Investigation of Failure Mechanisms and Migration of Organic Chemicals at Wilsonville, Illinois

by B.L. Herzog, R.A. Griffin, C.J. Stohr, L.R. Follmer, W.J. Morse, and W.J. Su

Abstract

Ground water contamination was discovered in 1981 in a monitoring well at the Earthline disposal facility near Wilsonville, Illinois. Organic chemicals had migrated at a rate 100 to 1000 times greater than predicted when the site received its permit to operate in 1978. Postulated failure mechanisms included migration through previously unmapped permeable zones, subsidence of an underground mine, organic-chemical and clay-mineral interactions, acid-mine drainage and clay interactions, trench-cover settlement, and erosion.

In this investigation, the Illinois State Geological Survey found the primary reason for the rapid migration: the presence of previously undetermined fractures and joints in glacial till. The inaccurate predictions of hydraulic conductivity were based on laboratory-determined values that did not adequately measure the effects of fractures and joints on the transit time calculations. Field-measured hydraulic conductivity values were generally 10 to 1000 times greater than their laboratory-measured counterparts, thus largely accounting for the discrepancy between predicted and actual migration rates in the transit time calculations. The problem was compounded, however, by the burial of liquid wastes and by trench covers that allowed excess surface runoff to enter the trenches. Organic-chemical and clay-mineral interactions may also have exacerbated the problem in areas where liquid organic wastes were buried.

Introduction

Earthline Corp., a subsidiary of SCA Services Inc. began operating a 130-acre (53 hectare) landfill in southwest Illinois near Wilsonville on November 15, 1976. It was a trench-and-fill operation that relied on a clayey till deposit for natural attenuation of leachate. The material, Vandalia Till, is native to the site. Supplementing the till in at least one of the 26 trenches was a liner of compacted native clay soil.

The Illinois Environmental Protection Agency (IEPA) had granted the company a permit to dispose of industrial and hazardous wastes at the site. Several months after the landfill began operation, the citizens of nearby Wilsonville objected to the disposal of hazardous wastes so close to their town. To stop the disposal of wastes and have wastes removed from the site, the citizens group and the Illinois Attorney General filed suit. A long court battle ensued during which Earthline continued to bury wastes.

In 1981, the Illinois Supreme Court affirmed a 1978 trial court ruling that the hazardous wastes be exhumed from the 26 trenches (each approximately 10 to 20 feet [3 to 6m] deep, 50 to 100 feet [15 to 30m] wide, and 175 to 400 feet [53 to 122m] long) and removed from the site. SCA Services announced in March 1982, after discovering that contaminants had migrated from the disposal trenches, that they were dropping further appeals and would comply with the court order. Preparation for exhumation began in the summer of 1982. The actual process of exhumation and removal, which began on September 7, 1982, took more than four years.

In January 1982, the IEPA confirmed that organic pollutants had migrated up to 50 feet (15m) in a three-year period. These migration rates were 100 to 1000 times faster than predicted by engineers who were consulted when the site was planned. The levels of volatile organic priority pollutants detected were reported by Johnson et al. (1983). This discovery, which was a separate issue from the court proceedings and exhumation order made before contamination was discovered, raised two obvious questions: (1) why were these organic compounds migrating faster than predicted, and (2) what were the implications for land disposal of similar wastes at other sites?

A research project was designed by the Illinois State Geological Survey (ISGS) for the U.S. Environmental Protection Agency to provide answers to these and many other questions regarding the efficacy of land disposal of hazardous wastes—particularly organic liquids. The scope of work included studies of several aspects of the site:

- Geological characterization—detailed descriptions of geologic materials and geomorphology.
- Hydrogeological characterization—determination of ground water flow directions and gradients, comparison of field and laboratory measurements of hydraulic conductivity, and evaluation of the significance of

fracture flow.

- Ground water quality—determination of the distribution of organic chemicals across the site, and establishment of a sampling methodology for volatile organic compounds in fine-grained sediments.
- Gob pile effects—investigation of the effects of acidity and high inorganic salt content of leachate from an adjacent coal refuse pile on the trench materials.
- Trench cover studies—observation of the condition of trench covers and the degree of differential settlement, determination of erodibility of cover materials, and determination of the effects of mine subsidence.
- Condition of drums and wastes—photographic documentation of the effects of leachate on drums.

Some individual items in the scope of work have been presented in previous reports. This paper summarizes all the work performed to determine the causes of site failure, and discusses the relative impact of each postulated failure mechanism.

Site Characterization

Geology

An extensive geologic investigation was conducted to place the site in the regional geologic framework and to collect sufficient baseline data for extrapolating the results from this site investigation to other sites. Four principal approaches were taken: (1) examination of all existing data and related information; (2) investigation of outcrops and exposures on and near the site (within about 5 miles); (3) study of the trenches, including the walls of backhoe pits located away from the trenches on and around the site; and (4) study of drillhole samples collected on-site. Samples were collected from each well nest (Figure 1).

