APPLICATION OF SEISMIC REFRACTION METHODS TO EVALUATE REGIONAL GROUND-WATER RESOURCES

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ABSTRACT
Seismic refraction methods played an important role in a comprehensive investigation of groundwater resources in a complex glacial sediment/fractured rock aquifer system that is present over an extensive region of northern Illinois. The thickness of the glacial deposits varies from 0 to greater than 250 feet. The bedrock is dolomite of the Silurian System and interbedded shales and dolomite of the Maquoketa Group. The velocity contrast between glacial deposits (4,500 to 8,000 ft/sec.) and the bedrock (10,000 to 20,000 ft/sec.) is ideal for application of refraction methods to map glacial drift thickness, bedrock lithology, and bedrock topography. Important objectives of the program were to map buried bedrock valleys beneath thick glacial deposits and Silurian Dolomite bedrock highs beneath thin glacial deposits. Both these environments have high potential to provide large groundwater resources. The large study area (600 square miles) required efficient geophysical methods that could operate in noisy cultural environments. Seismic data was acquired with a 24-channel signal enhancement system with high cut/low cut filters. Energy sources included 2-component explosives, class A explosives, and a selfpropelled high weight thumper.

Excellent seismic records were obtained by deploying geophones directly on pavement with energy introduced through the pavement with the thumper. Geophone spacings were typically 50 or 100 feet. A time efficient procedure was developed for end-on-end saturation coverage with seismic spread cables. The high resolution data that was gathered was interpreted with the SIPT program to create computer generated profiles that showed layering parameters beneath each geophone. The investigation was very successful in "discovering" significant groundwater resources in optimum locations to serve major municipalities in northeastern Illinois.

Traditional style drilling programs would not have resolved the location of the narrow bedrock valleys buried beneath glacial landscapes. Accurate mapping of these valleys was efficiently accomplished with the refraction technique. The seismic data optimized locations of wells within the buried valleys.

INTRODUCTION

Seismic refraction techniques were used to map the bedrock surface and drift thickness on a regional and local basis in northern Illinois as part of an Investigation of shallow groundwater resources.. The focus of the study was in Kane County, a region which covers over 600 square miles. The program involved approximately 1,140 seismic refraction lines, which represent over 150 line-miles of seismic data. Figure 1 is a location map of the study area.

Shallow groundwater resources became of interest when it was determined that the major bedrock aquifers for the region are over pumped (Sasman et al.,1982). These aquifers also yield water exceeding U. S. Environmental Protection Agency recommended levels for public drinking water supply of radium and, locally, barium (Gilkeson et al., 1984). Hence the need for an alternative groundwater supply.

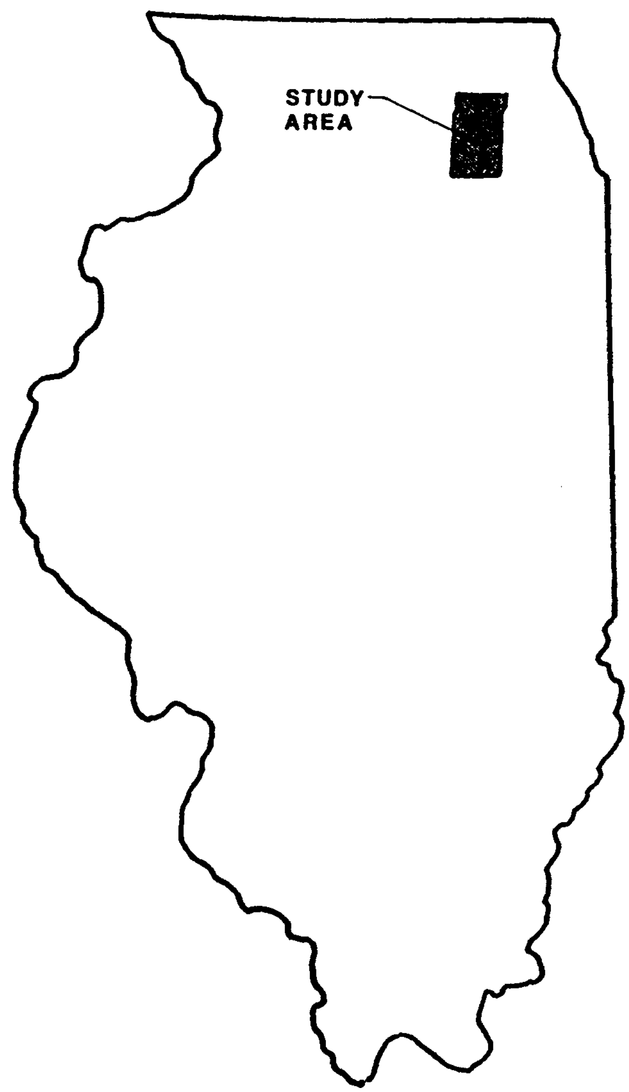

Figure 1 Location map of the study area.

A prime environment for production of large groundwater supplies Is where thick sand and gravel deposits are present in buried bedrock valleys (Gilkeson et al., 1987). The most productive resources are available where the sand and gravel deposits are continuous in the valleys and are in open hydraulic connection with fractures and crevices In the dolomite bedrock that forms the floor and walls of the buried valleys. In this setting, the shallow groundwater resource is regional and is derived from both the drift and the bedrock.

