**POWER AUGERS AND EARTH
RESISTIVITY UNITS AS
SUPPLEMENTS TO
DRILLING MACHINES**

**JANUARY, 1957
No. 1**

by

D. G. Shurig

**Joint
Highway
Research
Project**

**PURDUE UNIVERSITY
LAFAYETTE INDIANA**

FINAL REPORT
POWER AUGERS AND EARTH RESISTIVITY UNITS
AS SUPPLEMENTS TO DRILLING MACHINES

TO: K. B. Woods, Director
Joint Highway Research Project

January 24, 1957

FROM: Harold L. Michael, Assistant Director

File: 6-14-5
C-36-36E

Attached is a final report entitled, "Power Augers and Earth Resistivity Units as Supplements to Drilling Machines." The project has been performed by Mr. Donald Shurig, graduate assistant, under the direction of Professor E. J. Yoder.

This study utilized data taken during the subsurface exploration for the northeast extension of the Pennsylvania Turnpike. The capabilities and accuracy of power augers, earth resistivity equipment and drilling machines as well as analysis of cost for subsurface exploration are given.

Respectfully submitted

Harold L. Michael

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Attachment

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FINAL REPORT
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by

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Joint Highway Research Project
Project C-36-36E
File 6-14-5

Purdue University
Lafayette, Indiana

January 24, 1957

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ABSTRACT

Shurig, Donald G., M.S.E., Purdue University, January 1957. Power Augers and Earth-Resistivity Units as Supplements to Drilling Machines.

Major Professor: E. J. Yoder.

This thesis pertains to the use of power augers and earth-resistivity units to supplement drilling machines for highway subsurface exploration. Basis of study was the data taken during the subsurface exploration program of the Northeastern Extension of the Pennsylvania Turnpike System. Data obtained in the exploration of cut areas were selected for study for two reasons. First, only in these areas were all three machines used side by side in the same materials. Secondly, the exposed cut slopes afforded an excellent opportunity for study of the actual soil and rock conditions.

During a preliminary investigation of the complete excavations a definition of sound rock relative to highway cut slopes was developed. With this definition and Terzaghi's definition of soil for civil engineering purposes, the limits of unsound rock relative to highway cut slopes were automatically defined.

A system of classifying cut areas, or shallow conditions of the surface of the earth with which the civil engineer does considerable work, was devised. The classification system depends on the relative amounts of soil, weathered rock, unweathered rock and the structure of the exposed rock in a cut. The capabilities of, and especially the accuracy of locating the "top of sound rock" by each machine, were determined for

each group of cuts. An understanding of how each machine performs in various soil and rock conditions suggests how it be used in other explorations.

Before employing one of these units, the engineer in charge must anticipate the soil and rock conditions to be encountered. This he can do by means of geology maps, soils maps, photogrammetric maps and geomorphology, stereo-pairs of aerial photographs, and local field conditions and exposures.

Also considered herein is an analysis of costs of using drilling machines, power augers and electrical resistivity. From a review of the literature and from the author's field experience considerable general information and some more specific information is presented about each machine and use thereof. Some specific information of importance to engineers includes high core losses, their causes, means of minimizing, and significance. In reference to power augers, the latest boring and sampling devices are illustrated and their use described. Modifications of presently manufactured power augers are suggested to make the auger more suitable for subsurface exploration. Means of minimizing the boulder problem when augering, as well as the advantages of the use of power augers for highway explorations over the use of electrical resistivity, are given.

POWER AUGERS AND EARTH RESISTIVITY UNITS
AS SUPPLEMENTS TO DRILLING MACHINES

INTRODUCTION

Since World War II, new public road and toll road construction attained unprecedented heights. But it now appears that as a result of expanded federal aid to state highways, the toll road era is coming to an abrupt end. However, construction of high type roads will continue to grow and spread at an even faster rate. Much of the design criteria and many methods of exploration and construction developed on the toll roads will be used in the program sponsored by the national government.

Various features about super highways have greatly increased the required quantity of subsurface data and decreased the time to obtain it. The usual demand for accuracy and efficiency still persists. A feature that has created a demand for more data is the greater safety that is being designed into the modern thruways. Safety calls for wider roads, more overhead and underpass bridges; less curves and more gentle curves; deeper cuts and higher embankments.

Longer length, greater width, and more directness of route have increased the amount and complexity of geology and soils involved. In the past the tendency has been to follow the valleys or to run parallel to the strike of bedrock. At the present time there is as much a tendency to cross the strike at ninety degrees as to parallel it. This head-on approach or traverse causes a more rapid change of underlying bedrock and soil conditions.

The need for expediting design and construction requires that the design be correct the first time. Though the accuracy of data is primarily important for the safety of the structure, speed and accuracy are important for saving time and money. Bridge foundation design, cut slope design, embankment design, and the original grading plans of the contractor must be finalized at the earliest possible time.

Finally, competitive bidding has become keener. When subsurface information is considered sufficient and reliable, bid prices are usually equalized. Adequate information also prevents litigation, helps to increase smoothness of construction, and tends to keep the profits more evenly distributed among the various contractors.

Three machines that are becoming commonplace in the field of highway subsurface exploration are the diamond core drilling machine, power auger and the earth electrical resistivity machine. The diamond core drill, hereafter to be called a drilling machine or drill rig, was developed primarily in the mining industry. However since drill rigs have been adapted to take soil samples as well as rock cores, they have been extensively used by geological, soils, and civil engineers. In practically all big highway exploration jobs the drilling machine is a very essential tool but its sole use is unnecessary, too slow and too expensive. Therefore the power auger and electrical resistivity, which are considerably cheaper and faster but which yield data of lower quality and quantity, are used to supplement the drilling machines. The supplementary work is done essentially in excavation areas. In fill areas, very often the auger alone can be used to explore foundation

conditions. Up to the present time, very few people have dared to use a power auger alone or a resistivity unit alone for structure foundation investigation.

PURPOSE AND SCOPE

The primary purpose of this thesis is to compare costs, accuracy, types and amount, and value of data obtained by soil and rock drilling machines, power augers, and earth electrical resistivity machines and to compare the advantages and disadvantages of these machines when used in highway subsurface exploration. To accomplish this, a part of the purpose was to make a comprehensive review of these three methods of exploration and to outline special techniques that may be used. It was also desired to determine the most efficient means of exploring excavation areas, fill foundations, and structure foundations in or on various soil and rock formations with the use of one, two or all three units.

Data used for the study was accumulated from the files and field of the recently completed Northeastern Extension of the Pennsylvania Turnpike System. This extension lies between Philadelphia and Scranton and traverses parts of four major physiographic provinces. The main subsurface exploration program lasted one year, January 1954 to January 1955. Total cost of the program was \$364,000, which included the cost of using up to 15 drilling machines, one power auger mounted on a jeep truck and one electrical resistivity machine.

Comparison of the accuracy of original exploration data obtained by all three machines, especially data pertaining to the location of the top of sound rock, was made by a study of the slopes of 22 cuts. Cuts were examined, rather than foundation sites, because in the original exploration all three machines were used in most of these proposed

excavation areas. Two cuts representing one general bedrock type or soil formation were examined in the field for the actual location of the top of sound rock relative to slope stability. Advantages and disadvantages of the machines are given on the basis of $6\frac{1}{2}$ years of field experience in toll road subsurface exploration.

PROCEDURES

Pennsylvania Turnpike Cut Explorations

Before the Geology and Soils department of the turnpike used a power auger, cut areas were explored with drilling machines supplemented by electrical resistivity. Usually only one boring was required and it was placed at the crest of the cut where split spoon samples of the soil and cores of the rock were taken. If the cut was to be longer than 1,000 to 1,500 feet or if local surface conditions indicated an irregular rock profile, additional borings were justified. With the boring log which gave the depth of overburden and water table, type, condition and dip of bedrock, the geophysicist could usually decipher the resistivity curve made at the same site. With the aid of this information he could extend the bedrock profile through the entire cut by the interpretation of curves made at each station.

Since the use of the power auger was still somewhat experimental, it was used along with the resistivity to supplement the core boring in cut area exploration. However, instead of probing every 100 feet along center line as was done with the resistivity unit, the auger operated 40 feet left and right and at 200 foot intervals. The borings were made 40 feet from center line because this located them at the toe of the cut slopes. Subsurface information at this point yielded excavation information at the point of maximum excavation and slope design data at a point closest to the entire slope.

The general auger procedure was to penetrate three feet below grade. If it was felt that a boulder above grade caused refusal, a note was made on the log stating that refusal may have been caused by a boulder and another boring was attempted a few feet away. Soft rock was cored, and logged; if medium hard rock was encountered, it was slowly and carefully penetrated a foot or two before refusal was indicated on the logs. Contact with hard rock was usually indicated by a loud and violent clash of the machine, at which time an immediate withdrawal was made.

The auger log gave a visual description of the soil profile and weathered rock, depth of free water, depth of refusal or grade, and the location of soil samples taken for laboratory testing.

Procedure of Study to Determine the Accuracy of Original Field Data

For the purpose of comparing the accuracy of data obtained by the three machines under study it was necessary to compare data taken in proposed cut sites because within these relatively small areas of similar soil profiles and bedrock, all three machines were used side by side. The exposed cut slopes also afforded an excellent picture and study of the actual conditions for checking the original data. Some 22 excavations were investigated in the field but to avoid repetition only the results of 15 investigations are presented herein. Two cuts representing one bedrock type or soil formation were selected at random for the studies. The bedrock types with their residual soils, and other soils deposits examined were:

- 1) arkosic sandstone
- 2) clay shale

- 3) hard calcareous shale
- 4) siltstone
- 5) baked shales and hornfels
- 6) argillite
- 7) argillaceous limestone
- 8) siliceous and dolomitic limestone
- 9) conglomerate (fanglomerate)
- 10) granite gneiss
- 11) diabase
- 12) fissile shale (with alternate sericitic, siliceous and carbonaceous layers)
- 13) slate
- 14) chert
- 15) hard, fine to medium grained sandstone
- 16) Illinoian terminal moraine deposits of clay-like and granular soils.

Information observed during each cut survey was as follows:

- 1) Type, structure and weathering of bedrock
- 2) Strike and dip of the rock relative to turnpike center line
- 3) Soil classification
- 4) Depth to sound rock
- 5) Accuracy of the drill rigs, auger, and resistivity as to the depth of sound rock
- 6) Cut slopes as actually constructed
- 7) Some excavation problems

Depth to sound rock was measured on both slopes of a cut at each station, after the cut was exposed, with a hand level. By plotting this information on the respective cross-sections, the depth to sound rock at center line could be extrapolated. These latter depth-points were in turn plotted on longitudinal cut sections, to show the top of sound rock profile along center line. Where the top of sound rock was irregular the rock profile for both right and left slopes were drawn in order to emphasize this erratic condition.

To determine the accuracy of the resistivity, the interpretations of the depths to rock were plotted and connected by lines. The longitudinal location and depth of auger penetrations were indicated by vertical lines.

ROCK AND SOIL DRILLING MACHINES

Accessible test pits represent the ultimate in subsurface exploration. They provide the most detailed and reliable information on soil and rock conditions. According to Hvorslev (6), "They make it possible to examine, sample, and perform special field tests on the material in situ. Furthermore, the very act of advancing such an exploration gives valuable information on the difficulties to be encountered in and the probable costs of excavation for the proposed structure."

However this method of investigation is expensive and slow especially for highway work. At depths beyond 20 feet, the pits cost perhaps ten to 15 dollars a foot for average ground water conditions and 25 dollars a foot for difficult ground water conditions (9).

For a relatively insignificant sacrifice of quality and quantity of data, the use of drilling machines can produce significant savings in time and money when compared to the test pit method of exploration. Boring costs per foot for routine highway soil sampling and rock coring range from three to 15 dollars a foot. Drill rigs, with their diamond bits, core barrels, and various intricate soil sampling devices are extremely versatile and capable. In areas of high water table, driven casing prevents the hole from caving and permits a sample to be taken at the required depth. When boulders are encountered in the overburden, they can be either bored with the diamond bit, or they can be blasted and partially removed to permit physical samples from exact known depths to be obtained. Thus, they yield essentially the ultimate in complete-

ness and accuracy of data as compared to information obtained by sounding and probing devices.

Development of the diamond core drill took place in the ore fields and especially in the coal fields of Pennsylvania. At the present time the extensive uses of diamond drills are:

1. Exploration for and development of mineral deposits
2. Blast hole drilling
3. Foundation investigations and grout hole drilling
4. Oil structure investigations and oil well drilling

Extensive subsurface exploration for civil engineering purposes involving the use of drilling rigs took place around the early nineteen hundreds. Some of the first holes were bored for large structures in New York City. A large drilling company, born in the anthracite coal fields of Pennsylvania, did much of this work.

Cumming (3), on the history of diamond drilling, states that the ancient Egyptians were probably the first to use the principle of core drilling. The Egyptian cores were, however, measured in inches of length rather than in feet. The drills were tubular and hand-operated and more likely used abrasive powders rather than gem set bits. Cumming gives the following summary of the development of drill rigs.

Modern diamond core drilling, with holes up to a mile or more in depth, is the outgrowth of the experiments of Rudolph Leschot, a French engineer who in 1864 employed black diamonds set in annular bits for drilling blast holes in the Mount Enis tunnel between France and Italy. The method was introduced and developed in the United States in the late sixties. The first deep hole was drilled for coal in 1870 near Pottsville, Pennsylvania, by M. C. Bullock. This hole was seven hundred and fifty feet deep. It can be inferred that the diamond drill was introduced into Canada in 1871 when a bore-hole, known as Harper's bore-hole, was drilled for coal at Springhill Cumberland County, Nova Scotia. At the old Silver Islet Mine near Port Arthur, Ontario, the diamond drill was in use as early as 1872.

