# SUBSURFACE INVESTIGATIONS OF SEVERAL GLACIAL SUCCESSIONS RELATED TO ENGINEERING CONSTRUCTION

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**ABSTRACT.** Glacial environments, including subglacial, supraglacial and proglacial deposition, yield some of the most complex sedimentary deposits on Earth. Unsorted deposits of clasts in a finer matrix (diamictons) are common, both in flow tills and basal (or lodgement) tills. Using only hand-sized samples these till varieties are difficult to differentiate and may require extensive field investigation to do so. Stratigraphic detail of glacial deposits has a profound influence on the engineering properties of soil units. Geotechnical studies involve subsurface drilling and sampling, typically using Hollow Stem Auger (HSA) and Standard Penetration Test (SPT) methods. Other soil samples are obtained using pushed Shelby tubes. Standard laboratory tests are typically performed on soil samples to determine their engineering properties relative to the geologic conditions and the type of facility to be constructed. Four sites were selected for evaluation, ranging from simple glacial stratigraphy to a complex glacial succession requiring gamma ray logging to decipher details. Till features and various types of outwash are considered regarding two engineering construction objectives: foundations for buildings and sanitary landfill siting.

**Keywords:** Glacial geology, subsurface investigation, engineering geology, geotechnical engineering

Much of the Upper Mississippi River Valley and Great Lakes was repeatedly covered by massive continental glaciers during the Pleistocene Epoch. When the ice melted, layers of eroded materials were deposited, with younger layers overlapping older ones. This glacial debris (unsorted clay, silt, sand, and rock fragments) was either deposited directly by the melting ice or carried away to be deposited by streams formed from meltwater. As the source of glaciers shift with time and climatic conditions differ among regions, deposits from various glaciers differ in their physical and mineralogical properties. These details can be used to distinguish between individual glacial units.

Various glacial deposits exhibit a range of properties related to their potential use and limitations for geotechnical aspects. Description and characterization of glacial materials regarding the proposed environmental and construction activity are typically compiled for evaluation. An example data sheet (Fig. 1) illustrates the range of information obtained (after Skempton et al. 1991). British units (feet) are designated in this paper because those are the units normally used in the data gathering process.

## GLACIAL ENVIRONMENTS AND DEPOSITS

Glacial environments yield some of the most complex sedimentary deposits on Earth. Sedimentation occurs in three different environments: beneath the ice as subglacial, atop the ice or supraglacial, or in front of the ice margin as proglacial. The processes of subglacial deposition are the most poorly known as they are inaccessible to direct observation. Deposits formed by supraglacial processes are better known, but more complex, because sedimentation occurs on an unstable substrate (ice) and superglacial deposits commonly undergo several episodes of reworking or resedimentation prior to final deposition. Consequently, the sedimentary record, although conceptually simple, tends to be complex; and detailed description can be challenging.

Diamicton, a glacial geology term, refers to unsorted or poorly sorted deposits that are massive to crudely stratified and consist of a poorly sorted matrix with large clasts (< 2 mm) dispersed throughout. Although a term not typically used in engineering reports, diamicton, as a concept, helps to illustrate the extreme complexity of glacial stratigraphy. They form in a variety of environments—glacial (till, sediment or mudflow deposits, ice-slope colluvium, glacial lacustrine, glacial marine), slopes (colluvium, sediment flow) and volcanic (lahars, volcanic mudflows). Regarding glacial environments, most tills are diam-

1. Location: ______________________________
2. Project: ______________________________ Core file number: _____
3. Submitted by: ______________________
4. Type samples: ______________________ Elevation: _____

| Sample No. | Sample Depth | Unit Description | Graphic Log | Engineering Data: N BPF | Qu TSF | W % | LL % | PI % | Density (wet) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | | | | | | | | | |

| Grain Size: Gvl % | Sd % | St % | Cl % | X-ray Data, Mineral Content: DI % | M % | I % | C-K % | Cal % | Dol % | Vermiculite Index |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| | | | | | | | | | | |

Figure 1.—Data form for soil samples, Illinois State Geological Survey.

ictons; but, as indicated above, not all diamictons have a glacial origin.

Till is sediment aggregated by and deposited directly from glacial ice without subsequent disaggregation and resedimentation. A diagram of the ice-margin environment is shown in Fig. 2 (modified from Edwards 1986); the text by Eyles (1983) describes the complex nature of glacial successions.

Till can be subdivided into subglacial (basal) till and supraglacial till. Lodgement and deformation till are found only in the subglacial environment, but melt-out till accumulates in both the subglacial and supraglacial zones. Further consideration yields the following: lodgement till, deposited from or beneath active ice; melt-out till, from inactive or stagnant ice; and deformation till, involving a deforming layer beneath active ice. Melt-out till is sometimes referred to as ablation till.

Lodgement till is massive, poorly sorted, dense and relatively uniform in texture and composition. Sorted sediments, although not common, may occur in thin and irregular bodies or in isolated channel fills. Elongated pebbles in the till show a strong alignment parallel to the direction of ice flow. Subglacial melt-out till is less uniform than lodgement till, contains layers as well as stringers of silt and sand, and has more channel fills; some may have convex upper surfaces, suggesting a tunnel filling.

