Post-Closure Monitoring of Surface Settlement at a Hazardous-Waste Landfill in West Central Illinois

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ABSTRACT

Precision vertical surveying conducted over a 16 month period found no evidence of underground mine-related subsidence at an exhumed landfill in west central Illinois. Shallow, weather-protected monuments in undisturbed ground near burial trenches underwent substantial vertical movements which were not entirely explained by simple linear models of average daily temperature and precipitation, and shallow groundwater fluctuations. Tilt plates at depressions in the trench covers showed vertical movements to be more than 5 times as large as the shallow monuments on undisturbed ground. Largest movements occurred in the winter and late summer months. Tilt plates provide a satisfactory means for measuring angular movements which were very small, but they are not recommended for monitoring large-area landfill covers where depression features tend to be very localized.

BACKGROUND

The Illinois Supreme Court ordered Earthline Corporation, a subsidiary of SCA Services, Inc., to exhume all hazardous wastes buried in 25 trenches at a state-licensed facility near Wilsonville, Illinois (Figure 1). The decision made in March of 1982 was reached independently of the Illinois Environmental Protection Agency's discovery during routine monitoring that organic pollutants migrated as far as 50 feet from the trenches in a three-year period. A major concern of the Court was that subsidence caused by failure of mine openings beneath the site would contribute to the failure of the trenches (Illinois Legislative Investigation Commission, 1981).

The Illinois State Geological Survey (ISGS), in cooperation with the Illinois Environmental Protection Agency, U.S. Environmental Protection Agency, and SCA Services, Inc. undertook an extensive field study to determine the origin of the faster-than-predicted pollutant migration. As part of this study ISGS staff and Southern Illinois University-Edwardsville (SIU-E) staff constructed

Figure 1. Location of the Earthline landfill near the City of Wilsonville, Macoupin County, Illinois.

a series of monuments at the landfill and established a monitoring program for observing surface movements of the land surface and trench covers.

Mine-related surface subsidence has occurred to the west of the facility, but subsidence features associated with mining have not been observed or reported at the site. However, any low, shallow sag developing from mine subsidence at the site that might be overlooked or obscured by on-site construction activity probably would be detected by precision levelling.

Observations by ISGS and SIUE staff at four sites in St. Clair and Madison Counties show that subsidence activity can be measured for as long as three years after the event. Small increments of surface movement were measured by periodic high precision levelling over a network of carefully constructed monuments in those studies (Hanna and Cote, 1982). The surveys also proved to be valuable sources of information for determination of the magnitude of shrinkage and swelling of surface soils. This study used methods developed and improved in the earlier studies.

Post-closure settlement and tilting of trench covers also were of particular interest as possible contributing causes to the faster-than-predicted pollutant migration (Stohr et al., 1987). A review of technical literature about trench covers for low-level radioactive waste landfills revealed that infiltration of precipitation through earthen trench covers caused migration of radioactive pollutants from burial trenches (Herzog et al., 1981). Specific data concerning trench cover characteristics and movements are sparse.

PURPOSE

The purpose of this study was twofold: to determine if surface movements caused by mine subsidence were occurring at the landfill, and to measure the amount and type of trench cover movements in comparison with those located on undisturbed ground. Specific project tasks included:

- Measure subsidence activity at the facility by periodic monitoring of deep survey probes.
- Differentiate subsidence caused by failure of underground mining beneath the site from settlement of trench covers caused by consolidation and piping (subsurface erosion).
- Measure and analyze movement of shallow, weather-protected monuments.
- Measure and analyze vertical settlement occurring over trenches.
- Measure and analyze tilting occurring on selected trench covers.
- Determine post-closure settlement rate of trench covers.
- Measure movement caused by freeze/thaw and shrink/swell at the site.

GEOLOGY AND MINING HISTORY

The stratigraphy of the Earthline landfill site and descriptions of the units are summarized in Figure 2. Stratigraphic contacts determined in the field were refined by later study of continuous cores (Follmer, 1984). The landfill burial trenches were constructed in the Peoria Loess, Roxana Silt (a unit composed of soil similar in composition to loess), and the upper part (ablation phase) of the Vandalia Till Member of the Glassford Formation.

From 1917 to 1954 the Superior Coal Co. operated the Superior No. 4 underground coal mine with a shaft and coal cleaning operations at the landfill site. The coal cleaning refuse (gob) pile is a remnant of that former activity. The Herrin (No. 6) Coal was mined at a depth of approximately 100 meters (300 feet). The roof of the mine was the Brereton Limestone Member of the Carbondale Formation; the floor was composed of gray mudstone and clay.

The Superior No. 4 Mine, which underlies several square miles around the landfill, used the room and pillar method for coal extraction. Barrier pillars, which are long areas of unmined coal, are left intact for support of entries and ventilation openings. Chain pillars function as barrier pillars, but are constructed with gaps. Individual pillars are left between rooms of removed coal for roof support. DuMontelle et al. (1981) describe this mining method and its effect on roof stability. About 50 percent of the coal is extracted leaving the remainder for support.

The underground mining plan of the Superior Mine is superimposed upon a map of the Earthline landfill in Figure 3. Barrier pillars and chain pillars underlie much of the waste burial sites. The main mine shaft is on the north part of the landfill site.

INSTRUMENTATION AND DATA COLLECTION PROCEDURES

A third-order precision vertical survey was conducted monthly at the landfill site. The survey used second-order procedures including double-run levelling and a two-peg test. These procedures incorporated recommendations made by Paris and Berry (1984). The instrument operator and rodman were the same in all surveys. The levelling measurements were taken using a WILD NA2 Universal Automatic Level with a GPM parallel-plate micrometer, a wooden tripod and a GSLE 4 (metric) sectional rod with level. Figure 3 shows the locations of the surveying monuments at the Earthline landfill.

A two-peg test was completed during each data-gathering day using tilt plates 1026, 1034, and 1048. The first set-up was within 5 meters of plate 1034 with sightings on the other two plates. One survey was not included in the analysis due to a variation in procedure of the traverse.

Figure 2. Summary stratigraphic column at the Earthline landfill, Macoupin County, Illinois (from Stohr et al., 1985).

