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Hydrogeologic Investigations of Failure Mechanisms and Migration of Organic Chemicals at Wilsonville, Illinois

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Introduction

This study was initiated after the Illinois Supreme Court affirmed a trial court order requiring the exhumation and removal of wastes at a hazardous waste disposal facility near Wilsonville, Illinois (Macoupin County). The reason for the order was the proximity of the site to Wilsonville and potential for harm to the town from continued operation of the site. The order provided a unique opportunity to examine in detail the effects of the wastes on soils below and adjacent to the site and to measure the migration of contaminants from the trenches. Work is currently in progress; however, preliminary results have been obtained. These preliminary results and a description of the approach are presented here because they may be useful to others evaluating hazardous waste disposal sites.

The study of the site is a cooperative effort between several agencies and the site owner. The U.S. EPA has supplied a major part of the funding through a cooperative agreement with the Illinois State Geological Survey, whose personnel are performing a majority of the work. The Illinois EPA has provided a drill rig and crew for the field studies and is performing organic analyses on soil and water samples from the site. The site owner, SCA Services Inc., has provided access to the site, safety training and a substantial amount of the materials for construction of the monitoring wells.

Background Events

Earthline Corp., a subsidiary of SCA Services Inc., began operating a 130-acre landfill near Wilsonville, Illinois, on November 15, 1976. The operation was a trench-and-fill procedure that relied on a clayey glacial till deposit native to the site for natural attenuation of any leachate. A compacted clay liner was used to supplement native till in at least one of the trenches. The company had applied for and received a permit from the Illinois Environmental Protection Agency (IEPA) to dispose of industrial and hazardous wastes at the site. Several months after the landfill was in operation, the citizens of Wilsonville became alarmed at the disposal of hazardous wastes in the proximity of their community. They filed suit to stop the disposal of wastes and to have them removed from the site. A lengthy court battle ensued, and Earthline continued to bury wastes. In March 1982, the Illinois Supreme Court affirmed the May 1981 trial court's ruling that the hazardous wastes buried in the approximately 26 trenches (each 10 to 20 feet deep, 50 feet wide, and 250 to 350 feet long) at Wilsonville must be exhumed and removed from the site. SCA Services Inc. announced in March 1982 that they were dropping further appeals and would comply with the court order. The preparations began in the summer of 1982, and the actual exhumation and removal process, begun September 7, 1982, is expected to continue over a four-year period.

Earlier that year, in February 1982, the IEPA discovered that routine monitoring of wells at the site had shown migration of organic pollutants as far as 50 feet from the trenches in a three-year period. This discovery was a separate issue from the court proceedings and exhumation order. The migration rates were 100 to 1,000 times faster than predicted. Two obvious questions were posed: (1) Why were these organic compounds migrating faster than predicted, and (2) What are the implications to land disposal of similar wastes at other sites? This research project was designed to provide answers to these and many other questions regarding the impact of land disposal of hazardous wastes, particularly organic liquids.

Objectives

The project aims to determine why several organic contaminants detected in monitoring wells around the trenches are migrating faster than predicted and what the implications are to land disposal of similar wastes at other sites. The scope of work includes studies of several aspects of site behavior.

- Site characterization—Detailed descriptions of geologic materials, geomorphology and hydrogeology; comparison of field and laboratory measurements of hydraulic conductivity and effective porosity; significance of fracture flow.
- Organic chemical effects—Measurement of actual migration rates of organic chemicals through soils at the site; laboratory studies to determine effects of organic chemicals on permeability and pore structure of clay soils.
- Clay liner construction—Effects of waste leachate on 5-foot recompacted clay liner in Trench No. 24.
- Acid mine drainage—Effects of acidity and high inorganic salt content of leachate from adjacent coal refuse pile on clay soils.
- Condition of trench covers—Observations of condition of trench covers relative to surface erosion and differential settlement.
- Condition of drums and wastes—Photographic documentation of effects of leachate on drums.

Research Plan

Multidisciplinary Approach and Safety Procedures

A multidisciplinary/multiagency approach was adopted early in the planning of this project. Cooperation with the site operators improved access to the site and reduced legal problems. Consolidation of efforts also reduced the number of borings, samples and analyses.

The multidisciplinary nature of the project and the uncertainty over the potential hazards that would be encountered at the site demanded detailed preparations for the field work. These involved organizational meetings with representatives of the three government agencies and the operators of the site to delineate areas of responsibility, liability and allocation of resources. Special safety measures prescribed for all on-site staff were: (1) successful completion of an eight-hour first-aid training course, (2) instruction in use of protective breathing apparatus and (3) a thorough medical examination before beginning field work. In addition, a special first-aid kit was prepared, and the route from the site to the nearest hospital emergency room was traveled by the field team. Protective clothing routinely worn during field work includes hard hat, disposable coveralls, rubber boots and protective gloves appropriate for the particular task. Organic vapors are monitored during drilling and other activities, and when concentrations exceed 100 ppm, protective breathing apparatus is worn. Positive pressure breathing apparatus is worn at all times when working in the trenches. Explosive gas mixtures are monitored with an explosive gas meter. A fire truck is on-site at all times. Other routine and special safety precautions are also employed as deemed appropriate.

