines that extended over both the panels and the intervening gate road (see Fig. 9). Because these two panels share a gate road similar to panels D-3 and D-5, they also allow/require the subsidence over the gate road to be adjusted by varying the coal strength (see Table 2).

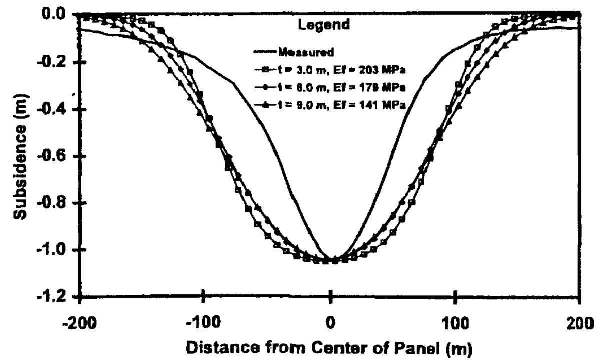

Figure 10 — The measured and fitted subsidence for the E-1 Panel.

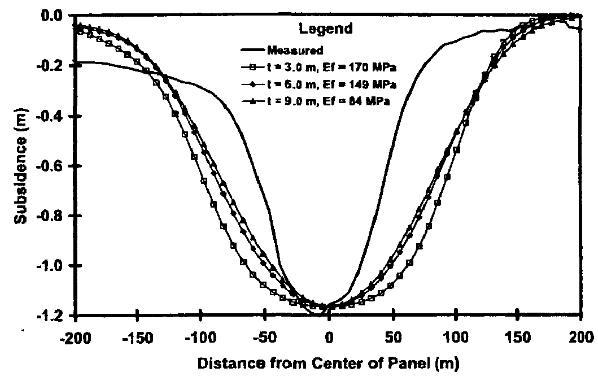

Figure 11 — The measured and fitted subsidence for the E-2 Panel.

For the subsidence calculation at these two panels, a single LAMODEL grid covered the initial half of both panels centering on the transverse profile line closest to the start of the panels. In the model, as in all the models in this paper, the elastic modulus of the rock mass was set at 20 GPa and the modulus of the coal was set at 2 GPa. The calibrated subsidence for these panels is shown in Figs. 10 and 11, and the associated calibrated parameters are given in Table 2.

Discussion

In this paper, surface subsidence from five northern Appalachian longwall panels and a room-and-pillar section was calculated in the process of evaluating the utility of using the LAMODEL program for subsidence calculation. This number of case studies provides a fairly substantial basis for understanding the subsidence predictive capabilities of the program, and the evaluation process has highlighted a number of characteristics and peculiarities of subsidence prediction with LAMODEL. First, it appears that the LAMODEL subsidence calculation is not as accurate as available empirical subsidence predictive methods. The program systematically produced subsidence troughs that were wider than observed. Also, the initial hope that one set of regional input parameters would be determined that would provide reasonable subsidence prediction throughout the given area was not achieved. The expected correlation between the geology and the optimum input parameters was not evident in this work. However, for a mechanics-based program, LAMODEL does provide moderately accurate subsidence calculations. Also, the laminated model demonstrated a considerable amount of flexibility for subsidence fitting through varying only two mechanical parameters, the lamination thickness and the gob modulus. LAMODEL is one of a few programs that can even attempt to calculate both underground stress and convergence and the resulting surface subsidence.

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