Site geology is shown in cross section in Figure 2, along the line shown in Figure 1. The first unit encountered at the land surface is the Peoria Loess, a windblown silt that has been weathered into a modern soil with the texture of clayey silt. It is brown to gray and ranges from 1 to 4 feet (.3 to 1.2m) in thickness across the site. Beneath the Peoria Loess is the Roxana Silt, throughout which the Farmdale Soil formed. This silt, which ranges from 1 to 3 feet (.3 to .9m) thick, has a higher sand content than the Peoria Loess.

Underlying the silty deposits is the Vandalia Till of Illinoian Age; it can be divided into four zones: (1) a brown, stiff, upper weathered zone; (2) a soft weathered zone; (3) a brown, brittle, lower weathered zone; and (4) a gray unweathered zone. A distinct buried soil, the Sangamon Soil, often referred to as a paleosol, forms the main body of Zone 1. Because of leaching, development of the Sangamon Soil in Zone 1 has influenced the character of Zones 2 and 3. The upper three zones of the till range from 8 to 12 feet (2.4 to 3.7m) in thickness at the site. Occasional bedding planes and inclusions with contrasting textures occur. Although discontinuous sand lenses are common throughout the Vandalia Till, they are more common at the base of Zone 4 and constitute a large part of Zone 2. Joints and fractures are numerous in the Sangamon Soil and decrease in frequency toward the base of Zone 3. The main part of Zone 4 has very few joints or fractures; it is uniform, stiff, and somewhat plastic. The thickness of Zone 4 typically varies 5 to 20 feet (1.5 to 6m).

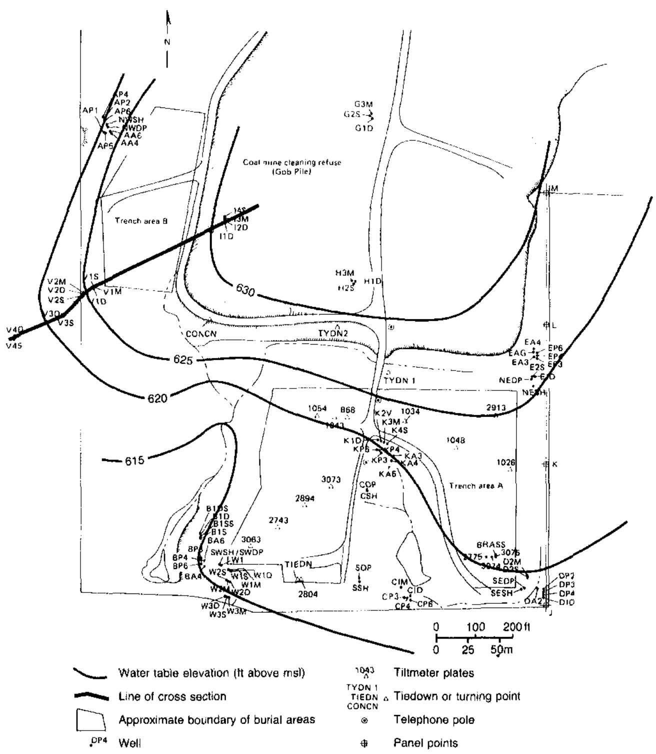

Figure 1. Site map showing elevation of potentiometric surface (feet) in April 1984; locations of trenches, wells and cross section. The first letter in each well or piezometer number designates the nest or profile. For wells within a profile, the second number designates the nest within the profile. The last item denotes well depth: S for shallow, M for medium, and D for deep. For piezometers, the second item is either P for piezometers or A for angled hole. The last item in the identification is a number signifying the order in which the piezometers were installed.

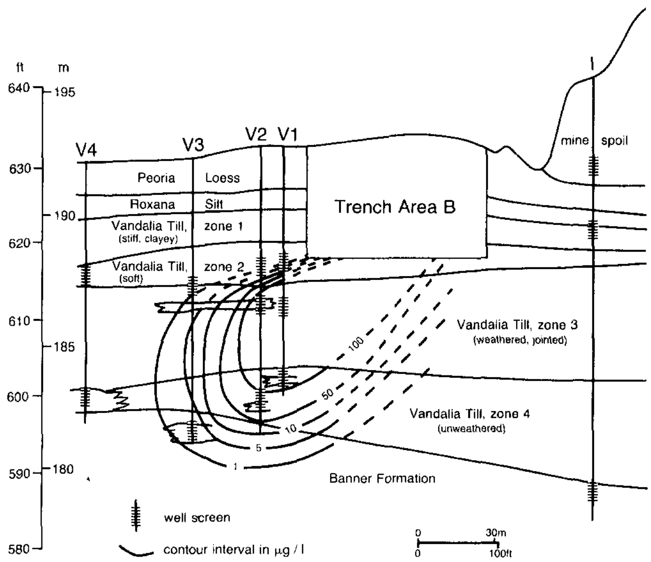

Figure 2. Cross section from Profile V through Trench Area B to the gob pile showing distribution of trichloroethylene (µg/L) in ground water.

