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Prediction of Surface Deformations Over Longwall Panels in the Northern Appalachian Coalfield

By Vladimir Adamek, Paul W. Jeran, and Michael A. Trevits

UNITED STATES DEPARTMENT OF THE INTERIOR

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PREDICTION OF SURFACE DEFORMATIONS OVER LONGWALL PANELS IN THE NORTHERN APPALACHIAN COALFIELD

Vladimir Adamek,[1] Paul W. Jeran,[2] and Michael A. Trevits[3]

ABSTRACT

This paper describes the Bureau of Mines development of a novel subsidence prediction methodology suitable to the mining and geologic conditions in the Northern Appalachian Coal Region. It describes the computation of vertical and horizontal movements, inclination, curvature, and horizontal strains. The substance of this method is the separation of the effects of lithology by introducing a correlation between hypothetically homogeneous overburden and existing lithologic conditions, while providing for different mining conditions, i.e., underground geometry and overburden thickness.

The effects of lithology have been expressed in the form of a variable subsidence coefficient within the subsidence trough. The subsidence coefficient is considered a constant for other predictive methods. Field data from 16 test sites at 11 Bureau longwall panel studies were used in the analysis. For each panel, the characteristics of the variability of the subsidence coefficient were defined. Regression analysis of the subsidence coefficients from all test sites on their locations relative to the edges of their respective panels yielded a third-degree polynomial equation. The results from additional longwall panel studies, not included in the regression analysis, were used to prove the validity of this method. To facilitate the use of this precalculation methodology, a computer program was written in BASIC for use on a personal computer.

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INTRODUCTION

Traditionally, mining in this country has been remote from population centers. Few were exposed to subsidence effects, and there was little concern for the alteration of the local environment. Today, the juxtaposition of mining, population, farming, and industry has made it necessary that each control its effects on the others. For underground mining, this means that a lack of concern for the local environment is no longer tolerable. Mining operations must be planned so that there will be minimal detrimental effects to the surface, ground water, and other potential resources overlying their workings.

The Bureau, since its creation, has studied the phenomenon of mine subsidence. Early work involved investigation of damages to surface structures and remedial activities on a site-specific basis. More recently, studies have been targeted toward understanding the process of subsidence and the definition of the parameters that affect it. It has been found that because of specific lithological conditions in the Northern Appalachian Coalfield, none of the existing predictive methodologies based either on influence or profile function yield acceptable results as to the prediction of surface deformations over longwall panels. The presence of highly resistive limestone and sandstone layers with relatively thin (400-1,000 ft) overburden is the most probable cause for discrepancies between measured deformations and deformations computed by methods developed mainly for European conditions.

In 1985, the Bureau published a model[4] for the prediction of vertical subsidence movements over longwall mining in the Northern Appalachian Coal Basin, based upon data collected in 11 longwall panel studies. A computer program was written for use on a personal computer to facilitate use of the model by government and industry personnel not familiar with subsidence theory. Because deformations result from both vertical and horizontal movements, the model has been expanded to include the calculation of inclination, curvature, horizontal movements, and horizontal strain. This report presents the expanded model and details its development. Comparisons are made between model predictions and field measurements.

DEVELOPMENT OF SUBSIDENCE PREDICTION METHODOLOGY

In predicting structural damage due to underground mining, both the vertical and horizontal components of ground movement must be considered. Structural damage is determined by the extent of the surface deformations as indicated by inclination (differential subsidence), curvature (differential inclination), and horizontal strains--tension and compression (differential horizontal displacements).

To develop the subsidence predictive model, a reasonable quantity of field data were needed. Field data used in this study were collected by the Bureau in 11 longwall panel studies. The conditions at each study site were different with respect to underground geometry, overburden thickness, and geology. Table 1 shows pertinent parameters at the various test sites of the panel studies. The shape of the subsidence profiles, as measured in the field, differed from each other and also from subsidence profiles calculated by known predictive methods. Figure 1 shows a typical subsidence profile as measured, compared with profiles calculated using some European methods.

It is important to note that the typical subsidence profile differs dramatically from the calculated profile. Therefore, one must define what part of the difference is due to mining conditions (width of panel, thickness of overburden, extracted thickness), and what part is due to geologic conditions. It is also necessary to establish relative

[4] U.S. Bureau of Mines, Staff. Mine Subsidence Control. Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, PA, September 19, 1985. IC 9042, 1985, pp. 34-56.

TABLE 1. - Overview of basic parameters at test sites

Test site	H, ft		m, ft	w, ft	sF at centerline, ft	a at centerline for γ = 25°	$\bar{a}$ (VS/VE)	w/H
	Range	At centerline						
1........	520-706	650	5.5	460	-2.62	0.513	0.30	0.71
2........	677-700	700	5.5	600	-3.25	.597	.35	.86
3........	645-700	700	5.5	600	-3.25	.597	.32	.86
4........	509-624	615	5.5	605	-3.65	.664	.44	.98
5........	652-781	652	5.5	605	-3.55	.645	.39	.93
6........	740-795	795	5.5	600	-3.09	.587	.32	.75
7........	732-795	795	5.5	600	-3.09	.587	.32	.75
8........	913-995	913	6.0	630	-3.42	.614	.40	.69
9........	803-913	913	6.0	630	-3.42	.614	.38	.69
10.......	802-855	855	6.0	630	-3.12	.547	.34	.74
11.......	717-780	717	6.0	630	-3.72	.623	.34	.88
12.......	702-719	717	6.0	630	-3.72	.623	.34	.88
13.......	368-402	402	6.0	940	-4.04	.673	.37	2.34
14.......	345-402	402	6.0	940	-4.04	.673	.39	2.34
15.......	700-845	845	5.5	600	-2.95	.571	.31	.71
16.......	747-866	747	5.5	510	-2.79	.547	.34	.68

a Subsidence coefficient.
$\bar{a}$ Average subsidence coefficient.
H Specific overburden thickness.
m Extracted thickness.
sF Measured subsidence.
VE Volume of coal extracted.
VS Volume of subsidence trough.
w Width of panel.
w/H Ratio of panel width to overburden thickness.
γ Angle of draw.

differences of lithologic effects on subsidence characteristics between individual test sites. This situation is like having one equation with two unknowns. To solve this equation, one must eliminate one unknown. For this purpose, a correlation was made between hypothetical homogeneous overburden and existing lithologic conditions, while providing for different mining conditions.

For homogeneous overburden (overburden without resistant rock units) or overburden behaving homogeneously, from the point of view of subsidence, the concept of the angle of draw as a functional parameter for predictive methodologies based on the principle of the area of influence has been proven valid. Among the European models, Bals' theory has achieved wide recognition and practical use. The theory assumes that displacement of any surface point is determined by the cumulative effects of the individual elementary parts of the extracted areas. Therefore, its substance is the definition of the efficiency coefficient (e). Based on Newton's law governing the attraction of masses, Bals assumes that each differential part of the mined-out area exerts an influence on the surface point inversely proportional to its distance from it. Using a computer algorithm developed by the Bureau, it was possible to compute and tabulate the values of e for different mining conditions (see table 2).

For the computation of efficiency coefficients, the value of the angle of draw (γ) must be known. Because one cannot define this value for hypothetically homogeneous overburden, the process of computation had to be done for several different values. Figure 2 shows a typical subsidence profile from the Northern Appalachian Coalfield in comparison with calculated profiles by Bals, using 15° and 25° angles of draw as functional parameters.