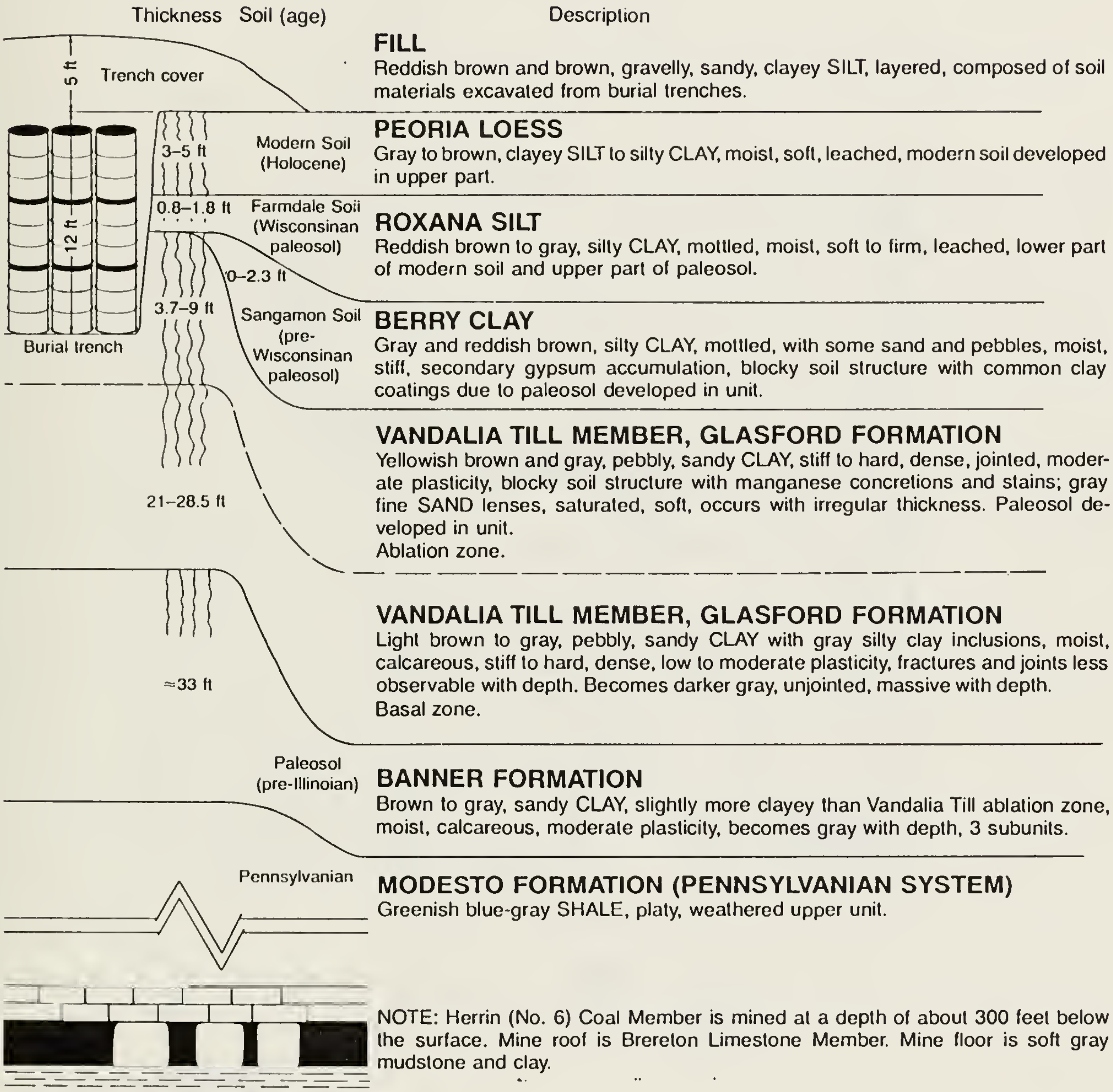
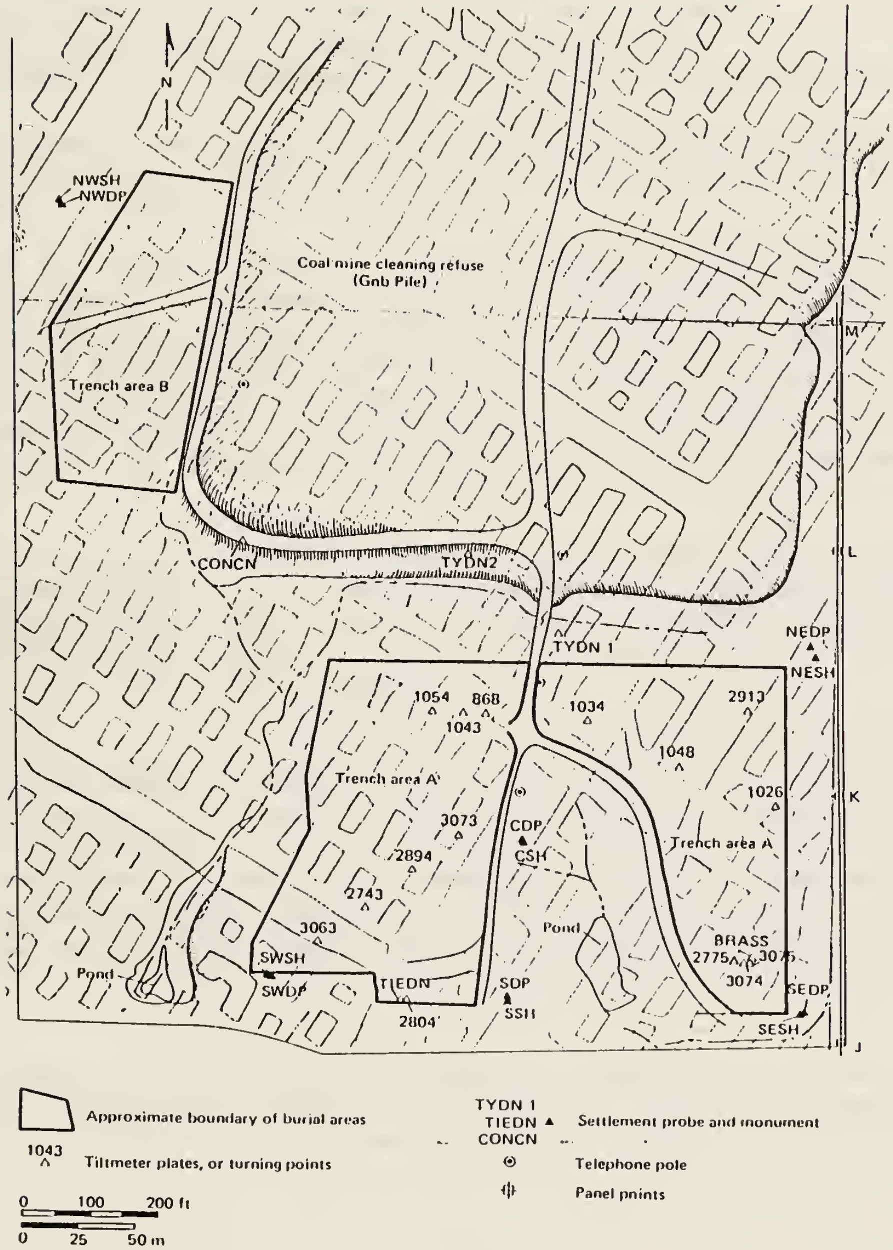


Figure 3. Map of the Superior No. 4 underground coal mine superimposed upon a surface map showing areas at the Earthline landfill, Macoupin County, Illinois (from Stohr, et al., 1985). Barrier pillars separate rooms with individual pillars. Chain pillars provide additional support along the haulage ways.



Data for each survey were reduced using shallow monument CSH as the vertical control benchmark. All survey circuits began and ended at CSH which was assumed to have an elevation of 100.000 meters. The actual topographic elevation of CSH is 620.72 ft (1929 Datum) as determined on August 29, 1983. Four types of surveying monuments were constructed:

deep probes constructed in undisturbed ground for the mine subsidence study and for local datum,
shallow monuments constructed in undisturbed ground,
tilting plates constructed on trench covers, and
miscellaneous anchored monuments constructed for turning points

Probes and monuments were constructed as shown in Figure 4. Deep settlement probes were pushed about 2 feet into the basal phase of the Vandalia Till which is about 20 feet below the surface.

The design of the shallow, weather-protected monument, in undisturbed ground are shown in Figure 4. Monuments originally installed with a detached casing shown in (A) were found to be unsatisfactory in two instances when soil piped into the opening below the protection pipe covering the metal pin. Concrete and a second pin, as shown in design "B", were added to solve the problem. Design "B" worked much better in protecting the pin; however, it is thought to be more susceptible to stresses from frost heaving and shrinking and swelling soil.

Tiltmeter plates were installed in compacted soil trench cover material near the center line of the trenches based on survey data supplied by the owner. A later ISGS magnetometer survey of part of the site showed an earlier survey by the owner contained some errors. Consequently, some of the tilt plates may be located off the center of the trenches.

Plates were installed over several trenches in order to measure tilting differences from trench to trench and along a single trench. Four plates were placed in and around a sag-type depression developed in trench 19 (see Figure 5). Plate 3075 was in the depression, plates 1111 and 3074 along the perimeter, and plate 2775 was placed immediately outside of an oval-shaped crack which encompassed the depression. Plate 2775 was placed to determine if the depression was actively growing deeper and larger. Additional information concerning soil properties of the trench cover are described in Stohr et al., 1988.

Tiltmeter plates consist of four (4) pegs on a ceramic or brass plate attached to a concrete base in the trench cover (Figure 4). Steel "tiedown" rods were used for turning points and for some tiltmeter stations.

