

LONG TERM SUBSIDENCE MOVEMENTS AND BEHAVIOR OF
SUBSIDENCE-DAMAGED STRUCTURES¹

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Abstract. Surface ground movement related to sag mine subsidence has been monitored above Illinois abandoned room and pillar coal workings for periods of more than 15 years. The long term movement related to a specific mine subsidence is typically small relative to the initial displacements but have caused crack and tilt damage in both repaired and unrepaired structures. Seasonal variations in ground surface elevations are superimposed on the downward movement related to mine subsidence. Thus it is necessary to measure long term subsidence movement at about the same time each year in order to minimize environmental factors.

This paper presents long term monitoring data from five subsidence sags in central and southern Illinois. The abandoned coal mine workings are located at depths of 160 to 460 ft below the ground surface. Measured residual mine subsidence ranges between 1.4 and 3.6 in. 4.4 to 15 years after mine failure. The magnitude of downward displacement is greater than settlement design values (1 in.) and are at rates (0.0004 to 0.0056 ft/month) that cause damage to structures. Most of the damage in unrepaired structures occurs along existing cracks and separations. In all five cases, the ground movements are continuing at residual rates. Sag subsidence movement in Illinois takes place for a minimum of five years after the damage is manifested at the ground surface. A classification of sag development is provided based on the displacement-time data.

Additional Key Words: mine subsidence monitoring, long term mine subsidence displacement, subsidence damage, classification of mine subsidence movement.

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Introduction

In general, the magnitude of ground displacement caused by sag subsidence associated with failure of an individual section of a mine decreases with increasing time. A classic displacement-time curve is given in Fig. 1 of this paper. The relationship has the same general appearance as a settlement curve produced by consolidation of a normally loaded clay. In Illinois mine subsidence, the duration of downward movement above abandoned room and pillar coal workings is at least 5 years. The length of time of long term (residual) subsidence which is required to reach equilibrium at mine level and in the overburden above the mine depends on

- nature of mine failure
- depth and geometry of abandoned mine workings and
- properties of the soil and rock extending to depths below the mine floor.

Two types of mine subsidence have been identified based on the magnitude and rate of movement observed at the ground surface:

- catastrophic and
- gradual.

In catastrophic mine subsidence, the greatest damage

occurs during the period of initial movement (1 to 15 months) when the ground displacements are largest. Residual mine subsidence in both catastrophic and gradual cases causes noticeable and significant damage to structures years after initiation of the mine failure.

This paper presents initial, intermediate and long term displacement and damage data of 5 individual mine subsidence sags in central and southern Illinois. The sags developed over abandoned room and pillar mines located at depths of 160 to 460 ft below the ground surface. Because of the relatively small incremental displacement in the residual phase, measurement of monitoring point elevations should be made at about the same time each year. Use of this procedure provides a baseline for assessing displacements and minimizes some of the environmental effects such as changes in ground water level and soil moisture content. In the residual mine subsidence phase, the downward movements are superimposed on the seasonal displacements which can be identified by surveying benchmarks outside the subsidence area.

The level line surveys were carried out using a Zeiss NI 22 level equipped with a micrometer that can be read to the nearest 0.1 mm. Closure of all surveys is within 1.5 mm.

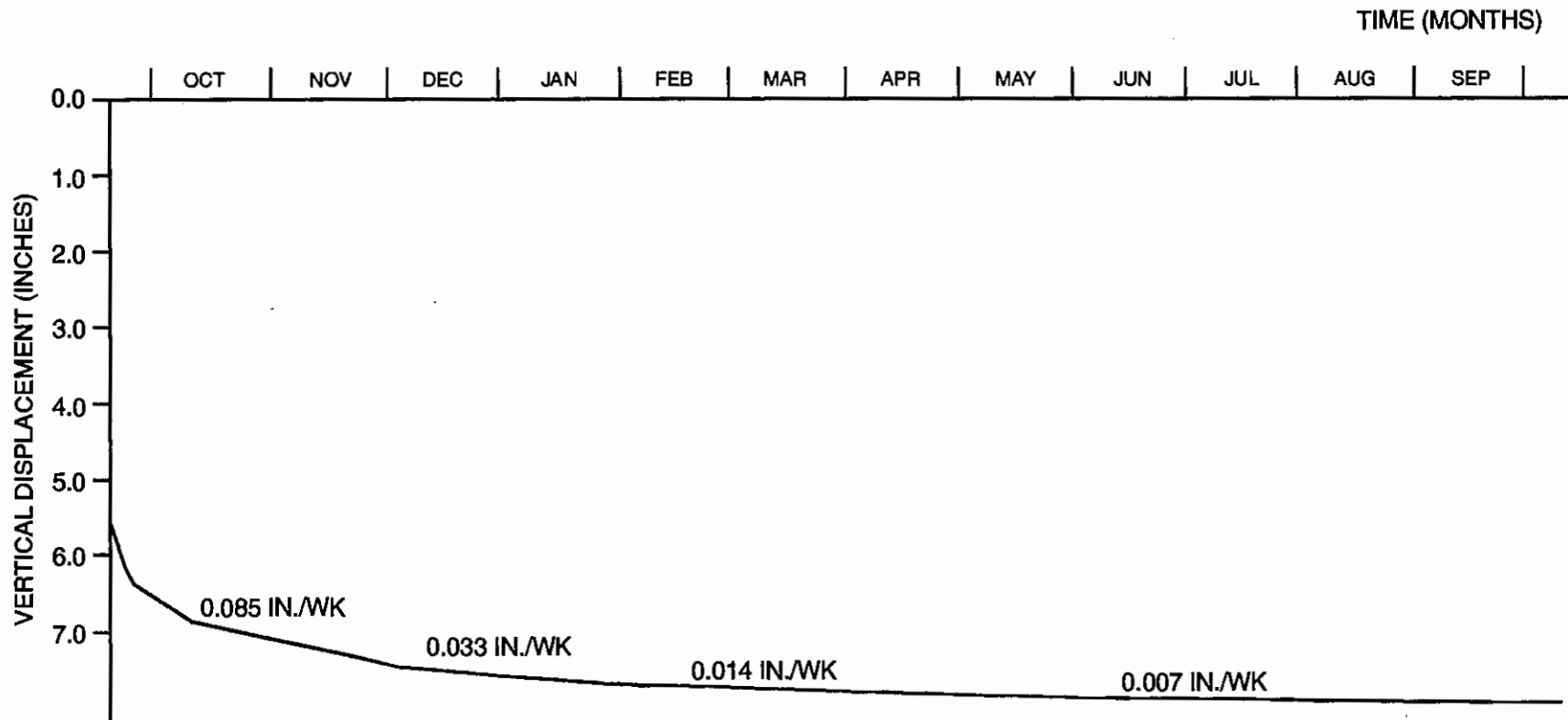


FIG. 1 TYPICAL GROUND DISPLACEMENT-TIME PLOT CAUSED BY COAL MINE SUBSIDENCE

Displacement and Damage - Illinois Sag Subsidence

Sag mine subsidence in Illinois takes two basic forms: catastrophic and gradual. In catastrophic mine subsidence the measured downward movement near the center of the sag is at least 0.5 ft with 50 to 80% of the total displacement taking place in the first year. Based on subsurface investigations sag subsidence involves either pillar crushing and/or floor punching. Small sags with some characteristics of pit subsidence can also develop as a result of roof failure in rooms. The settlement-time plot given in Fig. 1 is one such case. In catastrophic subsidence, the ground movements progress through three phases

- initial
- intermediate and
- residual.

The time required to reach residual subsidence ranges between 2 and 5.5 years. Mine subsidence involving gradual sag development occurs at residual rates and in the two cases described in this paper has been ongoing for 9 to 15 years.

Damage levels tend to be severe when mine subsidence is catastrophic depending on the location of the structure in the sag. Overall structural tilt typically ranges between 5 and 20 in. for buildings located near the maximum slope of the sag. Angular distortion of structures with masonry foundations are generally greater than 1/100 and some

crack widths typically exceed 1/4 in.

Damage levels are generally less severe in gradual subsidence but deformation occurs over a much longer period of time. Moreover the surface expression of a gradual sag subsidence is not visible or is poorly developed. The amount of damage experienced by structures as a result of residual mine subsidence depends on the type of construction, previous damage levels and soil shrink-swell properties.