The early diamond drill was a crude machine but was said to have been successful in drilling a hole about 130 feet deep in the Michigan iron-mining area about 1869. In other tests, however, the greatest depth attained was only 96 feet, the drill did not perform well, and bits were lost in two holes. An observer remarked further that since it was a steam machine, the drill had to be used near a town and could not be taken into the "woods." The advance per drill-shift with the early diamond drill was undoubtedly low and its usefulness very limited. Within a few years, however, it was being used to drill holes 400 to 1,100 or more feet and speeds of about one to two feet per drill-hour were reported.

The introduction of a swivel head that could be swung out of the way when the drill rods or casing were hoisted or lowered, the inclusion of a hoist integrated with the machine, the adaption of the double-tube core barrel, and the application of the hydraulic feed further raised drilling rates. There also was a pronounced improvement in the quality of the drill rods and accessories as well as major changes in bits and the development of a highly skilled class of drill runners.

Drilling machines are manufactured in a large number of types, sizes, and weights. Figures 2 (A) and 2 (B) show a drill rig that can be used for civil engineering studies. Some nomenclature is given on these figures, the general mechanics of operation is obvious. Essentially the machines have four requirements: (1) means for rotating the drill rods, (2) means for controlling the downward motion (feed) of the drill rods and bit, and pressure on the bit, (3) means for hoisting and lowering drill rods, casing and drop-hammers, (4) a pump for circulating water to the face of the bit.

The hydraulic and automatic screw feed swivelheads shown are the mechanisms through which both rotational motion and feed motion are supplied to the drill rods. Screw feed heads are made with either two or three sets of feed gears and any of these sets can be thrown into action while the drill is running. For instance, one set of gears will give an advance of, perhaps, one inch per 200 or 400 or 600 rpm, etc.

(A)

(B)

POWER UNITS

1. GASOLINE
2. DIESEL
3. ELECTRIC
4. AIR

HOIST ASSEMBLY

1. BRAKE LEVER & BRAKE BAND
2. DRUM & CABLE
3. CLUTCH LEVER

HYDRAULIC SWIVELHEAD

1. DRIVE ROD
2. PISTON RODS
3. HYDRAULIC HOSE
4. BODY
5. GATE HINGE (NOT VISIBLE)
6. FEED CONTROL (NEEDLE) VALVE
7. HYDRAULIC CYLINDERS
8. GUIDE RODS
9. CHUCK

BYPASS
CONTROL
VALVE

HYDRAULIC
FLUID
RESERVOIR
TANK

HYDRAULIC
PRESSURE
GAUGE

TOW PULLEY

CONTROLS

1. SWIVELHEAD SHIFTER
2. DIRECTIONAL (HYDRAULIC) FEED CONTROL LEVER
3. TRANSMISSION SHIFT LEVER
4. THROTTLE
5. CLUTCH HANDLE

ROLLER

FIG. 1 (A) DRILLING MACHINE WITH HYDRAULIC SWIVELHEAD
(B) SCREWFEED SWIVELHEAD

Gear ratios can usually be changed in accordance with the general character of the formations encountered. This type of feed gives satisfactory results in sound and uniform rock and requires a minimum of attention and experience. A rig with screw feed is dependable, durable, weighs less and costs less than a rig with hydraulic feed.

The hydraulic feed mechanism has more advantages and is generally replacing the screw type. Hydraulic feed, by means of the twin hydraulic rams, gives the operator sensitive and instantaneous control of the rate of advance and the pressure on the bit. It enables him to drill at maximum speed under any and all conditions by taking advantage of every change in strata, advancing faster in soft formations and slowing down only as much as necessary in harder formations. The bit pressure can be determined by a gauge indicating the oil pressure in the hydraulic cylinders and is for a given rate of feed and bit speed, indicative of the character of the formation being cored. The uniform pressure maintained with hydraulic feed also aids in yielding a higher percentage of core recovery.

A hydraulic rig with a medium large to large double tube swivel type core barrel is best for coring soft non-uniform rock and soil, if attempted. When subsurface cavities, limestone solution cavities or mined out areas, are encountered, the hydraulic system will allow the drill rods to drop slowly the instant the cavity is encountered. The free fall reveals the exact elevation of the cavity roof. By loosening the chuck, the vertical extent of the void is determined by the free falling drill rods. Finally, the hydraulic rams can be used to press thin walled sample tubes into the soil with a smooth and continuous thrust ($2\frac{1}{2}$ to 3 feet in 30 seconds) as is required for an undisturbed sample.

Each type of swivel head is suspended in the main drill body by means of a gate hinge. This hinge permits the head to be swung clear from over the bore hole to permit removal of drill rods, casing, and sampling tools, by means of the hoist, without moving the entire rig. Each head can be rotated a full 360 degrees so that holes can be drilled vertically, horizontally or at any desired angle. Feed strokes are usually 24 inches. At the end of a 24 inch stroke the chuck is loosened and raised to its top position for the next 24 inch stroke.

The drill rigs are mounted on skids, trucks, trailers, barges and rafts. A rig on skids can propel itself over rough terrain or deep into dense woods by means of its own engine and hoist. Barges are used for drilling in deep water, and rafts usually made of planks and 50 gallon drums, are used for shallow water work.

Soil Sampling with Drilling Machines

In a research report, "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes," Dr. Hvorslev has presented an authoritative reference work on subsurface exploration and sampling of soil and rock. The report includes general data and information on methods of subsurface sampling, with a complete bibliography for detailed information on specific topics. It is emphasized that the report is especially thorough in describing the specific methods and tools for the sampling of all types of soils in all states of consistency and moisture content. The report was in preparation some ten years and at the present time is approximately seven years old, so essentially none of the data is out of date. Individuals connected with the direction

or supervision of subsurface exploration for civil engineering purposes should be familiar with the report.

It is not the intention of this report to add to Dr. Hvorslev's report as such and no attempt is made to review such a detailed writing. The reader is referred to the report for a long list of soil sampling devices that have been or can be adapted to drilling machines. However, considering the extensive use of the standard penetration test in highway exploration work, and also since some reference will be made to the test later in this thesis, it is reviewed here. Also in connection with soil sampling and the standard penetration test, a cost saving technique used on the Turnpike is given below.

Terzaghi on the standard penetration test states (16):

The simplest method of obtaining at least some information concerning the degree of compactness of the soil in situ consists of counting the number of blows of the drop weight required to drive a 2 inch split spoon into the soil for a distance of one foot. A weight of 140 pounds and a height of fall of 30 inches are considered standard. [See Figure 2 (B)]. It is attached to the drill rods and lowered to the bottom of the drill hole after the hole has been cleaned by means of a water jet or an auger. After the spoon reaches the bottom, the drop weight is allowed to fall on the top of the drill rods until the sampler has penetrated about six inches into the soil, whereupon the penetration test is started, and the foreman records the number of blows required to produce the next foot of penetration. This procedure is referred to as the standard penetration test. Since this test furnishes vital information with very little extra effort, it should never be omitted.

When a drilling machine is used for soil sampling, one of two general procedures is used for advancing and cleaning the bore hole. In both methods, casing is driven to a point just above the sampling depth. In the first method, material in the casing is removed by a rotating chopping bit and wash water under pressure, see Figure 2 (A) . If there is a significant change of material, it may be recognized by a

FIG. 2 COMMON METHODS OF ADVANCING AND CLEANING BORE HOLES
 (A) CHOPPING & WASHING (B) DRIVING CASING OR LARGE SPOON

change in color of the returning wash water, some observable physical change of the soil particles, or change in the rate of advancement of the chopping bit. For each new strata encountered the cutting tools should be withdrawn and a split spoon lowered into the hole for a sample and penetration test.

If the soil is fairly cohesive and is not affected greatly by flowing ground water, the hole can be advanced and cleaned by a second method. This involves pulling the driven casing, using a steady pull and rotation, so that the soil adheres to the inside. The soil is then removed from the casing by jarring and vibrating it with a sledge hammer as shown in Figure 2 (B). Any change of material may be determined but a standard penetration test is not obtained for the different material. However, if the particular strata is very hard or very soft, the degree of hardness will be indicated by the recorded casing penetration blows.

The latter process is most suitable in cut or fill foundation sites, in homogeneous, cohesive soils above the water table. Fortunately these soils and conditions are quite commonly encountered in highway explorations. Some advantages of the method are that it is cheaper, and faster than the wash water method. Also, when sampling in cut areas (the soil of which will be used for fill construction), samples in ample quantity, between the smaller split spoon samples spaced at minimum intervals of three to five feet, can be obtained for Proctor compaction tests. Below is shown a table giving the approximate length of soil core required for a ten pound sample of soil, passing the number 4 mesh sieve, which can be used for a Proctor test.

		Unit Weight of Soil in Natural State Passing the Number 4 Sieve in Lbs. per Cu. Ft.					
Casing	1 ^D -in.	90	100	110	120	130	140
BX	2 3/8"	3.1	2.7	2.4	2.2	2.1	1.9
NX	3"	2.1	2.0	1.9	1.7	1.6	1.5
4"	4"	1.3	1.2	1.1	1.0	0.9	0.8

Table 1

On the Northeastern Extension of the Pennsylvania Turnpike, especially across the Great Valley, there exists a long stretch of deep, relatively homogeneous, clay-like soils; moraine, alluvium, deep residual limestone and shale soils, all with a low water table. To take advantage of the situation a special proposal was written into the specifications calling for the casing pulling method of advancing the hole, that is without chopping bit and wash water. Spoon samples were to be taken every five feet and changes of material were to be taken from casing soil. Holes were to be stopped either at refusal or at a depth specified by the engineer in charge and no rock cores were to be taken. These specifications produced the lowest boring contract price which amounted to 3 dollars a foot. It was also possible for turnpike inspectors to take disturbed samples for compaction tests when and where desired at no extra contract cost.

Dr. Hvorslev mentions in his report that opportunities for detailed experiments on sampling of soils by means of core boring were not afforded during the research. However, core barrels have been designed especially for taking soil cores. Regarding this he states (6):

It is difficult if not impossible to force a drive sampler into hard and brittle clays, dense cohesionless soils, and partially cemented soils without causing partial failure and disturbance of the soil before it enters the sampler. There is little doubt that less disturbed samples of such soils can be obtained by core boring. This may even apply to such relatively soft and loose but highly brittle soils as loess, provided vibrations of the core barrel can be reduced to a negligible amount.

Undisturbed samples of soils containing considerable amounts of coarse gravel and stones cannot be obtained by drive sampling; they can be obtained by core boring but only when the soil is frozen before coring.

Diamond Core Boring with Drilling Machines

Samples of rock, for foundation or excavation investigations, are generally obtained by rotary core boring. The cores obtained yield a much larger amount of information about the type and condition of the rock than the fragments returned in the wash water of a churn drill operation or similar wash boring operation. In fact, the amount of reliable information from wash samples is so small that they are practically never used for civil engineering studies.

Cutting of the rock cores is done principally by tubular bits which are set with industrial diamonds. The bits are attached to the lower end of long hollow core barrels which in turn are attached to hollow drill rods of a smaller diameter (see Figure 2). The drill rods are held fast by the chuck of the drilling machine and the entire string of tools is rotated at a controlled speed, feed, and downward pressure. Water pumped through the hollow string of tools at a controlled pressure, keeps the bit cool and forces rock cuttings from the bit face to the surface between the outer circumference of the tools and the wall of the hole. Clear water instead of drilling fluid is preferred for dia-

mond and shot core boring in sound rock because the water is cheaper, is quite adequate, and requires smaller fluid passages and pump pressures.

Rotary core barrels used in rock are roughly classified in accordance with the cutting medium in the coring bit; that is, diamonds, chilled shot, and steel teeth or hard metal inserts.

In a single tube core barrel, the core is exposed to the downward flowing wash water and to abrasion against the inner wall of the rotating core barrel itself. Therefore the single tube core barrel should not be used for materials which are subject to erosion, slaking or excessive swelling.

A double tube core barrel will protect the core against the action of the circulating wash water. The inner tube may be rigidly connected to the core barrel head, in which case it rotates with the outer barrel. A swivel head type, has the inner tube riding on bearings in the barrel head and the tube does not rotate with the barrel. This type not only protects the core from water erosion but also decreases inside friction, abrasion, and transmission of torsional forces to the core. The double tube core barrel is commonly used for sampling rock that is soft, friable, non-uniform, fissured, and in general when the diameter of the core is small. It should also be used if soil coring is attempted and the larger the diameter the better the recovered sample.

When the core barrel is withdrawn from the hole the core is prevented from slipping out of the barrel by a tapered and fluted ring which tends to wedge and lock the core. These devices, called core retainers, are located in the bit or in the shoe of the inner tube. Core springs or a basket type core lifter or flap valves are used to retain cores of soft and broken rock and of soil.

Core drilling has become an art. About the most important factor in good drilling, which is essentially high core recovery, is the skillfulness of the driller. Not only must the driller select the proper equipment, especially type and size of bit and core barrel, but he must control and coordinate bit pressure with rate of feed with rotation speed as well as coordinate the pressure and volume of wash water. The importance of selecting a skilled and experienced driller for a delicate exploration job cannot be over-emphasized.

When core drilling in rock, the civil engineer should pay close attention to the net core recovery ratio which indicates information about the strength and uniformity of the rock. Core recovery is expressed as the ratio of the length of core recovered, after properly fitting broken pieces reasonably well together, to the depth of penetration of the core barrel. It is usually computed for each drill run. The net core recovery ratio is better known as the percent core recovery and quite often its counterpart is used, percent core loss.

Core loss may be due to the softness or friability of the material being cored. In this case it disintegrates under the pressure of the bit and wash water, at the bit and in the core barrel, and is removed in the water. Often a piece of hard core from a thin stratum will become misaligned in the bit and jam the entrance. Continued drilling will completely grind away any other rock of softer quality in the path of the jammed bit. Jamming of the bit usually occurs when the rock being cored is not held firmly in place or when there is some malfunction of the core retainer.

Jamming may also occur in comparatively hard uniform rock. The barrel might become jammed by rock fragments wedging between the core and barrel wall or by the driller over-running the length of core that the barrel can hold. Both of these conditions result in the grinding of any other core attempting to enter the bit.