Figure 4. Construction details of shallow, weather-protected monuments and deep settlement probes, tilt plates and tie-down turning points at Earthline landfill. Note method of repair of shallow monument A.

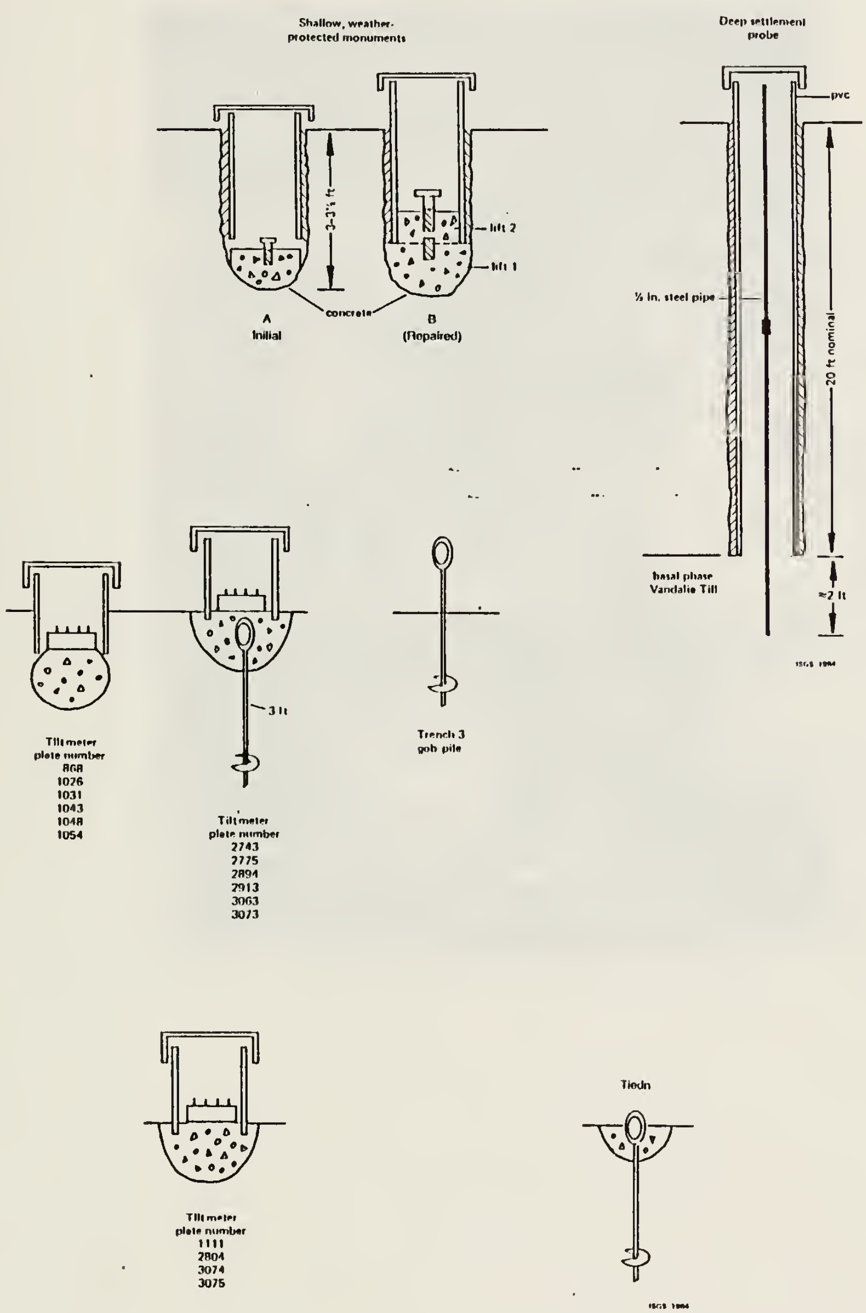
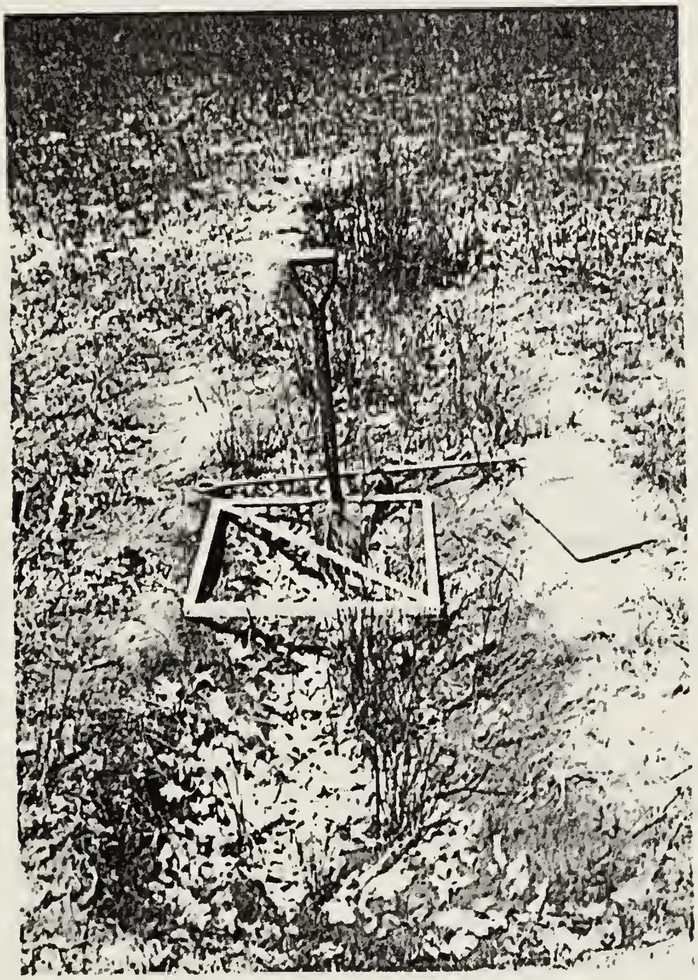


Figure 5. Sag-type depression developed in the cover over trench 19, Earthline landfill, Macoupin County, Illinois. The depression is about 26 cm (10 in) deep and 0.6 m (2 ft) wide as shown by the shadow trace. Note the slope of the shadow cast on the depression.



The four pegs of the tilting plates were set oriented roughly to the cardinal points north, south, east, and west. The trenches are oriented roughly east-west, consequently it was assumed that the east-west pegs of the plates were oriented in the long direction of the trenches. The two apparent dips of the tilt plate (NS and EW inclinations) were calculated from the Digitilt (TM) instrument readings as specified in the manufacturer's instructions (SINCO, no date). We used a numerical method by Su and others (1988) to determine the strike and dip.

Temperature and precipitation data were obtained from the U.S. Commerce Department Weather Bureau station at Carlinville, Illinois, approximately 24 kilometers (14.9 miles) due north of the landfill.

DATA ANALYSIS

Vertical surveying data were reduced using station CSH as the base (see Table 1). Initial study of the relative movements of the deep probes and shallow monuments was made by adjusting data to a single deep probe. Movement of all monuments relative to each other were similar to the deep probes. A definitive datum for the survey was determined by taking the average elevation of the five deep probes in the southern burial area. This datum is used for all statistical treatments of the vertical surveying data.

Statistical analyses used the computer programs of the SAS Institute, Inc., to calculate for correlation coefficients and Pearson product-moment correlations (CORR); multiple linear regression by least squares (GLM); and time series analysis by auto-regressive integrated moving linear modeling (ARIMA).

Pearson correlation coefficients were used to determine the influence of temperature, precipitation and groundwater level upon the elevation of the shallow monuments. Groundwater level data were analyzed for five survey dates where data were available.

Time series analysis was employed to further analyze the relationships of groundwater level, temperature and precipitation on shallow monument elevations. A response lag of 3 months in both directions was considered in calculating auto-correlations.