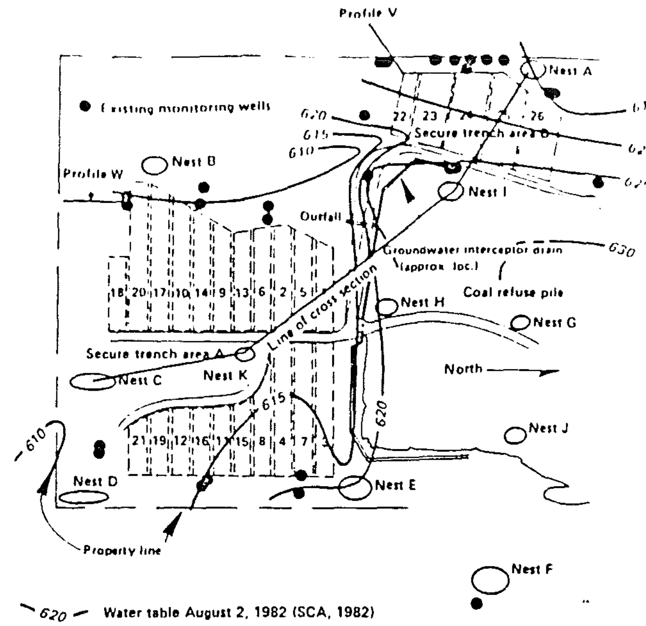

Figure 1. Site map showing water-table elevation on August 2, 1982, and the location of the cross section, as well as locations of trench areas and SCA monitoring wells and borings in relation to project well nests and profiles

Geological Characterization

An extensive geologic investigation and description of the site is being carried out to place this site in the proper regional geologic framework and to collect sufficient baseline data for extrapolating the results from our investigation to other sites.

The geologic characterization is being carried out by four principal means: (1) examination of all previously gathered data and information, (2) investigation of outcrops and exposures at and in the vicinity of the site, (3) study of the trench walls themselves and backhoe pits at selected locations on and around the site and (4) study of drill samples collected on and around the site.

A map of the site study area and the overall drilling plan appear in Figure 1. The drilling includes 11 nests of piezometers and monitoring wells labeled A through K and two profiles of monitoring wells labeled V and W, a total of more than 70 holes. The deepest hole at each nest and profile location was continuously sampled using push tubes near the surface and split-spoon methods for the deeper samples. The samples were logged in the field, preserved in core boxes and transported to the laboratory, where detailed sampling and descriptions are being carried out. Sixteen locations at the site were continuously sampled for stratigraphic, geologic and chemical characterization. These 16 holes were commonly 30 to 45 feet deep, but some holes were deeper, including a deep stratigraphic

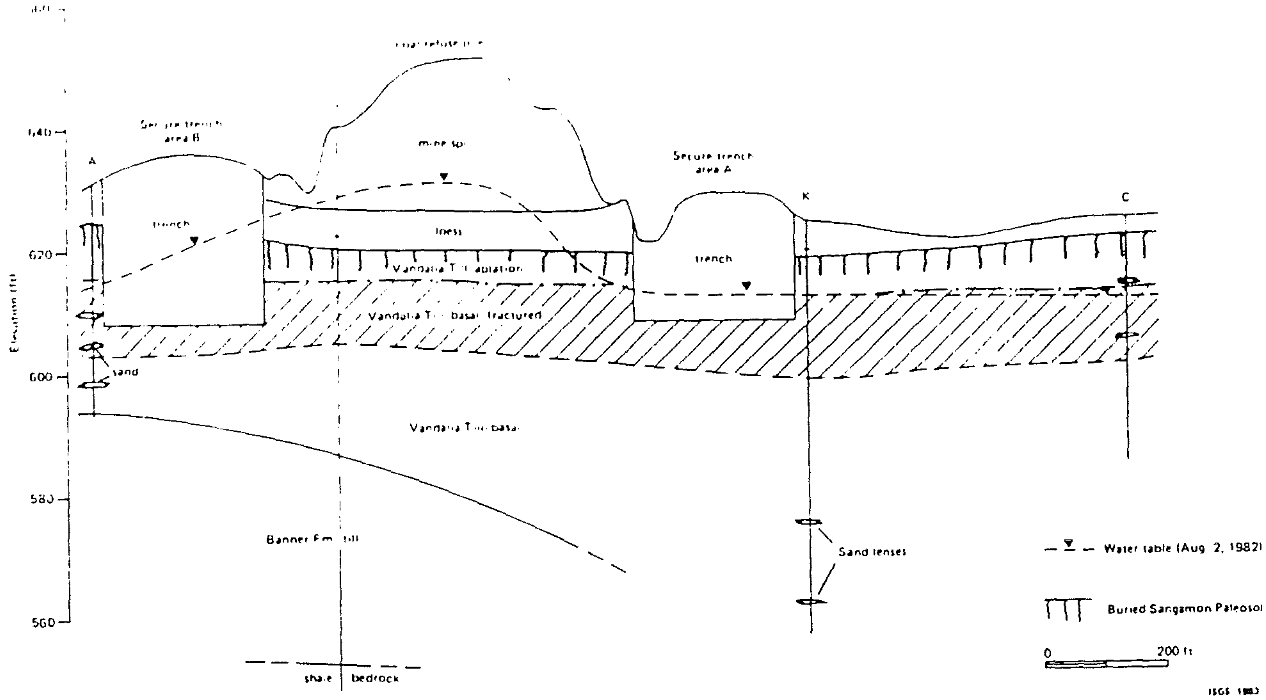

Figure 2. Schematic cross section of Wilsonville site showing the sequence of geologic materials interpreted from project borings and the water-table elevation in relation to trench areas. Elevations are approximate