Beneath the Vandalia Till are older tills of the Banner Formation. The thickness of this formation at the site is unknown except for one boring at Nest 1, which penetrated more than 40 feet (12m) of the Banner Formation before hitting bedrock.

Hydrogeology

Eleven piezometer nests, nine monitoring well nests, and two well profiles were installed for collection of hydrogeological and geochemical data. Well profiles consisted of three to four nests spaced in a geometric progression from the waste trenches (Figure 1). Piezometer nests consisted of three to six piezometers. Well nests contained two to four wells, and well profiles had eight to 10 wells. Details of piezometer construction were presented by Herzog and Morse (1986) and Griffin et al. (1984). These piezometers were initially used to test in situ hydraulic conductivity and later to establish the long-term potentiometric surface and measure the hydraulic gradient and flow of ground water across the site.

Core samples from borings were subjected to chemical analysis, but water was not analyzed because of interference caused by the addition of water during the slug tests for determination of hydraulic conductivity. Slug test data were interpreted by three methods: Cooper et al. (1967) with additional type curves by Papadopulos et al. (1973), Nguyen and Pinder (1984), and Hvorslev (1951). Results of the slug tests are presented in Table 1; these tests are discussed in detail in Herzog and Morse (1984 and in press).

Hydraulic conductivity along vertical joints was measured by angle drilling at separate locations. Three nests, containing three to four holes per nest, were drilled at a 45° angle to intersect possible vertical joints. In situ hydraulic conductivity (Table 1) was determined by the same methods used for the vertical tests.

Differences between vertical and horizontal hydraulic conductivity ranged from near agreement for the soft upper ablation zone to the till (Figure 2) to more than a factor of 10 in the unaltered basal Vandalia Till. The higher values for vertical flow in the weathered basal Vandalia (Zone 3) are believed to be due to joints in the till, which were observed to have a predominantly vertical orientation. Vertical desiccation joints were observed in nearby exposures of the till, in backhoe trenches at the site, and in continuous cores collected from angle-hole drilling. These joints were common in the Sangamon Soil portion, reached a maximum development in Zone 3, and decreased to near zero in Zone 4.

Hydraulic conductivity values, which were determined from slug tests and interpreted using different analytical methods, were consistent. Although not all data sets could be analyzed using each method, all could be analyzed by at least one method. Slug test values were 10 to 1000 times greater than the laboratory-determined values obtained by consultants for the site owner and reproduced as part of this study (Table 2). Differences are believed to be due to higher flow rates in the discontinuous joints present in the tills and to the different volume of material measured by laboratory and field methods.

A separate set of monitoring wells was constructed

TABLE 1
Geometric Means of Field Hydraulic Conductivity Data

		Slug Tests			
Material	**Orientation**	**Cooper et al. Method (cm/s)**	**Hvorslev Method (cm/s)**	**Nguyen & Pinder (cm/s)**	**Recovery Test (cm/s)**
Gob contact/Peoria Loess	vertical	n.d.	n.d.	n.d.	4.8×10^{-5}
Vandalia Till Zone 1—stiff, clayey	vertical	1.3×10^{-7}	1.2×10^{-7}	1.2×10^{-7}	2.0×10^{-6}
	45° angle		3.0×10^{-7}	4.5×10^{-7}	
Vandalia Till Zone 2—soft	vertical	3.8×10^{-5}	1.2×10^{-5}	1.9×10^{-5}	1.1×10^{-5}
	45° angle	5.3×10^{-5}	8.4×10^{-6}	1.7×10^{-5}	
Vandalia Till Zone 2/3—contact	vertical	n.d.	n.d.	n.d.	4.3×10^{-6}
Vandalia Till Zone 3—altered, jointed	vertical	1.2×10^{-6}	8.4×10^{-7}	2.3×10^{-6}	5.0×10^{-6}
	45° angle	6.0×10^{-6}	2.1×10^{-6}	8.2×10^{-6}	
Vandalia Till Zone 4—unaltered	vertical	8.4×10^{-8}	3.9×10^{-8}	6.5×10^{-8}	8.5×10^{-7}
	45° angle	4.0×10^{-7}	5.7×10^{-7}	6.6×10^{-7}	
Vandalia Till/Banner Formation contact	vertical	n.d.	n.d.	n.d.	1.4×10^{-6}
Banner Formation/shale contact	vertical	n.d.	1.1×10^{-7}	2.8×10^{-6}	1.7×10^{-7}

n.d. = not determined

TABLE 2
Summary of Laboratory Test Results (from Herzog and Morse 1986)