Multiple linear regression was used to analyze the influence of temperature and precipitation on shallow monument elevations over a 1.5 year period. There is a 3 month hiatus in the survey data from March to May 1984.

TABLE 1. Changes in elevation (in mm) of deep probes, shallow monuments, tilt plates and tie down-type turning points at the Earthline landfill, Macoupin County, IL. Measurements are from June 17, 1983 to October 19, 1984, using CSH as the base station.

STATION	061783	081183	082983	092283	102483	111783	121683	012084	021784	060184	070384	081784	091484	101984
Deep Settlement Probe, in undisturbed ground.														
CDP	0.0	.3	5.3	6.9	8.8	7.2	4.6	3.6	1.1	****	****	****	****	****
NEDP	0.0	3.4	4.5	5.7	7.4	6.5	5.3	3.0	-2.2	-2.5	-3.0	2.4	3.8	4.9
NWDP	0.0	4.6	5.8	16.0	11.7	13.3	9.8	****	6.2	1.4	3.1	5.3	8.4	5.9
SDP	0.0	1.7	5.7	7.5	10.1	8.4	5.8	4.4	1.6	-1.0	-1.9	3.4	4.6	4.5
SEDP	0.0	3.1	3.0	4.9	6.4	5.3	2.6	.1	-1.1	-2.8	-3.0	2.8	4.8	6.9
SWDP	0.0	.2	1.4	2.4	2.0	3.4	.9	-.8	-3.3	-8.0	-6.9	-3.1	-1.6	-1.1
Shallow, Weather-protected Monuments, in undisturbed ground.														
CSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NESH	0.0	2.1	2.7	3.2	4.7	3.5	2.2	2.8	-.7	.3	-1.1	2.9	1.8	3.3
NWSH	****	0.0	.9	6.9	4.1	5.5	4.9	****	5.4	.9	2.3	3.3	5.9	4.4
SSH	0.0	-.9	-.9	-.7	.5	-.7	1.7	.8	.8	5.6	3.3	1.7	2.4	3.7
SESH	****	0.0	-.5	1.1	2.2	1.7	.7	-.6	-.3	-1.3	-3.0	0.0	1.2	****
SWSH	0.0	.2	.5	.1	1.4	.3	****	****	-6.1	-.9	0.0	.9	1.2	.9
Miscellaneous Anchored Monuments, in disturbed ground.														
TYDN1	****	0.0	1.1	3.3	4.3	3.9	2.6	****	-2.2	-4.0	-3.1	-1.6	1.6	.4
TYDN2	****	0.0	1.7	4.5	6.1	5.9	6.3	****	.9	-2.1	-2.1	.3	3.9	3.5
TIEDN	0.0	.6	2.9	3.0	7.5	6.7	6.3	13.7	****	6.3	.7	.1	****	****
CONCN	0.0	4.1	5.2	12.9	9.4	10.2	0.2	****	5.8	1.9	2.2	4.5	7.8	7.3
Tilting Plates, on trench covers.														
1111	0.0	-3.5	-7.0	-11.3	-6.1	-5.1	-4.6	25.9	-2.6	-5.8	-12.4	-22.2	-21.3	****
1026	0.0	-.5	1.3	.1	5.9	5.6	5.5	****	1.1	.5	-1.7	-5.3	-.3	4.3
1034	0.0	-1.1	-1.1	-1.8	1.3	2.5	4.0	2.3	-1.5	-12.0	-14.5	-16.7	-18.4	-21.7
1048	0.0	.9	1.4	.9	2.9	5.2	5.7	5.1	1.0	-.2	-1.1	-2.5	-.7	****
2743	0.0	2.8	3.7	3.9	6.2	7.2	5.7	****	4.5	1.8	-1.6	****	****	****
2775	0.0	2.3	1.6	1.7	3.8	4.9	4.2	33.1	7.0	2.4	-.1	-1.8	-1.4	****
2804	0.0	-2.1	3.0	-1.6	5.5	5.0	4.5	21.1	6.5	3.4	-2.8	-9.6	****	****
2894	0.0	4.6	5.7	6.4	5.5	4.4	3.8	30.3	3.7	1.6	****	****	****	****
2913	0.0	3.2	3.2	4.5	6.5	6.7	7.7	13.7	8.5	6.6	3.8	5.3	4.8	6.9
3063	0.0	0.0	.4	-.3	2.6	2.6	2.2	8.8	.7	-2.0	-8.9	-13.0	****	****
3073	0.0	3.8	5.0	6.5	9.6	9.3	7.4	****	15.2	9.2	****	****	****	****
3074	0.0	-1.0	-3.0	-5.6	-4.1	-2.1	-.9	25.5	1.9	.4	-4.4	-10.9	-11.2	****
3075	0.0	-7.4	-7.7	-11.9	-10.1	-9.9	-9.0	13.8	.6	-1.0	-11.3	-23.3	-15.6	****

****: No data

The general model, determined by multiple linear regression is:

$$y = k + a_1x_1 + a_2x_2 \dots + a_mx_m$$

where

y = predicted movement of a shallow monument or tilting plate.
k = regression constant or intercept.
a = partial regression coefficient.
x = independent variable (temperature, precipitation).

Temperature data were taken as the average of the daily maximum and minimum for 3-, 7- and 14-day intervals, plus that of the survey date. Precipitation was taken as the total precipitation for the same intervals prior to the survey. Climate data were taken from the records of the Carlinville meteorological station, 24 kilometers(15 miles) from the site which is the closest station where precipitation and temperature data were available.

Groundwater elevation data were taken from the shallowest of the nested piezometers placed by ISGS adjacent to the shallow monuments and deep probes at the landfill. The piezometers selected were set in the soft, ablation phase of the Vandalia Till at depths between 3.72 m (12.2 ft) to 5.18 m (17 ft). Water level data used are for the interval during which slug and drawdown tests were not being conducted (August to November 1983) and collected within 0 to 7 days of the surveys.

RESULTS AND DISCUSSION

Mine Subsidence Study

Preliminary analysis of deep settlement probe movements (assuming NEDP as a base) showed that there were significant movements of all deep probes. Statistical analysis by Pearson correlation coefficients showed that movements of all probes except NWDP correlated well with each other. The base for detailed analysis was chosen as an average of all deep probes except NWDP. See Table 2.

Figure 6 shows the change in elevation of the deep probes over the survey interval. Four of the 6 deep probes fluctuate within a range of about 15 mm for the period of the survey. Two of the probes, SWDP and NWDP exhibit distinct movements. Probe SWDP which is situated near the edge of a steep slope shows a downward trend which is attributed to creep-type landsliding.