Seismic refraction was used extensively to evaluate this groundwater resource. The bedrock valleys that this resource is found in, range in width from a few hundred feet to over a mile. The large size of the study area and relatively small size of the bedrock valleys were conducive to using geophysical methods. The significant velocity contrast between the glacial drift and bedrock provide an excellent environment for mapping depth to bedrock, using seismic refraction techniques.

The location of bedrock valleys was of prime interest in the program. Seismic refraction proved to be more-cost effective and time efficient than an extensive drilling program might have been locating these environments. The regional shallow groundwater resources program is discussed extensively by McFadden et al., (In Press).

GEOLOGIC AND HYDROLOGIC SETTING

The glacial record in northeastern Illinois is complex. Within Kane County, the mapping of drift deposits shows several advances of Wisconsinan and Illinoian ice (William, 1971), (Kempton et al., 1985). The continental glaciers modified and buried the preglacial landscape. Bedrock outcrops occur only locally in the county and are generally restricted to areas along the major drainage ways. Drift materials are greater than 50 feet thick over most of the county and locally exceed thicknesses of 250 feet.

Shale and interbedded dolomite in the Maquoketa Shale Group form the bedrock surface over most of Kane County. In the eastern part of the county, the Maquoketa is overlain by dolomite of Silurian age that locally exceeds 100 feet in thickness. Isolated outliers of Silurian Dolomite occur locally throughout the county. These outliers seldom exceed 50 feet in thickness. The bedrock surface is highly erosional and cut by bedrock valleys.

The presence and course of buried bedrock valleys are hidden beneath the modern landscape. Continental glaciers greatly modified the shape of the valleys and filled them with drift displaying a range of lithologies that reflect different depositional environments. Valleys that were drainageways for meltwater may contain thick deposits of coarse sand and gravel. It is common for these deposits to be overlain and confined by clayey glacial tills. A second depositional environment occurred where ice blocked drainage in the valleys, resulting in thick sequences of lacustrine deposits formed in low energy environments. A third depositional environment is where advancing glacial ice scoured the valley floor and deposited clay-rich glacial till.

Cambrian and Ordovician sandstones are the major bedrock aquifers for municipal wells in the region with limestone and dolomite layers of the upper Maquoketa Group and Silurian locally supplying quantities of water sufficient for public water supply (McFadden et al., In Press). Two major shallow sand and gravel aquifers are distinguished in the glacial drift by McFadden et al., (In Press). These are the Lower Sand and Gravel aquifer and the Upper Sand and Gravel aquifer. The Lower aquifer is present in the bedrock valleys. The Upper aquifer is present in the bedrock upland areas (outside bedrock valley systems). These deposits are not hydraulically connected regionally within the individual aquifers. However, the Upper and Lower aquifer are locally interconnected over bedrock valleys.

SEISMIC REFRACTION THEORY

Seismic refraction requires the generation of a sound wave into the subsurface of the earth and an instrument to measure the return of the refracted waves. The instruments used include a seismograph and spread cable of geophones. The seismograph measures the travel times of elastic waves through the subsurface of the earth. Geophones sense seismic vibrations, convert them into electrical impulses, and send them to the seismograph to be recorded. The refraction waves are generated by a source such as dynamite or striking a steel plate with a sledge hammer.

Refraction wave paths cross boundaries between materials having different velocities in a way that energy travels from source to receiver in the shortest possible time (Dobrin, 1976). This travel time of source to receiver is used to calculate velocities and depths. The refracted waves travel through the surface layer and follow paths along tops of layers at velocities greater than the velocities in the above layers.

As these waves arrive at the surface, they are sensed by the geophones and recorded by the seismograph. It is this first arrival of refracted energy that Is of interest in the interpretation of the refraction data.

The first arrivals are plotted up in a time-distance curve or as time of arrival versus distance from shot received. Figure 2 shows an example of a time - distance curve for a three layer case. The geophones closest to the shot receive energy traveling through the first medium while geophones further away receive energy from deeper layers. Each layer is represented by a change in slope on the graph. The inverse of the slope is equal to the velocity of that layer. The extension of that slope to the time axis is the time intercept. These data on the time-distance curve of Figure 2 are used for calculations of depth and thickness of the subsurface layers.

There are two basic limitations to seismic refraction surveys. They are the occurrence of blind zones and hidden layers. Blind zones occur when an intermediate layer is thin or its velocity contrast is small. Refracted waves from blind zones are not detectible in the first arrivals of the seismic record. The hidden layer occurs when the intermediate layer has a lower velocity than the layer above and below ft. The presence of a hidden layer will result in erroneous depths to all interfaces below it. Erroneous depths