control hole at nest I that was continuously sampled to 92 feet, where bedrock was encountered. Split-spoon samples were also collected at intermittent depths from all the other holes drilled at the site.

The Wilsonville site is underlain by 50 to 100 feet of glacial drift that overlies Pennsylvanian age shale bedrock. The sequence of unconsolidated materials underlying the site is illustrated in Figure 2, a cross section of the site, and in the generalized stratigraphic column in Figure 3. Figure 3 also indicates the average texture of each of the geologic units underlying the site.

A coal refuse pile covers about 10 acres of the site with approximately 15 to 30 feet of rock debris from an underground coal mine. The surficial geologic materials at the site consist of 2 to 8 feet of windblown silt deposits, the Peoria Loess and Roxana Silt. Beneath the mantle of loess is a thick sequence of glacial tills with only occasional thin, discontinuous lenses of silt, sand and gravel.

The uppermost glacial till at Wilsonville is the Vandalia Till Member of the Glasford Formation, which ranges from 25 to 60 feet in thickness. The disposal trenches at the site were excavated into this unit to depths of approximately 10 to 20 feet (Figure 2). The upper portion of the Vandalia Till is weathered to a depth of as much as 15 to 20 feet. The upper weathered portion constitutes the Sangamon Soil profile formed prior to loess deposition. The Vandalia Till typically consists of four zones: 1) weathered, leached, clayey, stiff ablation till (Sangamon Paleosol); underlain by 2) weathered, leached, loamy, soft ablation till; 3) partly weathered, calcareous, loamy, brittle, fractured, dense basal till; and 4) unweathered, calcareous, loamy, stiff, semi-plastic, dense basal till.

The zone of fractured basal till was found to be locally highly jointed. In cores, these joints were typically stained with iron, were predominantly horizontal and dissipated with depth. The major factors in joint development within the till are thought to be related primarily to stress release and to the weathering

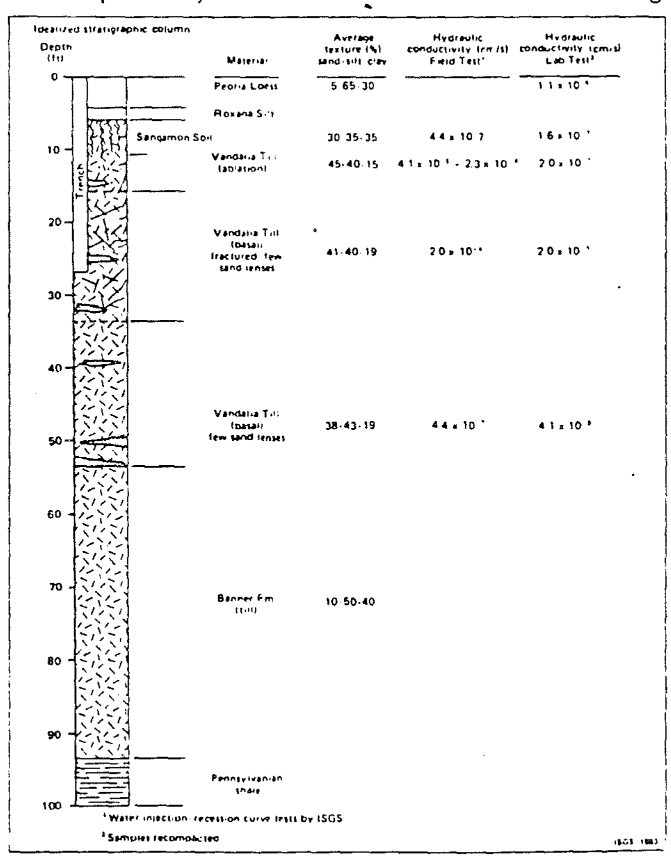

Figure 3. Idealized stratigraphic column, results of field and laboratory tests of hydraulic conductivity and texture of geologic materials at Wilsonville site. Actual trench depths generally ranged from 10 to 20 feet

processes of oxidation and carbonate cementation. These factors appear to make the upper basal material more brittle than the lower basal till.

The underlying unweathered, basal till phase of the Vandalia Till was generally unfractured. Between the base of the Vandalia Till and the underlying shale bedrock is a sequence of older, fine-grained glacial tills of the Banner Formation.