Supraglacial, melt-out till is less dense and may contain more sorted sediment than the subglacial variety. Because of the dynamic nature of its environment, supraglacial melt-out till is less likely preserved than are other till varieties. Deformation till is essentially lodgement till that has undergone squeezing and shearing.

In addition to till, there are four other major types of glacial deposits: a) sediment flow deposits and ice-slope colluvium, 2) outwash or glacial fluvial deposits, 3) glaciolacustrine deposits, and 4) glacioeolian deposits.

Sediment flow deposits and ice-slope colluvium are glacial features formed by mass wasting in a supraglacial environment. They are formed by plastic to viscous, to semi-fluvial flow of sediment/water mixtures. They are also known as flow tills, and typically are diamictons varying from a few centimeters to

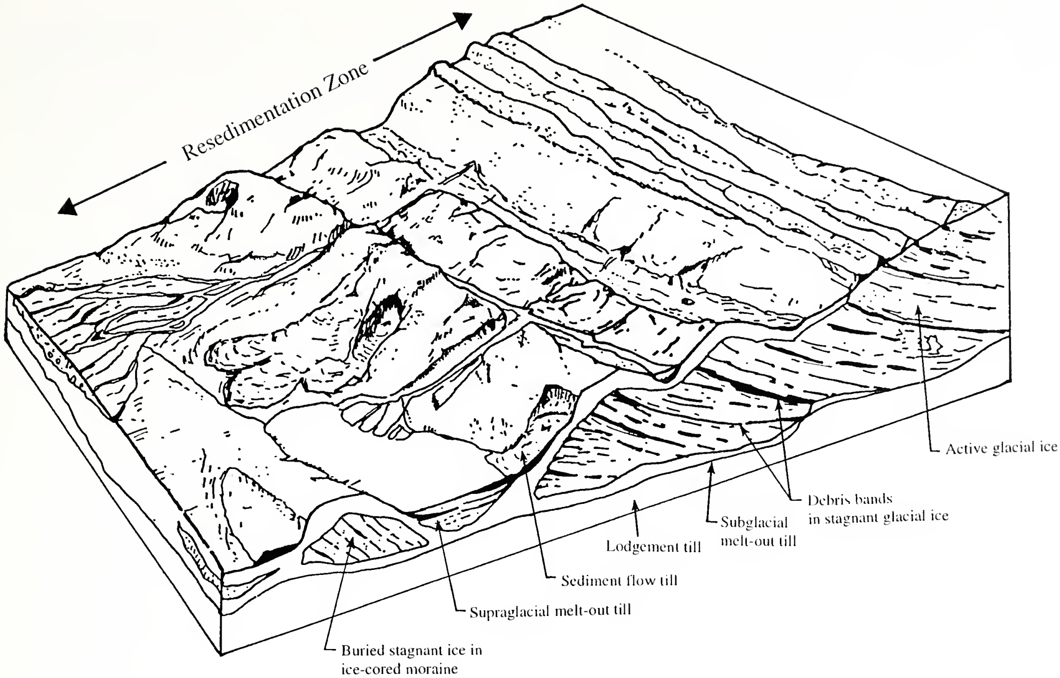


Figure 2.—Schematic diagram of supraglacial/ice-marginal environment. Lodgement till is deposited beneath the active ice; proglacial sedimentation occurs in left portion of the diagram, shows stacking of debris-rich basal ice and concentration of debris by ablation in supraglacial portion. The ice-marginal zone changes continuously during downwasting of the glacier, yielding resedimentation of the debris. (Modified from Edwards 1986.)

a few meters in thickness. In small exposures, without the appearance of flow features, flow till commonly cannot be distinguished from basal till.

Outwash is sediment deposited from meltwater derived from glacial ice. These are fluvial deposits formed by glacial melt water and commonly consist of sand and gravel that is stratified and crossbedded. Deposits generally become finer in the down-flow direction. Sediment flow deposits (flow tills that are diamictons) are commonly interspersed within the outwash.

Glaciolacustrine deposits are formed in lakes in the glacial environments. Lacustrine deposits are generally sorted, stratified and most are fine grained consisting of silt or clay and occasionally sand. Glacioeolian deposits are deposited by wind in the proglacial or periglacial environment. They are either bedload deposits (dune sand, sheet sand) or suspended load (loess) of wind systems that were effective in moving sediment. Loess, which is dominantly silt and usually massive, is deposited downwind of major glacial meltwater streams (see West 1995, Chapter 17, p. 397ff).

## GEOTECHNICAL ASPECTS

For engineering geology/geotechnical studies of the Midwest, the drift-covered regions comprise a major portion of the land surface. A simplified designation for the extent of continental glaciation in the eastern United States is as follows: the area north of a line from New York City across Pennsylvania to Pittsburgh, down the Ohio River to the Mississippi River, up river to St. Louis, and then along the Missouri River across the Great Plains into Montana. This boundary is not precise, as there are portions of southern Ohio, Indiana and Illinois that were not glaciated. However, it is a useful estimate of the southern extent of glacial advance. For a map view of this area see West 1995, Chapter 12, p. 254.

Of primary interest for site characterization in the glacial domain are: 1) landform type, 2) type of unlithified material (till, river alluvium, outwash, etc.), and 3) engineering properties related to the planned construction project. Subsurface investigations regarding building foundations and sanitary landfill siting in a glaciated domain are considered below.