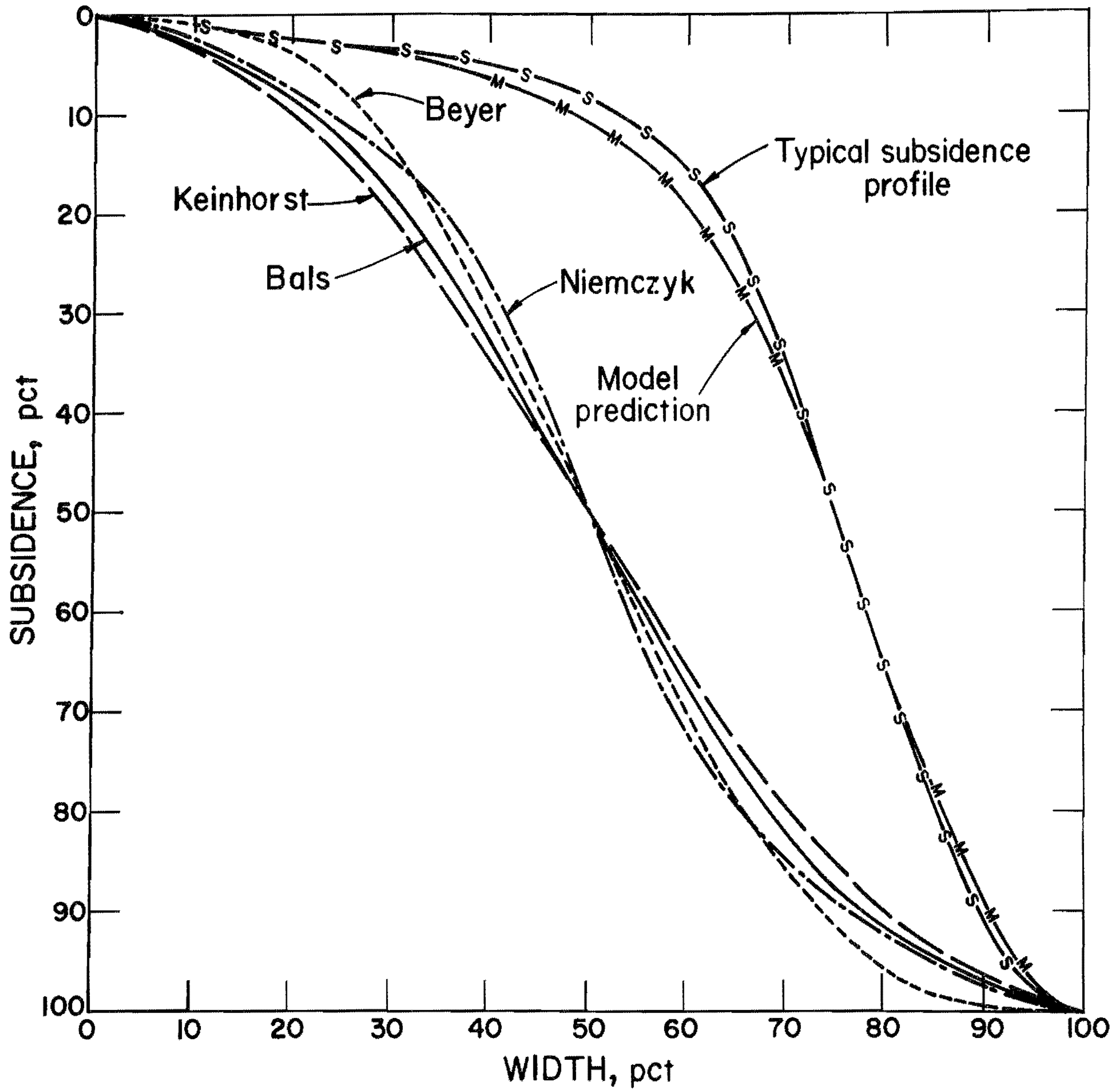

FIGURE 1.—Comparison of measured and calculated subsidence profiles.

It is evident that a reasonable congruency could not be reached between the measured and computed profiles using Bals' theory for any angle of draw from 0° to 90°. However, Bals' theory was used as a helping tool to establish the difference in subsidence characteristics between homogeneous overburden and existing lithologic conditions. This process enabled the separation of the effect of lithology from the effect of different mining conditions on subsidence characteristics. The results have indicated that the most appropriate angle of draw value is 25°.

To obtain congruency between computed and measured data, it was necessary to introduce the subsidence coefficient (a_v) as a variable:

$$a_{v\,l} = \frac{sF_l}{me_l}, \qquad (1)$$

TABLE 2. - Efficiency coefficients for 25° angle of draw

w/H	Distance inward from edge of panel as fraction of panel width										
	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05	0.00
0.1.....	0.289	0.289	0.289	0.286	0.286	0.280	0.277	0.268	0.258	0.250	0.237
0.2.....	.473	.471	.468	.466	.460	.449	.440	.428	.415	.389	.361
0.3.....	.609	.609	.606	.599	.590	.577	.563	.542	.520	.487	.439
0.4.....	.722	.719	.714	.706	.692	.676	.654	.629	.594	.554	.487
0.5.....	.811	.808	.801	.788	.772	.749	.723	.686	.643	.588	.500
0.6.....	.879	.877	.868	.853	.833	.803	.765	.720	.667	.600	.500
0.7.....	.934	.931	.919	.899	.870	.833	.793	.744	.686	.609	.500
0.8.....	.973	.969	.952	.927	.896	.858	.818	.765	.703	.622	.500
0.9.....	.998	.988	.972	.949	.920	.882	.841	.786	.720	.633	.500
1.0.....	1.000	.999	.987	.967	.939	.903	.861	.804	.737	.644	.500
1.1.....	1.000	1.000	.997	.982	.957	.921	.879	.823	.751	.656	.500
1.2.....	1.000	1.000	1.000	.992	.972	.939	.896	.841	.765	.667	.500
1.3.....	1.000	1.000	1.000	.999	.983	.953	.913	.855	.780	.677	.500
1.4.....	1.000	1.000	1.000	1.000	.992	.966	.927	.870	.793	.686	.500
1.5.....	1.000	1.000	1.000	1.000	.999	.977	.939	.884	.804	.692	.500
1.6.....	1.000	1.000	1.000	1.000	1.000	.986	.952	.896	.818	.703	.500
1.7.....	1.000	1.000	1.000	1.000	1.000	.987	.963	.909	.828	.711	.500
1.8.....	1.000	1.000	1.000	1.000	1.000	.993	.972	.920	.841	.720	.500
1.9.....	1.000	1.000	1.000	1.000	1.000	.999	.979	.929	.851	.728	.500
2.0.....	1.000	1.000	1.000	1.000	1.000	1.000	.987	.939	.861	.737	.500
2.1.....	1.000	1.000	1.000	1.000	1.000	1.000	.992	.949	.870	.744	.500
2.2.....	1.000	1.000	1.000	1.000	1.000	1.000	.997	.957	.879	.751	.500
2.3.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.964	.888	.758	.500
2.4.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.972	.896	.765	.500
2.5.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.978	.906	.772	.500
2.6.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.983	.913	.780	.500
2.7.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.988	.920	.786	.500
2.8.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.992	.927	.793	.500
2.9.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.996	.934	.799	.500
3.0.....	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.999	.939	.804	.500

See footnote at end of table.

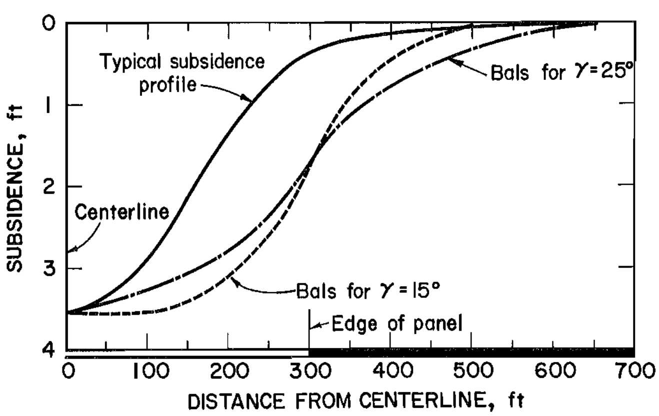

FIGURE 2.—Comparison of measured profile with Bals' predictive method.

where sF_i = measured subsidence,

m = extracted coal seam thickness,

and e_i = efficiency coefficient for each point.

For each surface point at all 11 study sites (16 half profiles or test sites) the value of the variable subsidence coefficient was defined. Figures 3 and 4 show the characteristics of this coefficient along individual profiles adjusted to the edge of the panel. Each of these curves represents a separated effect of lithology on subsidence characteristics,

TABLE 2. - Efficiency coefficients for 25° angle of draw--Continued

w/H	Distance outward from edge of panel as fraction of panel width										
	0.00	-0.05	-0.10	-0.15	-0.20	-0.25	-0.30	-0.35	-0.40	-0.45	-0.50
0.1.....	0.237	0.222	0.213	0.201	0.191	0.184	0.180	0.177	0.171	0.166	0.160
0.2.....	.361	.332	.304	.288	.274	.261	.246	.234	.224	.214	.203
0.3.....	.439	.392	.357	.331	.305	.286	.263	.244	.227	.209	.194
0.4.....	.487	.418	.375	.333	.297	.263	.235	.207	.182	.159	.139
0.5.....	.500	.412	.356	.308	.263	.228	.196	.166	.139	.116	.094
0.6.....	.500	.400	.333	.280	.235	.196	.159	.130	.104	.080	.061
0.7.....	.500	.391	.314	.256	.207	.166	.130	.099	.073	.051	.033
0.8.....	.500	.378	.297	.235	.182	.139	.104	.073	.048	.028	.013
0.9.....	.500	.367	.280	.214	.159	.116	.080	.051	.028	.012	.001
1.0.....	.500	.356	.263	.196	.139	.094	.061	.033	.013	.001	.000
1.1.....	.500	.344	.249	.177	.121	.077	.043	.018	.003	.000	.000
1.2.....	.500	.333	.235	.159	.104	.061	.028	.008	.000	.000	.000
1.3.....	.500	.323	.220	.145	.087	.046	.017	.001	.000	.000	.000
1.4.....	.500	.314	.207	.130	.073	.033	.008	.000	.000	.000	.000
1.5.....	.500	.308	.196	.116	.061	.022	.001	.000	.000	.000	.000
1.6.....	.500	.297	.182	.104	.048	.013	.000	.000	.000	.000	.000
1.7.....	.500	.289	.172	.091	.037	.007	.000	.000	.000	.000	.000
1.8.....	.500	.280	.159	.080	.028	.001	.000	.000	.000	.000	.000
1.9.....	.500	.272	.149	.071	.021	.000	.000	.000	.000	.000	.000
2.0.....	.500	.263	.139	.061	.013	.000	.000	.000	.000	.000	.000
2.1.....	.500	.256	.130	.051	.008	.000	.000	.000	.000	.000	.000
2.2.....	.500	.249	.121	.043	.003	.000	.000	.000	.000	.000	.000
2.3.....	.500	.242	.112	.036	.000	.000	.000	.000	.000	.000	.000
2.4.....	.500	.235	.104	.028	.000	.000	.000	.000	.000	.000	.000
2.5.....	.500	.228	.094	.022	.000	.000	.000	.000	.000	.000	.000
2.6.....	.500	.220	.087	.017	.000	.000	.000	.000	.000	.000	.000
2.7.....	.500	.214	.080	.012	.000	.000	.000	.000	.000	.000	.000
2.8.....	.500	.207	.073	.008	.000	.000	.000	.000	.000	.000	.000
2.9.....	.500	.201	.066	.004	.000	.000	.000	.000	.000	.000	.000
3.0.....	.500	.196	.061	.001	.000	.000	.000	.000	.000	.000	.000

w/H Ratio of panel width to overburden thickness.

expressed in the form of the variable subsidence coefficient. The dispersion of individual curves shows the differences of lithologic effect between individual test sites.