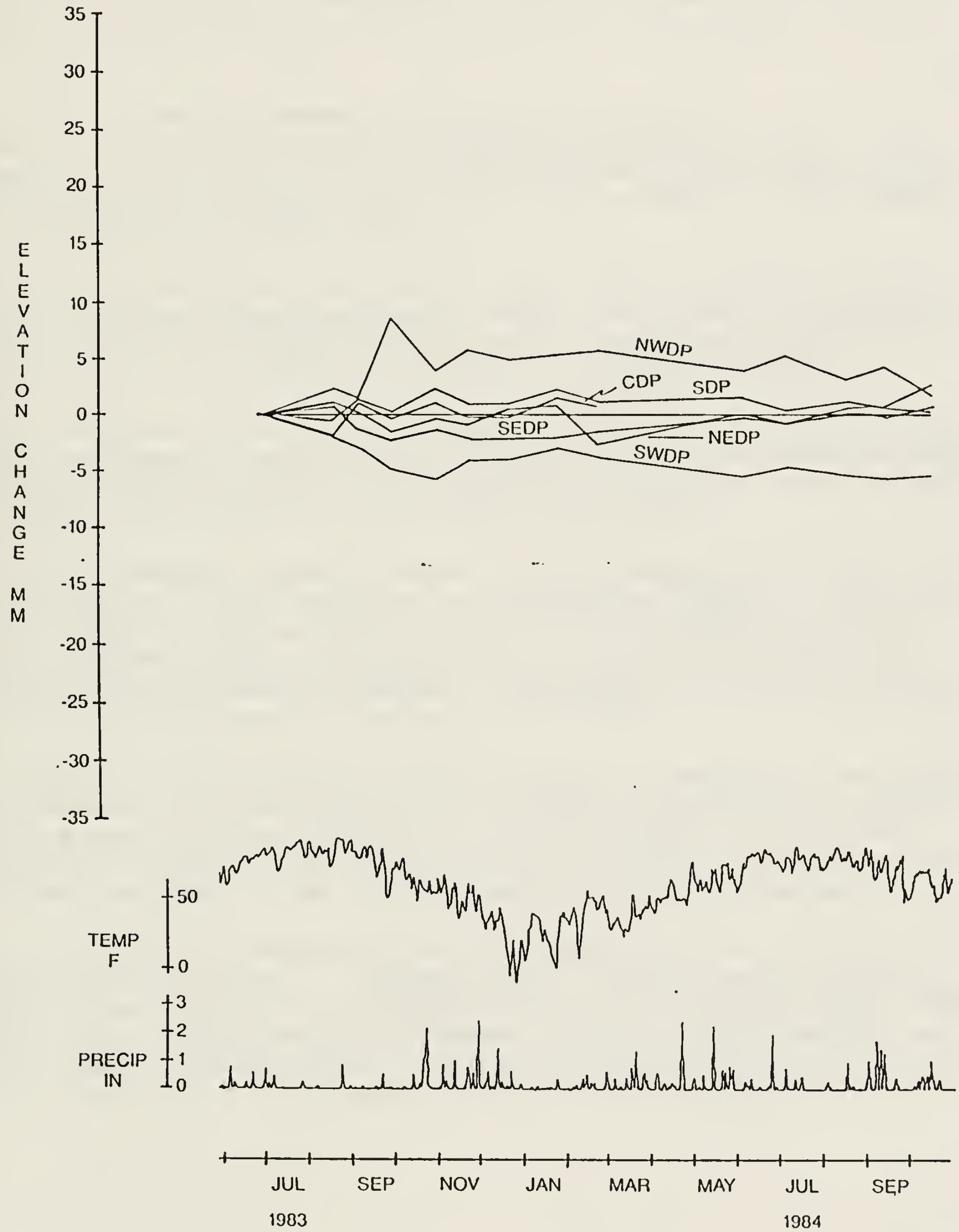
The elevation measurements of the northwest deep probe, NWDP, exhibit a distinct rise and fall, followed by perturbations similar to the other probes. The movements of this probe is not well correlated with the other deep probes, and has not been explanation to date. Probe NWDP is near a steep slope, and close to trenches which were among the first exhumed.

Table 2. Survey by survey comparison of average elevations of all deep probes with average elevation of all probes except NWDP.

OBSERVATION	DATE	AVERAGE OF ALL DEEP PROBES	AVERAGE OF DEEP PROBES EXCEPT NWDP
1	8-11-83	2.22	1.74
2	8-29-83	4.30	4.00
3	9-22-83	7.23	5.48
4	10-24-83	7.73	6.94
5	11-17-83	7.35	6.16
6	12-16-83	4.83	3.84
7	1-20-84	-2.06*	-2.06
8	2-17-84	0.38	-0.78
9	6-1-84	-2.58	-3.58
10	7-3-84	-2.34	-3.70
11	8-17-84	2.16	1.38
12	9-14-94	4.00	2.90
13	10-19-84	4.22	3.80

*NWDP not measured this date.

Figure 6. Graph depicting the changes in elevation of the deep settlement probes at the Earthline landfill, Macoupin County, Illinois. Base station is the average of all deep probes except NWDP.



The precision leveling shows no evidence of subsidence caused by collapse of underground mine workings. Six stations (NEDP, NWDP, SEDP, SWDP, CDP, and SDP) were monitored near the burial trenches (see Figure 3). As shown on the figure, the position of the probes with respect to the pillars and voids in the underground mine represents only a few of the possible locations where subsidence might occur.

Although all deep probes showed movement during this study, the movement can not be related to subsidence. Nevertheless, subsidence may have occurred historically, may have occurred at other locations not monitored, or may yet occur.

Shallow Monuments in Undisturbed Ground

Correlation coefficients were calculated between monument elevations, water levels, and 3-, 7- and 14-day interval temperature and precipitation values. Water levels were taken from the nearest shallow piezometers. Measurements were made from August to November 1983.

The 7-day precipitation value consistently shows inverse (negative) correlation for all 3 shallow monument movements; that is, when the 7-day cumulative precipitation is high, the monuments move down. However, when cumulative precipitation is low, there is a relative rise in monument elevation.

The correlation between water level and precipitation is also an inverse one, i.e., water level drops as precipitation increases during the period of study (see Table 3). These two correlations suggest that after the summer droughts the near-surface soils settled in response to precipitation.

Correlations for monument elevation response to groundwater fluctuation varies from high to low, and direct (positive) to inverse (see Table 3). The high correlation of CSH was inverse with piezometer KP3, but SESH correlated directly with piezometer DP2. Piezometer EP3 has little correlation with NESH. The relationship between movements of groundwater levels and shallow monument elevation is apparently complex at this site.

There is a high, direct correlation between changes in temperature and shallow monument elevation. The constancy of the high direct correlation of temperature and the moderate inverse correlation of precipitation with shallow monument movements suggests that these two factors together account for much of the observed movements of the shallow, weather-protected monuments.

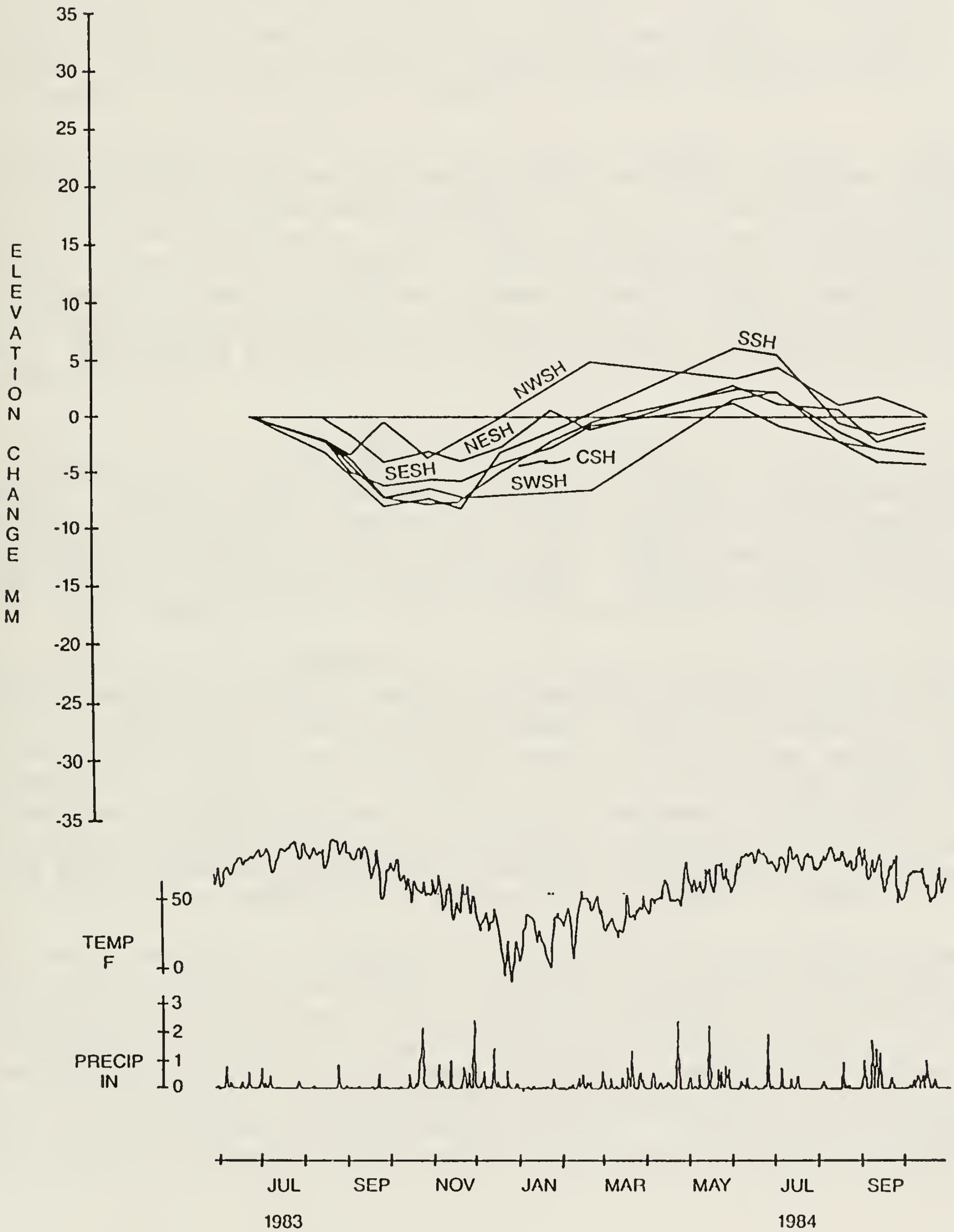
Movements of the shallow, weather-protected monuments for the period of the survey are plotted in Figure 7. The graph shows a coarse cyclical pattern with elevations descending in June-November 1983 and ascending December 1983 through June 1984. Comparison of the reduced raw data with temperature and precipitation shows that the cycles of temperature and precipitation are not visually correlative with the movements of the shallow monuments.