As with all site characterization, description of subsurface conditions is the first order of business. Obtaining background information is the initial step, followed by field reconnaissance, and then a drilling, sampling and laboratory testing program.

The common procedure for subsurface geotechnical investigations in the Midwest in glacial terrain involves HSA (hollow stem auger) drilling and split spoon sampling, using the SPT (Standard Penetration Test). This procedure provides N-values, a measure of density or stiffness of a soil, in blows per foot using the Standard Penetration Test. The split spoon sampler (SS) receives the soil sample, and when retrieved from the subsurface, provides a geologic description and soil samples for subsequent testing.

Some laboratory tests require an "undisturbed" sample to perform the needed testing. Standard penetration test samples cannot be used to perform these tests. Instead, a pushed Shelby tube (ST) is used to obtain samples for these laboratory procedures. Using Shelby tube samples, tests for density, hydraulic conductivity, unconfined compression strength and consolidation are obtained.

Many of the standard engineering tests can also be performed on split spoon samples. These include natural moisture content, Atterberg limits, grain size analysis, specific gravity of solids, and cation exchange capacity (CEC). This same list can be performed on pushed Shelby tube samples.

**Tippecanoe County, Indiana**.—A proposed landfill site in Tippecanoe County was located in an area of a broad, gently rolling ground moraine (Tipton Till Plain). The site was eight miles (13 km) south of Lafayette's center-city, at the intersection of US-231 and County Road 800 South. Fourteen, 30-foot (9.1 m) deep borings were obtained on this site. The log for Boring A is provided as Fig. 3. Note that the N-value for sample 3 equals 17, but for sample 7 it equals 47. Both 3 and 7 appear to be diamictons, but the high N-value for sample 7 indicates it is likely lodgment till. Sample 3 represents a flow till or ablation till.

Laboratory test results from the Tippecanoe County site are provided in Table 1. Shelby tube samples rather than split spoon samples were used for testing. Silts and clays are represented, but sand units are not included. Note the high dry densities, ranging from 109.5–133.4 lbs/ft$^3$ and the low moisture contents, ranging from 9.2–16.5%.

These high density, low moisture contents indicate a very dense, high strength soil that has been densified by the weight of the overriding ice. Such materials are designated as overconsolidated because the vertical stress at present is significantly less than it was when a great thickness of glacial ice existed above it. This is also consistent with the low values for the hydraulic conductivity, typically in the $10^{-6}$ and $10^{-7}$ cm/sec range. Note also that the cation exchange capacity values (CEC) are below 10 meq/100 grams of dry soil, which are fairly low for clayey soils. Also the plasticity index (PI) values are quite low (1.9–5.0) except for Borings F, M-6 and N-8. A low PI is consistent with low CEC values, both indicating a low clay mineral content.

**Indianapolis (Marion County), Indiana**.—Subsurface exploration, involving a foundation design for a large building, was conducted on the south side of Indianapolis in an industrial area within the White River floodplain. Although located in the Tipton Till Plain province, the White River floodplain was modified by late stage glacial outwash. One of the boring logs for the site is presented in Fig. 4, where drilling extended into the bedrock.

An upper sand layer (outwash) from 8.5–29 feet, a stiff, silty clay (till) from 29–38 feet and a lower sand layer (outwash) from 38–43 feet are indicated. Seven borings intercepting bedrock, averaging about 50 feet deep, were drilled using HSA and split spoon sampling. The blow counts for the stiff silty clay ranged from 29–57 with an arithmetic mean of 46 (Table 2). Eleven samples of natural moisture content were obtained for the stiff silty clay, yielding a range from 8.8–11.7%, with an arithmetic mean of 9.8%. Dense, overconsolidated till units are indicated by high blow counts (30 or greater) and low (about 10%) natural moisture contents. This is also indicative of a lodgement till.

The Southside Sanitary Landfill, on Kentucky Avenue is located in an area adjacent to

Project Name: Proposed Landfill Date of Boring: November 11, 1981 Boring: A
Drilling Method: HSA
File: Southwest corner-SR 231 & CR 800 South Project No.: ____ Sampling: AU, SS and ST
Tippecanoe County

| Description | Depth | Sample | N | $Q_u$ | $Q_p$ | $w_c$ | Remarks |
|---|---|---|---|---|---|---|---|
| -------Surface-------------- | | 1-AU | - | - | - | 25 | |
| Dark brown clayey silt to silty clay, trace organic mat. | | | | | | | |
| Brown silty clay, trace sand | | | | | | | |
| | 5 | | | | | | |
| | | 2-SS | 8 | - | - | 18 | Water level, 6 ft. @ 24HR |
| Brown silty fine to medium sand | | | | | | | |
| | 10 | | | | | | |
| | | 3-SS | 17 | 3.3 | 4.0 | 10 | |
| Gray silty clay to clayey silt, little sand, trace small gravel | | 4-ST | | | | | Taken 11'6" to 14'6" |
| | 15 | | | | | | |
| | | 5-SS | 21 | - | - | 16 | |
| Gray brown fine to coarse sand, trace small gravel | | | | | | | |
| | 20 | | | | | | |
| | | 6-SS | 50/5" | 10 | 4.5+ | 8 | |
| Gray clayey silt, some sand, Trace gravel (Till) | 25 | 7-SS | 47 | 7.0 | 4.5+ | 8 | |
| | 30 | | | | | | |
| | | 8-SS | 50/5" | 6.5 | 4.5+ | 7 | |