Lenses of silt, sand and gravel are present locally throughout the glacial drift sequence. Although these lenses are typically less than 2 inches thick, 6 feet of clean gravel was found in one boring. Where present, these lenses are commonly found between stratigraphic units and subunits; however, there appears to be no significant lateral continuity of these lenses.

Special emphasis has been placed on assessing the normal pedologic and geologic features (facies change phenomena, soil horizonation, etc.) in and around the trenches to develop a classification for materials that distinguishes classes of normal and disturbed materials. Assuming that all materials within the trenched area are disturbed to some degree, sites away from the trenches have been sought to establish the normal relationships. For increased confidence in the stratigraphic interpretations, cores from the surrounding region are being collected and evaluated. In addition, more than seven backhoe pits in undisturbed locations adjacent to the trenched area have been examined to complement the study of the exposures produced by the trench excavations.

The geologic characterization is focusing particular attention on morphological changes in the soil materials because it is suspected that organic solvents may affect soil structure. Meso- and micro-morphological features will be studied at selected distances from the trench walls and bottoms. These features will be compared with those of normal samples to determine whether the wastes have imparted patterns of change into the morphologies of exposed soils.

Detailed physical and chemical laboratory characterizations are also being conducted on selected samples from the drilling and trench sampling programs. These include particle-size analysis, clay and mineralogical characterization, petrographic (micro-morphologic) evaluation, hydraulic conductivity, pore size distribution, surface area, pore volume, moisture, density and other geologic and engineering tests as appropriate. Complete chemical characterization includes analyses of volatile and semivolatile organics and 30 to 45 inorganic parameters.

Hydrogeologic/Geochemical Studies

An extensive hydrogeologic and geochemical investigation of the site is under way and includes borings of 11 piezometer nests (nests A to K, in Figure 1) with three to six piezometers per nest. These piezometers are being used initially for in situ hydraulic conductivity tests at the various depths of the piezometers. Later these piezometers will be used to establish the long-term piezometric surface and in turn the hydraulic gradient and flow across the site. Core samples from these borings will be used for chemical analysis. Water chemistry will not be analyzed because of interference caused by the addition of water during the hydraulic conductivity slug tests.

A separate set of monitoring wells has been constructed for water chemistry samples. These include at least two monitoring wells at each nest and up to 22 wells positioned in a geometric progression from the trenches along two lines. These lines have been designated as V and W in Figure 1. Cores and disturbed samples from the drilling will be subjected to hydraulic conductivity and chemical measurements.

The elevation of the water table at the site measured in pre-existing monitoring wells at the site on August 2, 1982, is shown in Figure 1, and in the cross section, Figure 2. The effect of the coal refuse pile on shallow ground-water flow pattern is evident. A ground-water mound is present beneath the coal refuse pile resulting in shallow ground-water flow toward secure trench area B to the west and secure trench area A to the south. Disposal trenches in each area were apparently excavated below the water table; however, the trenches may have remained relatively dry during the disposal operation due to the very low hydraulic conductivity of the surrounding glacial till. The presence of the ground-water mound beneath the coal refuse pile is also significant because of the unknown effects of acidic, highly mineralized coal refuse leachate on the geologic materials and wastes of the disposal site.

Vertical fracture permeability will be measured by angle drilling at separate locations. Three nests containing three to four holes per nest will be drilled on an angle to intersect possible vertical fractures. In situ hydraulic conductivity measurements will be carried out, and the results will be compared with previous measurements of vertical and horizontal hydraulic conductivity. Measurements of effective porosity will be attempted where feasible.

The construction of the monitoring wells, screened piezometers and open-hole piezometers is shown in Figure 4. Monitoring wells were constructed by boring a hole to a selected depth with a hollow-stem auger drill rig. A 2-inch ID well casing with a slotted well screen was lowered to the bottom of the hole through the hollow-stem auger. All well screens were 2 feet long, and screen and casing materials were stainless steel for monitoring wells. Flush screw-joint PVC was used for screened piezometers.

Following placement of the casing and screen, the hollow-stem auger was withdrawn from the hole, and clean medium silica sand was placed to approximately 1.0 foot above the well screen. A plug of 2 to 5 feet of expanding cement was then placed above the sand pack. Expanding cement was used for sealing, rather than bentonite, to preclude the possibility of cracking because of the presence of organic solvents. A mixture containing 70 percent (by volume) clean silica sand and

30 percent granular bentonite was used to backfill the hole to within approximately 4 feet of the surface. If water was standing in the hole above the lower cement plug at the time of construction, a 5-gallon pail of bentonite pellets was occasionally used. To avoid vertical cross contamination, drill cuttings were not used for backfill. The annulus was then plugged to the surface with expanding cement and mounded slightly around the casing to promote drainage away from the well.

The open-hole piezometer was constructed in a similar manner. After drilling to the desired depth, a 2.5-inch ID PVC glue joint casing was lowered through the hollow-stem auger to the bottom of the hole. The augers were then withdrawn from the hole, the bottom sealed with 2 to 5 feet of expanding cement as a plug, and the hole backfilled as described above. A 2-inch Shelby tube was then lowered through the casing, and a 2-foot long sample was pushed and retrieved with the drill rig, leaving a 2-inch x 2-foot open hole at the bottom. The hole and casing were then immediately filled to the top with water, and the in situ hydraulic conductivity slug was initiated. The immediate introduction of water applied a positive pressure to the soil, which kept the hole from caving in. Changes in water levels were recorded as a function of time, and the hydraulic conductivity was computed. The Shelby tube sample was sealed and taken to the laboratory for hydraulic conductivity measurements, which can later be compared with field tests at each depth in each nest.