Table 3. Correlation between elevation of shallow monuments in undisturbed ground, temperature and precipitation from August to November 1983.

			Average daily temperature for # of days			Sum of daily precipitation for # of days		
	NESH	EP3*	T3	T7	T14	P3	P7	P14
NESH	1.000	0.0915	0.972	0.926	0.893	-0.109	-0.666	-0.112
EP3		1.000	-0.023	-0.149	-0.151	-0.584	-0.031	-0.282
	CSH	KP3*	T3	T7	T14	P3	P7	P14
CSH	1.000	-0.595	0.829	0.809	0.790	-0.609	-0.667	-0.679
KP3		1.000	-0.532	-0.576	-0.538	-0.141	0.936	0.111
	SESH	DP2*	T3	T7	T14	P3	P7	P14
SESH	1.000	0.640	0.533	0.514	0.473	-0.393	-0.491	-0.486
DP2		1.000	0.960	0.978	0.978	-0.447	-0.563	-0.594

*name of vertical piezometer.

Figure 7. Graph depicting the change in elevation of the shallow, weather-protected monuments in undisturbed ground at the Earthline landfill, Macoupin County, Illinois. Base station is the average of all deep probes except NWDP.



Time series analysis of all shallow monuments with 3-, 7- and 14-day average temperature and precipitation for the 1.5 year survey, lagged 1, 2 and 3 months in either direction, showed only moderate to low correlations (see Table 4). Temperature showed the highest correlations when lagged 2 or 3 months. Precipitation showed consistently low correlations. Note that the highest cross correlations occur with 2 or 3 month lags. The highest auto correlations (correlation between the same variable recorded at different times) occur when the climate variables are lagged for 1 month. Apparently there is not a simple cause-effect relationship between shallow monument elevation movements and changes in temperature or precipitation.

Linear regression modeling was used to determine the extent to which temperature and precipitation together influence shallow monument elevation changes. Temperature and precipitation were considered for 3-, 7- and-14 days prior to the survey. As seen from Table 5, the model accounts for only 31 percent of the movement of the shallow monuments. The data show that precipitation has a more predictable influence on shallow monument movements than temperature. However, temperature and precipitation fluctuations do not fully explain the movement of the shallow monuments given the constraints of the survey and the independent variables.

Tilt Plates on Trench Covers

Vertical movements of all tilt plates for the period of the survey are plotted on Figure 8. The tilt plates respond to climatic stresses in much the same gross manner as do the shallow weather-protected monuments. The range in movement of the tilt plates is more than 5 times larger than the shallow monuments particularly during the coldest period. Monuments near the sag-type depression over trench 19 (1111, 3074 and 3075) heaved more than 2.5 cm.

The authors were unable to determine a post-closure settlement rate for the trench covers owing to the large range of movement of the tilt plates (see Figure 8). Examination of the range in movement of the tilt plates (on trench covers) shows that many of the tilt plates moved about the same amount as the shallow monuments, except for tilt plates in or near the sag-type depression which experienced exaggerated ranges of vertical movement. Of the three tilt plates at other locations which also experienced exaggerated movements, only plate 2804 experienced the exaggerated movements consistently. These same monuments also settled substantially during the hot months of summer.

Multiple linear regression was employed to examine the relationships between tilting plates and climatic variables (temperature and precipitation) for 3, 7, and 14 days prior to survey. The regression accounted for only 34 percent of the movement of the tilting plates (see Table 6). The probability of random occurrence, or chance, in accounting for the movements (significance) is low (.17 and .20) for 3-day temperature and precipitation, but is increased to over 0.5 for the 7- and 14-day climatic variables. As with the shallow monuments there is no obvious correlation with temperature and precipitation.

Table 4. Summary of time series analysis of shallow, weather-protected monument elevations with temperature and precipitation

TIME SERIES ANALYSIS
Shallow Monuments and Temperature

Auto Correlation

Lag	Correlation
0	1.000
1	0.504
2	0.296
3	0.044

Cross Correlation

Lag	Correlation
-3	0.655*
-2	0.621*
-1	0.266
0	-0.306
1	-0.548
2	-0.750*
3	-0.685*

*Exceeds 2 standard errors.

Shallow Monuments and Precipitation

Auto Correlation

Lag	Correlation
0	1.000*
1	0.504
2	0.296
3	0.044

Cross Correlation

Lag	Correlation
-3	0.326
-2	0.154
-1	-0.222
0	-0.220
1	-0.046
2	-0.032
3	0.344

Table 5. Summary Table of Analysis of Shallow Monuments and 3, 7 and 14 days temperature and precipitation.

Source	Degrees of Freedom	Mean Square	F Value	R-Square
Model	6	71.098	6.77	0.313
Error	89	10.510		

Parameter	Estimate of Coefficient	Significance	STD Errorof Estimate
Intercept	0.009	0.9959	1.7486
T3	-0.150	0.4203	0.1855
P3	-0.399	0.2243	1.1432
T7	0.187	0.4450	0.2437
P7	-2.719	0.0064	0.9735
T14	-0.062	0.5124	0.0944
P14	2.588	0.0001	0.5239

Figure 8. Graph of changes in elevation of trench cover tilt plates on trench covers at the Earthline landfill, Macoupin County, Illinois. The base station is the average of all of the deep probes except NWDP. The shaded area shows the range of shallow monument movements.