$w_c$ = Natural moisture content
AU = Auger
ST = Shelby Tube
SS = Split Spoon Sample from SPT
SPT = Standard Penetration Test, N values

End of Boring

Figure 3.—Boring log, subsurface exploration, for a proposed landfill in Tippecanoe County. The site was located in an area of a broad, gently-rolling ground moraine.

the boring site described in Fig. 4. It began operations in 1971 and through a series of expansions now occupies over 200 acres (81 ha). However, it lacks a natural clay barrier below the solid waste. Subsurface geology similar to that indicated in Fig. 4 shows the presence of upper and lower sandy units with a silty clay layer between them. To prevent lateral movement of leachate within the upper sand unit, a slurry wall, cut-off trench through the upper unit into the silty clay layer, was proposed. However, the continuity of this silty clay layer throughout the site was questioned based on research by Sudar (1987). If this intermediate clay unit was flow till rather than basal till, it likely would be discontinuous across the site. Therefore, at certain locations, the upper and lower sand units might be directly connected. Field studies were conducted in gravel pit excavations near by, and evidence of both lodgement and flow till units was found. Consequently, field studies could not establish the existence of a continuous till section within the sandy outwash.

The Indiana Department of Environmental Management (IDEM) also concluded that the existence of a continuous layer of silty clay beneath the site had not been proven. Hence, they required that the slurry wall extend through the lower sand unit into the New Albany Shale bedrock. Consistent with IDEM's decision, Sudar (1987) used borings, cross sections, piezometric data and investigation of adjacent active gravel pits to conclude that a high likelihood exists that the silty clay layer is not continuous across the 200 acre (81 ha) site.

**Chicago, Illinois**.—(The Loop area). The Chicago River and Lake Michigan site are in the Loop area of downtown Chicago, Illinois on a portion of the Calumet Lacustrine Plain where a high-rise building was to be con-

Table 1.—Test results, Tippecanoe County study. * Falling head method, ST = Shelby Tube. CEC results: A, 15′, 6.9 meq/100 g; D, 20′, 8.3 meq/100 g, Avg. = 7.6 meq/100 g.

| Boring, Sample, Depth | Visual classification | Dry density (lbs./ ft.$^3$) | Natural moisture (%) | Atterberg limits: Liquid limit | Plastic limit | Plasticity index | Hydraulic conductivity* (cm/sec) |
|---|---|---|---|---|---|---|---|
| A, 4-ST, 11.5–14.5′ | Gray silty clay to clayey silt, little sand, trace gravel | 128.9 | 11.8 | 18.4 | 13.4 | 5.0 | $1.75 \times 10^{-7}$ |
| B, 4-ST, 15′–16′4″ | Gray sandy clayey silt, little gravel | 122.2 | 14.3 | 18.9 | 14.2 | 4.7 | $2.43 \times 10^{-6}$ |
| C, 4-ST, 12′–13′6″ | Gray brown sandy clayey silt, little gravel | 127.9 | 9.2 | | | | |
| E, 6-ST, 18′–20′ | Gray clayey silt, some sand, little gravel | 133.4 | 10.3 | | | | |
| F, 3-ST, 10′–12′9″ | Brown clayey silt, little sand and gravel | 109.5 | 16.5 | 38.4 | 22.9 | 15.5 | |
| G, 5-ST, 20′–21′2″ | Gray clayey silt, some sand, trace gravel | 127.5 | 8.5 | | | | |
| H, 5-ST, 20′–21′2″ | Gray clayey silt, some sand, trace gravel | 131.1 | 8.7 | | | | |
| I, 5-ST, 20′–22′9″ | Gray silty clay to clayey silt, little sand and gravel | 130.8 | 10.3 | 17.3 | 13.4 | 2.9 | $1.55 \times 10^{-7}$ |
| J, 4-ST, 15′–15′10″ | Gray clayey silt, some sand, little gravel | | 13.5 | 16.7 | 13.2 | 4.5 | $1.01 \times 10^{-7}$ |
| M, 4-ST, 12′–13′8″ | Gray clayey silt, some sand, trace gravel | 122.2 | 10.2 | 15.1 | 13.2 | 1.9 | $7.62 \times 10^{-7}$ |
| M, 6-ST, 17′–18′8″ | Gray clayey silt, some sand, trace gravel | 128.2 | 10.8 | 20.6 | 13.1 | 7.5 | $2.64 \times 10^{-7}$ |
| N, 6-ST, 17′–18′4″ | Gray clayey silt, some sand, little gravel | 125.1 | 11.8 | 17.9 | 14.4 | 3.5 | $4.9 \times 10^{-5}$ |
| N, 8-ST, 25′–26′ | Gray clayey silt, some sand, little gravel | 121.4 | 11.4 | 21.0 | 12.7 | 8.3 | $1.45 \times 10^{-5}$ |

structed. Two borings, drilled 155 and 120 feet (47.2 and 36.6 m) deep, intercepted a 15 foot sand layer, with a soft, silty clay and a stiff, silty clay below. A summary of laboratory test results is provided in Table 3. Soft lacustrine deposits extend from 23.5 to between 48–50 feet deep. Natural moisture contents for these softer soils range from 16.2–24.6% (arithmetic mean = 21.4%). A plasticity index of 19 or 20 was indicated. From 48.5–120 feet the natural moisture content ranged from 8.8–22.2 (arithmetic mean = 15.1%) and the plasticity index ranged from 5–18 (arithmetic mean = 10.2%). The unit extending from 53.5 to 115 or 120 feet is an overconsolidated, basal or lodgement till. Evaluation of N-values for the two borings indicated that three distinct silty clay layers can be discerned: lacustrine from 23.5–50 feet, stiff glacial till from 50–80 feet and a hard glacial till from about 80–120 feet.