Preliminary results of the in situ field tests of hydraulic conductivity calculated using the methods of Cooper et al. (1967) and Papadopulos et al. (1973) are compared to the results of reported laboratory tests of hydraulic conductivity of similar materials in Figure 3. The hydraulic conductivity of the Vandalia Till determined from laboratory tests of recompacted samples is very low, especially for apparently unfractured basal till. The hydraulic conductivity calculated from field injection (slug) tests, however, is generally significantly greater than that calculated from laboratory tests for the same apparent material. Laboratory-derived values for samples of Vandalia Till were all reported to be 2.0×10^{-7} cm/sec or less. Field measurements of the hydraulic conductivity of intervals of ablation till and fractured basal till, however, were found to be as much as three orders of magnitude greater. In the ablation till, this may be due to very thin sand seams or small interconnected fractures within the relatively soft till. The locally highly fractured nature of the upper portion of the underlying, more dense basal till probably results in much greater hydraulic conductivity values than those observed in recompacted samples of the same material.

The results of field tests of apparently unfractured basal till are significantly lower than the overlying till zones; however, they are still much greater than the results of corresponding laboratory tests. The reasons are not clear for this discrepancy in the apparently homogeneous, unfractured till; the difference may be related to the range of accuracy of both field and laboratory tests of materials of such low hydraulic conductivities.

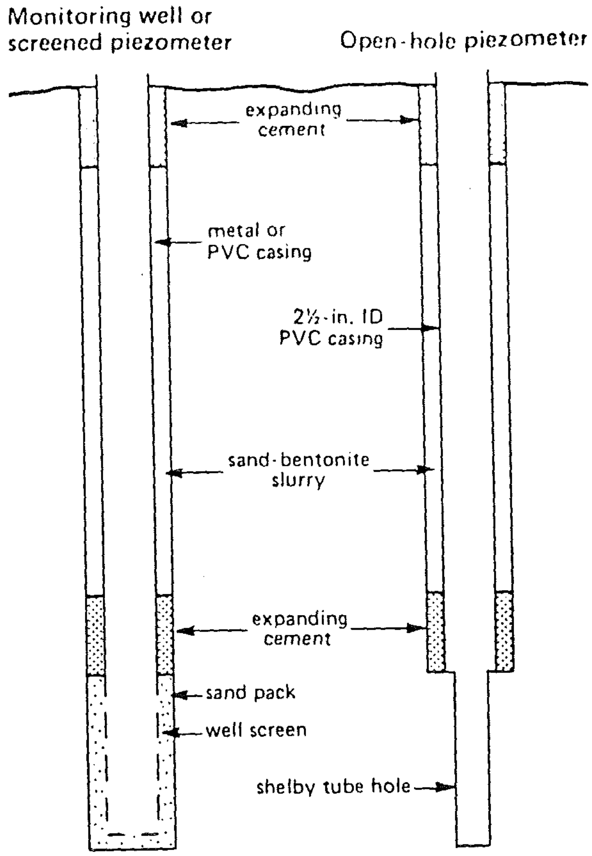

Figure 4. Diagram illustrating construction of monitoring wells, screened piezometers and open-hole piezometers used at the site

The similarity between field- and laboratory-derived values of hydraulic conductivity of the Sangamon Soil developed in ablation till is probably due to the clayey, relatively homogeneous nature of this weathered zone.

Although the water-quality monitoring wells installed for this project have not yet been sampled, monitoring wells previously installed by the site operator in the vicinity of the trenches have been routinely sampled and analyzed by the operator and the IEPA. As indicated previously, subsequent to the court order requiring exhumation of these wastes, contamination of ground water by organic pollutants was discovered by the IEPA in several monitoring wells as far as 50 feet from the trenches. Table 1 presents the range of concentrations of U.S. EPA priority pollutants found in ground water from 12 PVC monitoring wells in the vicinity of secure trench area B. Further sampling will be required to accurately determine the extent of ground-water contamination in the vicinity of the site.

The preliminary results of chemical analyses of soil samples collected for this project indicate that organic pollutants are present at various depths in several locations. Table 2 presents the range of concentrations of purgeable, volatile, organic compounds found to date in soil samples.