Regression analyses of the subsidence coefficients from all test sites on the location relative to the edge of the panel have yielded a third-degree polynomial equation for a 25° angle of draw:

$$a_v = AX^3 + BX^2 + CX + D, \quad (2)$$

where a_v = variable subsidence coefficient,

X = distance from the edge of the panel toward the centerline, ft,

$A = -3.587 \times 10^{-8}$,

$B = 1.628 \times 10^{-5}$,

$C = -9.105 \times 10^{-5}$,

and $D = 1.359 \times 10^{-1}$.

For points located outwards from the edge of the panel, X = 0. Then, the subsidence of any point toward the centerline will be

$$s_I = m \cdot e_I \cdot a_{vI}, \quad (3)$$

and outwards from panel edge

$$s_I = m \cdot e_I \cdot 0.1359. \quad (4)$$

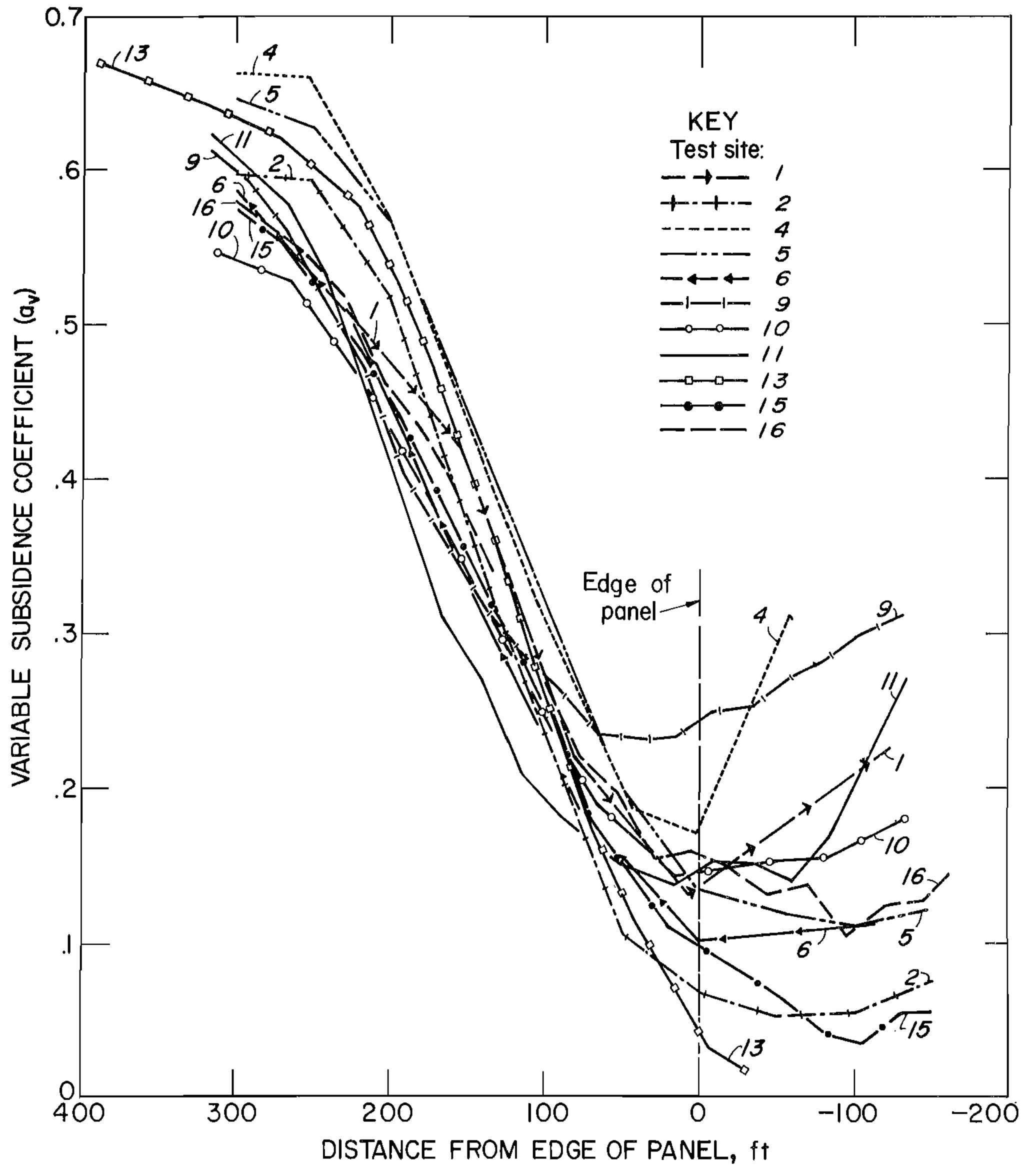

FIGURE 3.—Variable subsidence coefficient for 25° draw angle, right half profiles.

Efficiency coefficients are tabulated in table 2 for different mining conditions. Interpolation will be necessary where the ratio w/H and distance from the edge of panel as fraction of panel width do not match the values in the table.

The validity of this approach for subsidence prediction depends on one of two possibilities:

1. The lithological effect on subsidence characteristics differs at each site beyond acceptable limits as would be demonstrated by a large dispersion of individual curves. Therefore, in theory, the precise prediction of subsidence of any point over a longwall panel would require very specific knowledge of the lithologic characteristics of the overburden. However, even with such knowledge, reasonable predictions may be impossible, because the mechanism of overburden response during the process of subsidence cannot be predicted.

2. The lithologic effect at each site is acceptably similar. Then the standard deviations of the averaged values of subsidence coefficients would be satisfactory (table 3).

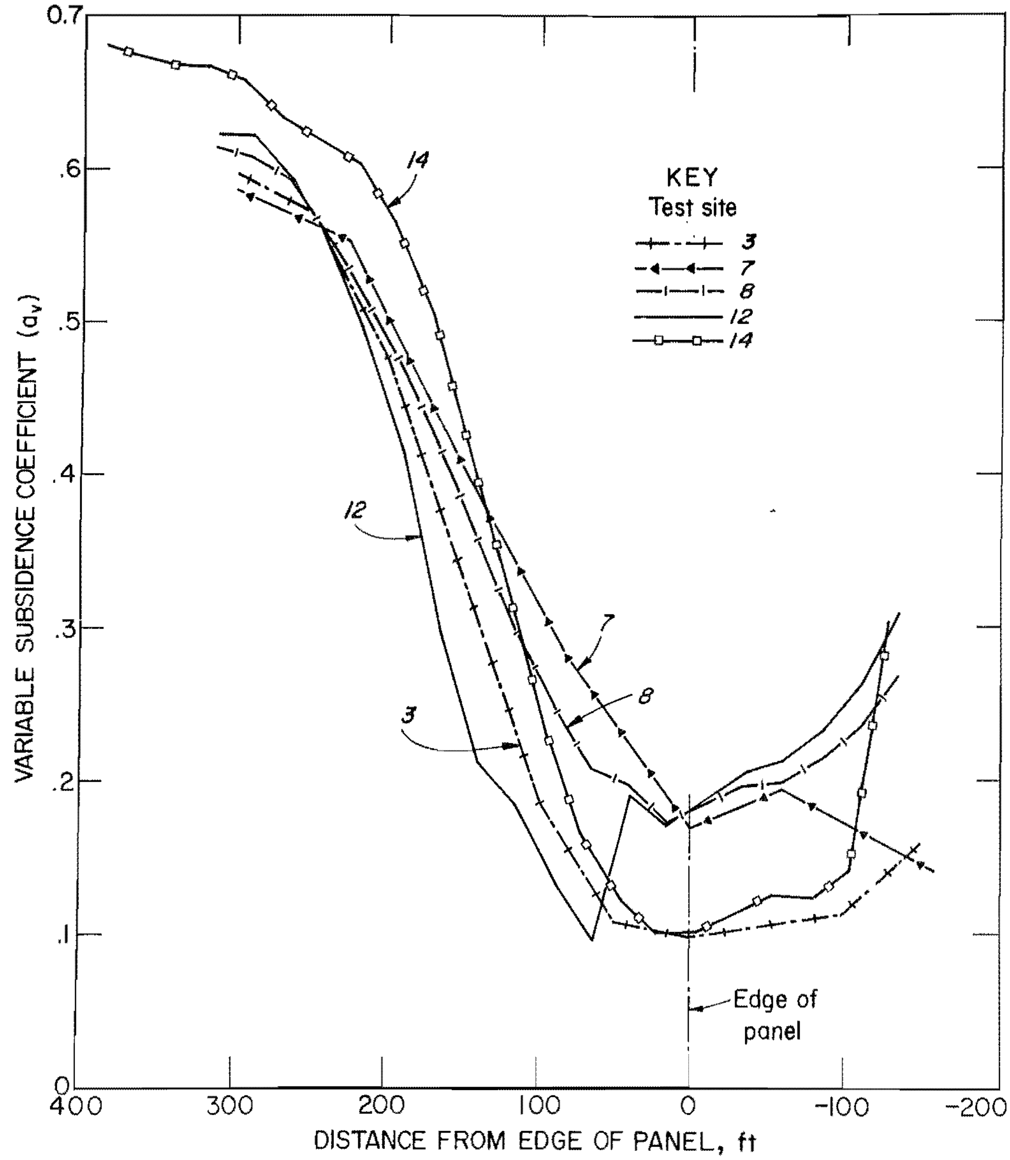

FIGURE 4.—Variable subsidence coefficient for 25° draw angle, left half profiles.