If the core retainer fails by malfunction or is unable to function because the core is too strong and has not been broken loose from the bedrock mass, the cored sample will slip from the bottom of the barrel. If the latter is the case, the driller may be able to pick up the core on the next run. However, if the core lies loose and off-center in the bottom of the hole the next run will probably destroy it and badly damage the expensive diamond bit, especially if the rock is hard. Diamonds are the hardest abrasives but they can be broken or unseated from the bit by shock or impact. To prevent this damage it is often necessary to use a special chopping bit to purposely break up and destroy the loose core.

The engineer in charge of the field exploration work should be able to judge whether high core loss is due to the condition of the rock, faulty equipment, or poor drilling. Listed below are some means that might be used when the highest possible core recovery is desired and when the added expense is justified. A thorough understanding of the list will also enable the engineer in charge to make a correct determination as to the cause or causes of the high core loss.

1. Employment of an experienced drilling crew known to have the special ability for obtaining high core recovery.
2. Use of a double tube core barrel, swivel type with ball bearings, with a beveled bit fitted with a core spring.

The Pickard core barrel besides having all the advantages of a double tube core barrel is provided with a water cut-off head which shuts off circulating water when the core blocks. Blocking is immediately indicated to the driller by a sharp rise in pump pressure recorded on a water pressure gauge on the pump. The drill is stopped to prevent grinding of the core and the core barrel removed from the hole.

In the Marquette Mining District, Michigan, where these core barrels were developed, core recovery in iron formations for years has averaged between 20 and 40 percent. With the Pickard barrels, the recovery is generally between 80 and 95 percent.

This core barrel is a special tool and should be used only as a means of obtaining maximum core recovery from critical horizons. (3)

3. Make short drilling runs and/or pull the core barrel out of the hole just as soon as it blocks (blocking is often indicated by a clicking, jerking, or chattering of the drill rods).
4. Dry blocking or burning in. For a few seconds or minutes before the core barrel is pulled out, it is run with the drill water shut off so that particles of sludge or ground core become wedged between the core and the inside wall of the core barrel or tube. This practice, however, should not be routine, and should be attempted or requested of an experienced crew only. Dry blocking is safer in soft rocks than in hard rocks and should be done just as little as possible in the latter. The heat generated when running without the wash water is so great that the diamond bit, costing several hundred dollars, can be destroyed or badly damaged within one to several minutes.
5. Reduction of vibration of drill rods and core barrel. Excessive vibration has a tendency to break up the core and

cause it to grind and wash away, or the broken core may jam the bit.

Some causes of vibration are as follows:

- (a) Drilling machine not rigidly mounted. Drilling rigs mounted on trailers, trucks and barges will usually vibrate more than skid mounted rigs.
- (b) Drill rods that are worn, bent, or out of balance dynamically, at the normal operating speed.
- (c) Lack of rod grease.
- (d) Loose couplings and poor threading of rods and fittings giving angularity and lack of concentricity of the assembly.
- (e) Higher rotational speeds. (3)

Most of these causes of vibration indicate their own remedy.

Guide rods, which are extra heavy drill rods, are sometimes inserted above the core barrel to prevent chattering and vibration of the bit.

6. Increase of the core size diameter. "Since the torsional moment of resistance of the core increases with the cube of its diameter, an increase in diameter is very effective in reducing breakage, increasing the recovery ratio and the length of core obtainable in a single operation." (6)

Following are several quotes about core recovery.

Peele: (3)

Core recovery is highest in hard uniform rocks in which it may reach 100 percent. It is lowest in loose, soft, cleavable and broken rocks where, unless the drill is run almost dry and rods are raised every few inches, recovery may not amount to more than 10 percent.

Vibration of rods causes poor recovery. For good recovery in hard rocks the drill should run with low speed and heavy pressure; in soft rocks, the reverse. Recovery is invariably less in upper than in lower portions of holes due to the decomposed character of rocks near the surface.

Legget: (7)

When drilling in some types of soft or disintegrated rock, it will sometimes prove difficult to obtain complete sections of core, and estimates will then have to be made, based on the operator's observations and his experience, with regard to the exact nature of the material penetrated. The amount of core recovered will naturally vary with the type of rock penetrated. Mr. W. Simpson gives the following averages: quartzite, 90 percent; granite, 85 percent; sandstone, 70 percent; limestone, 60 percent; shale, 50 percent; slate, 40 percent. These figures are naturally to be regarded as a guide only to what may be expected.

Cumming: (3)

In the Transvaal 19 drill holes ranging in depth from 78 to 2172 feet, gave core recoveries of 25.7 to 92.68 percent. Recoveries were also computed by rock types with the results shown:

CORE RECOVERIES, TRANSVAAL

Rock	Number of Holes	Arithmetical Average of Recovery
Shale	10	53.2%
Sandstone	4	73.2%
Quartzite	13	73.7%
Dolomite	2	60.1%

The geology of the recovered core can yield a great deal of general information which usually is sufficient to answer most highway construction problems without extensive laboratory tests. On-the-spot data revealed by the rock core are: mineralogy or chemical composition; general texture or fabric; structure, including folding, faulting, jointing, etc.; stratification, type and degree of interbedding, schistosity, etc.; type and strength of cementing materials; degree of weathering; and general compressive or crushing strength. In many cases, the civil

engineer can use this general information in a qualitative manner to:

(1) judge the rock strength for foundation support; (2) design a stable cut slope; (3) determine the suitability of a rock formation for base course, bituminous, and concrete aggregate; (4) determine blasting and crushing qualities; and (5) predict the general excavation problems.

However, if the percent of core recovery is low, it is obvious that some answers are left to the knowledge and judgment of the engineer.

If in the judgment of the driller and inspector the core loss is due to the softness of the material, the drilling tools should be withdrawn so that a split spoon can be inserted for a sample and standard penetration test. When core recovery is low while investigating proposed structure foundation sites in hard rock, hardness indicated by slow bit advancement at high bit pressure, it is reasonable to assume that foundation conditions are generally satisfactory for the bearing pressures created by typical highway structures. Core losses in these cases are usually always due to the blocking of the bit or core barrel and grinding of the hard bedrock. During construction, soundness of the rock can be checked by running drills five or ten feet into the rock with jack-hammers. Core loss in respect to slope stability is discussed under the heading "Results and Discussion of Results."

Often when drilling in shattered or loose rock, the drilling operation can become very troublesome to the driller due to "caving of the hole" below the bottom of the casing. The drillers say the hole is caving when bits of rock become loose along the side of the hole. These rock fragments snag the upper edge of the core barrel during core barrel withdrawal and catch the bit of the core barrel during insertion. At

insertion, the hole can be reamed but caving at withdrawal is considerably more annoying to the driller. However, this caving condition especially in hard rock formations is very seldom indicative of highway bridge foundation problems.

POWER AUGERS

Literature on the subject heading is scarce and pertains primarily to mining and especially to the digging of coal with horizontal power augers. Dr. Hvorslev devotes only about one page to power augers. The material in this thesis on this subject is derived essentially from the writer's field experience. Some small amount of data has been obtained from the trade catalogs of power auger manufacturers. More information on power augers will be found under the heading of "Results and Discussion of Results" of this thesis.

The general advantages of power augering over hand augering are obvious. Hand augering is relatively hard labor and in dry, frozen, gravelly soils and soft rock, is nearly impossible. Power augering is fast and even the above-mentioned soils are easily cut. The power augers can penetrate to great depths and wash water, including all the complications of its use, is unnecessary. Set-up time, or time to put the auger into operation, after reaching the site is only a matter of seconds or minutes. Power augers are relatively simple to operate and require only a nominal amount of manual labor.

The big users of power augers are utility, construction, and mining companies. The machines are used for power pole or post hole digging, blast hole drilling in soft to medium rock, and mineral exploration and excavation. To date no commercial power auger has been designed strictly for civil engineering subsurface exploration purposes.

Figures 3 (A), 3 (B), and 3 (C) show three typical types of soil augers developed primarily for power pole or post hole digging. Figure 3 (A) shows a single flight auger for boring shallow holes. Figure 3 (B) shows a double helix continuous flight auger which might be used to drill over a hundred feet by the addition of sections. Figure 4 shows a ^{single} helix continuous flight auger which is much more common than the double helix type. Figure 3 (C) shows a single helix three flight auger for boring holes to a maximum depth of approximately 20 feet. The three flights make it possible for this auger to carry a greater load than the single flight and so reduces the number of trips from the surface to the bottom of the hole.

The shaft supporting the single flight or short flight augers is called a kelly bar. It is made of very high grade steel to withstand great torsional stresses. Its length limits the depth of boring when using one of the short flight augers (1-5 flights). The present maximum length is 26 feet which makes it possible to drill a hole slightly over 20 feet deep. When long bars are used the whipping action of that portion of the bar above ground is significant; and if a hydraulic ram is used, a longer ram must be used. Thus, in contrast to depths of over a hundred feet drilled by the continuous flight augers the short flight augers are limited to depths slightly over 20 feet.

Just recently a very simple but ingenious device has appeared that makes it possible to obtain representative samples below the limiting twenty foot mark. It is the hollow continuous flight auger with a retractable plug-point shown in Figure 3 (D). It is patented by the Mobile Drilling Company of Indianapolis, Indiana. In essence, its use

FIG. 3 DRILLING AND SOIL SAMPLING TOOLS
FOR POWER AUGERS

amounts to augering a plugged casing into the ground. The plug-point is then withdrawn through the inside of the hollow continuous flight auger. Next a sampling spoon is inserted through the hollow auger and a soil sample taken below the "auger-casing."

Figure 3 (H) shows a sketch illustrating a single tube auger core barrel. The barrel represented here is a "Buda Screw Type Soil Sampler" and ranges in size from six to eight inches in diameter. Slightly offset teeth on the cutter head cut the core with a diameter about $3/8$ inch less than the inside diameter of the barrel. If the barrel does not contain a core retainer, the barrel is withdrawn empty and the core is recovered by lifting it or digging it out. If the barrel has a core retainer, it may be withdrawn with a more or less representative sample.

Hvorslev (6) reports that V. R. Smith developed a hand type double tube core barrel for taking shallow surface samples in 1944.

The core is preserved in the inner tube. The method is comparable to drive sampling with advance trimming. It is possible that the method, with certain modifications and further development, may be used to advantage in control sampling of strongly compacted but not too coarse-grained soils.

Data could not be found in the literature concerning deep soil core boring with double tube auger core barrels for power augers. Therefore, it is assumed that no attempt has been made to develop them. In general soil coring, without the use of some stabilizing agent, has been unsuccessful even with double tube rotary core barrels and wash water.

Figure 3 (I) shows a unique tool that can be used with a power auger in the construction phase. It is a Buda "Belling Tool" and its

purpose is to dig holes with belled bottoms which might be specified for pier or foundation holes.

Another unique construction device, not illustrated, is the Buda "Caisson Undercutter." It is essentially a single flight auger with retractable cutter knives which swing out to undercut a casing when the auger is rotated counter-clockwise and which swing in when rotated clockwise. When the knives have been retracted the auger can be pulled back up through the casing. It can be used to drill and case holes in one operation, such as for cesspools, cisterns, shallow wells, and sometimes access holes.

Below is a list of uses of power augers for all phases of highway construction.

1. Subsurface exploration
2. Guard rail, sign and fence post, and power pole installation
3. Coring pavements and concrete bridges
4. Pre-boring for piles
5. Foundation pier holes
6. Drainage holes (including cut slopes) and french drains
7. Shoring along roads, railroads, etc.
8. Access holes for gas, water mains, etc.
9. Blast hole drilling
10. Drilling of water wells and drainage wells
11. Tree and shrubbery planting

Only the first of the above items will be discussed in detail in this thesis.

Subsurface Exploration with Power Augers

The commercially available auger used most frequently for general subsurface exploration is the continuous flight type. Figure 4 shows a view of the jeep-mounted auger used by the Pennsylvania Turnpike Commission. Rotary motion is supplied to the four-inch continuous flight auger from a power take-off through a system of gears and chain drives. Vertical feed and pressure is supplied by means of a hydraulic ram, the pump of which is operated from the truck engine. While this type of auger machine is durable enough itself, considerable wear of the truck engine in operating the drill is generally experienced.

For exploration work, continuous flight auger diameters commonly used are four to six inches and the section lengths are three to four feet. Figures 3 (B), 3 (C), 3 (F) and 3 (G) illustrate a few of a larger number of cutter heads available. The finger types of cutter heads are mainly for hard or dense soils and soft rocks. The fishtail cutter head, Figure 3 (F), is for softer soils.

The continuous flight augers can penetrate faster than the short flight augers. As depth increases new auger sections are simply and quickly added and the material is automatically transported to the ground surface, eliminating repeated withdrawals.

A continuous flight auger can operate in both cohesive and non-cohesive soils. The writer has also used them successfully in some barrow pits to obtain some general information about soil below the water table. The auger shaft itself and the slurry being flighted to the surface, which acts as a viscous drilling fluid, prevent the hole from caving. In highway work, depth to bedrock is usually a very im-

portant factor and when determining this depth with a continuous flight auger, free ground water does not hinder the operation.

The main disadvantages of continuous flight augers in soil exploration are (1) as penetration depth increases, it becomes more difficult to determine the definite depth from which the soil, discharged by the auger, was excavated, and (2) there is some degree of mixing of the soil from various strata resulting in non-representative samples. These shortcomings suggest that the continuous flight be limited to deep homogeneous soils.

Small diameter continuous flight augers are used for drilling blast holes in rock of soft to medium hardness. The flights add rigidity to the shaft and support the shaft against the wall of the hole. In this manner the great downward pressure required, at very slow rotational speed, can be safely applied. It is fortunate, that in blast hole drilling, only small diameter holes are necessary as these small tools reduce the amount of rock to be cut as well as the cutting time and effort. Cutter heads, similar to the "finger" type illustrated in Figure 3 (G), are equipped with replaceable bits tipped with tungsten carbide. This manner of blast hole drilling can also be used for soft to medium rock exploration but one limitation is that very heavy rigs are necessary to develop the required downward pressure. Since it is desired to keep an exploration auger machine as light as possible, earth anchors would undoubtedly have to be used.