Material	Hydraulic Conductivity from Falling-Head Tests (cm s^{-1})[a]	Hydraulic Conductivity from Triaxial Tests (cm s^{-1})[b]	Hydraulic Conductivity from ISGS Miniature Permeameter Tests	
			Undisturbed Sample (cm s^{-1})	Recompacted Sample (cm s^{-1})
Peoria Loess		1.1×10^{-6}	7.5×10^{-8} to 2.2×10^{-7}	3.3×10^{-8} to 3.6×10^{-8}
Roxana Silt				7.0×10^{-9} to 8.6×10^{-9}
Vandalia Till Ablation Zone, Sangamon B_t Horizon (Zone 1)		1.6×10^{-7}		6.0×10^{-10} to 1.2×10^{-9}
Vandalia Till Lower Ablation Zone (Zone 2)			5.8×10^{-7} to 1.4×10^{-6}	2.6×10^{-8} to 3.5×10^{-8}
Weathered Basal Vandalia Till (Zone 3)	1.2×10^{-8} to 7.4×10^{-8}			1.4×10^{-8} to 4.7×10^{-8}
Unaltered Basal Vandalia Till (Zone 4)	1.3×10^{-8} to 2.7×10^{-8}	4.1×10^{-9}	3.3×10^{-9} to 5.1×10^{-9}	8.9×10^{-9} to 1.1×10^{-8}

[a] Tests conducted by John Mathes Associates (1976).
[b] Tests conducted by Geoengineering Inc. (1982).

for water quality samples. During well development, hydraulic conductivity at the monitoring wells was measured using the recovery test as described by Todd (1980). Recovery test results from the monitoring wells were generally higher than slug test results (Table 1), probably due to the location of monitoring well screens in more permeable zones.

Monitoring wells and piezometers installed by the ISGS and monitoring wells installed by the site owner were used to measure the potentiometric surface in each zone. The shallow potentiometric surface is shown in Figure 1. Potentiometric surfaces of deeper zones showed the same general pattern of flow directions as did the shallow potentiometric surface, but with lower water levels, indicating that the zones are connected and the vertical gradient is downward. Figure 1 also shows the influence of the gob pile on ground water flow at the site; ground water flows radially outward from the gob pile.

Geochemistry

Sampling Procedures

Because no protocol existed for collecting volatile organic compound samples from wells finished in fine-grained sediments, it was necessary to establish procedures for this project. Ground water was sampled in a time series from wells V1D, V2D, and V3D, and analyzed for several volatile organic compounds. These samples were retrieved using dedicated point-source bailers equipped with bottom-emptying devices. Samples were collected in VOA vials and analyzed by gas chromatograph in the laboratory.

These tests, described fully in Griffin et al. (1985), showed dramatic changes in concentrations with time after the wells were purged. Most volatile organic compounds were found at their lowest concentration before purging and their greatest concentration after two to 24 hours of recharge. Because of the result of these tests, water samples were collected two to 24 hours after each well was purged.

Contaminant Distribution

Soil samples from the deepest well in each nest and liquid samples from each monitoring well were analyzed for organic compounds. The soil was sampled during drilling of boreholes for placement of the monitoring wells. As reported by Griffin et al. (1984), the highest concentrations of organic chemicals were found over most of the site in the upper three zones of the Vandalia Till. Along profile V, the zone of highest contamination was in Zone 3 of the till. These zones had higher hydraulic conductivities than the underlying zones (Table 1). The overlying Roxana Silt and Peoria Loess are generally unsaturated. Figure 4 shows a typical pattern, using trichloroethylene as an example.

Monitoring well results indicated that organic compounds were also found in Zone 4, the unweathered Vandalia Till. The highest levels of contamination were found on the southwest corner of the site at Nests W1 and B in Zone 4. In these wells, endrin and dieldrin were present at concentrations greater than 1 percent and phase separation occurred. High levels of contamination in the unalterered Vandalia suggested that contaminants were moving downward through permeable materials or sand lenses, interconnected joints, or clay materials. The clays may have been altered by chemical interactions with a free liquid organic phase, thereby increasing the hydraulic conductivity in that area of the site.

Gob Pile Effects

The gob pile (coal cleaning refuse) was studied to determine whether acid mine drainage had increased the rate of contaminant migration. Soil pH was measured at vertical increments of approximately 1 foot (.3m) at Nest 1. In the gob, pH values ranged from 1.85 to 2.40, with the lower values occurring at the bottom of the pile. The recorded pH measurement immediately below the gob pile was 3.25. Within 8 feet (2.4m) below the bottom of the gob pile, pH values were greater than 7 and between 7 and 9 for the remainder of the stratigraphic column. The pH was also measured at monitoring wells in Nest A and Profiles V and W. All water samples had pH values between 6 and 7.