Long Term Displacements Above Illinois Room and Pillar Mines

CATASTROPHIC MINE SUBSIDENCE

WEST SPRINGFIELD

Mine subsidence has occurred in one area of west Springfield, Illinois starting in the fall of 1989. At least 15 individual and overlapping sags have developed in the area during the last 10 years. This area is above an abandoned room and pillar mine which was developed in a 4-ft thick layer of Springfield No 5 coal at a depth of approximately 188 ft below the ground surface.

Settlement data of monitoring point P-20 located near the center of one individual sag is plotted in Fig. 2. The elevation of the point was monitored starting in October 1989 some 4 years prior to initiation of mine subsidence. During the period 1989 to 1994, seasonal variations in ground surface elevations ranged between +0.15 and -0.2 in. for measurements

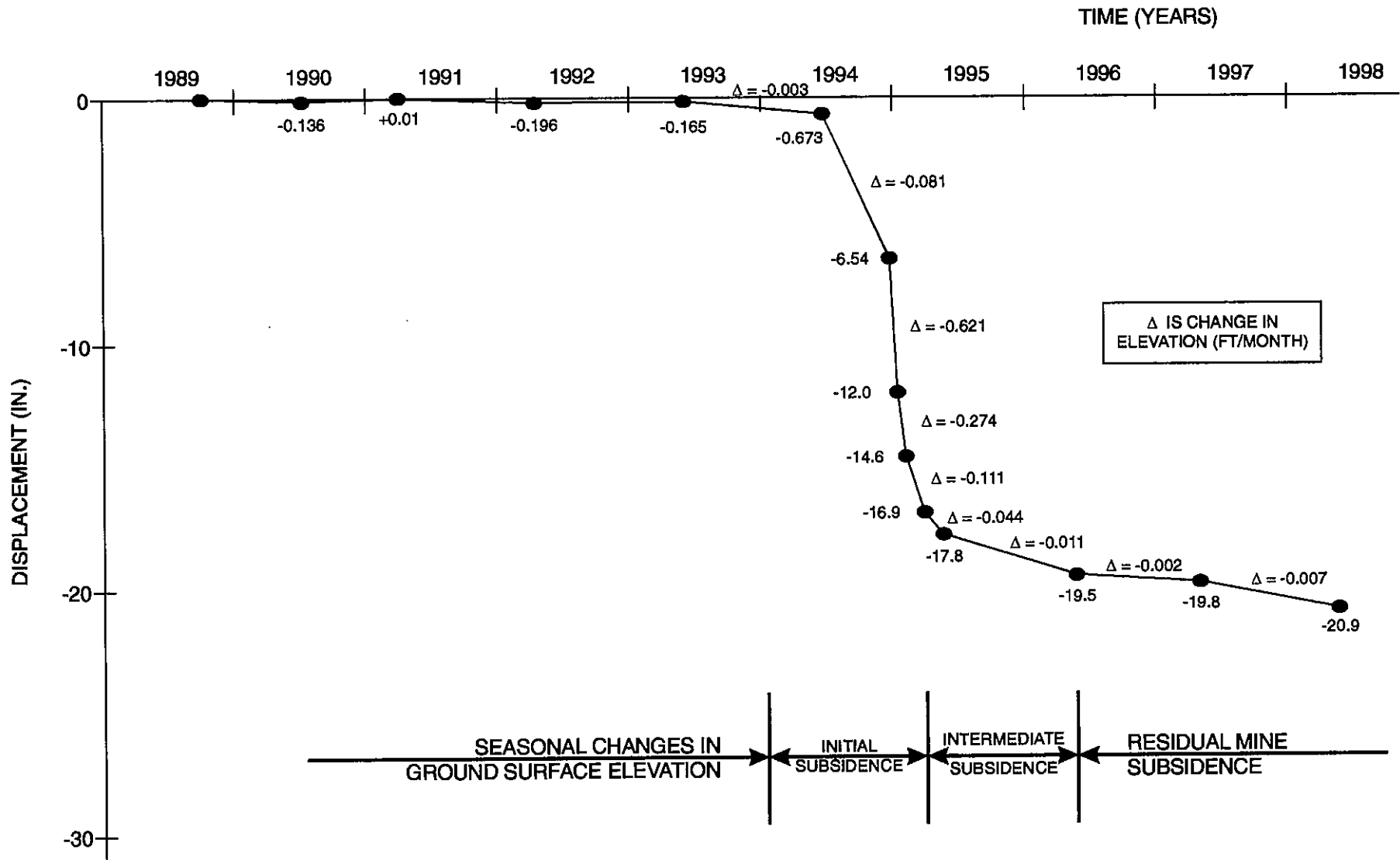


FIG. 2 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF MINE SUBSIDENCE SAG IN WEST SPRINGFIELD, ILLINOIS

taken in the April to June time period.

The level line survey data show that catastrophic mine subsidence in the sag was initiated sometime between June 1993 and June 1994. In 1994 the total downward movement of the monitoring point exceeded 0.5 in. (0.673 in.). Moreover the movement is at least three times greater than the previous 4-year seasonal variation in ground surface elevation. Clearly mine subsidence was active in December 1994 when the downward displacement reached 6.5 in.

The intermediate phase of mine subsidence took place between March 1995 and May 1996. The total downward movement during this period was 2.6 in. and occurred at rates of 0.011 to 0.044 ft/month (greater than 1.58 in./year).

Residual mine subsidence in the sag has taken place for at least 3 years and is continuing at the present time. The residual movement between 1996 and 1998 near the center of the sag is 1.4 of the total 20.9 in. The displacement between 1997 and 1998 is more than 1 in. which caused additional damage to unrepaired structures in the sag. New cracks developed and existing cracks opened in basement and superstructure elements. The rate of residual mine subsidence movement ranged between 0.002 and 0.007 ft/month (0.29 and 1 in./year).

SOUTHWEST TAYLORVILLE

Southwest Taylorville has the dubious distinction of

housing the largest number of damaged structures in a single mine subsidence. Based on reported home and utility damage, the subsidence began in mid-March 1991. The individual sag ultimately affected at least 64 homes in an approximate 18-block area. The abandoned room and pillar workings are in the Herrin No 6 coal at a depth of approximately 460 ft. The seam height measured in boreholes drilled in adjacent sections ranges from 5 to 8 ft.

The displacement-time data for P-31 located near the center of the sag is plotted in Fig. 3. Monitoring was started approximately 5 weeks after the initiation of movement. The pre-subsidence contours and recent ground surface profile across the sag were used to estimate the total downward movement (approximately 42 in. at P-31). Based on the displacement-time and subsidence profile plots, the initial subsidence period occurred during the first month with a downward movement of approximately 27 in.

The plot shows continuous downward movement at decreasing rates during the intermediate and residual periods. The intermediate phase of mine subsidence occurred over a long period (4.7 years) at rates ranging 0.01 to 0.06 ft/month (greater than 1.4 in./year). The total intermediate movement exceeded 13 in.