To obtain a truly accurate picture by power auger, an accessible test pit should be bored and samples removed by hand from the wall of the pit. A large single flight auger can be used for this and depth is

limited by length of the kelly bar, by soil cohesion, or by depth of water table. Figure 3 (J) shows a "Buda Reaming Tool" which provides a means for drilling holes larger than thirty inches to as great as sixty inches without resorting to the use of a very heavy, costly, and specially built drill. One person can be lowered into these large diameter holes to obtain very accurate soil profiles and to sample the soils in place.

The simplest and fastest way of using a commercially manufactured power auger to obtain a representative sample of cohesive soil above the water table and above 20 feet is to employ a single flight auger with a bucket attachment see Figures 3 (A) and 3 (E) .

A power auger designed strictly for civil engineering subsurface exploration should be as light as possible and be able to operate both continuous and single flight augers. It should also have drop-hammer apparatus but no facilities for using wash water. The latter equipment would add too much weight and the use of wash water would destroy one of the most essential features of a power auger, which is to bore quickly and to move to the next site quickly.

A rig of this type could use the single flight auger to take representative samples above 20 feet; the limitations are now obvious. A thin-walled sampler, for an undisturbed sample, can be attached to the kelly bar and forced smoothly into the soil by means of the hydraulic ram. The kelly bar and ram can also be used to operate a vane shear tester. The drop-hammer apparatus can be used for taking split spoon samples, making standard penetration tests, and for probing with various types of penetrometers. Below 20 feet the device shown in Figure 3 (D)

can be used for similar soil sampling or probing. An auger machine of this type can also operate most of the soil sampling devices described by Hvorslev.

EXPLORATION BY ELECTRICAL RESISTIVITY

The electrical resistivity method of subsurface exploration consists of identifying changes in the character of subsurface materials through measurements of the electrical resistance of these materials. In highway work, resistivity is used most efficiently in proposed excavation areas. Depth to bedrock, or depth of overburden, is determined by a procedure called vertical profiling. Also in highway explorations it is often desired to know the lateral extent of buried rock ledges, granular deposits, stream channels, etc.; this can be determined by horizontal profiling.

Since deductions are made from electrical measurements, the nature of the electrical properties of soils and rocks are considered. The reader is referred to a thorough discussion by Perret (14) for the principles which govern the use of resistivity measurements.

Soils and rocks are composed of solids, and pore spaces filled with water or gas or both. In general, the amount of pore space decreases with depth. Near the surface, the pores contain a mixture of water and air, however most soil and rock is saturated.

The relative abundance of water in a saturated earth mass is governed by its porosity, the ratio of pore volume to total volume of the mass. Clay porosities range from 80 to 40 percent, depending on the state of consolidation; sand and gravel ranges from 40 to 25 percent. Rock porosities range from 0.5 to 29 percent with the dense igneous rocks having a low of about 1 or 2 percent.

The solids of most soil and rock types have a high ohmic resistivity with negligible difference between the different types. The pore gases also have a high electrical resistance so it is therefore obvious that most of a current induced into the earth's surface will be conducted by ions of dissolved electrolyte in the pore water. The conductivity of the water in turn depends upon the amount of concentration of dissolved electrolyte as pure water is a very poor electrical conductor.

Most of the water involved in shallow explorations is fresh as it originates as absorbed rainfall or as seepage from streams. Exceptions are near bodies of salt water or where previous flow over salt masses or through arid, alkaline soil influences the ground-water character. Therefore if a material is to have a low resistance it is necessary: that the soil mass, or neighboring mass, have electrolytes available for solution; that conditions which promote solution exist; that the dissolved electrolyte be relatively abundant; and finally, that the porosity of the material be high.

Sand and gravel deposits are composed mainly of quartz and other slightly soluble silicates. In general, permeability is high and when relatively pure water moves freely through the deposit, the resistivity is high. Fine grained soils, however, have high porosity, low permeability, a relatively high proportion of soluble electrolyte in the solid phase, and large surface areas of small irregular and flake-like mineral grains exposed to solution. Organic acid from decayed vegetation, also more common in the fine grained soils, is an excellent electrolyte and tends to lower the resistivity.

The resistivities quoted in authoritative sources include ranges for soils of from 500-5000 ohm-cm in wet clays to 12,000-

60,000 ohm-cm in wet river gravels and for rocks in situ of from 1000-10,000 ohm-cm in sedimentary rocks to 10,000-1,000,000 ohm-cm in igneous and metamorphic rocks. Other soil and rock types will probably fall somewhere between the limits of these ranges. It is evident that the simple determination of the resistivity of a soil layer cannot be used to define its type. However, as will be shown later, the determination of variations of the soil resistivity can be used in many cases to determine the limits of stratified or lenticular soils and rocks, and to indicate the soil type roughly. (14)

The field procedure most frequently used to determine the electrical resistivity of earth materials, which in turn is used for depth profiling, is called the Wenner system. Two current stakes and two potential stakes, all collinear and equally spaced, are driven a few inches into the ground. Small B-batteries are used for inducing a measured current through the outer current stakes and the potential drop between the two inner potential electrodes is measured.

The Wenner configuration is shown in Figure 5. A current of I amperes flows through the ground from P to N due to the current source S . A drop in potential of V volts exists from H to L .

Figure 5. Wenner Configuration

From Ohms law for a linear conductor of wire

$$V = \frac{\rho l I}{S} \text{ --- (1)}$$

where:

l = the length of the wire in centimeters

S = the cross-sectional area of the wire in square centimeters

I = the current in amperes

V = the potential drop, in volts

ρ = a constant for the wire, depending on its composition.

For a three dimensional case, as is the situation in making an earth resistivity investigation, the formula can easily be derived and is found to be

$$\rho = 2 \pi a \frac{V}{I} \text{ --- (2)}$$

where:

a = distance between electrodes.

This is the basic formula for resistivity as determined by the Wenner configuration. The units for ρ are ohm-cm., ohm-meter, ohm-ft., etc., depending upon the units in which "a" is measured. Because earth materials are far from homogeneous in regard to the factors that effect resistivity, the quantity determined by the above equation is called the apparent resistivity. The latter, hereafter to be simply called the resistivity, is defined by Perret (14) as "the weighted average of the various true resistivities of the soil strata."

Since the current sources is a point near the surface of the earth, equipotential surfaces take the shape of hemispheres surrounding the

point. By controlling the radius of these hemispheres the depth of investigation is controlled. This is indicated in Figure 6.

Figure 6. Current Flow Diagram

In a homogeneous, isotropic media the effective path of current flow is between the surface and a depth equal to "a", the electrode spacing (see Figure 6). The shaded area represents the material being measured for any spacing "a." It can be seen that the lines of current flow will have the same pattern regardless of the spread of the current stakes and that the effective depth of penetration of the current will increase in direct proportion to the spread of the current stakes.

In layered earth systems the direct proportionality of current penetration to electrode spacing is not valid. The effective depth of measurement varies not only as the electrode spacing but is also a function of the resistivities and thicknesses of various strata.

When using the Wenner configuration for shallow investigations the first spacing is quite often three feet. After a current and potential reading is taken, the spacing "a" is increased to six feet and new readings taken. As the horizontal spacing is increased the depth of effective current, and so the investigation depth, is increased. If three foot increments are applied, the accuracy of the interpretation of the depth to rock is presumably plus or minus three feet. Accuracy can be increased or decreased by increasing or decreasing the horizontal increments. Upon computing the resistivity for each increment, a plot of resistivity versus feet of penetration is drawn and an interpretation of the graph gives the depth to bedrock at the center point of the electrode configuration system.

Another field procedure is the Lee Partitioning system. It is a variation of the four-point Wenner system where a third potential is used at the center point. This center electrode is not moved and for each spacing of the other electrodes the potential drop is alternately measured between the left potential electrode and the center potential electrode (V_1), and then between the right electrode and the center one (V_2). A difference between the left and right readings indicates a non-uniform horizontal condition. The latter could be due to dipping strata, lateral discontinuities of material, straddling of a fault zone, etc. The sum of these two potential drops should always equal V as determined in the Wenner system. When using V_1 or V_2 to compute ρ , the formula is $\rho = 4\pi a (V/I)$ rather than $2\pi a (V/I)$ which applies when using the total voltage drop, V .

Another method that is often used to determine whether a given profile actually represents conditions at a given station is to rotate the system about the station and measure the resistivity in several directions. This is known as azimuthal surveying.

When it is desired to determine lateral discontinuities in materials and structural discontinuities such as the boundaries of buried rock ledges, sink holes, granular deposits and stream channels, a basic type of resistivity surveying called horizontal profiling is employed. Here the electrode separation is maintained at a selected value, and the station or entire system is moved along the traverse. A constant or near constant value of resistivity indicates uniform conditions along the line to a depth equal to the electrode separation. A change in readings indicates the probability of a change in materials or structure starting at that point. A series of traverses, each held to a specific electrode spacing can be used to survey an area, the result being a map of resistivity contours.

Earth resistivity apparatus is relatively light and compact. All the gear required for shallow exploration weighs less than a hundred pounds and can be packed into a box 2 x 2 x 2 feet. When various parts are distributed among a crew of two to six people it is quite easy to carry the equipment considerable distances over rough terrain. The essential features are: (1) main instrument box containing a milliammeter to measure current flow, a potentiometer to measure voltage drop, and a hand-operated commutator to reverse the direction of current flow; (2) a power supply consisting of several 45 volt, radio-type, "B" batteries; (3) copper coated steel current and potential stakes; and (4) cable reels, leads, etc.

Apparatus utilizing a commutator for reversing the direction of current flow from one current stake to the other is better than the type of instrument in which direction of flow is reversed by a set of switches. Often the latter is not fast enough to cancel out the effect of natural ground currents. The latter also requires the use of non-polarizing potential electrodes which are extremely awkward in the field because they consist of small porous pots containing copper sulfate.

Resistivity units are durable and require practically no maintenance service. After several years of hard use, the equipment used on the Pennsylvania Turnpike showed little wear and tear and operated perfectly. When wires and electrode clamps do break in the field they can be repaired easily and quickly. Batteries last about a year and are very inexpensive to replace.

The deduction of the nature and extent of the various strata from a resistivity curve is known as interpretation. There are over a dozen published methods, both theoretical and empirical, available to aid in making interpretations. "Perhaps a third grouping should be made to include methods that are purely qualitative and are based almost wholly on intuition developed through experience." (8) As is often the case, the simplest and most direct methods were found to be the most feasible and successful and they are considered herein.

To explain these methods the nature of the resistivity curves are considered from a qualitative viewpoint. In the simplest and most ideal case, the resistivity graph for a semi-infinite, homogeneous, isotropic earth would be a straight line with an abscissa equal to ρ_x , the resistivity of the curve. In Figure 7 (a) is the case where the resist-

ivity of the top layer, ρ_1 , is greater than that of the bottom layer, ρ_2 ; in (b), $\rho_1 < \rho_2$. The shaded line represents the actual resistivity of each layer and the dashed line the boundary between layers. (c) and (d) are curves for ideal three-layer systems with the bottom layer infinite in depth.

The one important point to note is that there is no sharp break in the apparent resistivity curves at the layer interfaces. It has been demonstrated both by theory and controlled model measurements that apparent resistivity curves should consist of a series of smooth curves for two, three, four, or more layered systems.

Figure 7. Typical Theoretical Curves
(After Corps of Engineers)

An interpretation of the profile breaks in the basic resistivity curve is most generally always used, be it a preliminary or final determination. An increase of resistivity with increased electrode spacing indicates a material of relative low resistivity overlaying a material of higher resistivity, and conversely, a decrease of resistivity with increased spacing indicates a material of relative high resistivity overlaying one of lower resistivity. The interpreter must decide whether the peak in the curve, a maximum or minimum point, or the inflection point marks the depth of discontinuity.

One of the best methods of interpreting a basic curve is to compare it to a curve taken at a site where conditions are known. Similar subsurface conditions will produce similar curves. Relative changes between the two sites such as a decrease in depth of overburden from one to the other will be readily identifiable from the relative positions of the breaks and anomalies in the two curves.

Basic curve breaks are also the best way to interpret horizontal profiles. In Figure 8 note how the approximate boundaries of a deposit of sandy gravel of relatively high resistivity surrounded by a fine-grained soil of low resistivity is outlined.

Moore's cumulative method, which is also a simple and empirical approach, is used nearly as commonly as the curve break method.

In Moore's method, the resistivities are observed, or interpolated, for separations that are integral multiples of a common separation. After the resistivity profile for qualitative interpretation is plotted, the data are replotted using for each ordinate the sum of the resistivities to that point, selected for equally spaced abscissas. On this cumulative curve, he found by testing many curves, the slope changes near the separation that is numerically equal to the depth of a disturbing contact. He draws tangent curves near such slope changes and considers their intersection as having an abscissa equal to the depth of the bed. (8)

Figure 8. Resistivity Traverse
(After Moore)

At the fifty-fourth annual meeting of the American Society for Testing Materials, June 1951, a symposium on surface and subsurface reconnaissance was held and some half dozen noted geophysicists were generally favorable toward the use of electrical resistivity. However all were aware of the limitations and a few choice quotes are made to point up some of these. Bird of the New York State Bureau of Soil Mechanics, in explaining why the use of resistivity has been all but dropped in favor of the use of seismic methods, makes a number of critical remarks against resistivity. He states that the switch to seismic was due partly to geologic conditions peculiar to New York State and partly to the inherent characteristics of the methods themselves.

Basic seismic data can be correlated almost always with geologic units, while basic resistivity data often cannot. In many of our resistivity curves the most pronounced inflections have no meaning whatever to the geologist, whereas minor inflections have often accurately located significant geologic discontinuities.