Whether leachates from the gob pile had affected the rate of contaminant migration was investigated by analyzing the underlying Pleistocene deposits for possible chemical and mineralogical changes. This led to the detection of mixed-layered kaolinite/smectite (K/S), which is an indicator of intense weathering in soils. The irregular distribution of the K/S layer was congruent with the complex pattern of well-drained and poorly drained soils present when the Sangamon Soil formed (Follmer 1984). No alteration of feldspar to kaolinite was observed, as would be expected if the gob pile was affecting site mineralogy. This evidence, combined with soil and water pH analyses, indicated that acid mine drainage had not contributed to the migration of the organic compounds in ground water.

Trench Cover Studies

Trench covers were intended to prevent water from entering trenches containing buried wastes, and, thereby, to prevent leachate from flushing into the surrounding ecosystem. Field and laboratory studies of the landfill trench covers were undertaken to determine whether the covers contributed to faster-than-predicted leachate migration by allowing surface water to recharge into the trenches, thus increasing the local ground water gradients.

Surface hydrology of the covers was studied by interpretation of large-scale aerial photography. Photointerpretation showed that erosion control dikes and access roads blocked runoff, causing water to flow over some trench covers. At one trench where considerable ponding occurred, undisturbed side walls between two trenches were water-saturated and unable to support the vertical slopes of a shallow excavation; such excavations were possible where ponding had not occurred. Impediments to surface drainage probably contributed to pollutant migration by allowing rain water to infiltrate through the covers and recharge the burial trenches.

An open hole approximately 3 feet (1m) deep was discovered in a trench in Area B (Figure 1) during the initial site visit. A total of six depressions were located in the covers of the three burial areas. Subsequent stereoscopic interpretation of large-scale aerial photographs led to the identification of 22 additional depressions. Photointerpretation permitted the recognition of subtle features with gradual slopes over a large area. Because visual observation is often hampered by vegetal growth, close inspection is required to identify small, abrupt features (Stohr et al. 1985).

Ground-based, post-sunset thermal infrared imagery recorded three days after a rainstorm showed a distinct contrast between a few freely draining depressions and moisture-retaining depressions. Freely draining depressions had an emittance temperature of about the same intensity as surrounding trench cover material; however, moisture-retaining depressions were readily distinguished by their cooler temperature emittance (Stohr et al. 1985).

Depressions were probably either caused by irregularities in site grading and compaction, or formed after construction of the cover. While a depression holding water near the surface will allow longer time for recharge, some of the water will also be lost to evapotranspiration. Freely draining depressions, however, allow all the surface water to recharge the burial trenches, and consequently are of much greater concern.

Two types of freely draining depressions, sag and pipe, were observed. Sag depressions appear to have formed as cover materials settled over waste containers or voids collapsed between containers. The edges around the depressions cracked between the undisturbed and collapsed cover materials.

A pipe depression in the trench cover is an open hole that resembles "pipe" in loessal soil and earth dams (Sherard et al. 1976b). Piping might be due to dispersive soils (Sherard et al. 1976a, 1976b). Samples of local strata and the trench cover were analyzed using the pinhole test, which is a technique for determining solid susceptibility to internal erosion or piping (Sherard et al. 1976a, Figure 3). Loess shows both high and moderate susceptibility to piping. Some samples collected from trench Area B, where piping occurred, were found to be highly erodible. Piping of the trench covers was likely due to the use of highly erodible materials in the covers (Stohr et al. 1987).

Differential Settlement

The rate of post-closure settlement and flexure of trench covers was determined by construction of tilt plates on the trench covers and weather-protected monuments on undisturbed ground (Griffin et al. 1983). Vertical surveys and tilt plate measurements were made monthly for an 18-month period.

The tilt plates on the trench covers showed considerably more movement than the shallow monuments in undisturbed earth. Tilt plates in or near a freely draining sag depression in one trench exhibited movements more exaggerated than those in other areas, whereas plates in other locations showed comparatively less movement.

Analysis of differential tilting of the trench covers showed that except for plates directly in or alongside a sag depression, angular movements were less than 0.5°. Angular movements of the surface of the trench cover appeared to involve vertical, plastic movements with only minor tilting, except where a depression was actively developing. The largest vertical movements often occurred six months after the largest angular movements. Development of such depressions suggests the need for periodic inspection and maintenance of the area.