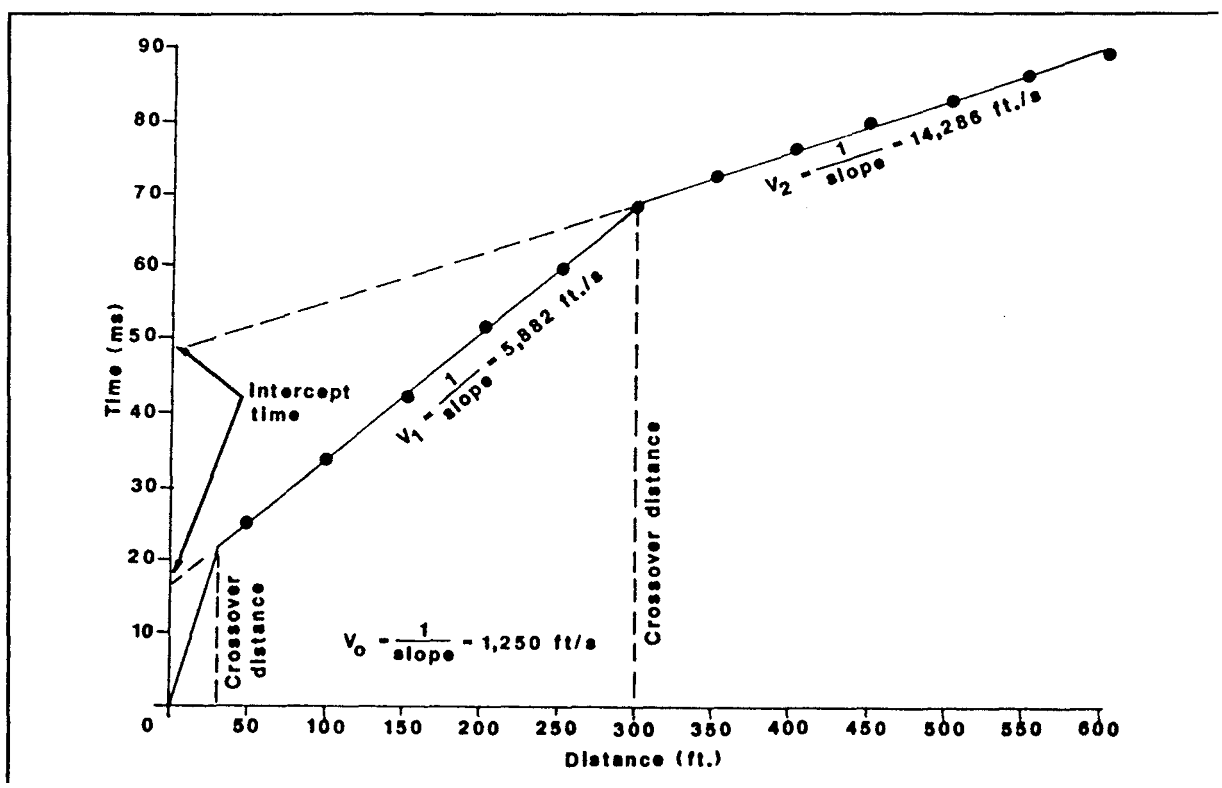

Figure 2 Time-distance curve.

can sometimes be used as an indication of the presence of such lower velocity layers. It was noted in the study area that when a thick, basal sand and gravel deposit in a bedrock valley is confined and hidden by a higher velocity clay till, the solution of the seismic profiles over the valley determine an anomalously greater depth to bedrock. These anomalies can be identified in the regional analysis and become preferential targets for groundwater resource evaluation (Gilkeson et al., 1987). Barring the presence of geologic conditions which are susceptible to the limitations of refraction surveys, refraction data is usually accurate to within 5% to 10% of actual depths.

APPROACH

Prior to conducting any seismic surveys, water well records at the Illinois State Geological Survey were reviewed for potential locations of bedrock valleys. Initial seismic refraction work was reconnaissance in nature using a two-shot reverse profiling method to locate the bedrock valleys. After the bedrock valleys were located, a high resolution method was used to profile the valleys in detail. The seismic data was placed in a data-base and areas of interest were mapped. This information was utilized in a program conducted by Gilkeson et al., (1987) for the development of shallow groundwater resources.

Water well records were analyzed for prime environments containing shallow aquifers. One such environment, is bedrock valleys that contain sand and gravel deposits. An environmental mapping program for the region conducted in 1975-1976 (Gilkeson and Westerman 1976) determined that drillers had cited erroneous locations for a large number of the water well records on file at the Illinois State Geological Survey. Therefore, prior to the assessment of the well data, the well locations were verified by the use of maps and files in the county building permits office. Once the locations of potential resources were determined, the seismic refraction program was initiated.

Two-shot reverse profiling seismic refraction was conducted in the targeted areas. This method of seismic refraction is common and provides a depth to bedrock under each shot location. The interpretation is based on Heiland (1946). This method was used as reconnaissance to locate the bedrock valleys. In most cases a 12-channel system was used.

Once the locations of the bedrock valleys were established, a high-resolution seismic refraction method was used. This method involved a 24-channel system, multiple shots, and end-to-end or over lapping spread cables to produce continuous profiling across the bedrock valleys. Depth to bedrock under each geophone was obtained using this method. This method is based on the SIPT method developed by Scott et al., (1972).

The field data obtained from the refraction surveys were interpreted with the aid of personal computers. The information was mapped and logged into a database. The continuous profiles were used to optimize the location of production wells. Aquifer tests were conducted in various bedrock valleys and are discussed by Gilkeson et al., (1987).

FIELD METHODS

Prior to collecting seismic data in the field, reconnaissance was necessary to determine the actual locations of the seismic lines. The seismic data was collected in a variety of environments, some of which included perimeter of open fields, road sides, old railroad grades, city streets and parks, parking lots, and property lines. The surveys were carried out in cultured and non-cultured areas alike. The lengths of the profiles varied from 300 feet to several thousand feet. Energy sources were either explosives or a self-propelled high weight thumper. Due to the nature of this type of work it was necessary to work closely with local government officials and land owners to gain permission and assistance in conducting the seismic surveys. Utility companies marked the location of the utilities to assure safe use of explosives.