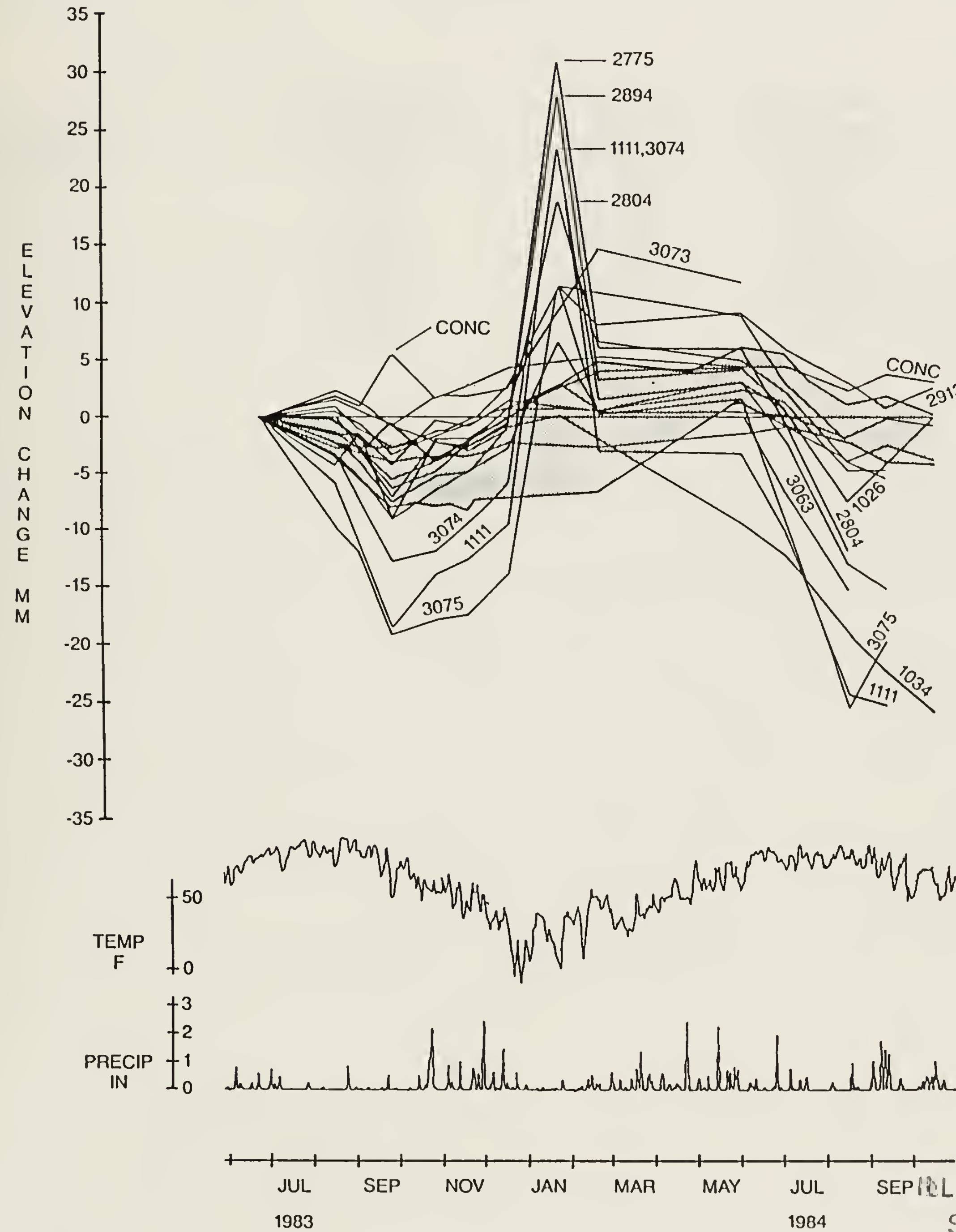


Table 6. Summary table for statistical analysis for tilting plates on trench covers and 3-, 7-, and 14-day temperature and precipitation data.

Source	Degrees of Freedom	Mean Square	F Value	R Square
Model	6	729.069	10.96	0.343
Error	126	66.502		

Parameter	Estimate of Coefficient	Significance	STD Error of Estimate
intercept	11.888	0.0010	3.539
T3	-0.507	0.2015	0.395
P3	-3.406	0.1676	2.454
T7	0.431	0.4016	0.512
P7	0.650	0.7630	2.150
T14	-0.142	0.4449	0.185
P14	-0.361	0.7561	1.159

Time Series Analysis of Shallow Monuments and Tilt Plates

Time series analysis of shallow monuments in undisturbed ground with tilt plates on the disturbed ground of the trench cover shows that any elevation change due to temperature and precipitation occurs within the 1 month interval of the surveys (see Table 7). The autocorrelation (correlation between the same variable recorded at different times) decreases as the lag increases. Cross correlation between the shallow monuments and the tilt plates also progressively decreases as the lag increases. Consequently, the movements of the tilt plates on the surface can not be used to predict movements of the shallow monuments or visa versa between the interval of measurements.

Anchored and Unanchored Tilt Plates on Trench Covers

Unanchored tilt plate, No. 2804 was placed next to a tiedown to provide a means of comparison between anchored and unanchored tilt plates on trench covers. Figure 9 shows the changes in elevation of the anchored and unanchored monuments on dates when both monuments could be measured.

Unanchored tilt plate No. 2804 shows a greater magnitude of elevation change than does the tiedown anchored at depth. However, both monument types responded in the same trend to climatic influences, indicating that surface soils of a trench cover respond more to seasonal changes than do the deeper layers of the cover.

Differential Tilting of Trench Covers

Locations of tilt plate installations are shown in Figure 3. Specific locations were chosen to be representative of the final landfill trench areas. Four plates were constructed in (3075) and near (1111, 3074, and 2775) a sag-type depression in trench 19 in order to obtain data regarding growth and movements of the depression. A study of soil properties and the origin of the depressions at the landfill is reported in Stohr et al. (1988).

Tilt plates were measured for dip and dip direction at the time of each monthly vertical survey. The plates were installed nearly level and corrected by mathematically transforming the recorded data to exactly level at installation for purposes of analysis. Measured orientation is approximate. However, changes in direction of tilting were too small to be analyzed.

All tilt plates experienced some angular displacement for the period of the survey (see Table 8). The smallest maximum movement was 0.01° (plate 1026); the largest movement is 3.67° (plate 3075). Plates near the known sag-type depression (Figure 5) experienced the largest movements. Plate 2804 experienced a tilt in excess of one degree, however, the plate lies near a vehicle trail which became well used after the plate was installed.

Table 7. Summary of time series analysis of shallow monuments and tilt plates.

Autocorrelation		Cross Correlation	
Lag	Correlation	Lag	Correlation
0	1.000	-3	-0.556
1	0.504	-2	-0.355
2	0.296	-1	0.044
3	0.044	0	0.675
		1	0.400
		2	0.503
		3	0.265

Figure 9. Graph depicting elevation changes of an unanchored tilt plate and an anchored tie-down at the Earthline landfill, Macoupin County, Illinois. Base station is the average of all deep probes except NWDP.