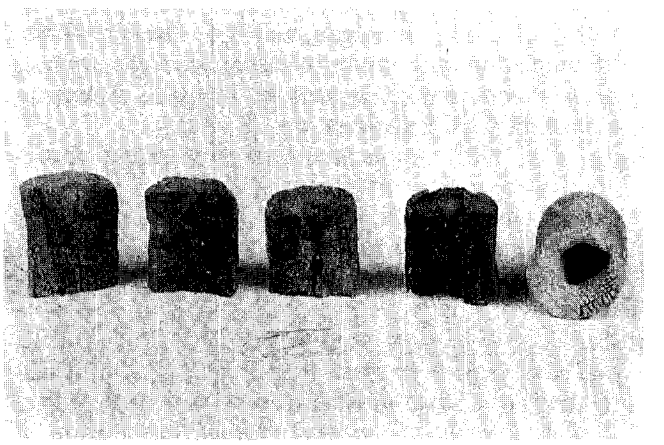

Figure 3. Pinhole tests of non-erosive materials on left, and highly erosive materials on right. The 1mm pinhole for each sample was the same diameter as a paper clip. The hole in soil sample at extreme right was formed in two minutes at a 2-inch (50mm) elevation head (from Stohr et al. 1985).

Mine Subsidence

Subsidence of an underground coal mine, located approximately 300 feet (90m) below the site, was considered for its possible effects on trench stability. Soil fracturing associated with trench instability might increase the rates of chemical migration. Stereoscopic examination of prelandfill aerial photographs indicated only one depression adjacent to the landfill site. Tree canopies obscured the ground in some areas; however, no pattern of tilting trees was observed. A ground reconnaissance survey prior to exhumation activities found no indication of mine subsidence at the landfill site.

Monthly precision (third order) vertical surveys of deep settlement probes set at or below the bottom of the burial trenches were performed to measure near-surface movements that would indicate possible instability from collapse of underground mines. Statistical analysis by Pearson correlation coefficients showed that most of the deep probes correlated highly with each other. The movement of one anomalous probe was believed to have been caused by slope instability due to its proximity to a steep slope. The conclusion was that no recent mine subsidence had occurred at the site, and therefore, that mine subsidence had no effect on the rate of chemical migration.

Condition of Drums and Wastes

The condition of the drums and other wastes was documented photographically as they were removed from the trenches. The data were used to help interpret the effects of leachate on the drums and earth materials, the relative strength of the leachate, and the life expectancy of the drums. The condition of drums exhumed was highly variable, ranging from well-preserved and intact to highly degraded. During the excavation of Trench 24, the paint was found intact on some drums buried three years earlier and sitting in an unidentified orange-brown liquid. The condition of these drums and some intact sacks of herbicide suggests that the longevity of waste containers in a landfill depends on their original condition, handling, and contents as well as the composition of fluids surrounding the container.

Stereo photography was used to record drum orientation using a 2-foot (0.6m) aluminum cube assembled on-site for orientation of stereo photography (Stohr 1983). Photographic observations of drums and other waste containers were made periodically during the landfill exhumation. Results from a study of drum orientation in Trench 24 indicated that inclination varied from 0° to 32° from the vertical as measured from a photograph externally oriented by means of the aluminum cube. Void space between the drums was calculated to range from 17 to 38 percent of the trench volume.

Conclusions

The primary reason that the Wilsonville industrial waste-disposal site failed to perform as predicted was that the earth materials were more hydraulically conductive than early laboratory tests had indicated. The original predictions, which were based on laboratory-determined values of hydraulic conductivity, were made in accordance with the accepted practices of the time. These laboratory values were reproduced in this study. However, the field-determined values of horizontal hydraulic conductivity were 10 to 1000 times greater than laboratory-determined values. In addition, the original investigation did not recognize the importance of vertical joints and unconnected sand lenses. These joints caused the vertical hydraulic conductivity to be up to 10 times greater than the horizontal value. Joints and sand lenses also presented preferential pathways for both horizontal and vertical movement of chemicals at the site.

Rates of chemical migration may also have been enhanced by differential settlement. Highly erodable earth materials allowed freely draining depressions to develop in the trench covers permitting surface water to enter the trenches, interact with the waste, and increase local ground water gradients out of the trenches.

Reactions of organic chemicals with clay minerals may also have been a contributing factor. The highest levels of contamination, found at Nest B and Profile W, were immediately downgradient of an area where large quantities of free liquid wastes (no drums) were buried. Interactions between these immiscible chemicals and the clay minerals may have opened joints, allowing an increase in downward flow. This mechanism does not appear to be significant elsewhere on the site where wastes were buried in drums.

The site was not affected by acid mine drainage or subsidence associated with the abandoned coal mine; however, the coal refuse pile created a ground water mound that affected the local flow direction and gradients of the shallow ground water flow system.