Three different seismographs were utilized in collecting the data. These included the 24-channel ES2415F and the 12-channel ES-1225 seismograph, both from EG & G Geometrics and the 24-channel Terraloc MK III made by ABEM Geophysics. All three units are signal-enhancement seismographs and automatically digitize incoming seismic signals and store them in internal memory. Signal enhancement allows the incoming seismic signal to be added to the signals already stored in memory of the seismograph. This is called "stacking". Stacking greatly improves the signal to noise ratio and depth of penetration.

The ES-2415E is a 24-channel, CRT display, printing, shallow and deep exploration seismograph. The ES-2415E has three filtering capabilities: a multistage high-cut filter, a multistage low-cut filter, and a notch filter which can be set to eliminate interference from either 50 Hertz (Hz) or 60-Hz power line sources. These filters can be utilized to help reduce extraneous noise and provide clearer signals. The multistage high-cut filter is often important for refraction surveys because it allows elimination of common high frequency sources such as wind, and related "rustling noise of dry grass and leaves". The ES-2415E also has an Automatic Gain Control (AGC). AGC decreases the amplitude on the seismic record of strong arrivals, and increases the amplitude of later arrivals and weaker events. The data was stored on printed hard copy and by the EG & G DMT-911 magnetic tape recorder. The data was then transferred to floppy disc on a portable laptop computer in the field or a desktop unit in the office.

The ES-1225 is a 12-channel, CRT display, printing, shallow exploration seismograph. The filtering capabilities are somewhat limited but still aid in filtering out extraneous noise and provide a cleaner signal. The ES-1225 is microprocessor based and battery operated. It is also equipped with an RS-232 output for transferring data to a microcomputer. The ES-1225 is lightweight and portable. This was useful when the equipment needed to be hand carried into the field site.

The Terraloc MK III is a 24-channel, CRT display, shallow and deep exploration seismograph. The MK III has high and low cut filtering capabilities and AGC. The MK III is microprocessor based and battery operated. The data was stored on built-in 3.5 magnetic discs in IBM DOS format. A hard copy of the data was made on a field printer.

The geophones used in the investigation are 14 Hz vertical geophones. The seismic data was processed on an IBM AT microcomputer in the office and an IBM compatible portable computer at remote locations.

Two different sources were used in non-cultured areas, dynamite and a two component explosive, Kinestik. The two components are non-explosive in themselves, but when mixed together are a cap sensitive high explosive. Seismic blasting caps were used to detonate the charge. The size of the charge varied from 1 /6 pound to 1 pound. The size of the charge used is dependent upon the amount of energy needed to record the refracted waves. This is related to the length of the spread cable and the geohydrologic conditions of the site. The thumper was used for a source in cultured areas. The spread cables varied in length from 325 feet to 1300 feet. Each cable had 12 geophone takeouts. The cables were used in pairs for the 24-channel surveys. The length of line used was dependent upon the estimated depth to bedrock as shown in Table 1.

TABLE 1

Length of seismic line and geophone spacing used for estimated bedrock depth in northern Illinois

LINE LENGTH (FEET)	PHONE SPACING (FEET)	ESTIMATED BEDROCK DEPTH (FEET)
275	25	<30
550	50	30-150
1100	100	150-300

The field procedure involved laying out the seismic line, connecting the geophones and placing them vertically into the ground. Shot holes were typically augered to a depth of 4-5 feet. An electronic blaster simultaneously set off the charge and started the recording process in the seismograph. If the thumper was used instead of explosives for the source, a start geophone was used in place of the blaster. The geophone was placed near the thumper and connected to the seismograph. At the time of impact the signal from the geophone started the recording process of the seismograph.

Field methods were developed to efficiently obtain high-resolution profiles of the bedrock surface using the SIPT program. Spread cables were laid out end-on-end, one geophone spacing apart. This procedure involved taking two shots at the end of each spread cable, or four shots per cable. The shot locations were at the end geophones (at geophones 1 and 12) and at an off-set equal to the geophone spacing of the cable. Locating shots at geophone 1 and geophone 12 allowed for quality control on the travel time records, as travel time from geophone 1 to geophone 12 should be the same in both directions. Using this spread cable layout, shot locations, and a 24-channel system, it was necessary to take only two shots between the two spread cables. One shot in these locations counted for two. The first cable was then picked-up and laid out on the other end of the second cable to advance the profile in a "leap-frog" like manner. The procedure was then repeated until the profile is completed. Figure 3 illustrates the spread cable layout.

In areas of culture where it was not possible to use explosives a thumper was used to generate energy into the ground. In order to get a good signal with the thumper, it was necessary to stack the data three to ten times at one shot location. In general, the records acquired using this system were excellent. There was, however a significant amount of noise generated in the stacking process while collecting some of the records. The noise made interpretation more difficult, and less accurate.

Noise in cultured areas was, at times, a problem. Noise was generated by passing autos, planes, trains, and the wind. The noise problem was overcome by waiting for the right moment to collect the data. This was accomplished by visual observation and by observing the noise monitoring capabilities built into the seismograph.