The subsidence of a point results from the cumulative effects of the lithologies present within the area of influence. The lithologic variation can be expressed in terms of a variable subsidence coefficient with acceptable deviations from the mean. This is the basis of the Bureau's predictive model. Where local field data are available and the overburden is demonstrably different from that in the Northern Appalachian Coal Region, the local values of the variable subsidence coefficient may be determined. By regression, a model tailored to the local lithology could be created and used locally.

Equation 3 is a combination of the principles upon which both influence and profile functions are based. The efficiency coefficient represents the principles of influence functions and the variable subsidence coefficient represents the principles of profile functions. Such a combination seems to be justified by at least two reasons:

TABLE 3. - Variable subsidence coefficients along individual profiles for 25° draw angles, with average values ($\bar{a}_v$) and standard deviations ($\pm\sigma_i$)

Test site	Distance inward,[1] ft--						Edge of panel (0 ft)	Distance outward,[1] ft--		
	300	250	200	150	100	50		-50	-100	-150
1........	NAp	NAp	0.480	0.410	0.275	0.182	0.135	0.170	0.210	0.240
2........	0.597	0.590	.515	.370	.235	.207	.068	.053	.055	.075
3........	.597	.571	.475	.335	.186	.106	.098	.105	.110	.150
4........	.662	.655	.565	.435	.308	.205	.175	.295	.230	.230
5........	.645	.627	.565	.440	.318	.200	.135	.120	.112	.124
6........	.587	.530	.445	.335	.230	.155	.100	.105	.112	.115
7........	.586	.564	.502	.405	.315	.235	.167	.190	.170	.150
8........	.600	.530	.425	.335	.270	.234	.245	.265	.295	.320
9........	.610	.571	.487	.380	.267	.200	.180	.196	.225	.225
10.......	.542	.505	.430	.340	.245	.175	.145	.153	.165	.190
11.......	.610	.545	.410	.285	.193	.152	.145	.145	.200	.300
12.......	.622	.571	.445	.250	.154	.150	.180	.210	.248	.248
13.......	.635	.600	.535	.405	.255	.130	.042	.015	NAp	NAp
14.......	.660	.621	.572	.432	.250	.128	.100	.122	.137	.300
15.......	.575	.525	.450	.350	.255	.152	.098	.065	.065	.055
16.......	NAp	.540	.460	.375	.265	.192	.157	.135	.110	.135
$\bar{a}_v$.......	.609	.570	.485	.368	.251	.169	.136	.147	.163	.191
$\pm\sigma_i$......	.033	.043	.053	.054	.045	.041	.050	.074	.070	.083

NAp Not applicable. [1]From edge of panel.

1. Whatever mining and geological conditions are involved, only a certain part of the mined-out area influences the movement of a surface point. The efficiency coefficient provides for that and also for variable mining conditions, namely for width of panel to overburden thickness ratio.

2. Concurrently, geologic conditions vary for different mining areas. The introduction of a variable subsidence coefficient seems to be the proper solution to the problem for mining areas where the effect of lithology on subsidence characteristics is so overwhelming.

The test site data, from which the polynomial equation was derived, show the range of overburden thickness from 400 to 1,000 ft and width of panels from 460- to 940 ft, with the overwhelming majority of panels being 600 ft or more wide. For this reason and to avoid guesswork, the equation was developed for points located within a maximum distance of 300 ft from the edge of the panel up to the centerline. It is obvious that the best results will be obtained for mining conditions similar to those from which the equation was derived.

SENSITIVITY TESTS

Table 3 contains the computed values of the variable subsidence coefficients along each profile with averaged values ($\bar{a}_v$) and standard deviations ($\pm\sigma_i$). For a better understanding of the meaning of the standard deviations, a random case was analyzed, namely the profile at test site 2. The width of the panel was 600 ft and the coalbed was 5.5 ft thick. The standard deviations, expressed in feet, are a function of standard deviation, extracted coal thickness (m), and the efficiency coefficient, which are different for each point along the profile:

$$\pm\sigma_i[ft] = \pm\sigma_i \cdot m \cdot e_i. \qquad (5)$$

Table 4 shows the differences between measured and computed subsidences (Δ_i) in comparison with standard deviations. The

TABLE 4. - Comparison of measured and computed subsidence for 25° angle of draw

	Distance inward,[1] ft--						Edge of panel (0 ft)	Distance outward,[1] ft--		
	300	250	200	150	100	50		-50	-100	-150
$\bar{a}_v$........	0.606	0.567	0.485	0.368	0.251	0.169	0.136	0.146	0.163	0.190
$\pm\sigma_i$.......	0.032	0.042	0.053	0.054	0.045	0.041	0.055	0.074	0.070	0.083
e_i........	0.990	0.971	0.933	0.878	0.802	0.692	0.500	0.309	0.198	0.121
$\sigma_i e_i$......	0.032	0.041	0.049	0.047	0.036	0.028	0.027	0.022	0.014	0.010
$\pm\sigma_i$...ft..	0.180	0.220	0.270	0.260	0.200	0.160	0.150	0.130	0.080	0.060
sF....ft..	3.250	3.170	2.650	1.800	1.040	0.410	0.190	0.090	0.060	0.050
sP....ft..	3.300	3.040	2.470	1.770	1.120	0.640	0.370	0.230	0.150	0.090
$\pm\Delta_i$...ft..	0.050	-0.130	-0.180	-0.030	0.080	0.230	0.180	0.140	0.090	0.040

$\bar{a}_v$ Average variable subsidence coefficient.
e_i Efficiency coefficient.
sF Measured subsidence.
sP Computed subsidence.
Δ_i Differences between measured and computed subsidences.
σ_i Standard deviation of average value of subsidence coefficient for individual conceptions.
σ_i(ft) $m e_i \sigma_i$, where m = extracted thickness.
[1]From edge of panel.

differences are far below standard deviations within the area of the panel and are about the same outside the panel.

Altogether, 189 surface points from 11 study sites were used in the regression analysis. Figure 5 shows the distribution of deviations between computed and measured subsidences with respect to distance from the edge of the panel. As indicated in table 5, 89 pct of the points show differences smaller than 0.3 ft and 74 pct less than 0.2 ft.

Such results must be considered satisfactory, especially if the possible sources of these deviations are considered:

1. Different lithology at individual test sites as shown by the dispersion of the individual curves in figures 3 and 4.

2. If the estimate of the extracted coalbed thickness is inaccurate, the error affects the precalculation.

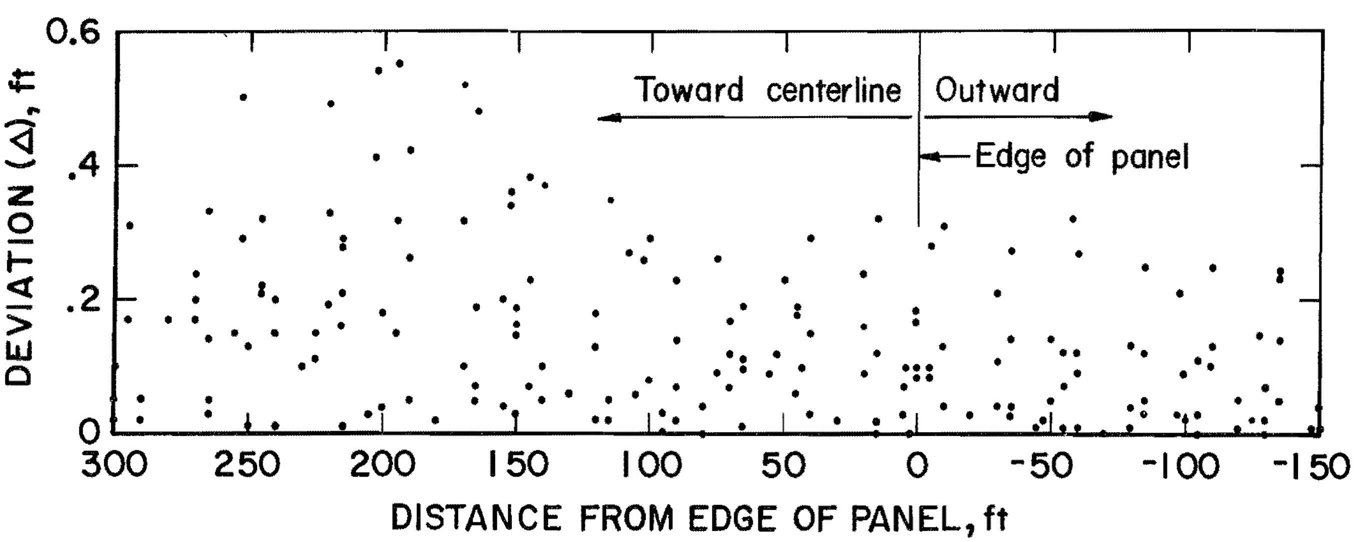

FIGURE 5.—Distribution of deviations between computed and measured subsidences.

TABLE 5. - Summary of deviation[1] distribution

Deviation, ft	Number of points	Pct of total	Deviation, ft	Number of points	Pct of total
0.00 to 0.10..........	81	43	0.40 to 0.50..........	4	2
0.10 to 0.20..........	57	31	0.50 to 0.60..........	4	2
0.20 to 0.30..........	29	15	Total............	189	100
0.30 to 0.40..........	14	7			

[1]Differences between computed and measured subsidences.