References

Cooper, H.H., J.D. Bredehoeft, and I.S. Papadopulos. 1967. Response of a finite-diameter well to an instantaneous charge of water. *Water Resources Research*, v. 3, pp. 263-269.

Follmer, L.R. 1984. Soil—An uncertain medium for waste disposal. In *Proceedings of the Seventh Annual Madi-*

son Waste Conference. University of Wisconsin-Extension, Madison, Wisconsin, pp. 296-311.

Geoengineering Inc. 1928. Proposed Remedial Action Plan, Earthline Site, Wilsonville, Illinois. SCA Chemical Services Inc., Boston, Massachusetts, 39 pp. plus appendixes.

Griffin, R.A., K. Cartwright, P.B. DuMontelle, L.R. Follmer, C.J. Stohr, T.M. Johnson, M.M. Killey, R.E. Hughes, B.L. Herzog, and W.J. Morse. 1983. Investigation of clay soil behavior and migration of industrial chemicals at Wilsonville, Illinois. In *Proceedings of the Ninth Annual Research Symposium of the Solid and Hazardous Waste Research Division.* U.S. Environmental Protection Agency, Cincinnati, Ohio. EPA-600/9-8-3-018, pp. 70-79.

Griffin, R.A., R.E. Hughes, L.R. Follmer, C.J. Stohr, W.J. Morse, T.M. Johnson, J.K. Bartz, J.D. Steele, K. Cartwright, M.M. Killey, and P.B. DuMontelle. 1984. Migration of industrial chemicals and soil-waste interactions at Wilsonville, Illinois. In *Proceedings of the Tenth Annual Research Symposium of the Soil and Hazardous Research Division.* U.S. Environmental Protection Agency, Cincinnati, Ohio. EPA-600/9-89-007, pp. 61-77.

Griffin, R.A., B.L. Herzog, T.M. Johnson, W.J. Morse, R.E. Hughes, S.F.S. Chou, and L.R. Follmer. 1985. Mechanisms of contaminant migration through a clay barrier—case study, Wilsonville, Illinois. In *Proceedings of the Eleventh Annual Research Symposium of the Solid and Hazardous Research Division.* U.S. Environmental Protection Agency, Cincinnati, Ohio. EPA-600/9-85-013, pp. 27-38.

Herzog, B.L., and W.J. Morse. 1986. Hydraulic conductivity at a hazardous waste disposal site: comparison of laboratory and field-determined values. *Waste Management and Research*, v. 4, pp. 177-187.

Hvorslev, M.J. 1951. *Time Lag and Soil Permeability in Ground-Water Observation.* Bulletin 36. Waterways Experiment Station. U.S. Army Corps of Engineers, Vicksburg, Mississippi, 50 pp.

Johnson, T.M., R.A. Griffin, K. Cartwright, L.R. Follmer, B.L. Herzog, W.J. Morse, P.B. DuMontelle, M.M. Killey, C.J. Stohr, and R.C. Hughes. 1983. Hydrologic investigations of failure mechanisms and migration of organic chemicals at Wilsonville, Illinois. In *Proceedings of the Third National Symposium on Aquifer Restoration and Ground-Water Monitoring,* National Water Well Association, Dublin, Ohio, pp. 413-420.

John Mathes and Associates. 1976.*Report of Subsurface Investigation: Proposed Site of Industrial Residue Management Facility, Earthline Corp., Wilsonville, Illinois.* Columbia, 38 pp.

Nguyen, V. and G.F. Pinder. 1984. Direct calculation of aquifer parameters in slug test analysis. In *Groundwater Hydraulics.* (Eds. J. Rosensheim and G.D. Bennet). Monograph 9, American Geophysical Union Water Resources. pp. 222-239.

Papadopulos, S.S., J.S. Bredehoeft, and H.H. Cooper. 1973. On the analysis of slug test data. *Water Resources Research*, v. 9, pp. 1087-1089.

Sherard, J.L., L.P. Dunnigan, R.S. Decker, and E.F. Steele. 1976a. Pinhole test for identifying dispersive soils. *Journal of the Geotechnical Division,* American Society of Civil Engineers, v. 102, no. GT1, pp. 69-85.

Sherard, J.L., L.P. Dunnigan, and R.S. Decker. 1976b. Identification and nature of dispersive soils. *Journal of the Geotechnical Engineering Division,* American Society of Civil Engineers, pp. 287-301.

Stohr, C.J. 1983. Applications of close-range photogrammetry for geologic investigations during the exhumation of a hazardous-waste disposal site. Technical papers of the 49th annual meeting of the American Society of Photogrammetry, Washington, D.C. American Society of Photogrammetry, pp. 267-273.