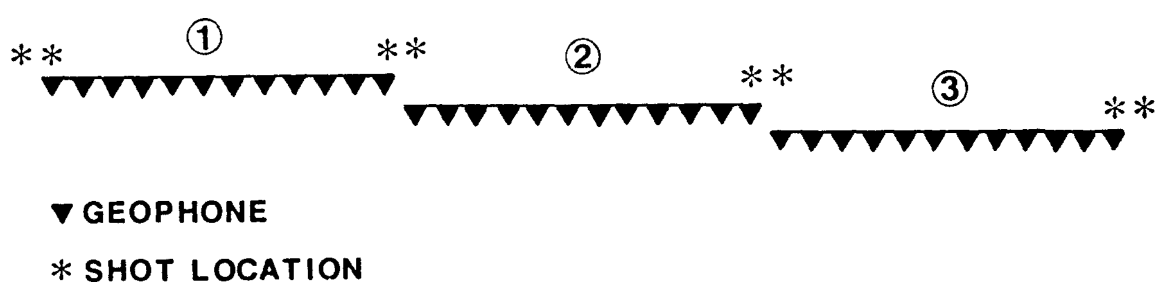

Figure 3 SIPT method spread cable layout.

Excellent seismic records were obtained by deploying geophones directly on pavement with energy introduced by striking the pavement with the thumper. Small wood blocks were constructed with a hole in the center to hold the geophone in a vertical position and in contact with the pavement. This system facilitated work in urban settings and many seismic refraction profiles were collected that were laid-out completely on pavement. Hence, important data was gathered in settings that conventional methods would not have allowed.

PROCESSING

The data was taken back to the office where it was processed. First breaks were picked by visual inspection of the data on the seismograph CRT and/or computer CRT using a cursor across the screen and by observing the printer records. Figure 4 is an example of a 24-channel refraction record. The time of the first arrival of the refracted wave was then plotted versus the distance from the shot for each corresponding geophone. This was done for all geophones on a single spread (Figure 2). Velocities were calculated using the inverse slope of a line connecting points representing the same layer. A 100 Hz high-cut filter was sometimes used on the data after it was recorded to filter out high frequency noise. A 50 Hz to 60 Hz notch filter was used, when needed, to filter out electrical noise. The final processing was done with two processing packages, FRAC and SIPT-1. The use of two interpretation techniques provided an internal check on data quality.

FRAC utilizes methods set forth by Heiland (1946) for interpretation of dipping beds. This process involves a shot at both end points of the seismic line. This method is called reverse profiling. The input data of the program FRAC includes the velocity and time intercept data from both the forward and reverse shots (Figure 2). The output includes depth to the top of each horizon under the shot location, and true velocity of each layer.

The program with highest resolution for processing the seismic data is SIPT-1. SIPT-1 is an acronym for Seismic Interpretation Program Two and was originally developed by Scott et al., (1972). SIPT-1 utilizes a two-dimensional modeling process in which the delay-time method is used to obtain a first approximation of model layers. Iterative ray tracing is then used to refine the model. This procedure

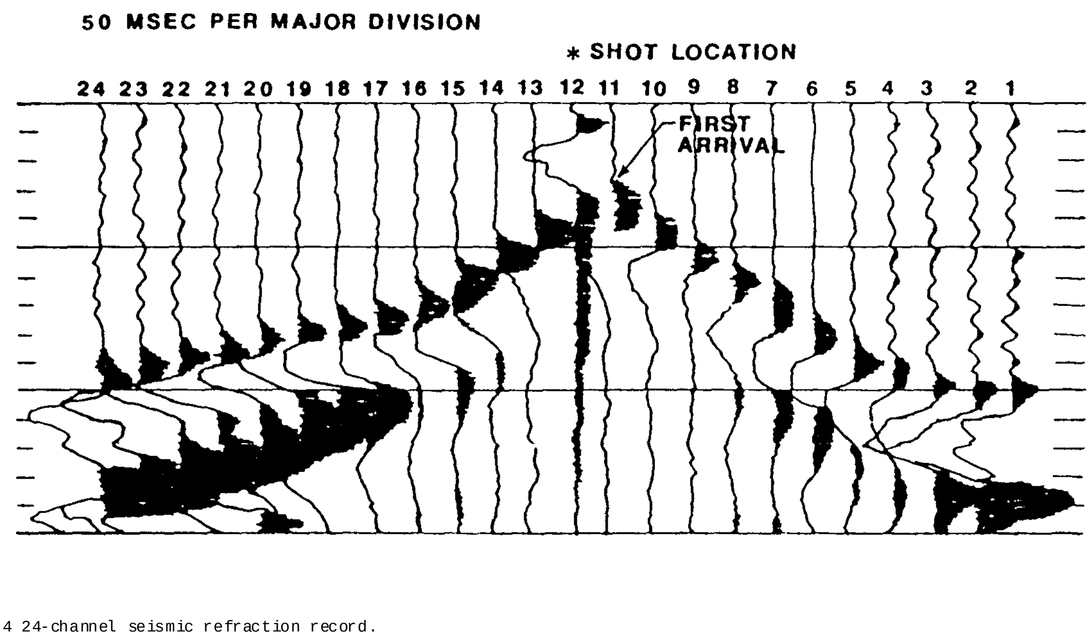

Figure 4 24-channel seismic refraction record.

compares field-measured travel times against computed ray travel times for the model. This comparison is done in an iterative manner to minimize discrepancies between the measured and computed times (Scott et al., 1972).