Boring logs reveal that the subsurface consists of a surface sand layer (likely beach or dune sand) to a depth of 23 feet with a silty bed (lacustrine) below that to a depth of about 50 feet and an extremely dense silty clay (lodgement till) below, extending to a depth of 120 feet. N-values and natural moisture contents were the primary engineering data used to delineate these contrasting glacial deposits. High-rise buildings in Chicago are founded today on the overconsolidated, basal till or on bedrock.

**Elkhart County, Indiana.**—(Steuben Morainal Lake Section). The Earthmover's Solid Waste facility, south of the city of Elkhart (Elkhart County, Indiana), is located six miles (3.7 km) northeast of Wakarusa and eight

DRILLING and SAMPLING INFORMATION

| | | | |
|---|---|---|---|
| Date Started | 5/22/00 | Hammer Wt. | 140 lbs. |
| Date Completed | 5/22/00 | Hammer Drop | 30 in. |
| Drill Foreman | J. Moore (E.E.) | Spoon Sampler OD | 2.0 in. |
| Boring Inspector | S. Marcum | Rock Core Dia. | 2.0 in. |
| Drill Method | HSA | Shelby Tube OD | -- in. |

| SOIL CLASSIFICATION / SURFACE ELEVATION 704.0 | STRATUM DEPTH | SAMPLE NO. | SAMPLE TYPE | GROUND WATER | BLOWS/6 INCH INCREMENTS THREE 6 INCH INCREMENTS | RECOVERY, percent | BORING AND SAMPLING NOTES |
|---|---|---|---|---|---|---|---|
| 0.7 ft Asphalt | 0.7 | | | | | | |
| 1.0 ft Crushed Stone | 1.7 | 1 | SS | | 4/6/6 | 90 | |
| Brown slightly moist Sand and Gravel with trace Silt (FILL) | | 2 | SS | | 7/8/10 | 90 | |
| | | 3 | SS | | 8/9/10 | 100 | |
| Brown slightly moist medium dense fine SAND (SP) | 8.5 | 4 | SS | | 6/7/7 | 100 | |
| Brown slightly moist medium dense SAND (SP-SM) with some Gravel and trace Silt | 10.5 | 5 | SS | | 7/8/8 | 100 | |
| | | 6 | SS | | 5/9/11 | 100 | |
| -wet below 17.0 ft | | 7 | SS | ● | 6/9/10 | 100 | |
| | | 8 | SS | | 10/12/17 | 100 | |
| | | 9 | SS | | 10/13/11 | 100 | |
| | | 10 | SS | | 9/10/15 | 100 | |
| | 29.0 | 11 | SS | | 16/21/19 | 90 | |
| Gray slightly moist hard SANDY SILTY CLAY (CL) with trace GRAVEL | | 12 | SS | | 17/26/30 | 100 | |
| Gray wet dense SAND (SP-SM) with some GRAVEL and trace Silt | 38.0 | 13 | SS | | 11/19/18 | 100 | |
| Dark brown to black severely weathered SHALE | 43.0 | 14 | SS | | 50/0.3' | 100 | |
| Black SHALE | 44.0 | Run 1 | SS | | | 88 | Run No. 1 Rock was cored from 44.0 ft To 49.0 ft RQD (%) = 30 |
| | 49.0 | | | | | | |

SAMPLER TYPE

SS – DRIVEN SPLIT SPOON
ST – PRESSED SHELBY TUBE
CA – CONTINUOUS FLIGHT AUGER
RC – ROCK CORING
CU – CUTTING
CT – CONTINUOUS TUBE

| | | | |
|---|---|---|---|
| AT COMPLETION | Dry FT.* | HSA | HOLLOW STEM AUGERS |
| AFTER HRS | FT. | CFA | CONTINUOUS FLIGHT AUGERS |
| ● WATER ON RODS | 17.0 FT. | MD | MUD DRILLING |
| | | HA | HAND AUGER |

Figure 4.—Indianapolis Project, showing a boring log for the site. The subsurface exploration, involving a foundation design for a large building, was conducted within the White River floodplain.