INCLINATION AND CURVATURE

For some existing predictive methods, it is possible to compute inclinations and curvatures as derivatives of the subsidence equation. In equation 3, both e and a_v are functions of the distance from the edge of the panel. Because the evaluation of the efficiency coefficient also requires the inclusion of the overburden thickness, the equation is not easily amenable to differentiation.

Inclination and curvature are functions of vertical displacements and can be expressed as

$$\text{inclination (I)} = \frac{s_1 - s_2}{X_1 - X_2}, \quad (6)$$

assigned to point $X_1 + \frac{X_1 - X_2}{2}$,

where s = vertical displacement

X = distance from edge of panel;

and curvature

$$(K) = \frac{s_1 - 2s_2 + s_3}{(1/2[(X_1 - X_2) + (X_2 - X_3)])^2}, \quad (7)$$

and the value is assigned to point X_2.

HORIZONTAL STRAINS

Strains are determined by the change in length of an element along a chosen direction. Their values are defined at a point but in order to obtain them by direct measurement, a measurement base of certain length is needed.

The results of the strain measurement depend not only on the direction but also on the length of the measurement base, the deformation gradient, and the heterogeneity of the overburden. The strain measurement, along a measurement base, yields average values instead of values at each individual point.

Different types of heterogeneous overburden subjected to the same conditions may show the same mean values of strain but with different strain fluctuations from point to point. This would imply that the magnitude of fluctuations are characteristic for different types of overburden.

The ideal length of a measurement base would be one that eliminated the influence of strain fluctuations and therefore the measured values of strain would approximate the mean values. At the same time, it seems necessary to know the magnitude of strain fluctuations to estimate the value of strains in excess of some a priori predicted strain values.

It is generally acknowledged that in most cases, the results of direct field strain measurements are erratic. Especially in hilly terrain, a "sliding effect" influences the magnitude and direction of horizontal movements. This condition results in extreme variation of measured horizontal strains. Under such conditions, it is practically impossible to define mean values and the statistical distribution of strains for the mining area.

Because horizontal strains (E) are proportional to curvatures

$$E = C \cdot K, \quad (8)$$

it appears that prediction of horizontal strains from curvature using an empirically defined coefficient (C) suitable to local conditions, gives the best results.

After analysis of the field data from the Northern Appalachian Coalfield, the value of the coefficient was found to be between 12 and 15 for strain, expressed in terms of millimeters per meter, and the curvature value as the inverse value of the radius of curvature, in kilometers.

Horizontal displacements can be computed from horizontal strains using the formula:

$$v_n = v_{n-1} + 1/2\ (E_n + E_{n-1})\ l, \qquad (9)$$

where l = length of measurement base.

COMPARISON OF MEASURED AND COMPUTED DEFORMATIONS

Figures 6 through 15 show the comparison of measured and predicted surface deformations from three test sites. The coefficient value of 14 was used for computation of horizontal strains. In all three cases, good agreement was found as to the vertical displacements, inclinations, and curvatures. In general, the values of maximum compression were at least twice as great as those of maximum tension. This was especially true for the narrower panels. At test sites 1 and 3 (figures 8 and 14), with relatively flat topography, the predicetd values of horizontal strains agreed closely with those computed on a 50-ft measurement base. The strains determined using a 25-ft base, at the same place, showed rather significant fluctuations. At test site 2, with hilly terrain, the sliding effect on horizontal displacements was evident from the difference between measured and computed horizontal movements (fig. 12). As expected, this resulted in a higher intensity of tension and smaller intensity of compression (fig. 11).

CONCLUSIONS

1. The validity of the prediction model has been proven not only by sensitivity tests but also by comparison of predicted values with field data gathered at test sites not included in the regression analysis.

2. The prediction of horizontal strains from the curvature gives the best results. Coefficients were empirically defined for local conditions. The predicted results approximate the mean values for measured ground strains. In some cases, the magnitude of strain fluctuations may reach more than double the values of predicted strains.

3. The developed methodology is relatively simple and fast. It eliminates the use of inaccurately estimated functional parameters, which are necessary for existing predictive methods.

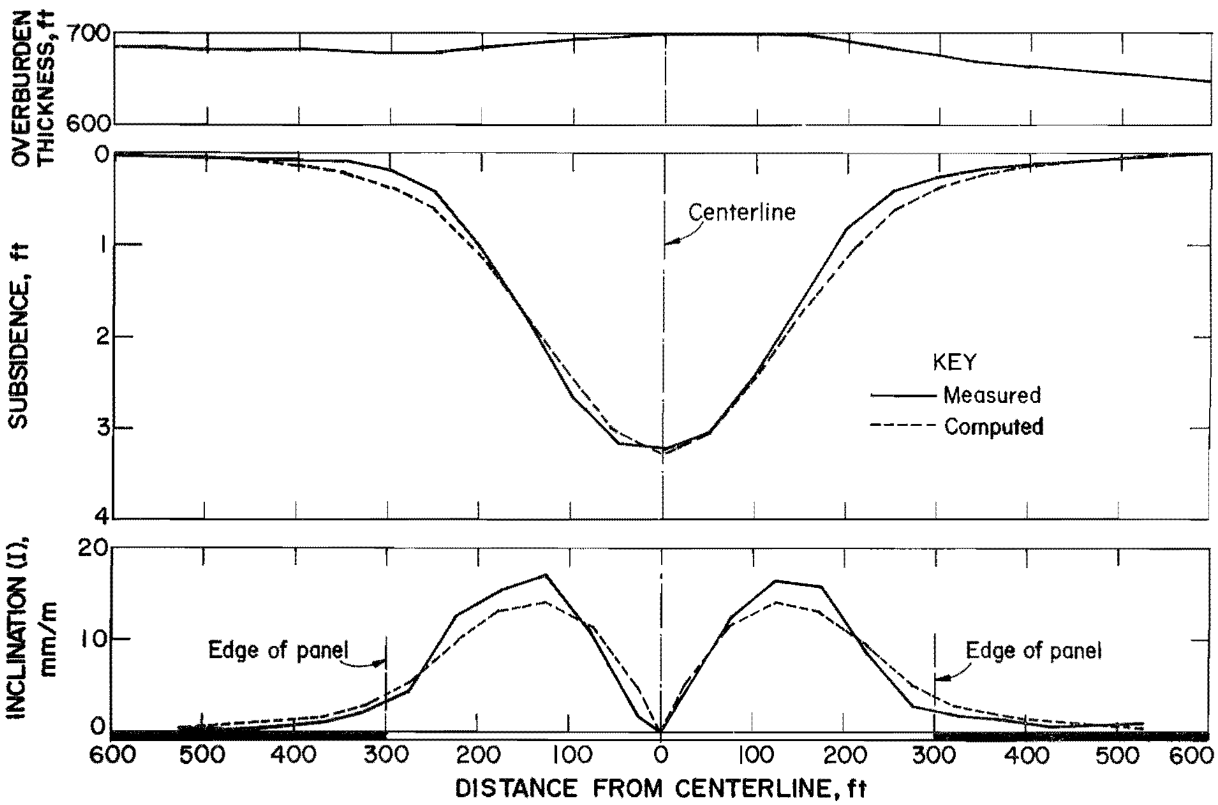

FIGURE 6.—Measured and computed subsidences and inclinations at mine 1.

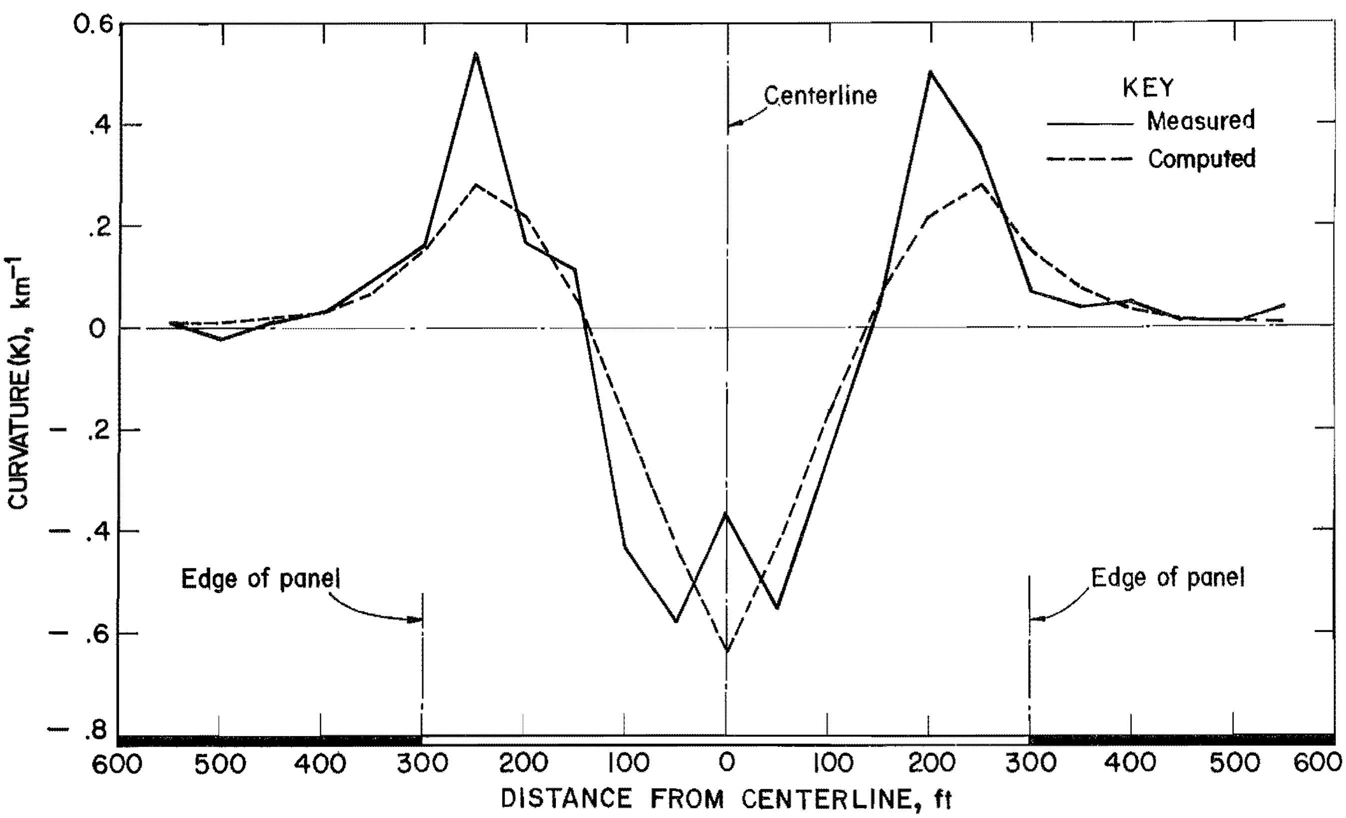

FIGURE 7.—Measured and computed curvatures at mine 1.