With a reasonable amount of experience the geologist can, in many cases, identify geologic units represented by a seismic graph; in many additional cases he can delimit the identification to two possibilities and rarely is it necessary to consider more than two possibilities. We have found the identification of geologic units from resistivity data extremely hazardous, except in the case of granular soils as opposed to all other earth materials.

The seismic graph carries within itself evidence of its quality or dependability, except in occasional cases and most of these can be eliminated by additional contiguous profiles. In contrast to this, the resistivity curve offers no inherent evidence of its quality.

Seismic curves can be duplicated over the same line through the full range of normal seasonal changes in ground conditions with negligible variations in depth determinations, except in ground that is uniformly frozen to considerable depth. Resistivity data shows notable variations over the same line even in average diurnal changes under some conditions, and such changes influence depth determinations by empirical methods. (2)

Moore (13) in speaking of specific values of resistivity states:

Just as is the case when using other methods of exploring the subsurface, there are some geologic formations, or combinations thereof, which are difficult to explore satisfactorily with the resistivity method of test. Extremely high resistivity in the overburden may mask out the presence of a rock formation having approximately the same resistivity or a much lower resistivity lying, at a considerable depth (40 to 50 feet) below the surface.

Resistivity values obtained for various materials found in one locality are not necessarily useful in classifying similar materials in other localities where geologic conditions are not similar. Materials easily handled by the large earth-moving equipment now in use have been found in one locality to have resistivity values 10 to 150 times that obtained for solid rock elsewhere in the country. Materials requiring blasting for efficient removal have been found to have resistivities ranging from 5000 ohm-centimeters to 5,000,000 ohm-centimeters, and conversely, soil or easily excavated weathered rock has been measured ranging from a few ohm-centimeters to as high as 1,500,000. Trial tests must be made with the resistivity apparatus in any new area before a definite answer can be given as to the practical use of the test in studying a particular subsurface condition.

PHYSIOGRAPHY AND GEOLOGY OF THE NORTHEASTERN EXTENSION
OF THE PENNSYLVANIA TURNPIKE

The general location and physiography of the Northeastern Extension is shown in the physiographic map of northeastern United States (Figure 9). Figure 10 shows the location and physiography in greater detail and includes the general geology. A working knowledge of physiography is significant in super highway construction because various provinces or sections have a number of outstanding engineering problems, such as location, shortage of aggregates, landslides, rigid pavement pumping, frost action, sink holes, embankment construction, alkali-aggregate reaction, water supply, and others.

The Northeastern Extension is unique in that it crosses parts of four major provinces: the Triassic Lowlands Province, the New England-Maritime Province, the Newer or Folded Appalachian Province and the Appalachian Plateau Province. It can be noted that the extension crosses the province boundaries at right angles. This is indicative of the fact that center line crosses the strike of bedrock at 90 degrees. It is also interesting to note that over half of the New York Thruway lies in the Central Lowland Province.

Beginning at Norristown, the first 27.5 miles of turnpike crosses the entire width of the Triassic Lowland Province. It is a great structural trough filled with Triassic sediments consisting mainly of red shales and siltstones and lesser amounts of friable arkosic sandstones,

FIG. 10 GEOLOGIC AND PHYSIOGRAPHIC MAP OF NORTHEASTERN PENNSYLVANIA

argillite, impure limestone, and coarse conglomerate (fanglomerate).

Three units, usually regarded as separate formations, Brunswick, Lockatong, and Stockton, intergrade and interfinger, and are thus facies representing partly-contemporaneous deposition. The strike is essentially 90 degrees to center line and the dip is usually less than 20 degrees north.

Locally hard, weather-resistant diabase sills and dikes (trap rock intrusive) have been exposed by erosion to form boulder studded hills. Surrounding the diabase core is a rim of rock up to several thousand feet thick that has been altered or metamorphosed by heat, pressure, gases and thermosolutions into baked shales, hornfels, and silicified shales. These rocks are often just as hard as diabase. The diabase has always presented the most difficult excavation problems.

Between mileposts 0 and 17 the gentle dip and slight variation of rock hardness combine to produce a rolling lowland. Elevation is generally between 250 and 350 feet with relief averaging 100 feet. Just north of Norristown, the Lockatong Formation with harder dark shales, black argillite, and impure limestone causes a swell rising slightly over 400 feet.

Near milepost 17 is a long deep cut in the baked shale and up to milepost 20 there are some poor to excellent cut-exposures of diabase. These rocks have caused grade to rise to an elevation of 500 feet. From here grade starts a gentle climb to 700 feet to the south edge of the next province at milepost 27.5. In this last seven miles of Triassic Lowland, right-of-way crosses and recrosses zones of altered shale, cores of diabase, and interfingering prongs of unaltered Brunswick

shales and conglomerates. Soils of the province are residual, averaging about ten feet deep and composed primarily of clayey silts and very silty clays of low plasticity.

At milepost 27.5 the northbound motorist enters the New England-Maritime Province. The largest section of the province is the New England Upland Section. It has a long finger-like extension projecting into Pennsylvania called the Reading Prong. The greatest area of the prong underlying the turnpike is Pre-Cambrian Byram granite and granite gressis which is characterized by the presence of quartz and alkali feldspar. Patches of other rocks present which have been intruded and assimilated by the Byram are the black Pochuck gneiss, and some ancient limestones and sandstones. Weather resistance of these rocks has made the general elevation high, but being extremely old and being exposed over a long geologic span, the residual silty soil is relatively deep, 20 to 40 feet.

A sudden 300 foot drop in elevation at a contact of gneiss and limestone marks the point where the Turnpike leaves the New England-Maritime Province and starts across the Folded Appalachian Province; probably better known as the Ridge and Valley Province (Fenneman). Its width at the New York-New Jersey line is about 14 miles; at Easton, nearly 25 miles, and in central Pennsylvania it attains a maximum of 80 miles. The turnpike crosses near the necking-down point between milepost 31 and 58. Here, more than three quarters of the width of the province is contributed by the Great Valley, one of the major physiographic units in the entire Appalachian region. It was by way of the

Great Valley that Confederate troops marched from the deep South to a high-water mark at Gettysburg.

The Great Valley, abutted on the north by Blue Mountain, is underlain by Cambro-Ordovician limestone, dolomitic limestones, shales and slates. The limestones are confined largely to the southern half of the valley and the shale to the northern half. The limestone portion is about 300 feet lower than the Martinsburg Shale Formation. In crossing the shale area (milepost 42 to 50) grade climbs from the Lower Martinsburg, mainly a clayey shale, at an elevation of 600 feet, to the more resistant sandy shales, with some sandstones, of the Upper Martinsburg at 800 feet. Another drop in elevation, and lower and more rounded hills, mark another zone of the clayey shale.

The soft shale of this zone near Blue Mountain formed the cushion material as the hard resistant sandstones and quartzites of the mountain were slowly folded upward by tectonic forces. The soft shales were squeezed into many tight folds and sheared by dragging. The shear planes so produced predominate structurally over the bedding planes. Heat and pressure produced caused a chemical change of the original shale minerals. In this manner a great slate belt was formed along parts of the base of Blue Mountain.

As the pike crosses the slate belt, it is in a continuous climb from 500 feet at milepost 48.6 to nearly 800 feet at milepost 50.6, where it enters a tunnel through Blue Mountain. The tunnel is approximately 4500 feet long; drops a 160 feet from south to north and is positioned an average of 850 feet below the mountain top and 800 feet above the Lehigh River in a nearby water gap.

For a distance of eight miles north of Blue Mountain grade crosses a more typical section of the Folded Appalachians. The Appalachian Revolution at the end of the Paleozoic Era left the bedrock folded and faulted. The resulting steeply dipping strata which were made up of interbedded hard and soft materials quite naturally developed into ridges and valleys with subsequent erosion. The ridge makers are all essentially sandstones of Devonian Age: Criskany, Cnandaga, Portage, and Catskill. The main mass of softer valley material is a dark finely laminated shale of the Hamilton Group. Through this eight mile distance, a rapid succession of 70 to 80 foot cuts and fills and two large river structures, 80 and 100 feet high, provide convenient passage which gently rises and falls between elevations of 450 and 600 feet.

In this Folded Appalachian Province, glaciation which extended to the southern border of the province in the vicinity of the turnpike, played a significant role in construction. On the geology and physiography map a narrow band of Illinoian terminal moraine is shown underlying that portion of the highway where it crosses the Great Valley. Since the completion of construction, it now appears to have been a bit of good fortune that the highway crossed the limestone belt of the Great Valley on this "bridge" of moraine. In adjacent limestone areas, where there was no moraine cover, personnel connected with the construction of U.S. Route 22 reported extreme sink hole problems both in excavation and bridge construction. However, the turnpike experienced a bare minimum of sink hole troubles compared to those of the Federal road and to a similar limestone area without moraine cover on the Delaware River Extension. The clayey and sandy moraine up to 60 feet deep, besides providing a "bridge" over the limestone provided a tremendous

amount of very cheap excavation.

At milepost 58, the super highway enters the Appalachian Plateau Province. While Lobeck and Fenneman use the same province name, Lobeck calls the section the New York State Section, and Fenneman, the Glaciated Allegheny Section. After entering the province the road goes into a steady climb for 6.5 miles up the escarpment area of the plateau. Elevation increases from 650 to 1600 feet. Rock is mainly a hard fine grained sandstone, Honesdale, and a red hard sandstone and shale of the Cherry Ridge Formation. Both belong to the Catskill Group of Devonian Age. Geologic maps show the Pocono sandstone as the primary cap rock of the Plateau but with recently completed turnpike excavations, geologists of a nearby university believe the cap rock to be Honesdale and Cherry Ridge, at least in the turnpike area.

Across the top of the Plateau, grade generally rides between 1600 and 1900 feet except at the Lehigh River crossing where it dips to 1300 feet. The northern rim of the plateau, near milepost 85, is at elevation 1900. From here to the Lackawanna River, milepost 100, grade is skillfully maneuvered back down the north escarpment to elevation 700 feet. The northbound traveler leaves the plateau near milepost 92.

Here the flat-lying Devonian and Mississippian rocks of the plateau take a steep 1000 foot dip under the city of Scranton and form the canoe-shaped Wyoming Valley. The valley is six miles wide and extends some 40 miles northeast of companion valleys of the Folded Appalachian Province.

Within the valley the Pottsville conglomerate and sandstone, Pennsylvanian, forms a second rim around part of the valley. Within

this rim the other Pennsylvanian rocks, including the fabulous anthracite coal deposits, are folded and faulted into a complex system. The folding and faulting produced heat and pressure which completely indurated or obliterated the soft clay shales and fire clays of the Monongahela, Conemaugh and Allegheny Formations. The latter were notorious landslide producers on the Western Extension and the West Virginia Turnpike but here they were not troublesome. However, the coal mining operations have made the valley crossing one of the most expensive sections on the turnpike.

From the Lackawanna River in the center of the valley, the pike makes a final climb to 1500 feet to the Appalachian Plateau Province, milepost 107. Present construction has stopped at milepost 110 on Catskill shales and sandstones.

RESULTS

The data appearing in this section are divided into four basic parts, (1) detailed information on 15 cut areas, (2) comparison of costs for various types of exploration, (3) classification of cut types, and (4) comparison of the accuracy of the three methods of exploration studied. The data in the first part of this section are shown in the Appendix and were used to formulate the data presented under items (3) and (4) above, while the cost data also shown in the Appendix represent a composite analysis of all the work done on the Northeastern Extension of the Pennsylvania Turnpike.

Classification of Cut Types

A result of a preliminary survey of the cuts selected for this study was a general definition of sound rock relative to turnpike cut slopes. It became apparent that this definition would have to be devised in order to determine the accuracy of subsurface data. Thus a homogeneous rock mass was considered to be sound rock if any one of the following conditions were satisfied:

- (1) If the rock required blasting for excavation;
- (2) When the rock resisted and withstood the efforts of a tractor-drawn rooter;
- (3) When during exploration it yielded a rock core with core recovery greater than 50 percent (plus or minus 10 percent) when drilled with a single tube core barrel;

- (4) If by visual inspection the rock ^{appeared} able to stand permanently, with a very minimum of ravelling at a slope no flatter than $3/4$ to one.

Terzaghi's definition of soil, which is generally used by civil engineers, is as follows: "Soil is a natural aggregate of mineral grains that can be separated by such gentle mechanical means as agitation in water." (16) Therefore unsound rock, relative to the turnpike cut slopes, would be defined as material falling between the limits of the two above definitions. On occasions, when using general terms, the unsound rock will be called highly weathered rock.

After a more detailed study of the cuts was accomplished a classification system for highway cuts and excavations and a grouping of the cuts into six classes or categories resulted. The basis of classification depended on the relative proportions of (a) soil, (b) highly weathered or unsound rock, (c) sound rock, and (d) structure of the exposed rock mass. The six groups are listed below. They might also be called shallow conditions of the surface of the earth with which the civil engineer works. It became necessary to group these cuts in order to explain the accuracy of the drill rig, auger, and resistivity.

1. Those cuts containing essentially all soil;
2. Those cuts containing essentially all sound rock;
3. (a) A two-layered type with only soil and sound rock
(unsound or highly weathered rock zone negligible).

An example would be limestone or quartzite dipping
0 to 45 degrees with a residual soil overburden.

- (b) A two-layered type but with a very jagged sound rock profile. An example would be thin bedded limestone or dolomite dipping 90° to 45° and differentially weathered.
4. A three-layered type, composed of a layer of soil, a relatively thick layer of weathered rock and a layer of unweathered rock. The layers or zones are horizontal, variable in thickness, and intergrade into each other. Dip in these cuts usually is not effective. Clay shales usually weather in this manner.
 5. The boulder type. In very general terms this type might consist of 50 percent boulders, 25 percent soil, and 25 percent sound rock or some other percentages with the percent of boulders being relatively high. Diabase cuts are good examples.
 6. Deep cuts with a layer of soil and alternate layers of sound and unsound rock. Dip of these rocks is more often relatively flat as movement frequently indurates the softer beds. Good examples are found in the soft coal regions where interbedding might include sandstones, soft clay-shales, coal, and fire clays.