Residual mine subsidence started in December 1995 and has continued for at least 3 years. The total residual movement thru December 1998 is 1.6 in. at rates of 0.003 to

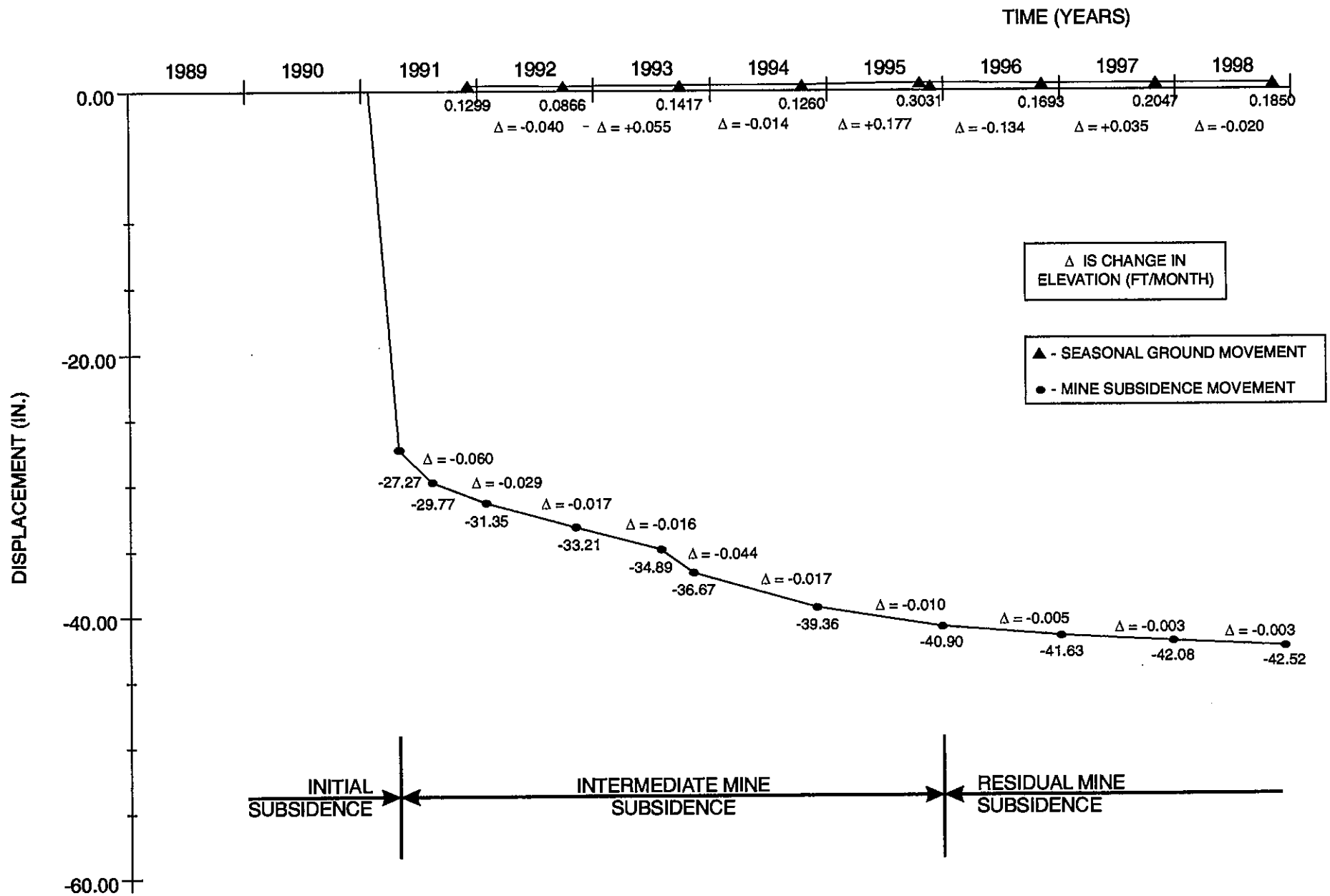


FIG. 3 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF SAG SUBSIDENCE IN SOUTHWEST TAYLORVILLE, ILLINOIS

0.005 ft/ month (0.43 to 0.72 in./ year). The residual downward movement was sufficient to cause further crack damage to both repaired and unrepaired structures in the sag limits.

Seasonal variations in ground surface elevations at the site were measured using monitoring points well outside the area of movement. A plot of typical values is included in Fig. 3. The overall displacement of the ground surface between 1991 and 1998 was upward but the difference in elevation at the times of the survey varied between +0.177 and -0.134 in.

DIVERNON

Mine subsidence has damaged 12 homes in Divernon, Illinois which is located in the west central portion of the state. The mine was developed at a depth of approximately 300 ft in the Herrin No 6 coal and the seam height is 7 ft.

Settlement Point SP-8 is located in the compression zone near the center of the sag. Based on homeowner interviews damage was first noticed in August 1992. The level line survey was established in January 1993. The initial mine subsidence extended over a period of roughly 1 year with a total measured downward displacement of 1.85 in. (Fig. 4). Initial measured rates of movement ranged between 0.166 and 0.173 ft/month.

The initial 5-month portion of the mine subsidence movement was not measured because of homeowner delay in

reporting the damage and the subsequent time gap in establishing level line survey control. However comparison of the total measured ground movement (6.45 in.) with the overall tilt of the structures in the mine subsidence sag (0.8 to 8.3 in.) indicates that the subsidence between August 1992 and January 1993 was not more than 2 in.

Residual mine subsidence has occurred for a period of 4 years and was continuing at the time of the last survey (November 1998). The total residual mine subsidence movement to date has been 1.72 in. at rates of 0.0011 to 0.0056 ft/month (0.16 to 0.81 in./ year). In general, the rate and magnitude of downward movement are decreasing but the most recent rate (0.24 in./year) has been more than sufficient to cause additional damage to structures.

By contrast the seasonal ground movement shows upward and downward displacement during the 6-year monitoring period. Moreover, monitoring point P-3 located well outside the sag limits shows ground elevations differences in the range of -0.091 to +0.123 in.

GRADUAL MINE SUBSIDENCE

Gradual mine subsidence is illustrated by two individual sags: one in northwest Taylorville and a second in west Belleville, Illinois.