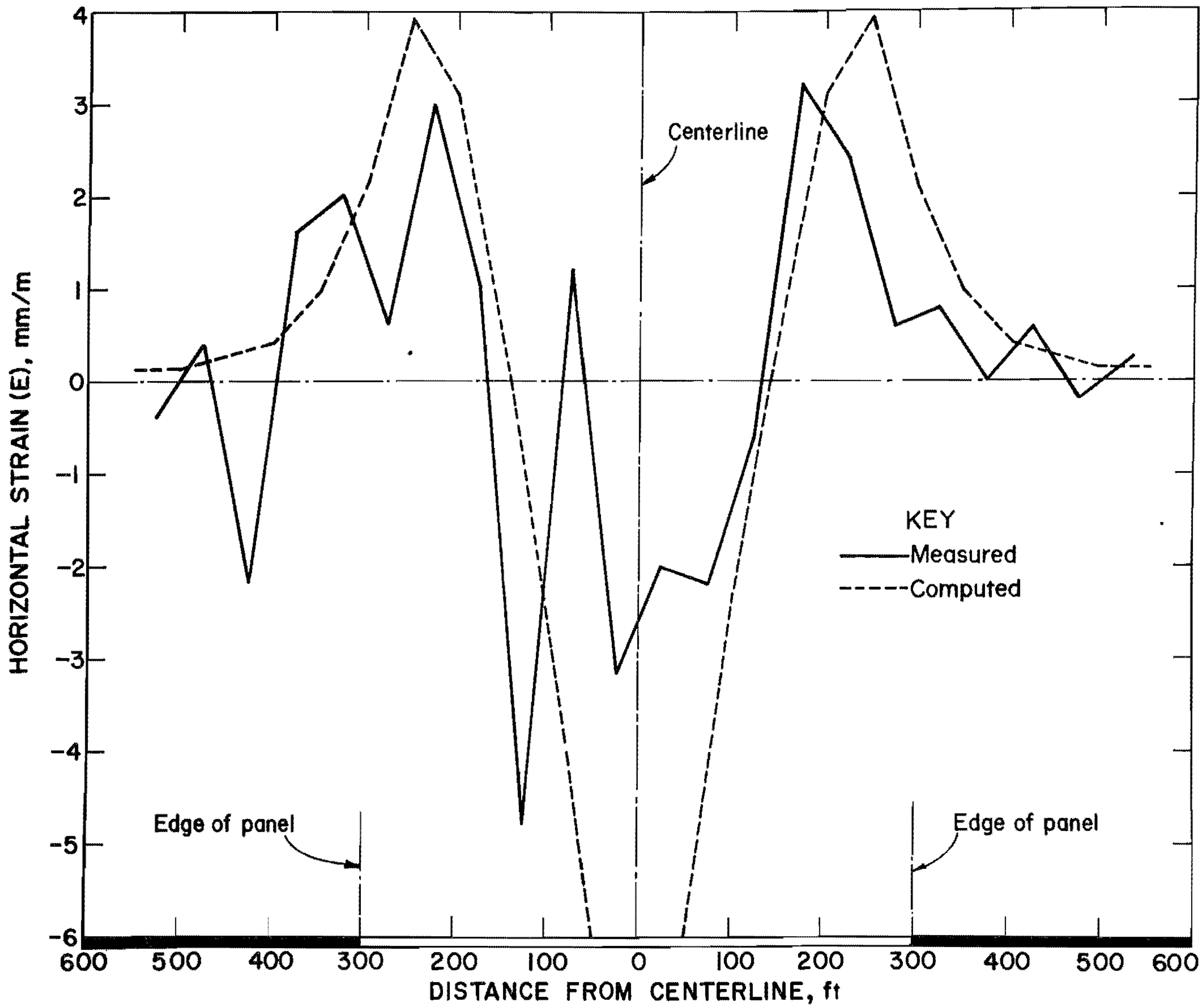

FIGURE 8.—Measured and computed horizontal strains at mine 1.

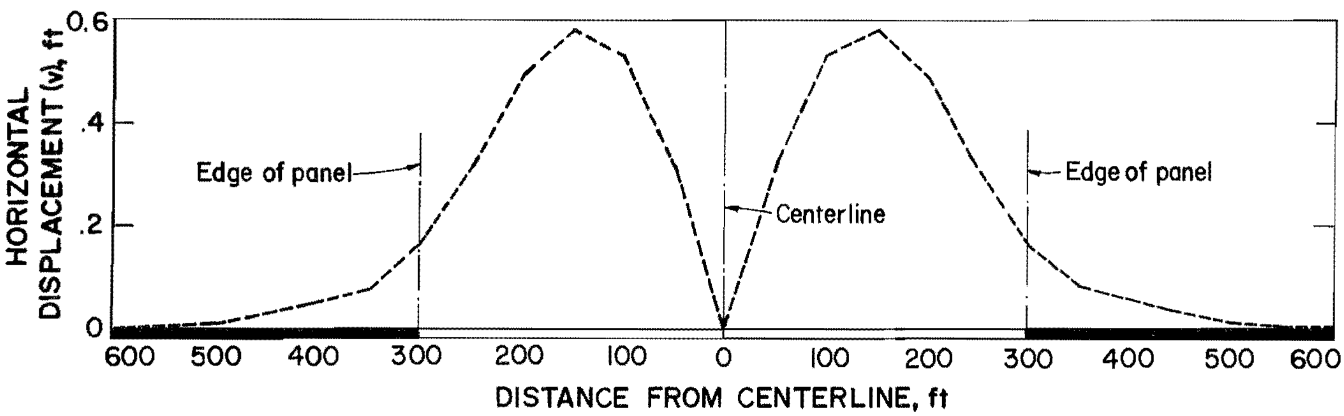

FIGURE 9.—Computed horizontal displacements at mine 1.

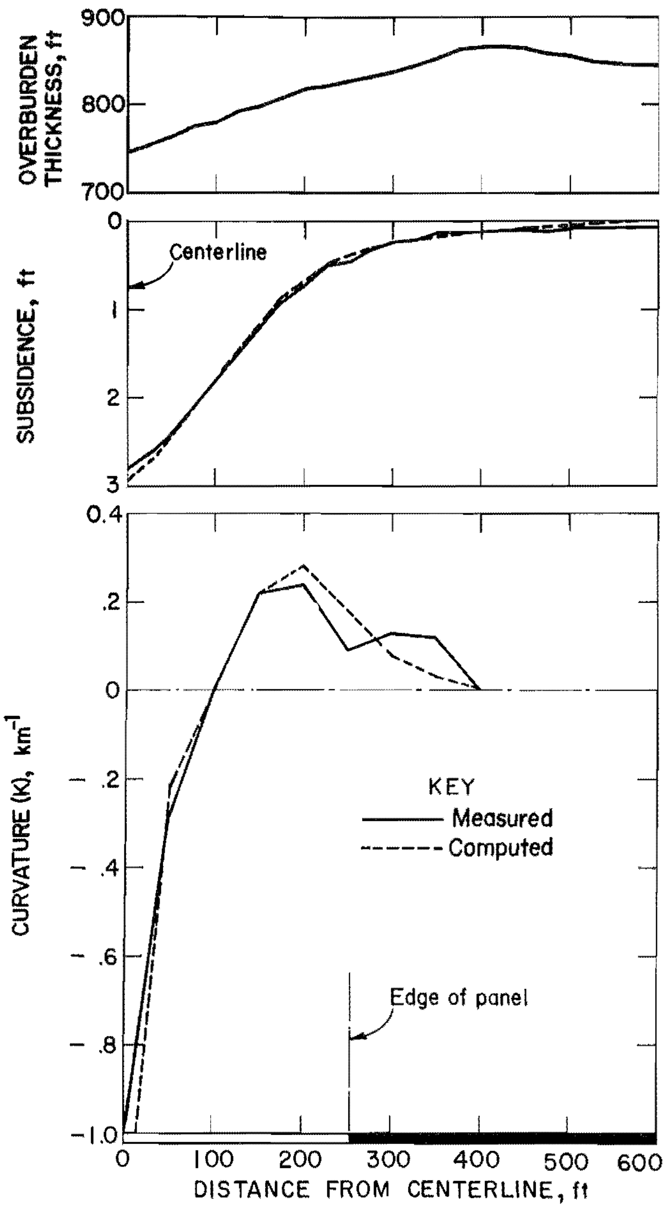

FIGURE 10.—Measured and computed subsidences and curvatures at mine 2.