With these capabilities SIPT-1 provides for acquisition of high resolution profiles in regions where the surface and subsurface are both rough topographically. The high resolution is obtained by overlapping spreads of 12 geophones by up to 6 geophones and by locating shots at the end of spreads and offset from the ends. The program can handle up to 5 spreads and 7 shots per spread.

The input data to the program included shot location and elevation, geophone location and elevation, and first arrival times with their representative layers. Four shots per spread were used typically in this study to implement SIPT-1. However, overlapping sequential spread cables-by up to 6 geophones was used when optimum resolution was required for siting production wells. All of the input data for SIPT- must be properly formatted in an input file for SIPT-1 to run. A computer program entitled DIRT developed by Laymon (1986) efficiently performs this operation and is essential when SIPT-1 is used on a production basis. The output of SIPT-1 includes velocity data, ray tracing data, and depth to each layer below each geophone along with the corresponding elevation. Also included in the output is a geological cross section of the seismic profile.

The seismic geologic environment in the study region is considered a three layer case. The layers typically include the weathered zone, glacial drift, and bedrock. The weathered zone consists of the organic topsoil layer and the upper zone of soil which is affected by freezing and thawing. It is usually not detected on the seismic record because of the layout of the seismic line to target the bedrock. A velocity of 1,250 feet per second (ft/sec) is assumed for the weathered layer and input into SIPT-1. This is consistent with the measured velocities of the unsaturated weathered zone in Illinois (Heigold and Ringler 1979).

In most cases, the bedrock profile that was automatically generated by the SIPT program, was within 10 percent of the actual depths. If actual depth to bedrock was known at discrete locations along the profile, it was possible to model the data to get a best fit profile. This was accomplished by changing the layer assignment in SIPT-1 of the first arrival that corresponds with cross over distance, illustrated on the time distance curve in Figure 2. Assigning the layer 2 or 3 to this geophone location will raise or lower the depth to bedrock in the seismic profile.

Information pertaining to each seismic line was stored in a database program (Rbase). The database information on each line includes location (Township, Section, and Range), length, number of shots, velocity of each layer, and depth to each layer. The database allows for quick reference of seismic data from a specified location.

EXAMPLES

Figure 5 is a seismic refraction profile over a buried bedrock valley. The profile is located in the southeast corner of Kane County and is part of a bedrock valley that runs under the southern half of the city of Aurora. The general trend of the buried valley in this location is west to east. The seismic refraction profile is south to north. The profile is 1,850 feet in total length. The profile consists of three spreads of 12 geophones, 550 feet long and laid out end-to-end. The spreads are 2 geophone spacings apart. The geophones are spaced 50 feet apart. Dynamite was used for a source. Four shots were taken at each spread, one at the ends of the spread (at geophones 1 and 12), and one shot at a 50 foot offset from the ends of each spread. The data was interpreted using the SIPT-1 program.

Depth to bedrock inferred by the seismic profile ranges from 50 to 150 feet. The elevations in the deepest part of the valley are near 520 feet, Mean Sea Level (MSL) while elevations along the edge of the valley are 630 feet, MSL. The average velocity for the glacial drift was 6,100 ft/sec. The average velocity for the bedrock in Figure 5 was 14,150 ft/sec. The seismic refraction profile indicates that the width of the buried bedrock valley is approximately 1,700 feet.

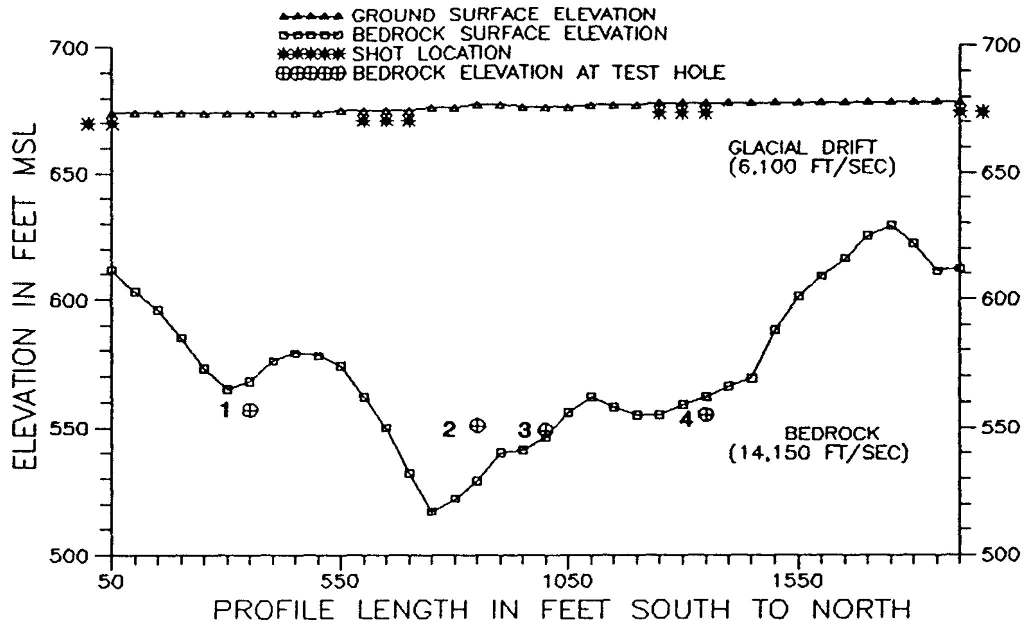

Figure 5 Seismic refraction profile of the orchard Road bedrock valley.