NORTHWEST TAYLORVILLE

The subsidence sag in northwest Taylorville is

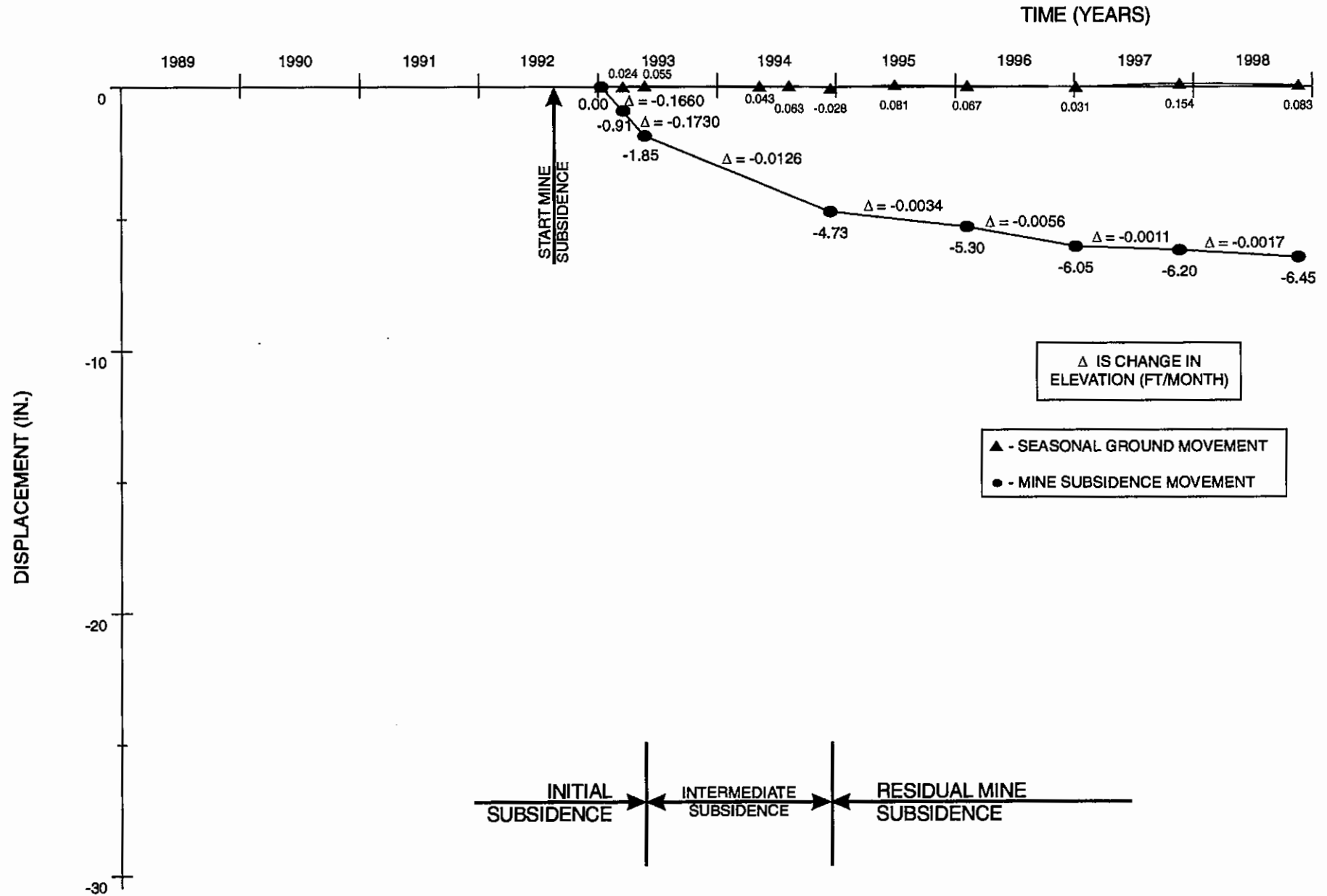


FIG. 4 PLOT OF DISPLACEMENT - TIME OF MONITORING POINT NEAR CENTER OF MINE SUBSIDENCE SAG IN DIVERNON, ILLINOIS

located above the same mine as discussed in the previous section but in a more recent portion of the workings where the room and pillar extraction was more systematic. The mine is in the Herrin No 6 coal at a depth of roughly 460 ft. The area affected by the gradual subsidence covers three street blocks with only 4 reports of damaged homes. Based on boring logs the seam height ranges between 5 and 8 ft.

Based on elevation data of monitoring point P-12, the center of the sag has moved downward since 1989 (see Fig. 5). The rates of mine subsidence movement have been at residual levels except for one period between April and July 1991 (0.0124 ft/month). Mine subsidence damage was first noticed by homeowners in late 1989 after elevations were established on monitoring points. The total downward displacement between August 1989 and November 1998 is 3.06 in. In spite of the relatively small downward displacement, mine subsidence has caused all or a portion of the 0.9 to 4.3 in. of total inward movement of concrete block basement walls in the compression zone. In the zone of maximum curvature, moment/tension cracks up to 3/8 in. wide have developed in masonry walls and concrete floor slabs. The overall rate of residual downward movement ranges between 0.0009 and 0.0098 ft/month (0.13 to 1.41 in./year).

During the 1997 to 1998 time period, new moment/extension cracks 0.03 to 0.09 in. wide developed in masonry walls of the damaged structures located in the

extension zone. In addition the overall tilt in one home that spans the inflection point increased 0.7 in. toward the center of the sag. The increased tilt represents a combination of additional ground movement (0.3 in.) and residual deformation (0.4 in.) in the structure.

The requirement for taking ground movement measurements on a yearly basis is illustrated in the 1995 to 1996 time period. The 20 November 1995 measurement showed no downward displacement whereas the yearly change (27 June 1995 to 2 July 1996) showed a downward movement of 0.21 in. Subsequent displacement measurements made between 1996 and 1998 confirm the downward movement trend.

Seasonal variations in ground surface elevations outside the sag show a downward trend between 1989 and 1991 and then an upward trend between 1991 and 1998. The upward trend related to seasonal variations helps explain some of the positive displacements in P-12 during intermediate readings. For example, between 15 July 1991 and 1 February 1992 the ground surface elevation went up 0.22 in. and the elevation of P-12 increased 0.06 in. The net difference is a downward movement of 0.16 in. Subsequent P-12 elevations measured at approximately the same time each year confirm the subsidence trend.

The overall change in ground surface elevation outside the subsidence limits at the time of the level line surveys ranged between -0.079 to +0.276 in. The seasonal

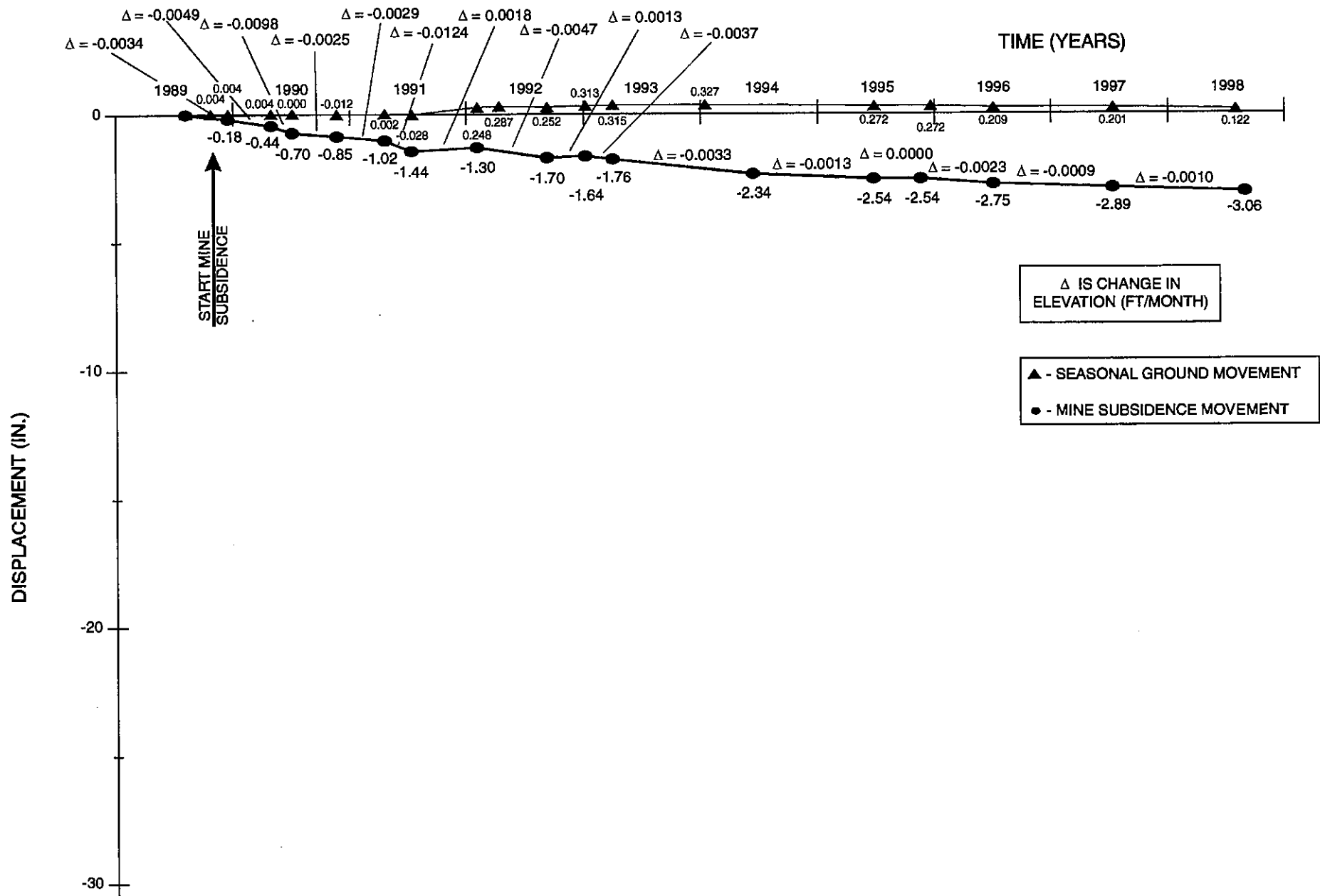


FIG. 5 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF SAG IN NORTHWEST TAYLORVILLE, ILLINOIS

changes are generally upward and are at least 10 times less than the measured subsidence displacement.

BELLEVILLE

The final case is located in west central Belleville, Illinois. The subsidence has damaged at least five homes in the sag limits. The abandoned room and pillar mine was developed in the Herrin No 6 coal at a depth of 160 to 175 ft. The boring logs show a seam height of 5.5 to 7 ft.

The ground movement data for monitoring point P-17 are summarized in Fig. 6. Mine subsidence movement began slowly in 1983 and the area has continued to move downward during the 15-year monitoring period. The measured rate of movement has remained at residual levels (0.0004 to 0.0058 ft/month). In gradual subsidence the rate of movement tends to increase and decrease between monitoring intervals rather than show a relatively uniform decrease with increasing time. Thus variations in the rate of displacement can range up to 0.005 ft/month 8 years after initiation of subsidence movement. Total downward displacement in the Belleville sag is at least 3.57 in. The overall tilt in the home closest to the monitoring point is 3 in. which is compatible with the measured ground displacement.