Stohr, C.J., W.J. Su, L.R. Follmer, P.B. DuMontelle, and R.A. Griffin. In press. Engineering geology investigations of a hazardous-waste landfill in west-central Illinois. *Bulletin of the International Association of Engineering Geology*, v. 37.

Stohr, C.J., W.J. Su, P.B. DuMontelle, and R.A. Griffin. 1987. Remote sensing investigations at a hazardous waste landfill. *Photogrammatric Engineering and Remote Sensing*, v. 53, no. 11, pp. 1555-1563. American Society of Photogrammetry, Falls Church, Virginia.

Stohr, C.J., W.J. Su, P.B. DuMontelle, and R.A. Griffin. 1987. Engineering geology investigations of a hazardous west-central Illinois. In review.

Todd, D.K. 1980. *Groundwater Hydrology.* 2nd Ed. John Wiley and Sons, New York, New York, chapter 4.

Acknowledgments

This research was carried out under Cooperative Agreement R810442-01 of the U.S. Environmental Protection Agency, Land Pollution Control Division, Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio. Dr. Mike H. Roulier was the project officer. Colleagues at the Illinois State Geological Survey performed field or laboratory work in conjunction with this project. The Illinois Environmental Protection Agency provided the drilling. SCA Chemical Services Inc. provided site access, safety equipment, and material for monitoring well and piezometer construction. Waste Management Inc. also provided site access, disposal of waste water, and provided some analytical support. Daniel Cole of Southern Illinois University participated in the site surveying and engineering geology measurements.

Although the research described has been funded in part by the U.S. Environmental Protection Agency, this article has been been subjected to Agency review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Biographical Sketches

Beverly L. Herzog, CGWP #257, is an associate hydrogeologist with the Illinois State Geological Survey (615 E. Peabody Dr., Champaign, IL 61820). She earned a B.S. in geology from the University of Wisconsin-Oshkosh (1976), and an M.S. in hydrology from Stanford University (1978) and has completed course work for a Ph.D. in civil engineering from the University of Illinois. Her research interests include ground water monitoring and modeling and landfill hydrology. Herzog has been a member of the National Water Well Association since 1978 and serves on the editorial boards for Journal of **Ground Water** ***and*** **Ground Water Monitoring Review.**

Robert A. Griffin is principal chemist and head of the Environmental Geology and Geochemistry Branch of the Illinois State Geological Survey (615 E. Peabody Dr., Champaign, IL 61820). He has a B.S. (1966) and an M.S. (1968) in soil chemistry from the University of California, and a Ph.D. (1973) in soil physical chemistry from Utah State University. His primary research interests are in contaminant transport processes in earth materials.

Christopher J. Stohr obtained a B.S. in geology from St. Joseph's College, Rensselaer, Indiana, and an M.S. in engineering geology from Purdue University, West Lafayette, Indiana. As an engineering geologist with the Missouri Geological Survey he investigated many landfills and waste disposal facilities, directed a statewide inventory of 3600 dams, and conducted a regional investigation of the state for hazardous waste isolation. He is an associate engineering geologist and remote sensing coordinator at the Illinois State Geological Survey (615 E. Peabody Dr., Champaign, IL 61820) where he has conducted research in soil properties, waste management, and remote sensing since 1980. Stohr also lectures at the University of Illinois Geography Department on photointerpretation.

Leon R. Follmer is coordinator of Quaternary Studies, vice chair of the Quaternary Geology Committee, and chair of the Radiocarbon Dating Committee, Illinois State Geological Survey (615 E. Peabody Dr., Champaign, IL 61820). He obtained a B.S. from Western Illinois University, and an M.S. and Ph.D. in pedology from the University of Illinois. He holds adjunct appointments in the Department of Geology and Geography, and collaborator status with the College of Agriculture at the University of Illinois, and participates in graduate student research programs and serves as a field research advisor in pedology, soil-geomorphology, and glacial geology. Current research activity is in glacial mapping, pedostratigraphy, and field identification of paleosols.

Walter J. Morse is an associate staff geologist in the Groundwater Resources Section of the Illinois State Geological Survey (615 E. Peabody Dr., Champaign, IL 61820). He has lived most of his life in Illinois, and has a B.S. from the Geology Department of Illinois State University. Current research projects include exploration for and mapping of ground water resources, and investigation of ground water depletion by overpumping of aquifers. Surface and downhole geophysics are important components of these projects. Other research interests include ground water contaminate migration and hydrogeology of karst terrain.

Wen-June Su, an assistant engineering geologist at the Illinois State Geological Survey (615 E. Peabody Dr., Champaign, IL 61820), was born in Taiwan in 1951. He obtained a B.S. and an M.S. in geology in Taiwan. He worked as an engineering geologist in a consulting company in Taiwan from 1978 to 1980. He also taught an engineering geology course at the University of Chinese Culture, Taiwan, in 1979.