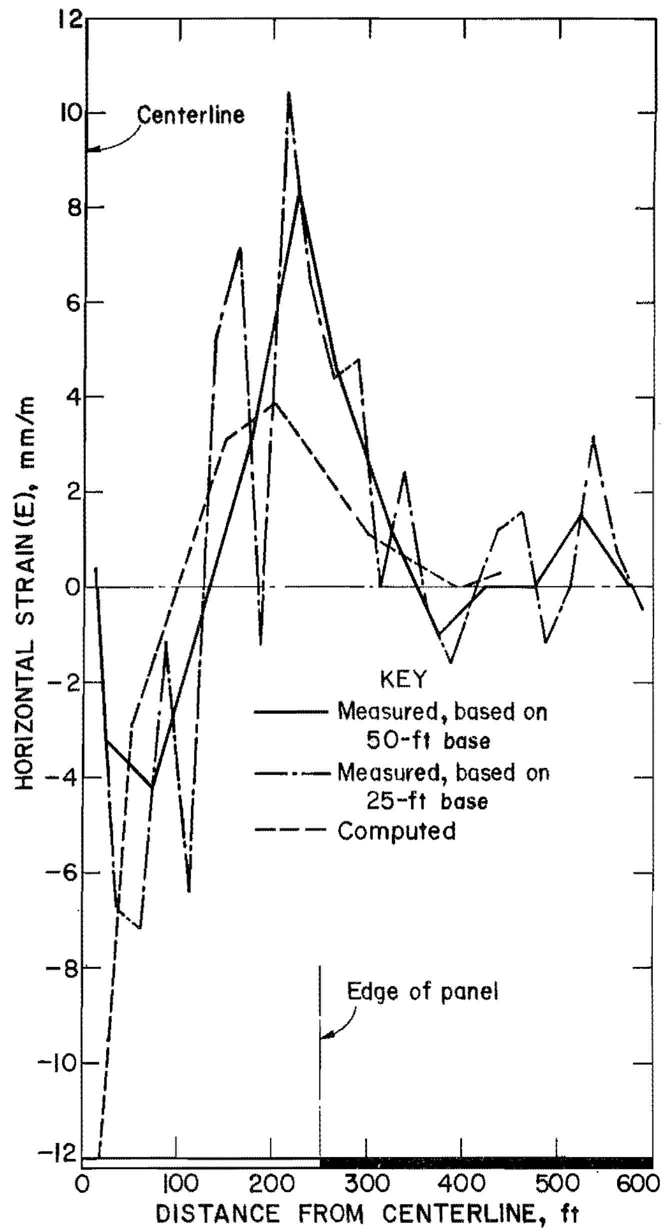

FIGURE 11.—Measured and computed horizontal strains at mine 2.

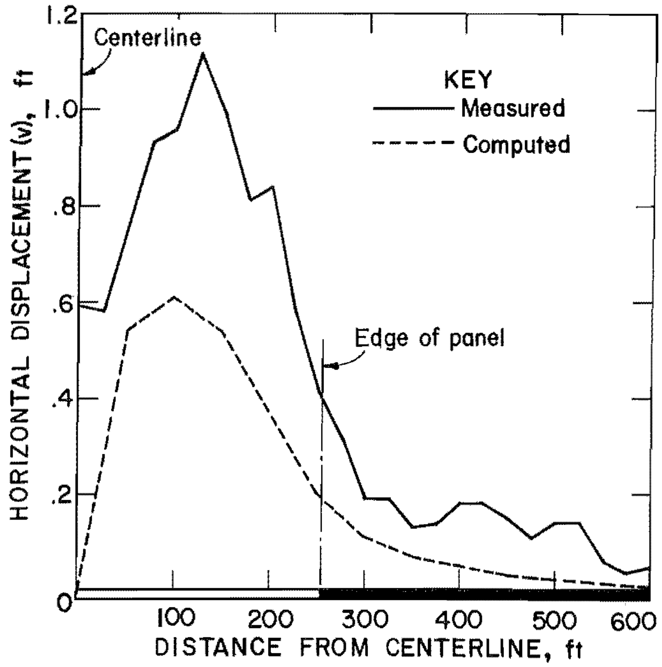

FIGURE 12.—Measured and computed horizontal displacements at mine 2.

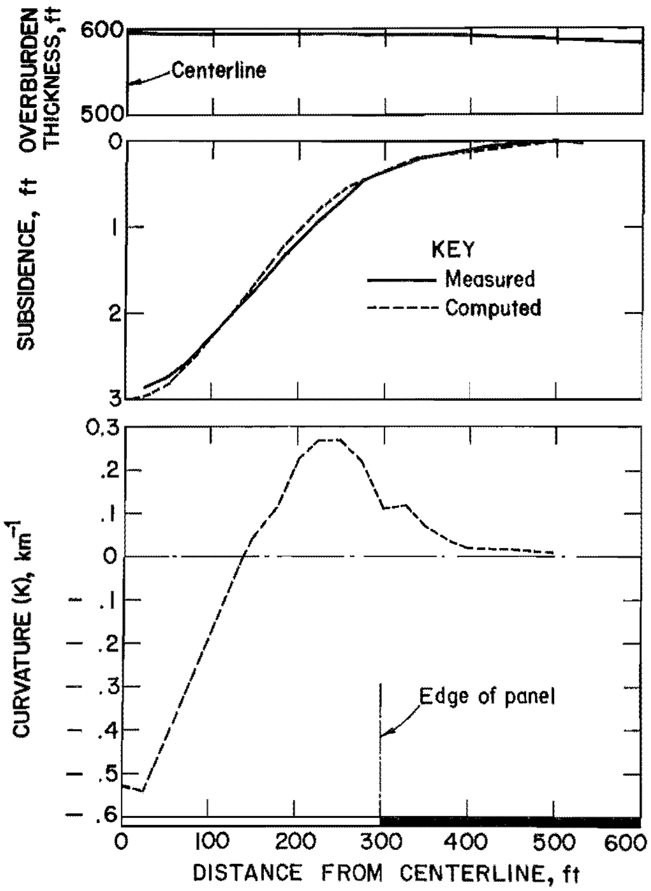

FIGURE 13.—Measured and computed subsidences and curvatures at mine 3.

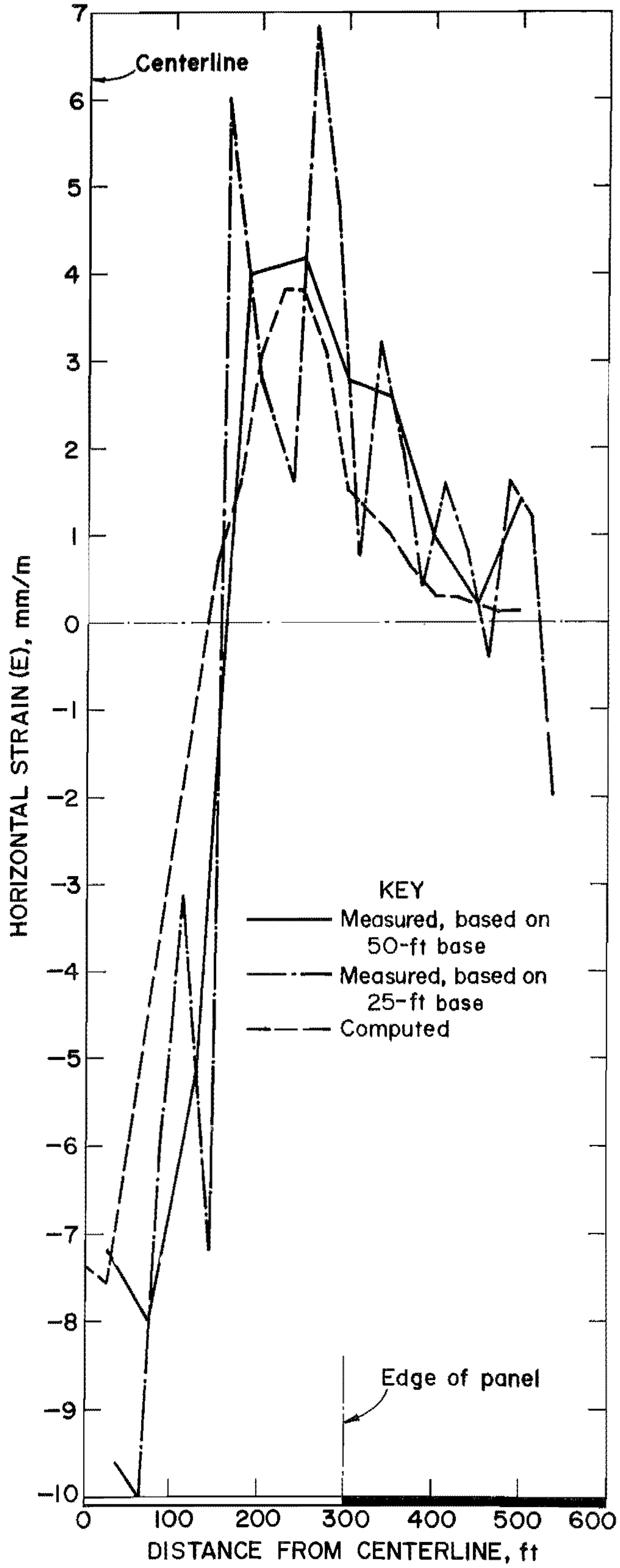

FIGURE 14.—Measured and computed horizontal strains at mine 3.