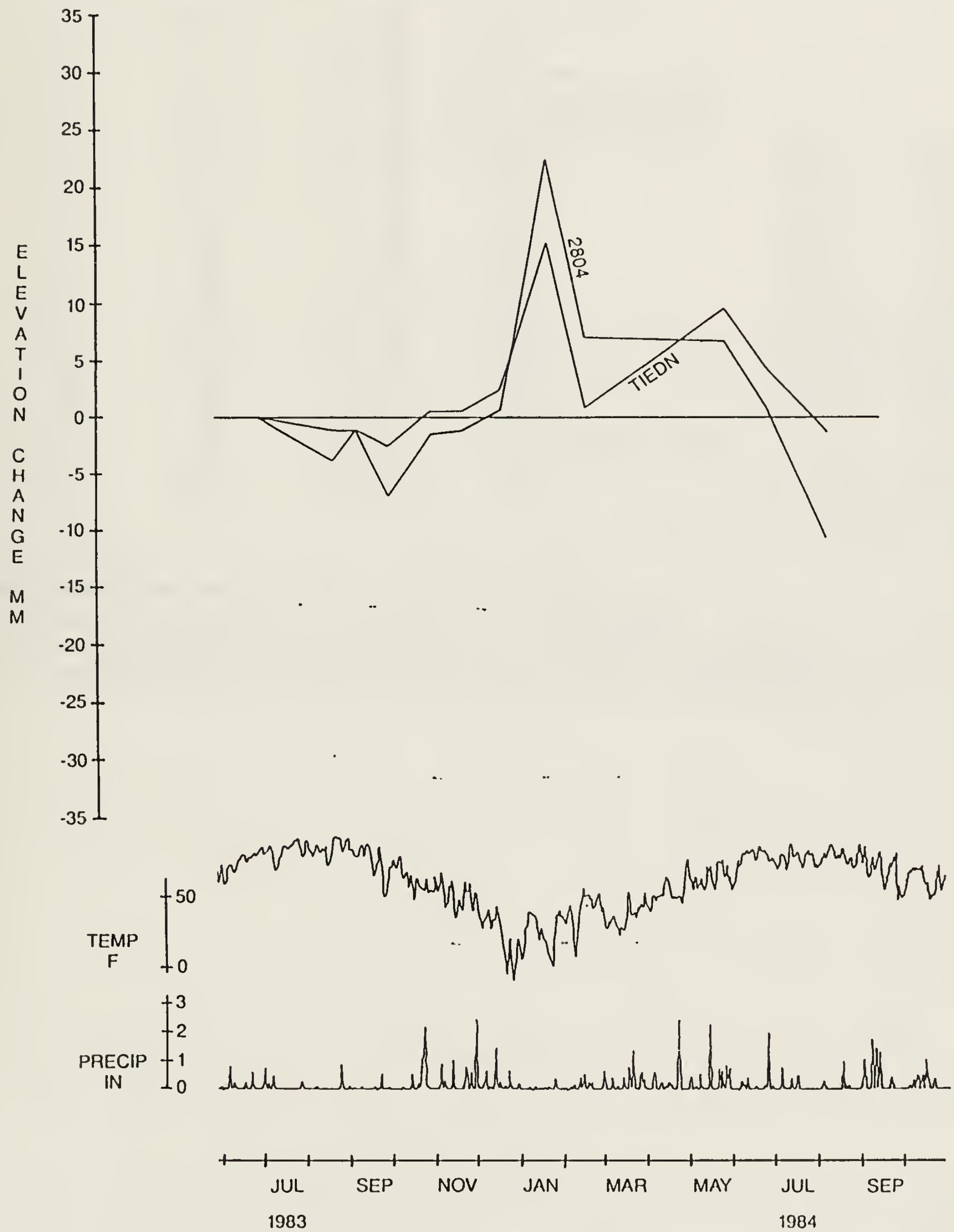


Table 8. Summary of Tilt Plate Data at Earthline Landfill

Plate #	Max Tilt (in degrees)	Largest Incremental change in tilt dip***	Date	Max Elev**** (in mm)	Largest Incremental change in Elevation (mm)***	Date
1026*	0.01	0.07	1-7-82	No elevation data		
1034	0.30	0.27	9-22-83	-25.5	-7.3	8-17-84
1043*	0.17	0.17	9-29-82	No elevation data		
1048*	0.07	0.04	1-7-82	No elevation data		
1054	0.07	0.03	3-2-83	No elevation data		
1111	1.37	1.36	1-19-84	28.0	-36.4	1-20-84
2743	0.12	0.07	11-17-83	5.4**	3.4	2-17-84
A 2775	1.18	1.13	1-19-84	35.2	34.8	1-20-84
2804	1.07	1.02	1-19-84	23.2	22.5	1-20-84
A 2894	0.95	0.95	1-19-84	32.4	32.4	1-20-84
A 2913	0.60	0.58	9-14-84	15.8	11.9	1-20-84
A 3063	0.62	0.37	8-11-83	-14.4	-9.2	8-17-84
A 3073	0.13	0.10	7-15-83	16.0**	12.4	2-17-84
3074	1.25	0.61	5-3-85	27.6	32.3	1-20-84
3075	3.67	2.45	2-17-84	-24.7	-17.1	8-17-84
868*	0.11	0.05	9-29-82	No elevation data		
91026*	0.53	0.17	9-22-83	6.7	-8.7	8-17-84
91048*	0.11	0.08	1-17-83	7.2	-5.4	2-17-84

A Anchored tilt plate.
* Short measurement period or plate required repair.
** Large incremental movement after hiatus in measurements.
*** Largest incremental change in tilt plate dip, WTi-Ti+1, in degrees.
**** Elevations with respect to average of all deep probes except NWDP.

The dates on which the tilt plates experienced their largest increments of tilting movement suggest that the greatest stresses on the trench cover surface are in midwinter and mid summer. However, the time of the largest incremental change in tilt frequently differs from the time of the largest incremental change in elevation. Most plates (10) experienced their largest incremental tilt and elevation changes near the same time, but a few (4) plates experienced their largest tilting about 6 months before or after their largest incremental elevation change. The movements are not considered important as the measured tilting is generally small.

Tilting measured inside and on the perimeter of a sag depression (Plates 1111, 3074, and 3075) is felt to accurately represent the range of movement of a developed depression. The movements of plate 2775 indicate that the depression was expanding. New cracks developing in the cover around the plate confirm the measurements of the expanding depression.

CONCLUSIONS

There does not appear to be evidence of surface subsidence due to collapse of underground mine workings. Neither precision leveling nor surface observations indicated the presence of active mine subsidence. However, these observations do not prove conclusively that there has been no mine-related subsidence at the site, nor do they preclude the occurrence of mine-related subsidence in the future.

The shallow, weather-protected monuments underwent substantial vertical movements. These movements are roughly cyclic, but are not explained by simple linear correlations with available climatic data. Seasonal temperature changes showed the highest correlation with shallow monument movements.

Multiple regression analysis shows that, for the period of study, precipitation was not important in the roughly cyclic movements of the monuments. However, this does not exclude the possibility that precipitation is important in short term phenomena such as shrinking and swelling of soil, nor does this preclude the possibility that precipitation may have a larger influence in other years. Statistical analysis of this relatively short-term study found that total annual rainfall was not an important factor controlling monument movements, however the influence on soil moisture content and groundwater recharge suggests that precipitation measurements at frequent intervals must be recorded at the site.

The interrelationship of temperature and precipitation was not examined, however, this might prove worthy of investigation. Insufficient groundwater elevation data were available for long term analysis.

Tilt plates did not show appreciable tilting (angular) movement. Most showed tilts of less than one degree. Plates in and near a sag-type depression indicated tilts of a little over 3 1/2°. There appears to be little differential tilting of the trench covers. Movements of surface tilt plates tend to be vertical.

Vertical movements of tilt plates appear to be greatest either during the winter or summer. Eight plates indicated maximum change in elevation (positive) during January to March probably in response to volume changes of freezing water. Six plates indicated maximum change in elevation (negative) during August, 1984, probably in response to

shrinkage caused by drought conditions. A comparison of anchored and unanchored tilt plates shows that the two experience the same types of movements, but that unanchored plates experienced a greater range in movement over time.

Maximum changes in tilt generally occurred at the time when there was maximum change in the elevation. Although both undergo a cyclic pattern of seasonal fluctuation, vertical movements of the tilt plates on the trench covers are poorly correlated with movement of the shallow monuments in undisturbed ground. Time series analysis shows that there is no seasonal lag between the monuments and the plates; apparently one can not be used to predict the other.

Largest incremental vertical (elevation) movements of tilt plates do not correlate well with largest incremental angular movements. With a single exception (plate 2804), only those plates surrounding a sag depression in trench 19 experienced consistent, extreme vertical fluctuations probably caused by soil disturbance in relation to settlement (sag) of the trench cover.

Except for those plates which surrounded the sag depressions in trench 19, most of the tilt plates did not show exaggerated vertical movements. Since most tilt plates did not experience large movements this suggests that the designed compaction and hydraulic characteristics of the cover remained intact and relatively unaffected by climatic factors during the 5 years after the landfill was closed in 1979. Nevertheless, the presence and growth of the sag depression demonstrates the need for periodic inspection and maintenance of the trench cover to insure its long term function of shedding rainwater from the cover and diverting runoff away from the landfill.

Tilt plates provide a satisfactory means for measuring vertical and angular movements on a trench cover at specific points, however the use of tilt plates for monitoring the overall condition of a trench cover is impractical. A few tilt plates would not be representative of a large area, and a large number of plates would be too expensive to construct and monitor. Periodic reconnaissance by aerial photography and remote sensing in combination with field inspections would provide more complete monitoring of surface conditions.

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