The seismic refraction profile along with electrical earth resistivity vertical soundings were used to locate exploratory borings and to assist in the design of an aquifer test (Gilkeson et al., 1987). Four borings, including the pumping well, were located along the profile inside the buried valley. The borings indicated that depth to rock inside the valley was 107 to 128 feet. The drift consists of sandy, silty clay with interbedded lenses of sand and gravel over a basal sand and gravel. The bedrock is fractured Silurian Dolomite. Yields from the aquifer test were 1,000 gallons per minute (gpm).

The seismic interpretation along the profile was accurate to within 10 percent of the depth determined at 3 test hole locations (test hole 1, 3, and 4 on figure 5). The seismic profile shows a markedly greater depth to bedrock at the location of test hole 2 than was determined by drilling. The location of test hole 2 is where the thickest section of coarse-grained sand and gravel was found to be present in the floor of the valley buried beneath glacial till. The greater depth to bedrock predicted by the refraction survey is due to the low-velocity sand and gravel acting as a "hidden layer" beneath the higher velocity glacial till. The production well was constructed at the location of test hole 3. The seismic profile on Figure 5 predicts the greatest depth to bedrock at a location that is 100 feet south of test hole 2. A test hole was not located at this location because of difficulties with site access.

Success of the aquifer test, and several others performed in the investigation (Gilkeson et al., 1987), was dependent on the location of the observation wells and pumping well. Optimum locations were determined with the seismic refraction and electrical earth resistivity data.

Figure 6 is a seismic refraction profile over the eastern flank of a buried bedrock valley that is located In the northeastern part of the study area. This bedrock valley is known as the Newark Valley and is the major bedrock valley in the study area. The general trend of the valley at the refraction profile is south to north.

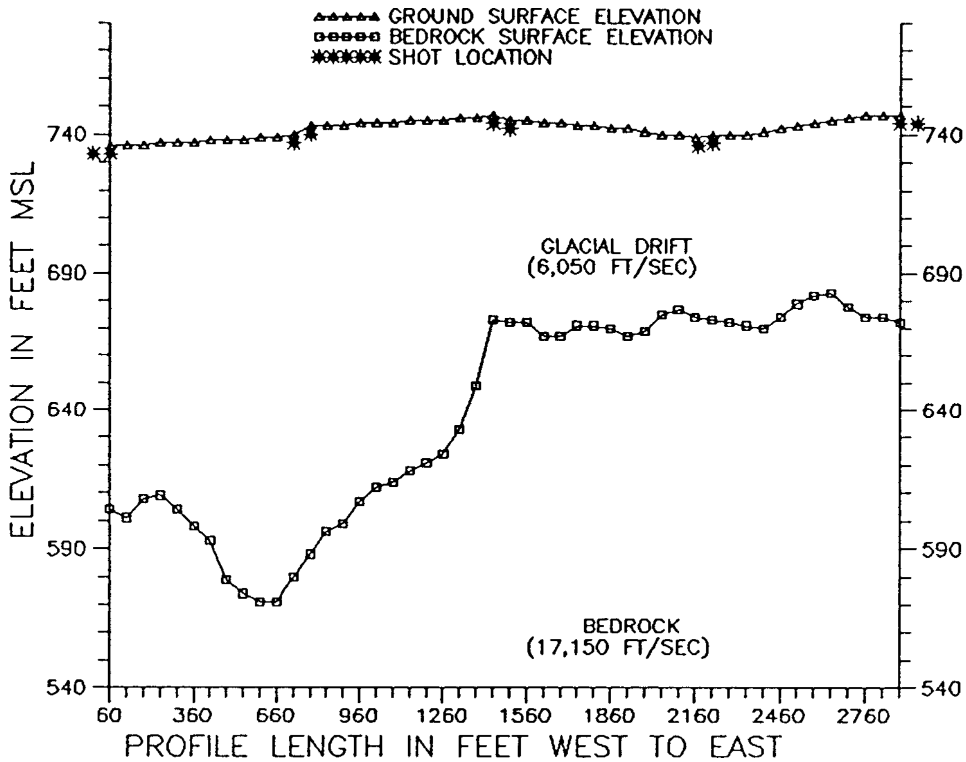

Figure b Seismic refraction profile of the Newark bedrock valley.

The seismic profile, illustrated in Figure 6 is laid-out west to east. The profile is 2,820 feet in total length. The profile consists of four spreads of 12 geophones, 660 feet long and laid out end-to-end. The spreads are 1 geophone spacing apart. The geophones are spaced 60 feet apart. A two-component explosive was used as the source. Four shots were taken at each spread, one at the end of the spreads (geophones 1 and 12) and one shot at a 60 foot offset at the ends of each spread. The data was interpreted using the SIPT-1 program.

Depth to bedrock inferred by the seismic profile ranges from 60 to 170 feet. The elevations of the bedrock in the valley are near 570 feet, MSL and 680 feet, MSL on the bedrock upland area. Other seismic profiles in the region show the deepest part of the valley at an elevation of 550 feet, MSL The average velocity for the glacial drift was approximately 6,050 ft/sec. The average velocity for the bedrock was 17,100 ft/sec.