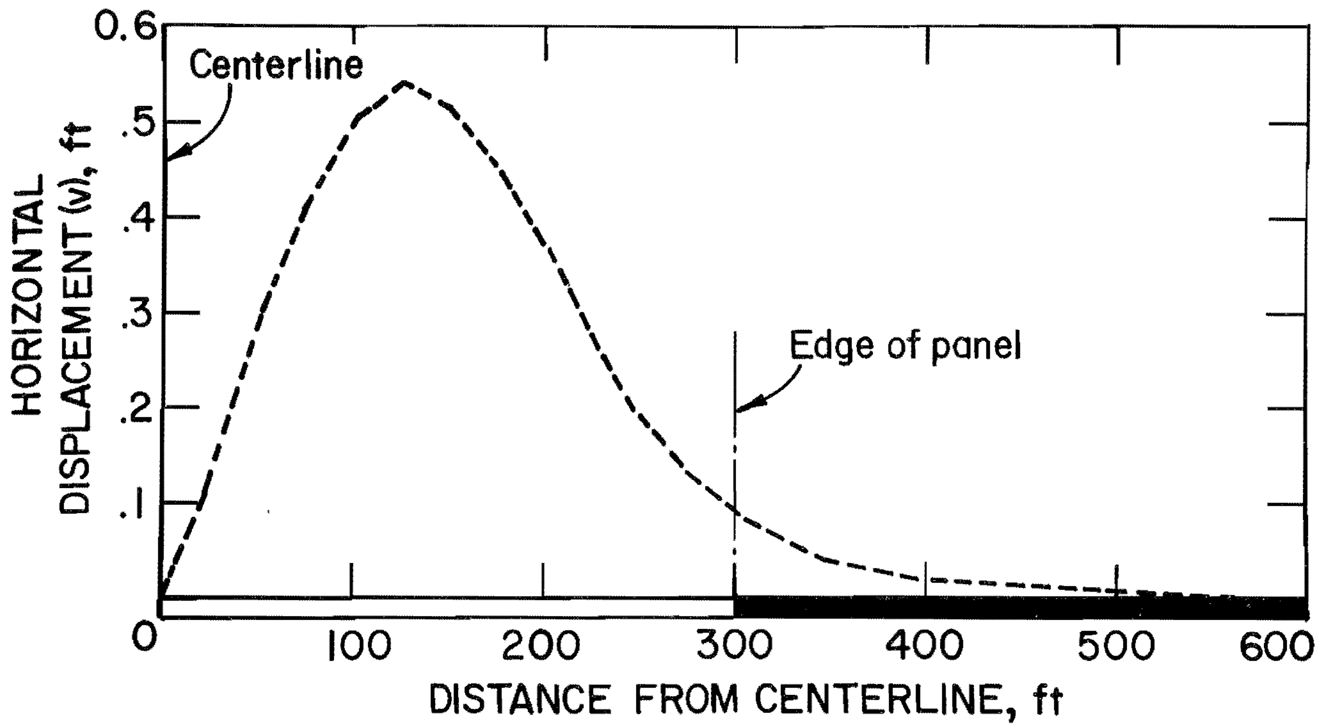

FIGURE 15.—Computed horizontal displacements at mine 3.

BIBLIOGRAPHY

Adamek, V., and P. W. Jeran. Evaluation of Existing Predictive Methods for Mine Subsidence in the U.S. Paper in Proceedings, First Conference on Ground Control in Mining, ed. by S. S. Peng. West Virginia University, July 1981, pp. 209-219.

_____. Evaluation of Surface Deformation Characteristics Over Longwall Panels in the Northern Appalachian Coal Field. Paper in Proceedings, International Symposium on Ground Control in Longwall Mining and Mining Subsidence--State of the Art (Honolulu, Hawaii, 1982). AIME, 1982, pp. 183-197.

_____. Precalculation of Subsidence Over Longwall Panels in the Northern Appalachian Coal Region. Paper in Mine Subsidence Control. Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, PA, September 19, 1985 (comp. by Staff, Bureau of Mines). BuMines IC 9042, 1985, pp. 34-56.

Bals, R. Beitrag zur Frage der Vorausberechnung Bergbaulicher Senkungen (A Contribution to the Problem of Precalculating Mining Subsidence). Mitt. aus dem Markscheidewesen, v. 42/43, 1931/1932, pp. 98-111 (in German).

Jeran, P. W., V. Adamek, and M. A. Trevits. A Subsidence Prediction Model for Longwall Mine Design. Paper in Proceedings of Longwall USA Conference (Pittsburgh, PA, June 17-19, 1986). Industrial Presentations West, Inc., 1986, pp. 101-112.

Niemczyk, O. Bergschadenkunde (Study of Mine Damages). Verlag Gluckauf, G.m.b.H., 1949, p. 107 (in German).

APPENDIX

The computer program, written to facilitate the use of the Bureau developed subsidence prediction model by industry, has been expanded to include the prediction of horizontal strains. The modification, based upon the results of the research presented in this report calculates the horizontal strains from the values of curvature derived from the predicted subsidence.

The program, written in BASIC for use on IBM-PC compatible personal computer, is user friendly and requires no knowledge of subsidence theory. Figure A-1 is a flow chart of the program.

The input data, for which the user is prompted, are the name of the mine, the extracted thickness, and the width of the panel. The user is then given the option of obtaining a prediction using an

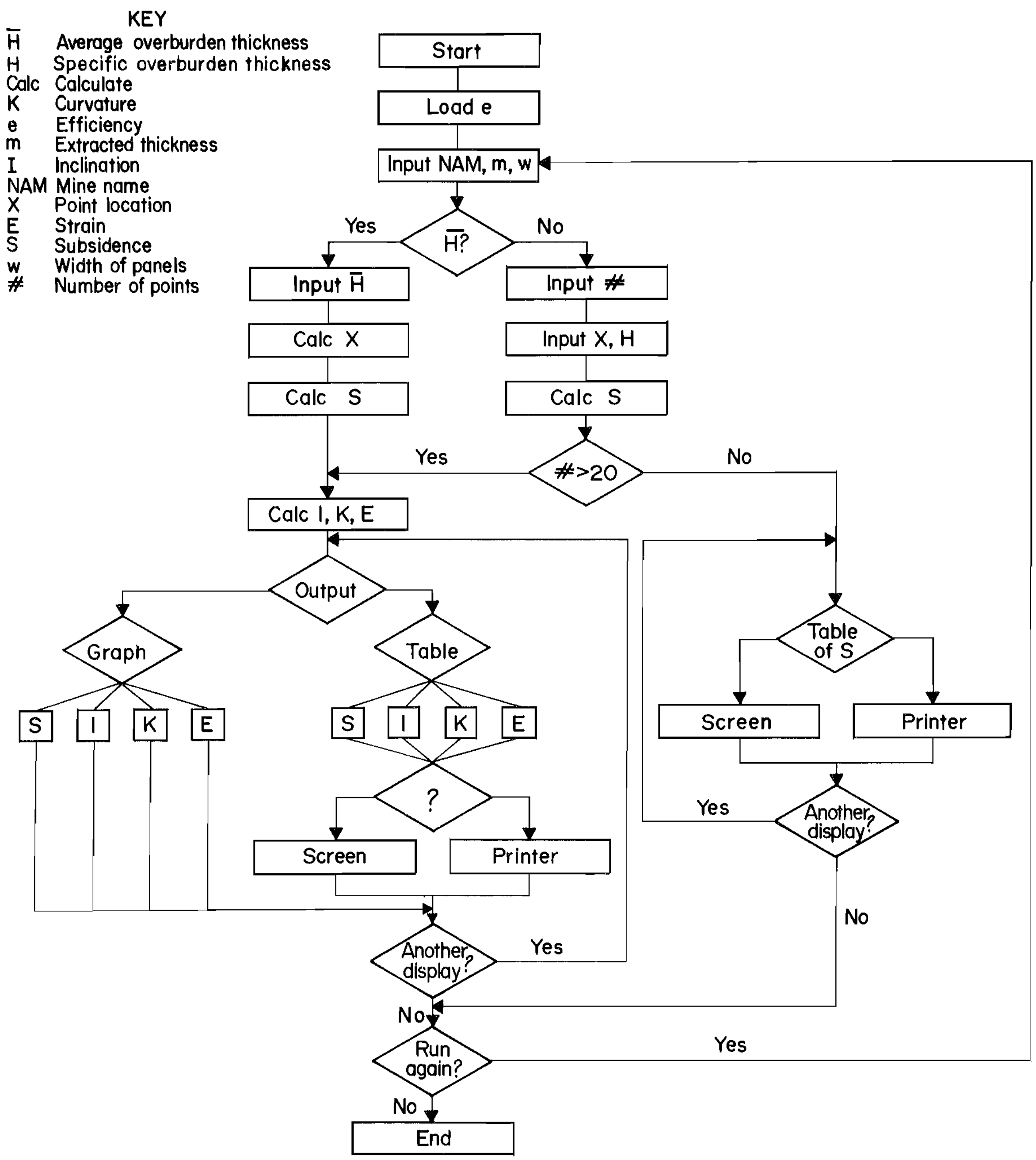

FIGURE A-1.—Computer program flow chart.

average overburden thickness or inputting specific points, by location, relative to the edge of the panel and their associated overburden thicknesses. If the user chooses the average overburden option or inputs more than 20 points, the program will predict the subsidence and compute the values of inclination, curvature, and horizontal strains.

Separate displays can be selected from menus for subsidence, inclination, curvature, and horizontal strain; graphic displays on the screen or tabular displays on the screen or printer.

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