Table 1
Concentrations of Volatile, Organic Priority Pollutants in Ground Water from SCA Monitoring Wells, Wilsonville Site (SCA 1982)

	Concentration ($\mu g/L$)	Number of wells (of possible 12)
Benzene	18	1
Chlorobenzene	10	1
Chloroform	53	1
1, 2-Dichloroethane	42 - 228,100	12
Methylene chloride	12 - 89	4
Toluene	11 - 1,030	4
1, 1, 1-Trichloroethane	79 - 10,650	6
Trichlorofluoromethane	10	1

Table 2
Maximum Concentrations of Purgeable, Volatile Organic Compounds in Soil Samples from Project Borings (Analyses by IEPA)

	Concentration (ppb)
1-Bromo, 2-chloroethane	14
Chloroform	430
Carbontetrachloride	400
Dichloroethane	100
Dichloroethylene	120
Ethyl benzene	360
Trichloroethane	30
Trichloroethylene	150
Tetrachloroethylene	130
Toluene	1,300

Engineering Geology Investigations

The engineering geology investigations include: (1) measurement of surface response to potential coal mine subsidence at the site, (2) measurement of settlement and condition of trench covers, (3) determination of physical properties and characteristics of geologic materials composing strata and fill at the site, (4) recording of trench conditions using close-range photogrammetry, stereograms and mapping, and (5) obtaining and using aerial photography to prepare a model for the final base map of the site and to interpret geologic features.

Measurement of surface and near-surface response to subsidence of the underground coal mine workings involves careful construction of monuments and precise surveying measurement. The construction of the survey monuments and settlement probes is illustrated in Figure 5.

Trench cover settlement data from this phase of the study will provide unique information in this regard. These data will be of particular value in designing limited-infiltration, multiple-layered earth trench covers that appear likely to be sensitive to settlement stresses.

The condition of the cover is important as a potential failure mechanism because any reduction in the effective thickness of the soil cover by external or internal erosion or by cracking because of waste subsidence would increase the amount of water percolating into the waste cells. The amount of leachate released from the cells may be due to increased hydraulic head on the bottom and side walls of the trenches. The condition of the cover will be studied in place and as it is removed to determine the extent to which external examination can identify such problems.

The number and condition of the drums and their contents relative to other wastes will be investigated during the waste removal process. This information will help interpret the observed effects on soils in the context of predicting whether maximum leachate strength has occurred. The information will also help estimate the effective service life of steel drums in landfill cells in this environment.

In conjunction with the trench investigations and sampling, the condition of drums and backfill in the trenches will be recorded by still photography, employing techniques for stereographic recording. Stereograms have been made of the features in the surface of one trench cover and are being applied to studies of features in the trenches.

To better extrapolate the measurements taken in the trench and to record the location of samples taken, a 2-foot aluminum cube with holes drilled on centers will be incorporated into stereographic photographic pairs and triplicates. Plumbing and orientation of the cube

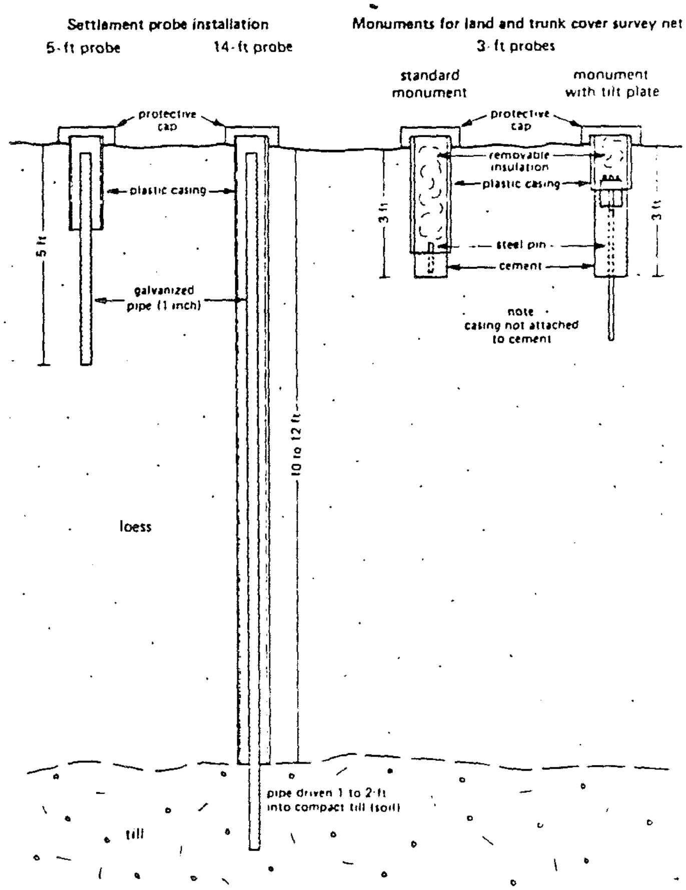

Figure 5. Diagram illustrating the construction of the settlement probe and monument installations used at the site

will enable researchers to orient directions in space. Negatives can be placed into a stereoplotter to make exact measurements of thickness and area. In addition, where joints occur, measurements of slope magnitude and direction can be made where the use of a clinometer would be clumsy or impractical.

Aerial photographs of the study site will be obtained for use as a base map and for interpretation of geologic features. An effort will be made to differentiate bedrock from glacial features. Lineaments of unknown origin will be examined by field studies. The authors are attempting by this study to incorporate into waste disposal site selection the current photointerpretation techniques used for mineral, oil and gas exploration and structural geologic mapping.