The data desired by the grade designer and the excavation contractor is essentially the same and is basically of such quality and quantity as is necessary to classify the cut as one of the six groups previously mentioned. For example, if a cut is to be long and deep and a three-layered type, it becomes quite important to define the limits of these zones both vertically and horizontally. Accurate data yields the best

design which includes the best selection of the number and length of benches with the most efficient intervening slopes and the proper length of transition areas between sets of benches (transition in a horizontal direction).

With good data the contractor can accurately compute the amount of material that can be removed with self-loading equipment or elevating graders; the amount of material that can be loosened with rooters or perhaps removed with shovels without blasting; and the amount of material that must be blasted and removed by shovels.

Accuracy of the Three Methods Compared

The drilling machine, with various auxiliary soil and rock sampling tools, quite naturally produced the most accurate and most complete data in each of the six groups. In over 75 percent of the excavation borings, the top of sound rock was indicated by casing refusal. For the remainder of the borings the top of sound rock was located below the bottom of the casing at a point where the core recovery became and stayed greater than 50 percent.

Evaluation of resistivity results throughout the country have indicated various degrees of success. The degree of success seems to depend primarily on subsurface conditions over which the resistivity is applied. For this study the accuracy of results was excellent for cut groups 1 through 3 (a), that is, where rock was below grade, near the surface, or where there was a relatively sharp contact between soil and sound rock. Auger results for these same groups were also excellent.

It should be emphasized, however, for group 1 where the cut consists entirely of soil, the resistivity will not give an indication of

types of soils except in rare cases. Such a case may be where soft clay exists over a thick bed of gravel. Therefore, for routine work in deep soil areas such as the glaciated region of Indiana, the resistivity method is not too satisfactory. It will, however, indicate depths to ground water or depths to solid rock at bridge sites. It can also be adapted for delineating depth and extent of gravel deposits. Even so, the ease of using the power auger, along with economical considerations, would indicate the feasibility of using this type of equipment in these situations.

In the case of group 3 (b), thin bedded and differentially weathered limestone dipping 90 to 45 degrees, resistivity accuracy begins to decrease. While the resistivity will tend to give an average depth to sound rock for a relatively large horizontal area the auger will give the depth to sound rock for a pinpoint location. Thus the auger will indicate that the saw-tooth condition exists and a number of borings will show the magnitude of differential weathering. The order of magnitude of differential weathering on the road studied was not great but in some cases it may be. For the latter case borings, only several feet apart, would often show the difference in the top of rock to be as much as 10 to 50 feet. The data indicate the preference of the auger to the resistivity for cut exploratory work in rock of this type. However the longitudinal interval, between holes left and right of center line, should be reduced to about fifty feet.

In group 4, the three-layered type in which soil grades slowly into weathered rock and then slowly into hard unweathered rock, the auger was at its best in locating the top of sound rock. Resistivity

results were poor by comparison, therefore, resistivity investigation of proposed cuts in deeply and gradationally weathered rock is generally unsatisfactory. The top of sound rock, relative to a $3/4$ to one cut slope, is usually somewhere in the thick gradationally weathered zone. In this zone, and even in the transition zone to unweathered rock, electrical characteristics change slowly. Therefore both the basic and cumulative resistivity curves are relatively smooth and gently curving for this vertical depth range. There is no sharp break or definite inflection point to indicate the top of sound rock. In these formations the transition from soil into weathered rock is generally faster than the transition from weathered rock to unweathered rock and so the former transition generally forms a distinctive but rounded break in the resistivity curve.

If the geophysicist indicates the "Top of Rock" to be just below the "C" soil horizon and at the top of a thick weathered zone, a situation is produced which is in the excavation contractor's favor. While the resistivity might be technically correct by the definition of soil and rock it would be incorrect for the depth of sound rock as previously defined. Thus the contractor would be able to move a great deal of material called rock nearly as easily as he might move soil. Also there would probably be slope failures or excessive ravelling which in turn would cause excessive maintenance.

Fortunately, in these gradationally weathered formations in which resistivity cut data are poor, the power auger data are exceptionally good. It has been noted repeatedly in this study that auger refusal very closely matched casing refusal or the point where core recovery

became greater than 50 percent. In other words, auger refusal, in certain commonly encountered formations, accurately located the top of sound rock for a $3/4$ to one cut slope.

A review of Figure 3, and the various soil auger cutterheads, will indicate that these heads cut by ripping and tearing or by means of a shearing action. To emphasize this point, they are compared to: diamond core bits which cut by abrasion; churn drills which penetrate by shattering through impact; and oil well rotary drilling bits which combine chipping and abrasion. Thus the action of a power auger can be compared to that of a tractor-drawn rooter used in construction. Numerous checks with resident engineers on the job have shown that auger refusal, rooter refusal, top of sound rock, and the start of required blasting all were very close to the same point in the group 4 cuts.

For group 5, the boulder type of cuts, neither the auger or the resistivity, alone, is satisfactory as a supplementary tool to the core drilling machine. Suggested exploration procedures are: (1) use only drilling machines and bore a relatively large number of holes; (2) bore a smaller number of holes with the drilling machines and make a relatively large number of both auger borings and resistivity soundings. The latter method was the procedure used in exploration of diabase cuts on the turnpike.

Group 6, interbedded sound and unsound rock, was practically nonexistent on the Northeastern Extension but they are mentioned to help express the capabilities and limitations of the auger and resistivity. This type of interbedding is more common in the Pittsburgh area and is typical of most soft coal regions. The soft beds are the fire clay

and clay shales and the harder ones, in which they interbed, are sandstones, limestones, hard shales, and siltstones. Augers and resistivity are practically useless for deep cuts in these materials. Since the dip is most often relatively flat and the strata limits fairly sharp, several core holes in a cut of a 1,000 feet would probably suffice. However it would be necessary to concentrate on high core recovery by using double tube core barrels of a large diameter, at least four to six inches. It would also be advisable to split the cored sample and subject parts of it to wetting and drying, freezing and thawing tests or other tests.

SUMMARY

Since the auger and resistivity perform more efficiently in certain shallow surface materials, it becomes the responsibility of the engineer in charge to select the more suitable or feasible sites in advance. A geological engineer with a year or two of experience in a state can easily and accurately make these predictions. A study of geological maps, soil maps, geomorphology, local exposures, and stereo-pairs of aerial photographs makes the selection fairly simple and relatively positive.

Rock formations that produce ridges, which are usually tree covered and often boulder strewn, also produce subsurface conditions which are unfavorable for the use of augers. Fortunately, where surface conditions are best for truck mobility, flatter terrain and open fields, subsurface conditions are also the best for augering. When auger and resistivity are used in combination the auger more or less becomes a lowland tool and the resistivity an upland tool.

The following example is given to show a comparison of the speeds of operation of the resistivity unit, drilling machine and power auger. If the electrical equipment is on location but not set up for a test, a four to six man crew can make a complete 40 foot sounding in slightly less than a half hour. Soil and rock conditions do not influence the amount of time required for a field run. By way of comparing this speed or rate to that of a diamond core drilling machine and power auger it is assumed that bedrock is 30 feet deep and that a stream, as a

supply of wash water, is several hundred feet from the site of the hole. To unload a diamond drill rig, casing, drill rods, water pump, water hose, drop hammers, etc. from the truck and set up all the equipment, including the laying of a water hose to the stream, and then taking six disturbed soil samples and ten feet of rock core, it would take an experienced crew of two a full day. If a continuous flight power auger was used and no boulders were encountered, refusal would be at a depth of 30 feet. A two man crew on the auger could take six disturbed samples in slightly over a half hour. In the above example, ideal surface and subsurface conditions are assumed for the auger. It can be noted that time difference for auger and resistivity is not great. However, in rugged terrain slow maneuverability of the truck-mounted auger cannot begin to compete with the fast portability of the resistivity.

It should be apparent from the above example as well as data which compared the accuracy of the various methods, that the choice of method of exploration depends primarily on the subsurface condition rather than cost alone. The resistivity method is the cheapest method but its wholesale use, in light of accuracy of results and types of terrain, certainly is not warranted. A method of classifying soil conditions along with the advantages and disadvantages of each method has been given. The choice of proper equipment should logically depend on these data coupled with economics. Therefore, hard and fast rules cannot be made but rather each situation should be analyzed individually and the choice made on the basis of all factors including cost, accuracy, and terrain.

The discussion of power augers is more extensive than the discussion of the other machines for two reasons. First, the use of power augers for highway subsurface exploration is relatively new. While much is known and has been published on the use of electrical resistivity and drilling machines, there is very little information available on the augers. This is probably the first extensive study ever made. Secondly, since they have done so well and since the greater percentage of future mileage in Indiana and the United States will be constructed on materials most feasible for power auger use, namely, deep soils, clay shale, shales and soft sandstones, it is felt that their greater use and development should be urged.

Data from this study have indicated, in general, the advantages of power augers over resistivity methods for most routine cases. The advantages for boring into soils and rock formations which are deeply and gradationally weathered are listed below.

1. Point of depth of auger refusal is usually a measure of the relative shear strength of the material drilled.
 - (a) Above this point the material will not require blasting and the cut slope should be designed as a soil slope.
 - (b) At or slightly below this point, material will require blasting and will stand permanently on a three quarter to one slope or steeper.
2. The actual depth of soil, weathered rock, and/or unweathered soft rock can be obtained. With this information the engineer can compute the material that can be moved by:

- (a) Self-loading equipment or elevating graders in combination with trucks;
 - (b) Rooters combined with self-loading equipment or shovels alone without blasting;
 - (c) Blasting and shovels.
3. Results are immediate, on the spot, and plainly interpreted by all concerned. The resistivity data requires a large number of simple but time-consuming mathematical computations. Frequently resistivity graphs are complex and the interpretation difficult and uncertain.
 4. Accurate location of the free water level can frequently be determined with greater certainty by augers than by resistivity.
 5. Actual samples of soil and/or partially disintegrated rock are easily brought to the surface for identification and a visual description of texture and mineral composition.
 6. An auger machine that can operate continuous and single flight augers, recently developed auger soil sampling tools, and drop hammers, can obtain excellent representative and undisturbed samples from a comparatively large number of soil types for laboratory testing. Results of laboratory tests yield a wealth of data for construction design and control which cannot be obtained with resistivity.

When the accuracy of power augering is questioned, one of the first questions is: "What about the boulder problem?" A number of approaches have been found and used which help toward minimizing the problem. The following methods were learned or developed in exploring cut areas and

most of them could be used when investigating structure foundation sites.

The list follows:

1. With a rock coring bit, some weathered boulders or rock up to medium hardness can be cut.
2. Continuous flight augers are suspended from a universal-type joint and so are free to glance off to the side of a boulder in any direction. Single flight augers have the same ability due to the flexibility of the kelly bar.
3. Sometimes in soft soils, the boulders are simply pushed to the side.
4. High speed boring is one of the outstanding characteristics of power augers, so frequently when it is felt that a boulder has been encountered, the auger is retracted and another hole attempted several feet from the previous hole. Thus with several attempts at the same site it is frequently possible to make a break-through to grade or the desired depth.
5. The high speed digging is also utilized by drilling a relatively large number of sites in a particular area under study. By plotting the holes on a profile and drawing a line from the deepest hole in one cluster to the deepest hole in another cluster, it is usually possible to come close to the sound rock profile.
6. When working in boulder country (especially diabase) and when auger refusal was reached considerably above grade the following note was placed on the auger log: "Refusal may be due to a boulder. See diamond core boring logs of adjacent holes and resistivity data for nearby electrical soundings."

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26. Pengo Bulletin I-A 10M 4-56; Pengo Bulletin F-5R 15M 1-56; Pengo Bulletin A-6; Pengo Bulletin PL-SR 15M 1-56; Pengo Bulletin SB-2 10M 7-55, Petersen Engineering Co., Manufacturers, Santa Clara, California.
27. Sterling Earth Boring Machines, catalog, Wyoming Valley Equipment, 714 Wyoming Ave., Kingston, Pennsylvania.

28. "Northeastern Extension and Delaware River Bridge," Civil Engineering Report submitted to Pennsylvania Turnpike Commission by J. E. Greiner Company, 1948.
29. Geologic Map of Pennsylvania, Pennsylvania Topographic and Geologic Survey Prepared in Cooperation with the United States Geological Survey, Harrisburg, Pennsylvania, 1931.

A P P E N D I X

1. Detailed Cut Information
2. Cost Analysis

Detailed Cut Information

Cut Stations 40 to 86 Montgomery County

Geologic Classification

<u>Time</u>	<u>Rocks</u>
Era - Mesozoic	System - Triassic
Period - Triassic	Series - Upper Triassic
Epoch - Late Triassic	Group - Newark
	"Formation" - Stockton Lithofacies

Rock. The rock in this cut is chiefly yellow, coarse grained, friable, thin bedded and fractured arkosic sandstone (composed of feldspar and quartz grains) with some red soft, argillaceous shale and lesser amount of red argillaceous sandstone.

Strike and Dip. Strike is 90° to center line and Dip is 10° to 30° north.

Soil. Soil in the cut over the sandstone ranges from a residual clay of low plasticity near the surface to a silty sand above the weathered rock. Over the red shale the range was clay of medium plasticity to silts of medium compressibility just above the weathered rock.

Water Table. See Figure 13.

Comparison of Auger and Resistivity Data to Core Boring Data and to the Top of Sound Rock as Determined by Field Check. The cut slopes show a vertical profile composed of three layers. The top layer, two to four feet thick, is composed of fine and coarse grained soil. The middle layer ten to fifteen feet thick is composed of weathered rock. The main mass of sound bedrock is essentially a friable arkosic sandstone.