The structures in the sag limits show extension and rigid body rotation damage. Cracks are open 0.03 to 0.25 in. and door/window frames are racked

(1/16 to 3/16 in./2 ft) generally toward the center of the sag. Seasonal changes in ground surface elevations are included in the plot. The background displacements (ranging between -0.1378 and + 0.1102 in.) are well below the 3.6 in. mine subsidence in the compression zone.

Classification of Subsidence Displacements

Displacement-time data for the five mine subsidence areas described in this paper are summarized in Table 1. Based on long term subsidence measurements in Illinois, a classification is proposed for evaluating displacement-time relationships as follows:

CLASS	TIME RATE DISPLACEMENT (FT/MONTH)
INITIAL	>0.1
INTERMEDIATE	0.1 TO 0.01
RESIDUAL	<0.01

All three classes are present in catastrophic mine subsidence. For gradual subsidence, the ground movements are at residual levels throughout development of the sag.

One of the most important findings of the long term observations and measurements is that mine subsidence as well as the damage caused by the ground movement continues for years after initiation of failure at mine level. The

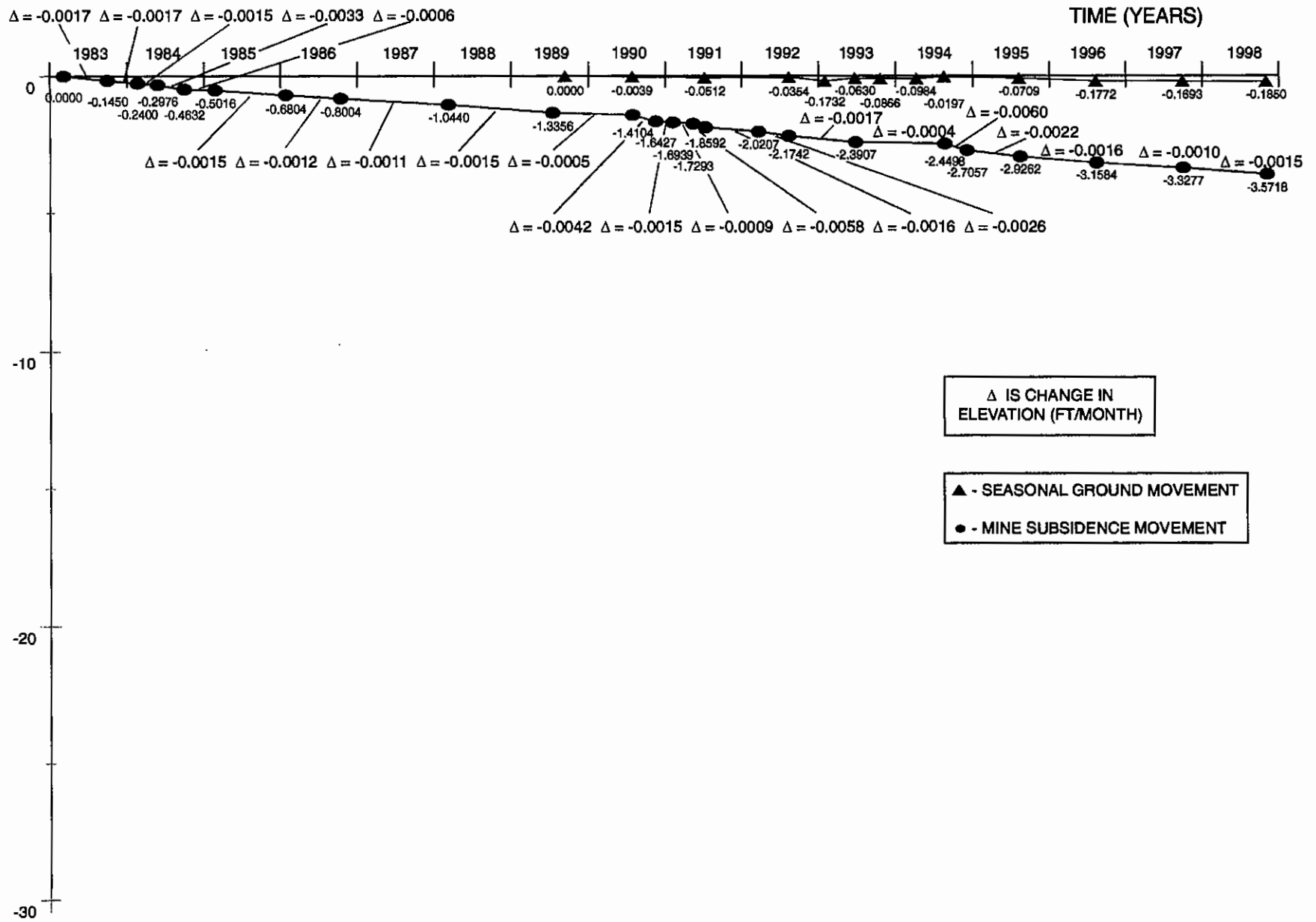


FIG. 6 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF SAG IN WEST BELLEVILLE, ILLINOIS

TABLE 1 SUMMARY OF DISPLACEMENT - TIME MEASUREMENTS:
ILLINOIS SAG SUBSIDENCES

CATASTROPHIC

LOCATION			TOTAL		INITIAL			INTERMEDIATE			RESIDUAL		
	D (FT)	SH (FT)	S _{MAX}	T	S	T	R	S	T	R	S	T	R
WEST SPRINGFIELD	188	4	20.9	1599 4.4	16.9	452 1.24	0.081- 0.621	2.6	420 1.15	0.011 0.044	1.4	727 1.99	0.002- 0.007
SOUTHWEST TAYLORVILLE	460	5 to 8	42.5	2820 7.7	27.3	40 0.11	20.4	13.6	1720 4.66	0.01- 0.06	1.62	1076 2.95	0.003- 0.005
DIVERNON	300	7	6.45	2135 5.85	1.85	133 0.36	0.166- 0.173	2.9	568 1.56	0.0126	1.72	1435 3.93	0.0011- 0.0056

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GRADUAL

LOCATION	D	SH	S _{MAX}	T	R
NORTHWEST TAYLORVILLE	460	5 to 8	3.06	3390 9.29	0.0009- 0.0124
WEST BELLEVILLE	160	7	3.57	5475 15.0	0.0004- 0.0058

- D - APPROXIMATE MINE DEPTH
- SH - APPROXIMATE SEAM HEIGHT
- S_{MAX} - TOTAL GROUND SETTLEMENT (IN.)
- T - TIME (DAYS/YEARS)
- S - INCREMENTAL SETTLEMENT (IN.)
- R - TIME RATE OF SETTLEMENT (FT/MONTH)

data show downward movement during residual mine subsidence at magnitudes well above seasonal changes in ground surface elevations. Residual displacements measured to date range between 1.4 and 3.6 in. and are greatest in gradual subsidence which occur over longer time periods. It is important to note that the initial 2-year average rates of residual movement (0.0033 to 0.0051 ft/month) are similar for both catastrophic and gradual failures. Residual mine subsidence movement is at levels that cause crack development in both repaired and unrepaired structures. Total residual downward displacement exceeds design limits for settlement of structures (1 in. over life of building).

Summary and Conclusions

Sag mine subsidence above abandoned room and pillar mines in Illinois occurs in two basic modes: catastrophic and gradual based on the displacement-time relationship of the ground movements. In catastrophic subsidence the maximum settlement is at least 0.5 ft and the sag evolves through three phases: initial, intermediate and long term or residual each with the following rates of displacement:

- INITIAL
> 0.1 FT/MONTH
- INTERMEDIATE
0.1 TO 0.01 FT/MONTH
- RESIDUAL
< 0.01 FT/MONTH.

Gradual mine subsidences usually have poorly developed sags with little or no surface expression (less than 0.5 ft of total downward displacement) and develop at residual rates (less than 0.01 ft/month).