There were no observation borings located near the profile. Borings in the region suggest the data consists of a thick till unit overlying a sand and gravel. Thin layers of sand and gravel exist locally near the surface In this particular region. The bedrock is of the Maquoketa Group. The sand and gray deposits of the Newark Valley make up a significant aquifer in the region. The thickness of sand and gravel, in Newark Valley near the profile in Figure 6, ranges from 25 to 100 feet (McFadden et al., Press).

CONCLUSIONS AND OBSERVATIONS

Seismic velocities, in northern Illinois for the glacial drift range from 4,500 ft/sec to 8,000 ft/sec. These velocities are characteristic of glacial tills, and sand and gravel. The velocities for the bedrock range from 10,000 ft/sec to 20,000 ft/sec. The higher velocities are characteristic of elastics found in the area. The lower velocities are characteristic of weathered elastics and shales found in the study area. Table 2 lists approximate ranges for velocities of these type of materials. The bedrock elevation along the seismic profiles in northern Illinois ranges from 450 feet, MSL to 800 feet, MSL The elevations in the deeper parts of the buried bedrock valleys in northern Illinois appear to be at similar elevations which range from 520 feet, MSL to 550, feet MSL.

Seismic refraction methods played an important role in the evaluation of important groundwater resource in northern Illinois. The program accomplishments are listed as follows.

1) The seismic refraction program in northern Illinois was very successful in "discovering" significant groundwater resources in optimum locations to serve major municipalities. Wells produced yields ranging from 750 gpm to 3000 gpm.

2) The seismic refraction program was useful in locating and providing significant detail of buried bedrock valleys, resulting in considerable savings in exploratory drilling expense.

3) Efficient field procedures for collecting continuous seismic refraction profiles were developed that use the SIPT method for accurate data processing, and a database was developed for future reference.

4) A high production rate was accomplished collecting data in the field. As much as 10 spread cables of data were collected per day. This amounted to 1 to 2 miles of seismic refraction data per day, depending upon the length of the spread cable used.

5) Techniques were developed for the successful collection of seismic refraction data in cultured areas.

6) The methodology developed in this study serves as a model for other groundwater resource investigations in urban environments.

TABLE 2

RANGE OF VELOCITIES

MATERIAL	APPROXIMATE VELOCITY (FT/SEC)
Weathered Material	1,000 - 2,000
Gravel or Dry Sand	1,525 - 3,000
wet Sand	2,000 - 6,000
Clay	3,630 - 8,250
Shale	9,020 - 14,000
Limestone (Dolomite)	7,019 - 20,000

Adapted from Benson et al., (1982) and Dobrin (1976).

REFERENCES

Benson, R. C., Glaccum, R. A., and Noel, M. R., 1982, Geophysical Techniques for Sensing Bur Wastes and Waste Migration: United States Environmental Protection Agency, Contract Number 68- 3050, 236 p.

Dobrin, M. B., 1976, Introduction to Geophysical Prospecting: McGraw - Hill Book Co., 630 p.

Gilkeson, R. H., S. S. McFadden, D. E. Laymon, and A. P. Visocky, 1987, Hydrogeological Evaluation of Groundwater Resources in Buried Bedrock Valleys, Northeastern Illinois, Proceedings of the Conference on Midwestern Ground Water Issues, NWWA, p. 145-167

Gilkeson, R. H., E. C. Perry, Jr., and R. B. Holtzman, 1984, Isotropic Studies of Natural Sources Radium in Groundwater In Illinois: Water Resources Center Report no 84-187, University of Illinois Urbana-Champaign, Illinois, 50 p.

Gilkeson, R. H., and Westerman, 1976, Geology for planning in Kane County: Illinois State Geological Survey Open File Report prepared for Northeastern Illinois Planning Commission, 41 p.

Heigold, P. C., R. W. Ringler,1979, A Seismic Refraction Survey of the Lower Illinois Valley Bottomland State Geological Survey Circular 507, 18 p.

Heiland, C. A., 1946, Geophysical Exploration: New York, Prentice-Hall.

Kempton, J. P., R. C. Vaiden, D. R. Kolata, P. B. DuMontelle, M. M. Killey, and R. A. Bauer, 19r Geological-Geotechnical Studies for Siting the Superconducting Super Collider in Illinois: Preliminary Geological Feasibility Report: State Geological Survey Environmental Geology Notes 111, 63 p.

Laymon, D. E. 1986, DIRT (Data Input for Refraction - Analysis Technique): Illinois Geological Survey Unpublished Open File Report, 8 p.

McFadden, S. S., R. H. Gilkeson, D. E. Laymon, C. R. Gendron, C. D. Wegscheid, M. E. Holden, and P. Visocky (In Press), Shallow Groundwater Resources of Kane County, Illinois: State Geological Survey Contract/Grant Report, 46 p.

Sasman, R. T., C. R. Benson, R. S. Ludwigs, and T. L. Williams, 1982, Water-Level Trends, Pumpag and Chemical Quality in the Deep Sandstone Wells in Northern Illinois: Illinois State Water Survey Circular 154.

Scott, J. H. Tibbetts, B. L., and Burdick, R. G., 1972, Computer Analysis of Seismic Refraction Data Bureau of Mines, 817595, 99 p.

Willman, H. B., 1971, Summary of the Geology of the Chicago Area: State Geological Survey Circule 460, 77 p.

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