Table 2.—Natural moisture contents and N values, stiff, silty clay samples, Indianapolis, Indiana. Tsf = tons per square foot, N value = number of blows to drive sample one foot.

| Boring No. | Depth (ft) | Natural moisture content, % | Unconfined compression strength (Tsf) | N value (blows/ft) |
|---|---|---|---|---|
| 1 | 28.5–30.0 | 11.7 | | 40 |
| | 33.5–35.0 | 10.8 | | 56 |
| 2 | 33.5–35.0 | 8.9 | | 53 |
| 3 | 33.5–35.0 | 10.4 | | 45 |
| 4 | 38.5–40.0 | 10.0 | | 40 |
| 5 | 28.5–30.0 | 8.8 | | 29 |
| | 33.5–35.0 | 9.6 | 7.91 | 47 |
| 6 | 33.5–35.0 | 9.7 | | 57 |
| | 38.5–40.0 | 9.3 | | 47 |
| 7 | 33.5–35.0 | 9.5 | | 32 |
| | 38.5–40.0 | 9.4 | | 53 |

miles (12.8 km) northwest of Goshen. It involves a 45-acre (18.2 hectare) expansion near a complex geologic boundary within the Maxinkukee Moraine. The site is part of the Steuben Morainal Lake Section, with intersecting deposits of the Lake Michigan Lobe from the north and the Huron-Erie (Saginaw) Lobe, from the northeast. For this boundary area, with its complicated glacial stratigraphy, the subsurface is best characterized using the megasequence procedure proposed by Bleuer & Melhorn (1989).

Earthmover's facility, displaying Wisconsin age till at the surface, was only a few miles southeast of the St. Joseph Aquifer System (Reussow & Rohne 1975; DNR 1987), a major regional outwash aquifer, which had to be protected from contamination. Bleuer & Melhorn (1989) proposed that the uppermost unit at the facility is the Post Wakarusa Fan Complex and below it lies the Wakarusa megasequence, consisting of a Wisconsin age till and kame-fan sequence. Underlying are pre-Wisconsin deposits, the Nappanee-Bremen megasequence. Interpretations were made using gamma-ray logs conducted in existing water wells. Details of the Wakarusa megasequence depict an upper clay-rich blocky till with a coarse sandy interval below. The Nappanee-Bremen megasequence consists of clay-rich tills and a clay-free (clean) coarse sand interval.

The clay-free coarse interval within the Nappanee-Bremen megasequence apparently corresponds to the Nappanee aquifer discussed by DNR (1987). The coarse sand intervals (Bleuer & Melhorn 1989) typically occur between elevations 750–780 feet (229–247 m), MSL, with the base of the landfill ranging from 794–811 feet (242–274 m). Bedrock below the site is the green-to-black Ellsworth Shale (Reussow & Rohne 1975), Devonian to Mississippian age. Based on regional data, the depth to bedrock ranges from 200–250 feet (61–76 m) and the ground surface elevation, prior to landfilling, ranged from 806–820 feet (245–250 m).

An idealized gamma ray log and stratigraphic section for the site are provided in Fig. 5. Shown chronologically are the Post-Wakarusa Fan Complex, Wakarusa Megasequence and Nappanee-Bremen Megasequence. Gamma ray logging responds to the clay content because of the increase in radiation typically occurring in clay minerals.

The Post-Wakarusa fan complex, prevalent in the north central portion of the landfill extends offsite to the north. According to test borings it exists from the ground surface (typically about 810 feet) to an elevation of about 796 feet. Sands in the unit are fairly clean, but gamma ray response (Fig. 5) suggests a significant presence of silt and clay. The deposit is interpreted as a pro-glacial fan complex with a typical braided stream pattern. Because of its relatively small extent, the fan complex likely was deposited by a small, lingering lobe of melting ice during final glacial retreat. Initially, meltwater eroded the underlying Wakarusa megasequence; and, as melting progressed, the cut was backfilled with these fan deposits.

Table 3.—Laboratory test results and N values for silty, clay samples, Chicago, Illinois.

| Boring No. | Depth (ft) | Natural moisture content, % | Atterberg limits LL | PL | PI | N value (blows/ft) |
|---|---|---|---|---|---|---|
| 1 | 23.5–25.0 | 18.0 | | | | 12 |
| | 28.5–30.0 | 16.2 | | | | 5 |
| | 33.5–35.0 | 19.7 | | | | 11 |
| | 38.5–40.0 | 21.3 | | | | 8 |
| | 43.5–45.0 | 22.3 | 39 | 19 | 20 | 8 |
| | 48.5–50.0 | 19.4 | | | | 24 |
| | 53.5–55.0 | 19.1 | | | | 18 |
| | 58.5–60.0 | 19.6 | 35 | 17 | 18 | 34 |
| | 63.5–65.0 | 19.6 | | | | 38 |
| | 68.5–70.0 | 17.6 | | | | 23 |
| | 73.5–75.0 | 18.4 | 27 | 16 | 11 | 52 |
| | 78.5–80.0 | 16.1 | | | | 41 |
| | 83.5–85.0 | 16.0 | | | | >121 |
| | 88.5–90.0 | 14.7 | 28 | 16 | 12 | 65 |
| | 93.5–95.0 | 8.8 | | | | >124 |
| | 98.5–100.0 | 11.0 | 21 | 16 | 5 | >110 |
| | 103.5–105.0 | 11.4 | | NP | | >120 |
| | 108.5–110.0 | 9.5 | | | | >200 |
| | 113.5–115.0 | 9.3 | | | | >200 |
| 2 | 23.5–25.0 | 23.0 | | | | 2 |
| | 28.5–30.0 | 23.5 | | | | 7 |
| | 33.5–35.0 | 20.3 | | | | 12 |
| | 38.5–40.0 | 23.3 | | | | 9 |
| | 43.5–45.0 | 24.6 | 37 | 18 | 19 | 8 |
| | 48.5–50.0 | 23.0 | | | | 10 |
| | 58.5–60.0 | 17.1 | 32 | 18 | 14 | 22 |
| | 63.5–65.0 | 16.3 | | | | 25 |
| | 68.5–70.0 | 15.2 | 28 | 17 | 11 | 40 |
| | 73.5–75.0 | 12.8 | | | | 35 |
| | 78.5–80.0 | 11.8 | | | | 60 |
| | 83.5–85.0 | 12.5 | | | | >100 |
| | 88.5–90.0 | 18.7 | | | | >100 |
| | 93.5–95.0 | 12.1 | | | | >100 |
| | 98.5–100.0 | 22.2 | 19 | 13 | 6 | >100 |
| | 103.5–105.0 | 14.0 | | | | >100 |
| | 108.5–110.0 | 11.7 | | | | >100 |
| | 113.5–115.0 | 10.8 | 19 | 14 | 5 | >100 |
| | 118.5–120.0 | 20.8 | 39 | 19 | 10 | >100 |