In this paper measured displacements of five sag subsidences in central and southern Illinois are summarized in displacement-time plots. Three of the areas have experienced catastrophic movement in which the total settlement is at least 6.5 to 42 in. Damage levels are moderate to severe and most of the serious damage occurred in the first 1 to 15 months after failure at mine level. Gradual subsidence has affected two of the areas discussed in this paper. Subsidence has been ongoing for a period of 9.3 to 15 years at variable but generally declining rates. Ground movements from mine subsidence have not ceased in the five sags (4.4 to 15 years after mine failure). Based on past experience, mine subsidence is expected to cease in all of these areas but at some unknown time in the future.

Measured residual mine subsidence movement in both catastrophic and gradual sags occurs at rates of 0.0033 to 0.0051 ft/month after the second year. This rate is equivalent to 0.5 to 0.7 in. in 1 year. Even after 15 years, the rate of movement in one of the sags is 0.0015 ft/month (0.22 in./year). The displacements in residual mine subsidence have been sufficient to cause additional cracking of foundation and superstructure elements. In conducting long

term mine subsidence investigations it is important to carry out surveys at about the same time each year in order to establish a measurement baseline and to help eliminate some of the seasonal effects on ground surface elevations.

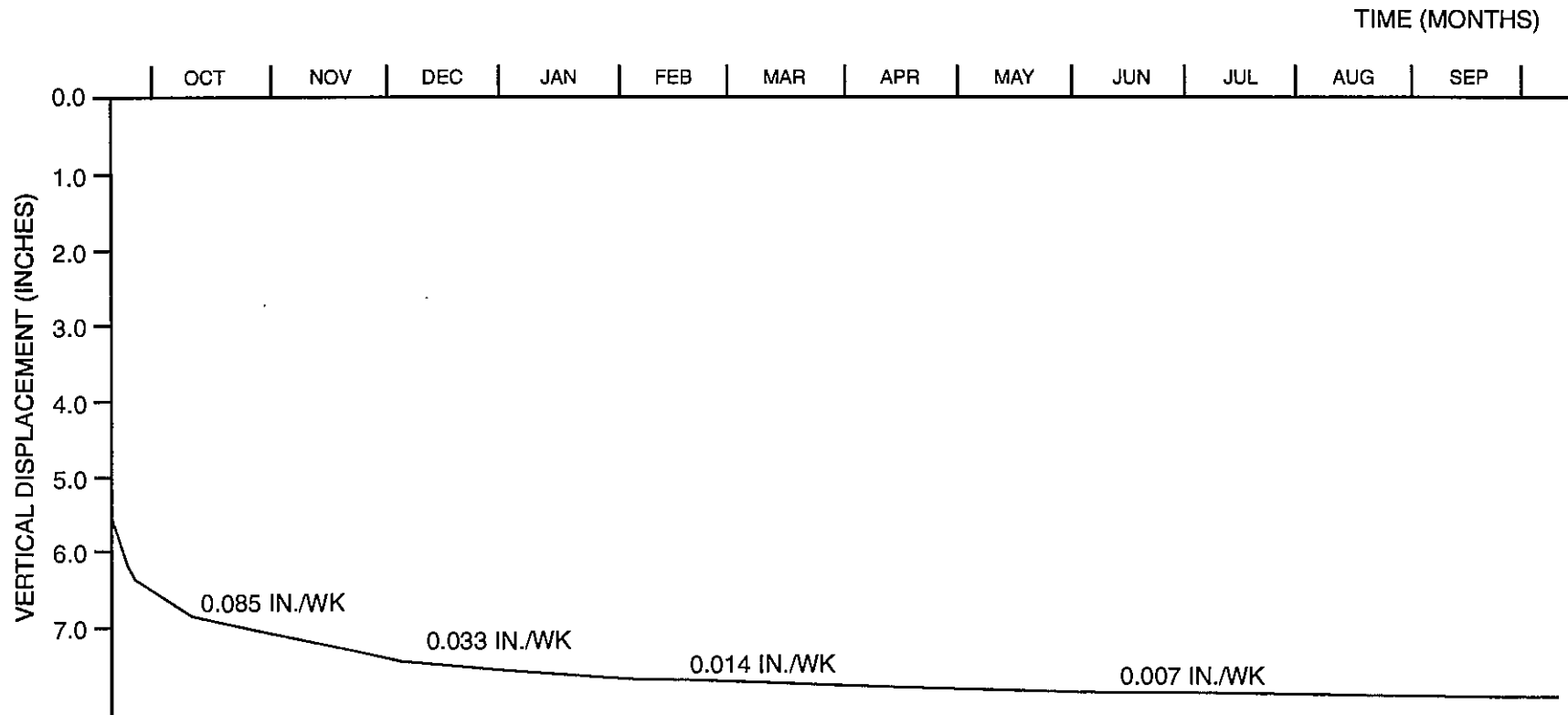


FIG. 1 TYPICAL GROUND DISPLACEMENT-TIME PLOT