Laboratory Investigations

Hydraulic Conductivity Studies

Laboratory studies are designed to provide data to help interpret field measurements and observations. These studies involve laboratory measurements of hydraulic conductivity using selected aqueous and organic liquids. These results will be compared with those obtained in the field. In addition, we will measure the effects of varying concentrations of an organic solvent (such as methylene chloride) on hydraulic conductivity. These data will help interpret the in situ hydraulic conductivity measurements and correlate laboratory measurements with field data for predictive purposes.

Additional laboratory studies will include determination of moisture release curves, measurements of effective porosity and delineation of unsaturated flow characteristics of soil materials from the site. These measurements will be carried out in aqueous media and as a function of organic solvent concentration.

Screening Test for Leachate Effects on Clay

A related question that this project will attempt to answer is how can the potential for clay liner failure from leachate attack be identified at operating and closed facilities. Because it is difficult to predict leachate composition (particularly for mixed-waste facilities), and because leachate composition changes gradually with time, it is possible that incompatible waste/clay liner combinations may fail to be identified during the design of the facility. If reference samples of the clay are taken during construction and preserved, then testing can be conducted during facility operation or after closure using samples of leachate taken at those times. If appropriate tests have been previously identified and correlated with the behavior of clays in the field, then the potential for clay liner failure can be evaluated with greater confidence than is possible during the design phase of a facility. In this project, samples of currently produced leachate, affected clays from the facility and unaffected clays from outside the facility are available. This situation presents a unique opportunity to evaluate the feasibility of developing a screening test for clay liner failure.

Measurements of the viscosity and filtration rates of leachate-clay suspensions will be evaluated for use as a screening test to identify leachate effects on the hydraulic conductivity of clays and as aids in interpreting the field observations and measurements. If the results of these studies correlate with the effects observed in the trenches, these tests could be used for post-closure tests at other facilities.

The authors anticipate that organic solvents will play a major role in the migration of pollutants through earth materials at the site. The reason is that large increases in permeability to organic liquids in landfill liners could possibly develop by at least two conceivable mechanisms: (1) interlayer collapse of clay minerals because of dehydration or (2) flocculation resulting from changes in surface properties of clay minerals. A test of the cause of these failures is essential. If the sudden increase in permeability is due to flocculation of clay particles, a viscosity test could provide an excellent means of quantifying the effect. Changes in viscosity of clay suspensions can be related directly to degree of flocculation of the suspension. A viscosity test will allow a rapid screening of different chemicals, give a quick test of synergistic interaction between chemicals and provide an evaluation of any corrective actions. Viscosity tests can be run on all earth materials, and experimental consistency can be maintained by adding water or clay to achieve a comparable starting viscosity for each test.

A measure of the filtration rate of liquids from dilute suspensions of clay materials could also be used to study the failure of clay liners. A filtration rate experiment is probably a better simulation of the response of a clay liner material, but the test cannot be used to distinguish between permeability changes resulting from flocculation and those owing to shrinkage of the clays caused by organic-induced dehydration and interlayer collapse of clays. Once the mechanism of failure is clarified, a filtration rate measurement could represent a rapid method of screening numerous chemicals and clays.

If part or all of the increased permeability (syneresis effect) that is due to organic chemicals results from shrinkage of clays (because of dehydration and replacement of associated interlayer water), this phenomenon should be measurable by X-ray diffraction. This experiment would be carried out using smectite clay and indigenous materials. Appropriate quantities of organic chemicals will be added to the test samples, and X-ray diffraction will be used to check replacement of intercrystalline water. If the rate of replacement is determined to be a significant factor, this variable will also be measured with diffraction techniques.

All of the above field and laboratory data will serve as input for computer models that will be used to attempt quantitative predictions of water balance, ground-water movement and pollutant migration across the site. Predictions made with the computer models will be compared with actual field measurements, and the implications of predicting future migration of contaminants from the site will be discussed. Discrepancies between predicted and actual observations will be interpreted with respect to the design of earthen liners and covers for landfills, and with regard to the implications to the permit process for new waste disposal sites and post-closure processes for existing sites.

Current Status

The major efforts of this project to date have been the installation of wells and the collection of samples outside of the disposal pits. Soil borings and installation of monitoring wells have been completed. Analyses of water, leachate and soil samples are continuing. Preliminary examination of samples from the soil borings and observations made in backhoe pits on and around the site indicate that sandy layers within the clay till are not continuous and thus cannot account entirely for the observed contaminant migration. The significance of discontinuities and joints exposed in the till by backhoe pits remains to be determined. Laboratory studies of hydraulic conductivity, contaminant adsorption and screening tests for leachate attack on clays are currently being initiated.

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Biographical Sketch

Thomas M. Johnson is an associate geologist in the Hydrogeology and Geophysics Section of the Illinois State Geological Survey where he has worked for eight years. He obtained his B.A. from Augustana College (Illinois), M.S. in geology and water resources management from the University of Wisconsin—Madison, and is completing a Ph.D. in geology at the University of Illinois. In his work at the survey and in part-time consulting, Johnson specializes in field investigations and computer modeling of contaminant migration resulting from the disposal of hazardous chemical wastes and low-level radioactive waste. He also has experience in the monitoring of contamination and modeling of soil-water movement in the unsaturated zone and is working on a project to design and test infiltration-limiting covers for waste disposal sites.