A laboratory hydraulic conductivity of 2.3 $\times 10^{-5}$ cm/sec was obtained at the base of this fan, at elevation 798 feet (243 m). This is too permeable to provide a suitable barrier below the waste, and a 10-foot thick, recompacted clay, base liner was required where this unit occurred. This silty material, was suitable, however, for daily cover of trash during landfilling. Hydraulic conductivities for soils samples taken below the landfill base are given in Table 4. Boring WB-25 intercepted the Post-Wakarusa fan complex.

Underlying this fan complex is the Wakausa Megasequence (Fig. 5), typically consisting of a till overlying a coarser sequence of silty and clayey sand. Till below the base of the facility (at 810 feet) is gray to blue-gray, homogeneous silty clay. Percentage of fines (silt and clay combined) typically ranges between 50–90%. Blow counts varied from 20–70 per foot, suggesting that the unit is supraglacial rather than subglacial (or lodgement), which in this area sustains blow counts exceeding 100 per foot. Clay and silt facies of the Wak-

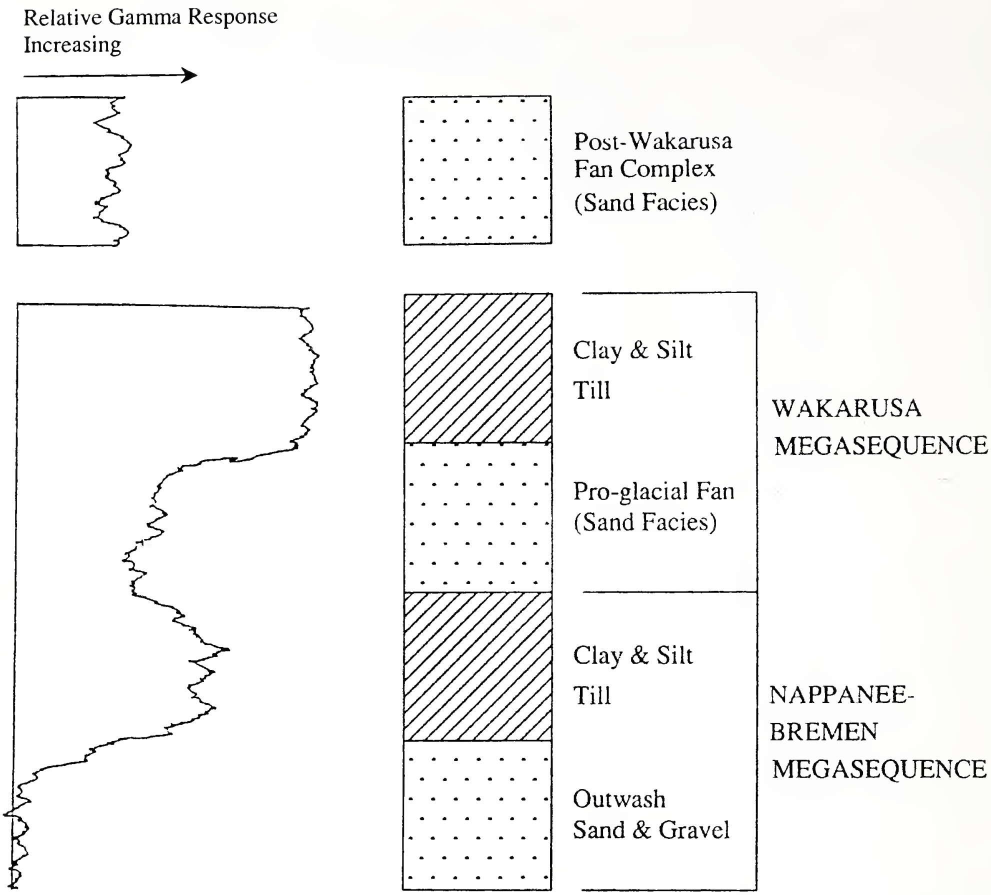


Figure 5.—Idealized gamma Log and Stratigraphic Section, Earthmover's Site, Elkhart, Indiana.

arusa Megasequence are extensive throughout the site, absent only where the Post-Wakarusa Fan complex occurs and the Wakarusa was eroded away. The base of the till unit was found between 770–789 feet elevation. Laboratory hydraulic conductivity values for this zone (Table 4) ranged from $3 \times 10^{-8}$ to $1 \times 10^{-6}$ cm/sec (geometric mean = $8 \times 10^{-8}$; arithmetic mean = $1.4 \times 10^{-7}$). In Table 4 the last entry, $2.3 \times 10^{-5}$ cm/sec, as indicated above, pertains to the Post-Wakarusa Fan Complex.