CAUSED BY COAL MINE SUBSIDENCE

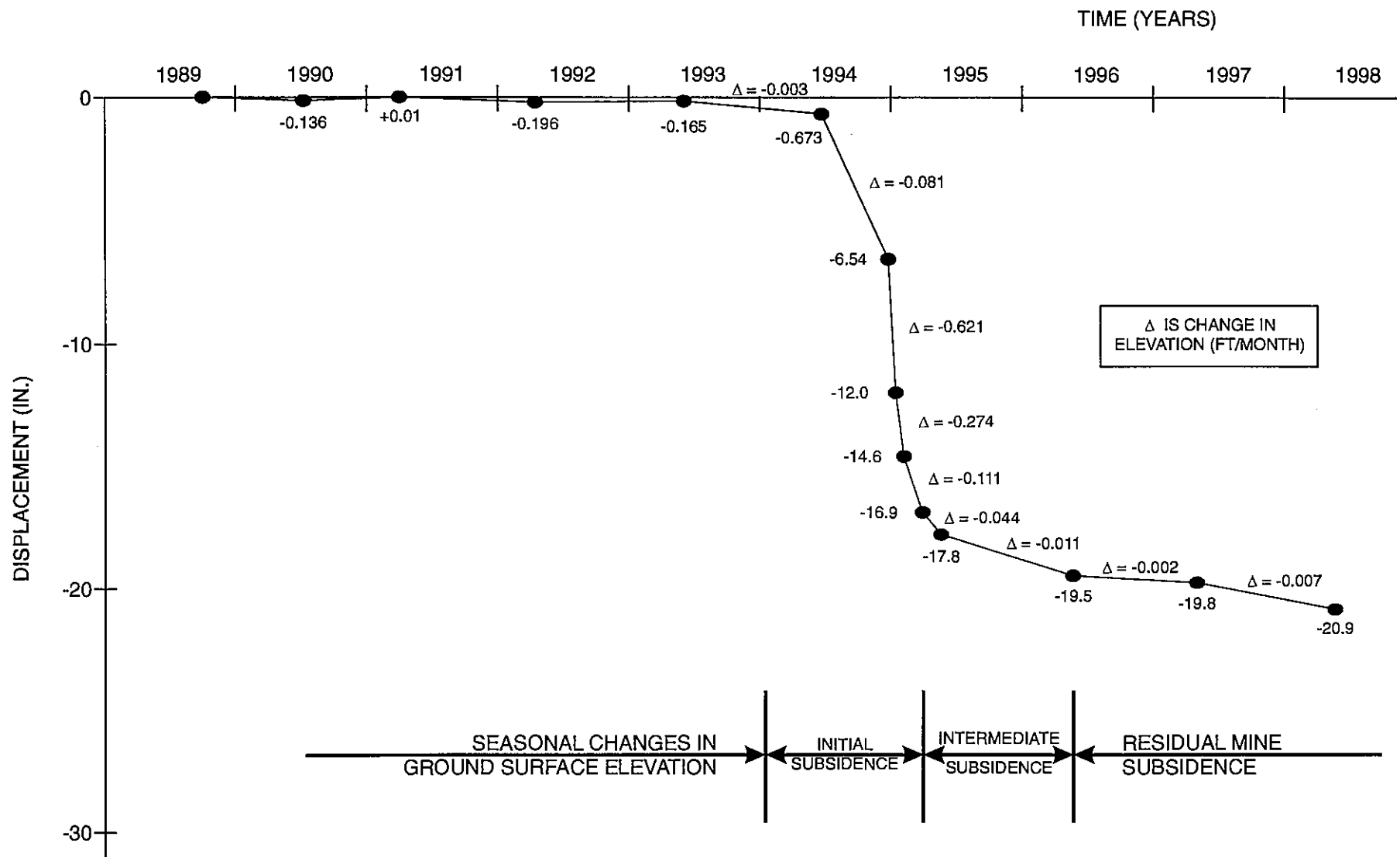


FIG. 2 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF MINE SUBSIDENCE SAG IN WEST SPRINGFIELD, ILLINOIS

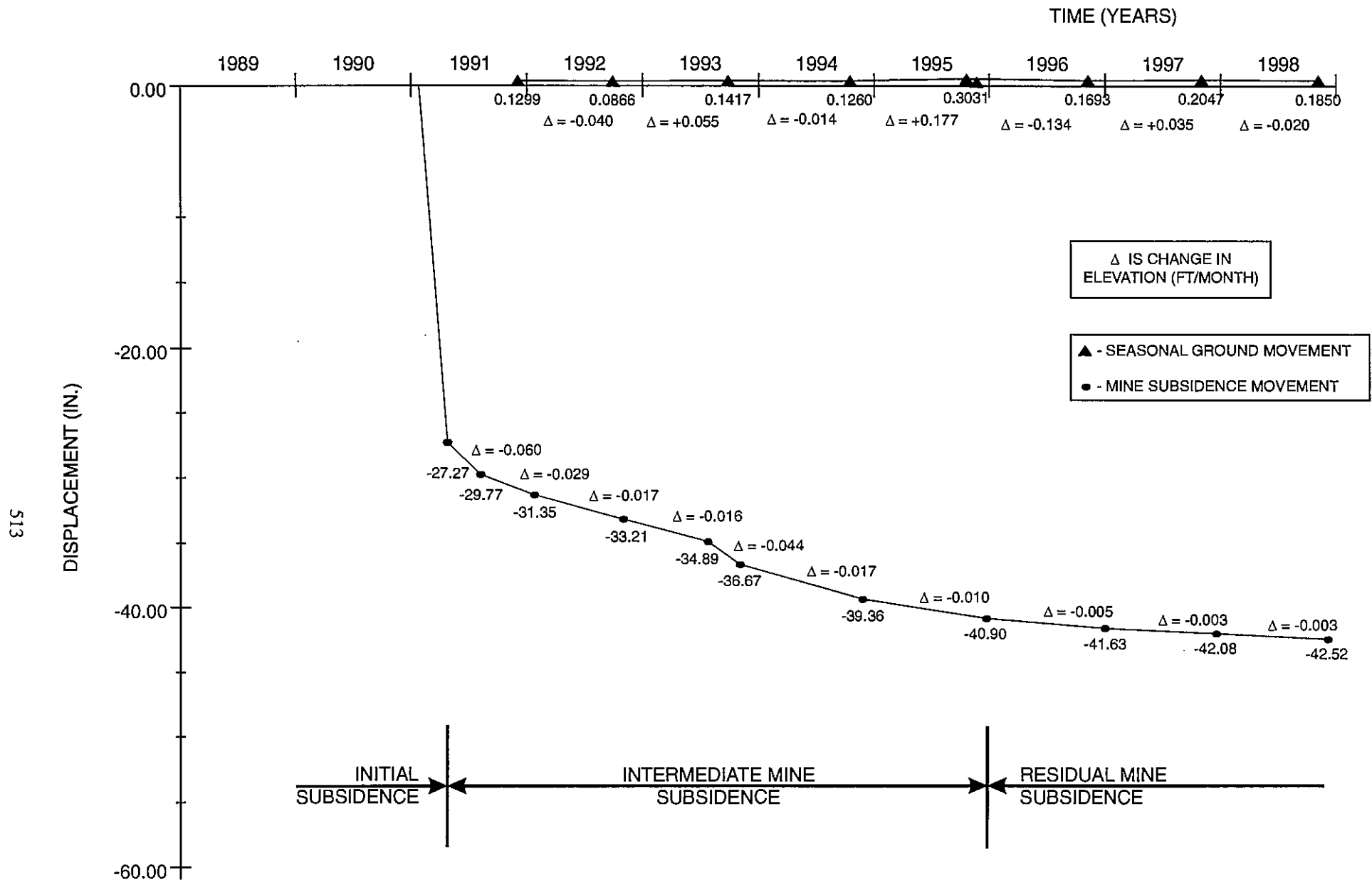


FIG. 3 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF SAG SUBSIDENCE IN SOUTHWEST TAYLORVILLE, ILLINOIS

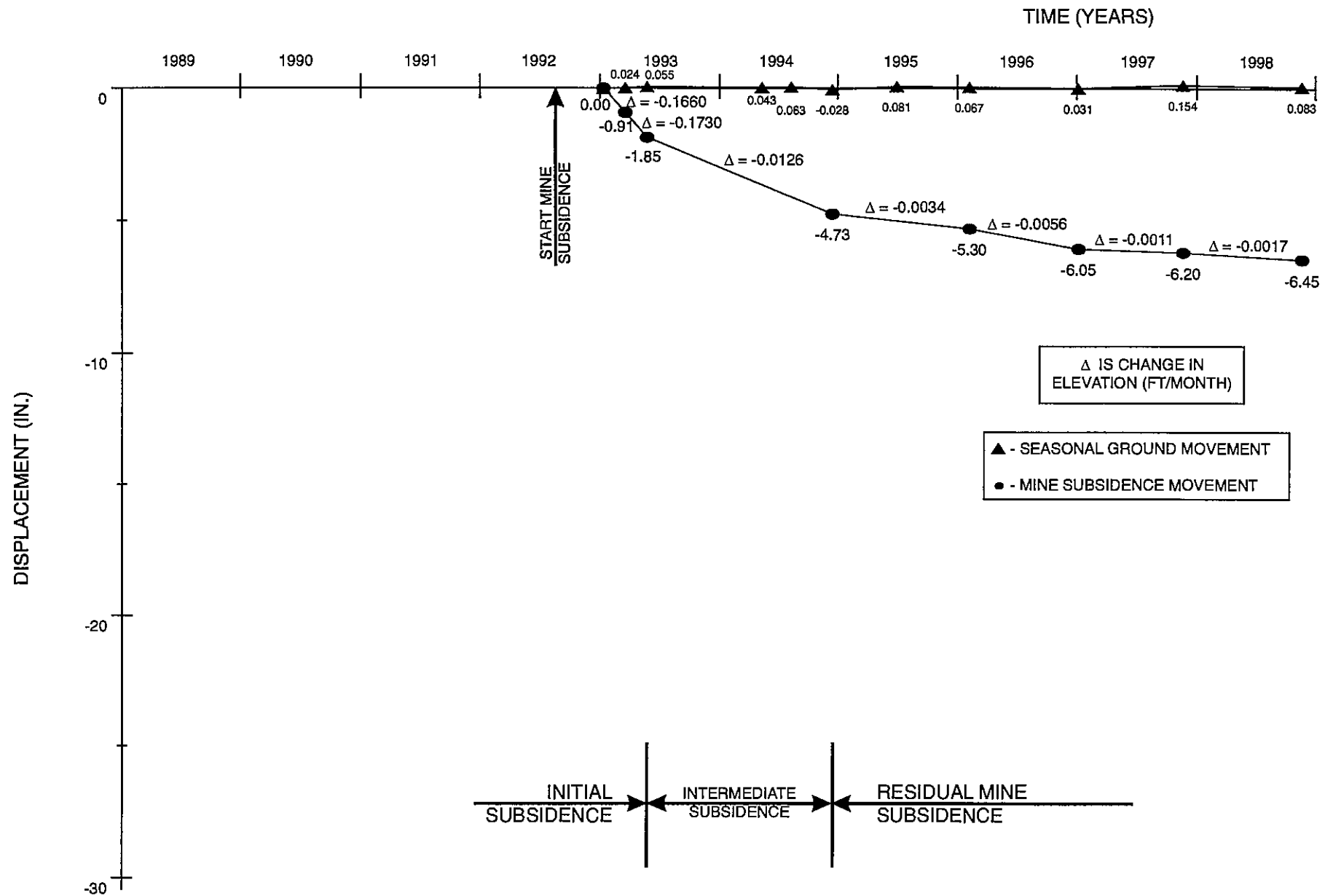


FIG. 4 PLOT OF DISPLACEMENT - TIME OF MONITORING POINT NEAR CENTER OF MINE SUBSIDENCE SAG IN DIVERNON, ILLINOIS

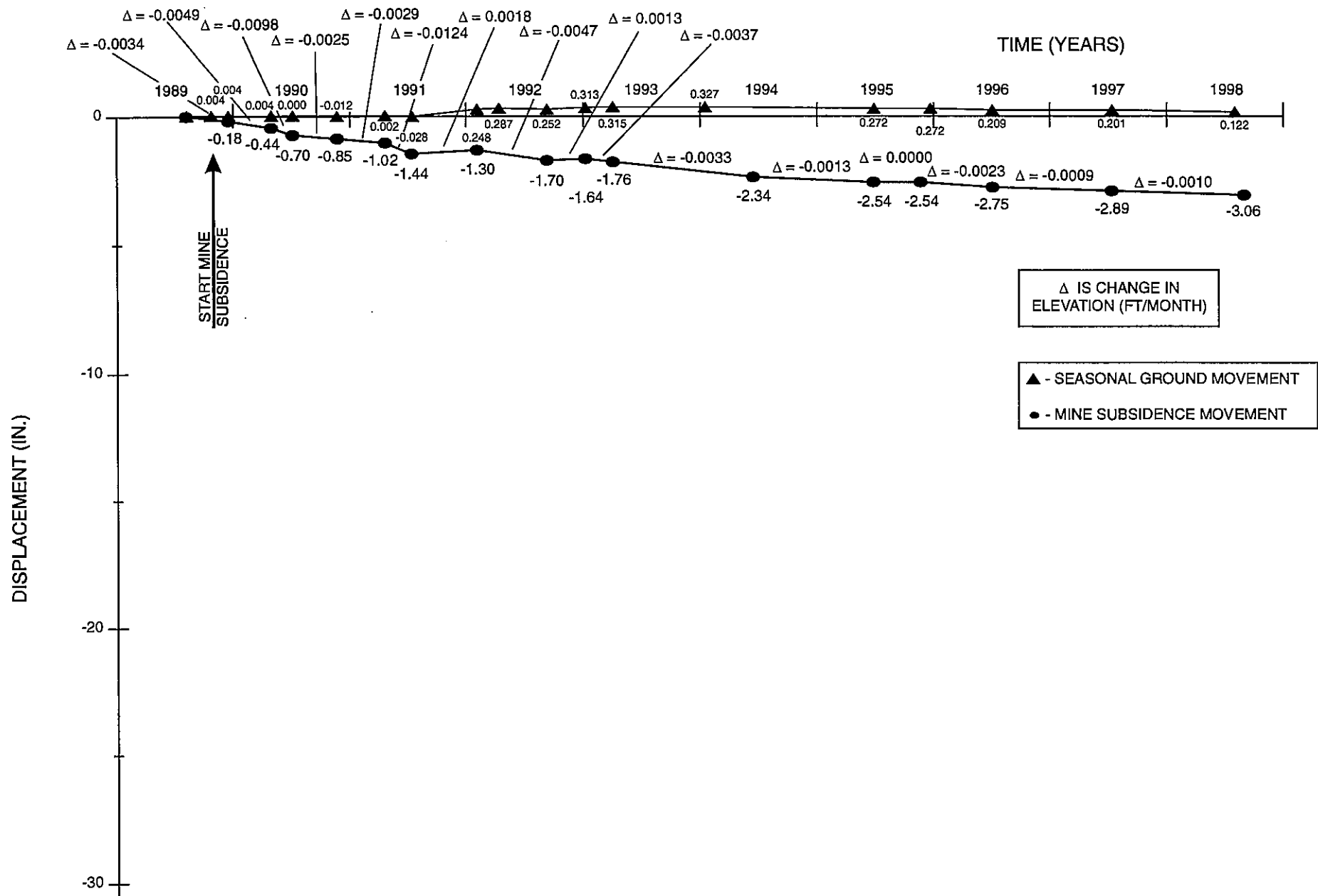


FIG. 5 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF SAG IN NORTHWEST TAYLORVILLE, ILLINOIS

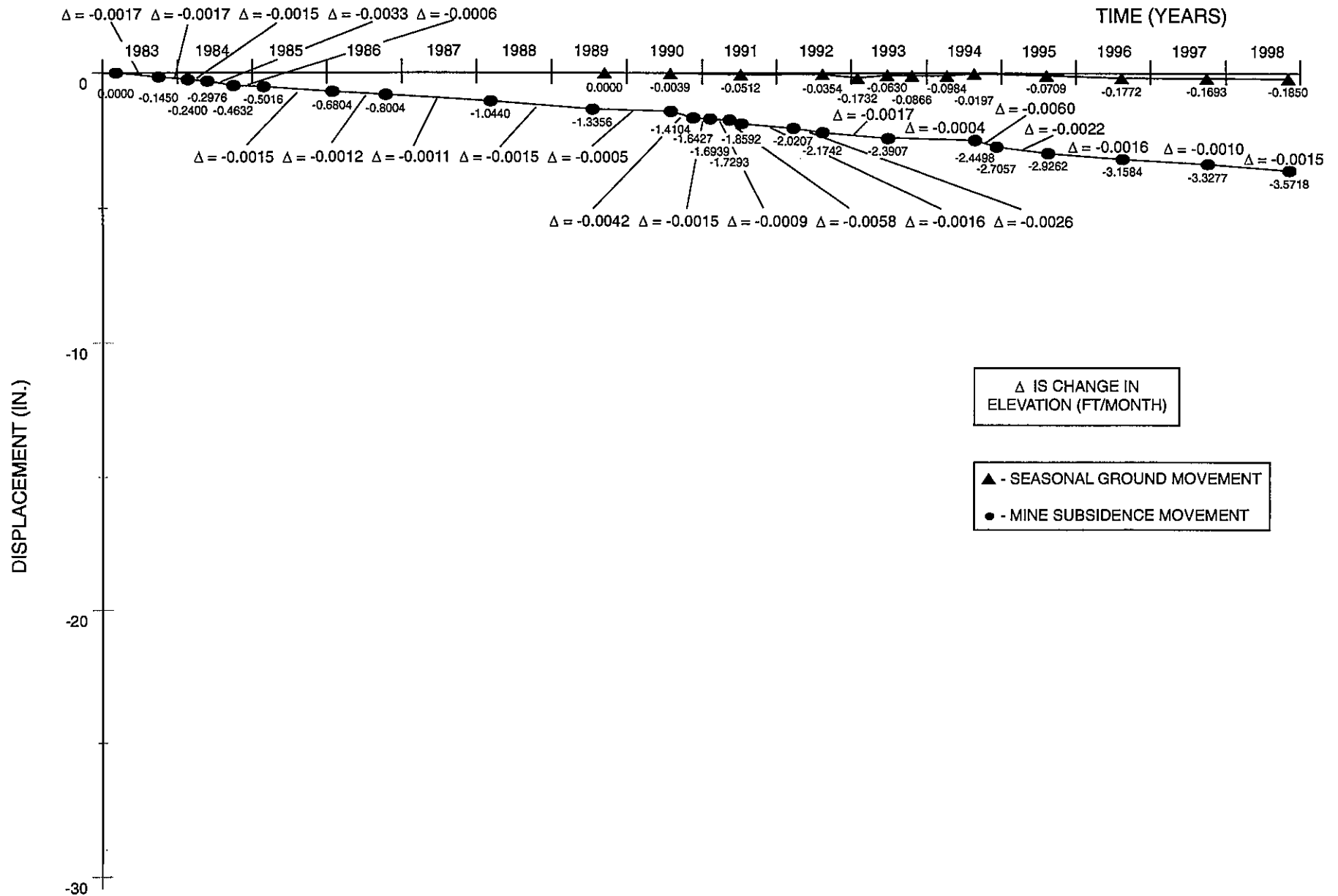


FIG. 6 DISPLACEMENT - TIME PLOT OF MONITORING POINT NEAR CENTER OF SAG IN WEST BELLEVILLE, ILLINOIS