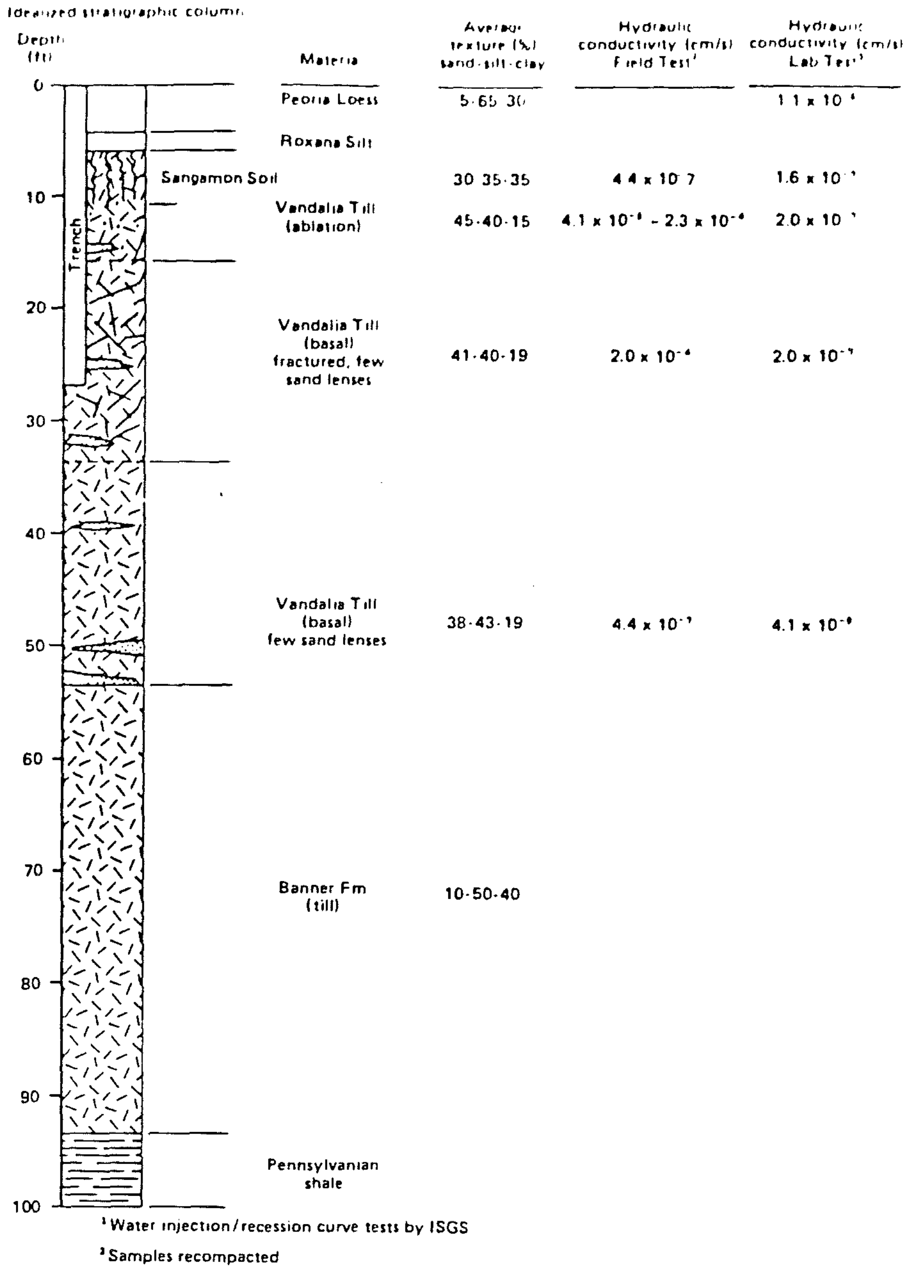

FIGURE 4.3 Comparison of field and laboratory hydraulic conductivities at Wilsonville, Illinois (from Johnson *et al.*, 1983).

the distance between a landfill and a water well unless other factors critical to the protection of the well (such as well construction, well depth, groundwater gradient, and the hydraulic conductivity of the intervening earth materials) are also considered in the regulation.

A performance standard should stipulate the maximum effects disposal can have on surrounding land uses. For example, a standard might be written to limit the volume and concentration of the contaminant allowed to be discharged from the landfill and specify the water-quality criteria as related to a specific water use and/or the degree to which ambient water quality can be altered. The performance standard can be a general statement specifying drinking-water standards or designating specific-ion concentrations, or a combination of both. The standard should clearly specify the area at which the criteria for water quality are to be applied (such as at the property line or the nearest aquifer or body of surface water). If a mixing zone is acceptable (as in the case of a point-source discharge into surface water), then the performance standard should specify the size of that zone. These specifications must be realistic; specifying that there must be a "zero discharge" immediately adjacent to the waste is not realistic.

The performance standard presumes that it can be demonstrated in advance how fast and where the contaminants will