FIG. 11. PROFILE NO. 1

FIG. 12. PROFILE NO. 2

At station 66, four inch casing was halted at twelve feet using a 380 pound drive hammer free falling thirty inches. Penetration resistance reached 200 blows per foot. Between depths of twelve and eighteen feet a coring attempt, with a single tube core barrel, yielded sixteen percent core recovery. At the two holes between stations 72 and 74, a bridge site, casing was stopped at 13 and 14 feet. Casing penetration resistance reached 239 and 217 blows per foot. Attempts to core the soft rock above 27 and 22 feet yielded no core, so spoon samples were taken or tried. In some cases when the two-inch spoon sampler was driven with a 140 pound hammer, either the spoon could not penetrate or else the beveled edge of the spoon was badly damaged after a few inches of penetration. For these reasons, some samples were taken with heavier and tougher three-inch casing, driven by the 380 pound hammer.

Though the penetration blows, at the bridge site, indicate an allowable pressure of five or six tons per square foot, even as high as 13 and 14 feet, the high core loss from this depth to grade strongly indicated slope instability for slopes of $3/4$ to one and steeper. It is also understood that the material in the vicinity of these two core borings was removed by power shovel without previously blasting. Thus, as shown on Figure 13, the resistivity, in this vicinity, is several feet to 10 too high for the top of sound rock as defined for a cut slope. However throughout the remainder of the cut, the auger and resistivity are essentially 100 percent accurate.

In shallow rock country, casing refusal, probably more than 75 percent of the time, marks the top of sound rock relative to typical highway bridges and cut slopes. However, when core loss below the casing

is greater than 50 percent, it is a very strong indication that the cut slope should be made flatter than $3/4$ to one. Note how the auger holes, centering around core hole station 66, have penetrated to the elevation where the core loss changes from greater than 50 percent to less than 50 percent. Around station 54, the knob in the surface topography indicates shallow rock near the surface in the immediate area of core boring. This explains why the auger had gone much deeper than the depth of casing refusal in adjacent holes.

A study of the resistivity graphs for stations 54 and 66, at center line cut-borings, shows that the basic curves are better than the cumulative curves for interpretation. At station 54 the first break in the basic curve marks the top of sound rock while at station 66 the second break in the curve marks to top of sound rock. These graphs are typical of slow gradational weathering and sound rock often lies anywhere at or between these first two breaks in the basic curve. Since both auger and core boring data were available for the resistivity interpretations, this investigation is more an evaluation of the auger data than the resistivity.

By studying the auger data, note how it is possible to obtain a good approximation of the percent of excavation that will be shale and the percent that will be sandstone. Between stations 42 and 54 it is indicated that most of the material will be shale. From stations 54 to 76 sandstone only is indicated. From stations 76 to 86, interbedded shale and sandstone is shown. A field check of this information proved it to be correct. It was also reported that the general line of auger refusal depths marked the blasting line.

When most of the auger holes do not reach grade in a long, deep cut of this type, it becomes necessary to put down a few core holes to obtain more information about sound bedrock. It must also be determined if there are any soft layers that might cause slope instability below the general line of auger refusal.

The consistency of penetration depth and the smoothness of a line drawn through the bottom point of the auger holes gives some evidence of their dependability.

With this subsurface data, note from the cut drawing how it is possible to make an accurate slope design and to make a cut smooth and clean with lines of engineering beauty. Also by making the slopes in the softer material flatter and by making wide benches at the top of sound rock, it is possible to use a maximum of the softer material and a minimum of the harder rock.

Cut Stations 290 to 316 Montgomery County

Geologic Classification. See page 76. "Formation" - Lockatong Lithofacies.

Rock. Rock in this cut is mainly dark gray and black, hard, thin-bedded and interbedded shale and argillite, with some sandstone and impure limestone. Argillites are very finely indurated argillaceous rocks devoid of slaty cleavage and can be considered to be weakly metamorphosed mudstones.

Strike and Dip. Strike is 90° to center line and Dip, 15° to 20° north.

Soil. Soils are brown residual silt of medium compressibility.

Comparison of Auger and Resistivity Data to Core Boring Data and to the Top of Sound Rock as Determined by Field Check. In this cut the soil and weathered rock cover are very thin--the transition into firm sound rock being relatively fast (see Figure 15). Both the auger and resistivity are considered accurate. Around station 294 the auger penetrated one to two feet into sound shale but where the argillite, sandstone or limestone were encountered the auger stopped one to two feet above sound rock. A recheck at station 300 showed the auger more accurate than the resistivity. Note how auger refusal checks with casing refusal. In the field check also, it was observed that the auger could and did cut one or two feet into sound shale and stop one or two feet short of rock in the more brittle limestone and argillite.

An advantage of the resistivity over the auger can be cited by the situation between stations 295 and 300. Here the owner of a landscaped plot did not want the truck-mounted auger to enter but he would permit the resistivity crew to work as the latter would cause absolutely no property damage.

Because of the depth, and consistency of auger depth, and because the area between stations 305 and 313 was relatively low, it was possible to eliminate subsurface exploration on the assumption that rock was below grade. Field examination proved the assumption correct. The cut north of station 316 was similar to the lower part shown so it is not presented.

In design, the soil and weathered rock was simply rounded off to blend smoothly into the $3/4$ to one rock slope.

FIG. 14. PROFILE NO. 3

FIG. 15. CUT NO. 2

Since the transition from soil to rock is rather quick the basic curve shows a sharp break but because weathering is still gradational, the cumulative curve does not show a break for sound rock.

Cut Stations 471 to 491 Montgomery County

Geologic Classification. See page 76. "Formation" - Brunswick Lithofacies.

Rock. All rocks are red hard calcareous shale.

Strike and Dip. Strike is 90° to center and Dip, 10° north.

Soil. The soils are mainly residual clays of medium plasticity.

Comparison of Auger Data to Core Boring and Field Data. No resistivity was taken in this cut. A comparison of auger depth to the depth where core loss becomes less than 50 percent would indicate that four of the auger holes have penetrated five to seven feet into sound rock. The cut slopes were also designed for rounded slopes to about six or eight feet and $3/4$ to one below this. However these upper slopes were failing down to depths of 13 feet in spots.

In design, it was assumed that the core boring was correct and that the auger actually did penetrate a considerable distance into sound rock. However, both core boring and the auger data were correct. It was merely that the rock at the crest of the hill came closer to the surface than in the remainder of the cut.

Cut Stations 748 to 775 Montgomery County

Geologic Classification. See above.

Rock. Rocks are red hard, thin-bedded and interbedded, shale, siltstone and sandy shale.

STATIONS MONTGOMERY COUNTY

FIG. 16. CUT NO. 3

Strike and Dip. Strike is 35° right ahead and Dip, 25° northwest.

Soil. Soils are red residual clay of moderate plasticity and silt of moderate compressibility.

Comparison of Auger Data to Core Boring Data and to Top of Sound Rock, as Determined in the Field. No resistivity was taken here because previous work showed the auger to be very successful for this particular formation. A field check showed the auger to be 100 percent accurate and the original slope designs correct. Figure 17 shows the greater part of the slopes to be $3/4$ to one with a rounding off of the top four to seven feet.

In the vicinity of station 756, on the right slope, there was a small slide. The designers assumed the auger had penetrated sound rock as the nearby core holes showed sound rock at five feet. However the shale was weathered and soft to a depth of 11 feet, as shown by the auger hole, and a sliding failure occurred. Auger refusal and casing refusal are exactly the same for similar rock conditions.

There were also a couple of rock slides along the right slope. These were caused by the cut slope being steeper than the dip of the bedrock which had the same effect as removing the supporting toe of the slope. In general, if the toe of a slope is cut away there is increasing danger of a slide as the dip becomes steeper, as the strike becomes closer to being parallel to center line, and as the bedding planes of the rock become smoother. Had the strike remained at 90° , as in previous cuts, no rock slides would have occurred here. Though the dip was obtained from recovered rock cores, there were no local outcrops to determine the strike.

FIG. 17. CUT NO. 4

Cut Stations 920 to 960 Montgomery County

Geologic Classification. See page 86.

Rock. Rocks in this cut are dark gray to purplish black, hard thin-bedded and highly fractured baked shale and hornfels. Heat from diabase intrusions has caused the grains of the shale to swell or expand and interlock which in turn has produced a very hard durable rock. Hornfels are non-schistose rocks composed of a mosaic of equidimensional grains without preferred orientation. They are the products of contact metamorphism.

Strike and Dip. Strike is 70° right ahead and Dip, 15° to 20° northwest.

Soil. Soils are brown residual silt of moderate compressibility.

Comparison of Auger Data to Core Boring and Field Data. The auger is essentially in perfect agreement with the core boring and field data. Note (Figure 15) that casing refusal is about a foot deeper than average auger refusal. Also since bedrock is very hard, brittle, and fractured, there was a layer of broken and loose rock over the sound rock, through which the auger could not penetrate. Note again that consistency of auger refusal is some indication of data reliability.

Cut Stations 48 to 82 Bucks County

Geologic Classification. See page 86.

Rock. These rocks are dark gray, massive, extremely hard diabase.

Soil. The soils are a very silty clay of low to medium plasticity.

Discussion of General Rock and Soil Conditions. The diabase is a sill that has penetrated the Brunswick Lithofacies and has been exposed by erosion. Tension cracks formed by cooling of the original molten mass, produced a fairly well developed joint system which in turn left the

rock as a mass of more or less rectangular blocks. Where cooling was slow, the blocks measure 30 feet across and the texture is coarse grained. Where cooling was fast the tension joints have shattered the rock and the texture is fine. Often, where the diabase is shattered, weathering is deep. This is probably due to the greater surface area exposed by the smaller pieces.

At or near the ground surface, the rock would weather by spalling and generally develop an oval shape. In the overburden, where there was more soil than boulders, the old rock jointing system could not be recognized but with depth the boulders became bigger and more rectangular with a lesser amount of soil filling the old joint system. At a depth of 600 feet it is said that the joints become so tight that it is generally useless to drill deeper for water.

Cuts in diabase have proved to be the most difficult or troublesome of all rocks on both the Philadelphia and Northeastern Extension for the following reasons:

1. Hardness and great strength of the rock. Blast hole drilling was slow and costly. Breaking of medium boulders with a drop ball was slow and the drop balls broke excessively.
2. The high degree of jointing and the joints being filled with clay or sand of decomposed rock. Much blasting energy was lost through the soil filled joints. Frequently, blast holes were drilled closer to a joint than to the center of a block and rather than shatter the block, a relatively small piece would be blown off the side of the boulder.

3. A high water table and a "sensitive" soil composed of a highly silty clay with a relic soil structure. Vibration of digging equipment and trucks would cause the equipment to sink deep into the soil which appeared dry at the start of the operation.

Comparison of Auger and Resistivity Data to Core Boring and Field Data.

Because of pronounced irregularity in the top of sound rock, the top of rock was determined on both the left and right cut slopes and plotted as such rather than extrapolated to a single profile along center line as in previous examples.

Diabase ridges are usually densely wooded and boulder strewn. These conditions quite naturally worked more unfavorably against the jeep mounted power auger than the resistivity. The auger crew was instructed to auger wherever possible with the idea of keeping longitudinal spacing near 100 feet and lateral spacing near to 40 feet left and 40 feet right. It can be observed that 17 stations were completely missed by the auger and a few others were missing holes on either the left or right side. The resistivity, however, missed only six of the stations ordinarily sounded (these are marked "nr").

On nearly every auger log of borings that did not reach proposed depth of grade or very near to it, the following note was placed "Refusal may be a boulder and not bedrock; see core boring and resistivity data." So auger data alone would have been very unreliable. Even for holes that reached grade, the drill could have penetrated a very narrow clay seam. But using auger and core boring data as a guide, the accuracy of the resistivity was increased.

Of the first six auger holes between stations 50 and 53, the holes on the right side are accurate but the three holes on the left are eight to 20 feet in error. At station 53 - 50, excellent core was obtained from 13 to 63 feet but within the next 100 feet along center line three auger holes penetrated to 24 feet, 32 feet and 26 feet respectively. The four holes combined were helpful in suggesting the irregularity of top of rock.

From the start of the cut to station 55, the resistivity, which was run on center line, gave a very good average for the top of rock. It would have been near perfect if it had given rock ten to three feet lower between stations 50 to 52.

Between stations 55 and 66, 1100 feet, bedrock on the left cut slope is essentially below grade. On the right side, rock contains a number of thick vertical seams of clay to station 61 where it also goes below grade. It reappears near station 66. Note that the two auger holes at station 57 are extremely useful in that they indicate bedrock considerably lower than that given by the core hole at station 59. The two auger holes at station 59 - 50 hit boulders at 20 feet and four feet above bedrock. Between stations 55 and 57 the resistivity gives a good average. Between stations 57 and 61 the resistivity puts rock roughly eight feet too high. Between stations 60 and 68 boulders on the surface were so numerous and so big that all eight stations were inaccessible to the jeep, and four so densely strewn with boulders that the four resistivity electrodes could not be driven properly into the ground.

However, at two strategically located points, stations 63 and 64, resistivity was run and sound bedrock accurately given as being below

grade; but the overburden contained numerous boulders, which sometimes were as much trouble as sound rock. But again, however, this condition could have been anticipated by boulders observed on the surface.

Between stations 68 and 75, the auger, resistivity and the core boring data combined, suggest a relatively uniform or regular top of rock profile. This rock surface is actually even more irregular than the previous part of the cut. However, it can be seen that the resistivity gives a fairly good average for the quantity of sound rock. Most of the auger holes have hit boulders and are far too shallow.

Between stations 75 and 77, eight core borings were made for a small three-span bridge over the turnpike. Three holes are shown. The center hole near station 76 had its entire length probably along the edge of a boulder which at points was indented by the adjacent clay filled joints. The other two core holes hit sound rock at 13 and 14 feet. The auger hole at station 75 penetrated 34 feet into clay and still did not encounter rock. Fortunately, the clay seams were narrow so that they could be bridged by the bridge footer. With rock on the left side essentially below grade in the area, it was not possible to judge the accuracy of the resistivity along center line.