The Wakarusa sand facies, a discontinuous silty, clayey, sand body, lies beneath the Wakarusa clay and silt facies. It represents a meltout feature of Wisconsin glaciation and is probably a fan complex much like the Post-Wakarusa Fan Complex described above. However, it is more widespread. The top of the Wakarusa sand ranges in elevation between 778–804 feet, whereas the bottom elevation ranges from 775–783 feet. Since it is unsuitable barrier material for preventing leachate migration, where the sand occurs less than 10 feet below the bottom of the base grade, a 10-foot recompacted clay liner was added.

The Nappanee-Bremen Megasequence differs from the Wakarusa Megasequence in two major ways: 1) based on its gamma ray signature (Fig. 5) and on borings, it is more variable and not as well defined, and 2) the sand sequences are much cleaner than the Wakarusa sand. The clayey and silty facies of this megasequence have less clay and more silt than the Wakarusa till, but still show low hydraulic conductivities, from $8 \times 10^{-8}$ to $2 \times 10^{-7}$ cm/sec. The sand facies are generally continuous from about elevations 775–730 feet, on the eastern half of the site.

Groundwater maps for the Nappanee aquifer at the Earthmover's facility were obtained

Table 4.—Earthmover's Facility, Elkhart County, Indiana. Hydraulic conductivity (k) and Cation exchange capacity (CEC) tests. Tests taken below landfill base. * In-situ test. # = Sample gotten by redrilling B-19 to the specified elevation and obtaining a Shelby tube. B = Early borings, WB = Wehran Company borings.

| Boring | Ground elev (ft) | Landfill base elev (ft) | Test elev (ft) | Depth below landfill base, (ft) | k (cm/sec) | CEC Meq/100 g |
|---|---|---|---|---|---|---|
| B-14 | 817 | 808 | 798 | 10 | $4.7 \times 10^{-8}$ | |
| B-14 | 817 | 808 | 798 | 10 | $3.3 \times 10^{-8}$ | 13.9 |
| B-15 | 817 | 809 | 798 | 11 | | 13.2 |
| B-17 | 807 | 794 | 791 | 3 | $3.3 \times 10^{-8}$ | |
| B-17 | 807 | 794 | 790 | 4 | | 20.8 |
| B-17a* | 807 | 794 | 791 | 3 | $2.0 \times 10^{-7}$ | |
| B-18 | 806 | 798 | 795 | 3 | | 15.2 |
| B-19 | 806 | 800 | 795 | 5 | | 16.8 |
| B-19b# | 806 | 800 | 794 | 6 | $10.0 \times 10^{-6}$ | |
| WB-6 | 808 | 800 | 785 | 15 | | 12.9 |
| WB-9 | 813 | 802 | 792 | 10 | $7.5 \times 10^{-8}$ | |
| WB-9 | 813 | 802 | 792 | 10 | | 16.0 |
| WB-10 | 808 | 798 | 793 | 5 | $2.0 \times 10^{-7}$ | |
| WB-10 | 808 | 798 | 792 | 6 | | 16.7 |
| WB-11 | 812 | 804 | 791 | 13 | | 15.2 |
| WB-22 | 804 | 798 | 789 | 9 | $3.5 \times 10^{-8}$ | |
| WB-23 | 806 | 803 | 796 | 7 | $5.1 \times 10^{-8}$ | |
| WB-24 | 819 | 811 | 805 | 6 | $6.9 \times 10^{-8}$ | |
| WB-25 | 820 | 808 | 798 | 10 | $2.3 \times 10^{-5}$ | |

on a monthly basis. The Wakarusa sand was unsaturated, and groundwater piezometer data from other units were used to find horizontal and vertical gradients. Groundwater pressure in sand units below the landfill base was a concern. If uplift pressures exceed the downward stress of the overlying soil, a soil pop-up can occur, yielding a spring-like feature in the base of the excavation.

Cation exchange capacity (CEC) data for the site (Table 4) ranged from 12.9–20.8 meq/100g of dry soil, with an average of 15.6. These values are relatively high for clayey soils in Indiana. Recall, for the clayey silt samples in the Tippecanoe County study (Table 1) the CEC values averaged 7.6 meq/100g, which, by contrast, is below average for cohesive, Indiana soils.

Using the megasequence procedure of Bleuer & Melhorn (1989) to develop geologic detail, Wehran Engineering was able to depict the complicated stratigraphy of the site to the satisfaction of IDEM. The landfill extension was designed based on this geologic interpretation, and landfill expansion was accomplished. As indicated above, a 10 foot (3 m) thick, recompacted clay liner was added in areas where sandy zones were found immediately below the landfill base.

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