At stations 78 and 79 there were too many surface boulders to run resistivity but at stations 80 and 81 the resistivity correctly gave rock below grade.

Figure 19 shows a typical resistivity curve for relatively sound diabase. This data was taken for station 53 and the boring was actually made at station 53 + 50. The official interpretation for sound rock is 7.5 feet while the field examination lists 10 feet. Since 10 feet was

FIG. 19. PROFILE NO.4

FIG. 20. CUT NO. 6

obtained by extrapolation, and the top of rock was so irregular, the resistivity interpretation must be called satisfactory. Note that sharpest break in the basic curve is at the depth of ground water and that none of the cumulative breaks is near sound rock.

Cut Stations 72 to 101 Lehigh County

Geologic Classification. See page 86.

Rock. These are red fanglomerate with the matrix being primarily shale, sandy shale and argillaceous sandstone. The coarser material, consisting of subangular gravel and boulders up to 10 inches, was composed of quartzite, limestone and sandstone.

Soil. Soils are red residual silt of medium compressibility.

Comparison of Auger and Resistivity Data to Core Boring and Field Data.

Between stations 72 and 87, 1500 feet, all subsurface information indicates sound rock below grade. The field check showed this information 100 percent correct.

Between stations 87 and 101 (see Figure 23), the difference in elevation of the starting points of the auger holes indicates the upward slope from left to right. Note that casing refused at 29 feet with 210 blows of a 250 pound hammer. From 29 to 47 feet attempts to core drill yielded no core recovery, so spoon samples were taken without casing being required to hold the hole open. In other words the material was too weakly cemented to core but cemented just strongly enough to prevent the hole from caving. Core recovery was also prevented by conglomerate-gravel working loose and either jamming the core barrel or eroding the soft core already in the core barrel.

FIG. 21. PROFILE NO. 5

FIG. 22. PROFILE NO. 6

FIG. 23. CUT NO. 7

This cut is a three-layered type with soil grading into weathered fanglomerate and the latter very slowly into fresh rock. Any point along the sound rock line could possibly be moved five to ten feet up or down. However the cut was constructed with the slopes and benches shown and judged stable by the field engineers. It can be observed again that the material augered, and nearly all of the material that could not be successfully cored, was constructed to a $1\frac{1}{2}$ to 1 slope.

The resistivity curves for stations 72 to 87 are the typical gentle curves for gradationally weathered shale. The basic curve for station 92, Figure 22, has a sharp break for the top of weathered shale, which is indicated in the boring. However the shale here and for some 10 feet below was not considered firm enough for a $3/4$ to one slope. In other words the resistivity seems to do well in locating a point, that might reasonably well be called the point of separation between soil and weathered shale, but it fails to locate the point that could be called the top of sound rock for a cut slope in gradationally weathered shale.

Cut Stations 212 to 236 Lehigh County

Geologic Classification. The era is Pre Cambrian and the formation is Byram.

Rock. These consist of a number of granitic rocks characterized by the presence of quartz and alkali feldspar. The Byram gneiss was an igneous intrusive and it shows great variation in composition, texture and structure depending on the type and amount of other Pre Cambrian formations assimilated. The Byram of this portion of the Reading Prong, also contains valleys of Paleozoic sandstone and limestone.

Soil. The soils are tan to brown residual clayey silt of moderate compressibility. They range as deep as 30 feet and contain numerous partially decomposed boulders.

Comparison of Auger and Resistivity Data to Core Boring and Field Data.

Because of the railroad tunnel indicated at station 216 about 40 feet below grade (Figure 26), extensive investigation was instigated overhead. The investigation through the entire cut was intensified for several reasons. First because a number of auger and core borings showed that a preliminary resistivity investigation, which was performed without the use of correlating data, was badly in error. The resistivity report originally indicated that bedrock was very shallow over the railroad tunnel area. Secondly the bedrock profile was showing up to be very irregular. The core boring at station 223 yielded an excellent core of hard, unweathered granite gneiss from six to 68 feet but within several hundred feet the auger was penetrating to depths of 23, 29 and 33 feet. Thirdly it was obvious that some auger borings were hitting boulders. Thus auger borings were made left and right of center line at every station and they definitely proved that about half the big excavation job would be soil and highly weathered rock rather than the hard granite gneiss.

At the time of design only core boring and auger data were available. Above the bench, between stations 220 and 226 the original right slope was designed for $3/4$ to one. However, during construction it was determined that the exposed rock contained too many clay-filled joints and so it was laid back to a $1\frac{1}{2}$ to one slope. Other than this (note

FIG. 26. CUT NO. 8

on Figure 26), the intricate design of this long deep cut can be perfectly matched with the position and depth of the auger and core holes.

Between stations 212 and 218, the resistivity, with the aid of a large number of borings correctly shows sound rock below grade. Between stations 218 and 223 the sound rock surface was so erratic and the basic curves so broken that no honest interpretation of them could be made. Between station 223 and 228 the resistivity has the top of sound rock five to 10 feet too high. It is correct from here to the end of the cut but no interpretations were possible for the stations between 232 and 234.

Cut Stations 360 to 382 Lehigh County

Geologic Classification.

<u>Time</u>	<u>Rock</u>
Era - Paleozoic	System - Cambrian
Period - Cambrian	Formation - Allentown Limestone

Rock. These are blue gray, thin bedded, highly fractured, differentially weathered, dolomitic and siliceous limestone.

Strike and Dip. Strike is 90° to center line and Dip is 90° .

Soil. The soils are moderately plastic silty clays.

Comparison of Auger and Resistivity Data to Core Boring and Field Data.

Between stations 359 and 370 (Figure 28) all subsurface data were 100 percent accurate. All bedrock was below grade. From station 370 to the end of the cut the top of rock surface was extremely irregular. This was primarily due to differential weathering of the vertically dipping beds of various chemical composition and various resistance to weathering by solution. The more siliceous and the greater the magnesium

FIG. 27. PROFILE NO. 8

content of the rock, the more durable it would be compared to the more pure limestone strata. Some of these less resistant beds either individually or in groups, would be completely removed and marked by deep vertical clay seams one or two feet to 30 feet wide. In Figure 28 only a few of the larger ones are shown, many of the others were too small to show because of the scale of the drawing. It can be seen that some of the auger borings penetrated some of these undrawn vertical seams. The auger is suspended from a universal joint, making it free to glance in any direction and thus the auger found its way down some of these vertical clay seams.

Actually in the first portion of the rock area the auger and resistivity indicate rock about 10 feet too low. But mapping the top of sound rock in the field was very difficult. What was mapped was the contact between soil and rock which is usually very sharp in limestone. So considering this and the fact that the resident engineer informed the writer that the first few feet of rock were removed with a shovel, without blasting, it can be said that both the auger and resistivity did very well.

Figure 27 shows the basic curve breaking sharply at the relatively sharp contact of soil and rock. This is a typical curve for shallow soil over limestone. Note that with depth, resistivity of the limestone increases.

Cut Stations 825 to 849 Lehigh County

Geologic Classification. The era is Cenozoic, the period is Cenozoic, and the epoch is Pleistocene.

Soil. These are materials of the Illinoian terminal moraine. The top five to 10 feet consists of sandy, gravelly silt. The main mass of material is dry (it is above the water table) unstratified sand, gravel, and silt over a layer of fine sand near grade.

Comparison of Auger and Resistivity Data to Core Boring and Field Data.

Both the resistivity and core boring were completely accurate in indicating all sound rock below grade (Figure 30). The auger, however, had trouble with boulders and a binding condition caused by the unstable dry granular soil. As the soil was flighted to the surface the caving walls tended to squeeze it and stop rotation of the auger. Binding became apparent around 20 feet. Logs for the shallow auger holes state that refusal was probably due to a boulder. Because of the geology of the cut was so obvious only a fast check was made with the auger and no additional attempts made to bypass the boulders.

Figure 29 shows a resistivity curve, the shape of which was almost exactly similar to curves for all other stations. Note that the resistivity values for the dry sand are relatively high.

Cut Stations 875 to 895 Lehigh County

Geologic Classification. The era is Paleozoic, the period is Ordovician, and the formation is Lower Martinsburg.

Rock. These rocks are gray, weathered to brown, fissile and brittle shale. The formation in general is described as blue gray clay shale and slate, containing beds which are alternately siliceous, sericitic (a mica), or carbonaceous. These various beds produce a characteristic banding.

FIG. 29. PROFILE NO. 9

FIG. 30. CUT NO. 10

Strike and Dip. The Strike is approximately 90° to center line, the Dip not recorded.

Soil. The soils are brown residual silty clay and reddish brown glacial till which ranges from a plastic clay to sand and gravel.

Comparison of Auger and Resistivity Data to Core Boring and Field Data.

In general, the Martinsburg shale usually has only a very thin cover of top soil. Just below the surface one can usually find flakes and plates of loose light brown shale. With depths these shapes increase imperceptibly in size, hardness, and darkness of color. The flakes or plates become firm continuous sheets of fresh fissile shale, with depth in such a slow gradational manner, that even after the cut is opened it is impossible to draw a line on the cut slope and to precisely designate weathered rock above and unweathered rock below the line.

From station 875 to 884 (Figure 32) resistivity data shows rock below grade "bg" and is accurate. From 884 to 888, it is impossible to judge the accuracy due to the slow gradational weathering. From 888 to 892 the resistivity is in error.

The core boring hole at station 887 yielded slightly over 50 percent core recovery. The auger, however, is at its best in these particular materials. It showed the loose till soil and that most of the shale was weathered to a fairly soft state even though it was possible to core. Practically the entire cut was worked with self-loading equipment and rooters. A very slight amount of blasting was done near the center to aid the rooters. Slopes were designed, and correctly so, for $1\frac{1}{2}$ to one.

FIG. 31. PROFILE NO. 10

The basic resistivity curve, Figure 31, shows a very sharp break between soil and highly weathered shale and another break at 16 feet, casing refusal. But a resistivity plot simply does not indicate anything about degree of rock hardness or its stability in a cut slope.

Cut Stations 66 to 79 Carbon County

Geologic Classification. The era is Paleozoic, the period is Devonian, and the Group is Onondaga, and the Formation is Bowmanstown chert.

Rock. This ridge is supported primarily by sandy and silty white chert interbedded with sandstones and siltstone. Just to the left of the near vertical line marking sound rock is ^ahighly weathered and decomposed bed of hematite (see Figure 34).

Strike and Dip. Strike is 80° left ahead and the Dip is 70° south.

Soil. These soils are sandy silts.

Comparison of Resistivity Data to Core Boring and Field Data. Because numerous boulders on the surface as well as thick brush and woods, it was not feasible to use the jeep-auger. However, except for a 200 foot stretch between stations 70 and 74 the resistivity did very well. Rock was below grade as shown for the first 400 feet of cut and as shown by the resistivity and borings for the remainder of the cut. Resistivity correctly located rock below grade for the first 400 feet of cut. However, between stations 70 and 74 resistivity was considerably in error as shown by Figure 34. It seems that where the slope of bedrock is much steeper than the slope of the ground surface, resistivity interpretations are more difficult and the possibility of error is greater. In Figure 33 the boring is actually at station 75 + 50 while the center of the resistivity configuration was at station 75. The official

FIG. 33. PROFILE NO. 11

FIG. 34. CUT NO. 12

resistivity interpretation of this graph was eight feet to bedrock. Undoubtedly an inflection point was used to indicate the contact.

Cut Stations 92 to 105 Carbon County

Geologic Classification. The Era is Paleozoic, Period is Devonian. The rock group is Onondaga and the Formation, Palmerton Sandstone. The other group is Hamilton and the Formation, Marcellus Shale.

Rock. The Palmerton sandstone is a brown massive sandstone and one of the ridge makers in the Ridge and Valley Province. At the point of turnpike crossing the rock makes an impressive looking hogback. The Marcellus shale is a black carbonaceous shale and slate in this cut.

Strike and Dip. Strike is 90° to center line, and Dip 40° south (beds have been overturned). Because the drawing scale (Figure 35) is 20 feet to the inch horizontally the dip appears as 90° rather than 40° .

Comparison of Auger Data to Core Boring and Field Data. Because of the large number of core and auger holes to support the resistivity, the latter is not evaluated. Note that most of the auger holes have penetrated several feet below the point where core recovery is greater than 50 percent in the cut hole, station 95, Figure 35. A careful study of the slope and bench design shows an excellent match between design and auger hole data. The core boring was placed slightly north of the sandstone because the sandstone was exposed and more information could be obtained from the exposure than the core. When the core boring indicated soil and highly weathered rock to 53 feet it was feared that the boring had penetrated a fault zone or just a highly weathered contact. However, the auger quickly verified the deep depth of the weathered shale. It

FIG. 35. CUT NO. 13

also appeared that the auger might have cut some 10 to 15 feet into sound shale. Here too weathering was so gradual that it was impossible to separate weathered shale from sound shale.

Cut Stations 882 to 890 and 970 to 994 Carbon County

Geologic Classification. The era is Paleozoic, and the period Devonian.

The rock group is Catskill, and the Formation, Honesdale Sandstone.

Rock. These are gray, hard fine grained sandstone, argillaceous sandstone and siltstone.

Soil. The soils are sandy silts.

Comparison of Resistivity Data to Core Boring and Field Data. These cuts were located so deep in dense woods and rugged terrain that the jeep-mounted auger could not reach them. A study of these cuts indicated that the harder and closer the rock to the surface, the more accurate the resistivity data is. Note the high resistivity values. Figure 36 shows that again the basic curve is used for interpretation. The break of six feet is the contact between soil and weathered rock, which is considered sound in this case. At nine feet there is a sharper break indicating the top of unweathered rock.

Cut Stations 1182 to 1222 Carbon County

Geologic Classification. It is the same Honesdale sandstone as in the previous cut. Illinoian lateral moraine also previously given.

Rock. The rock was highly weathered to grade. It undoubtedly sustained a good deal of weathering before being covered by the Illinoian Moraine.

Soil. These are mainly fine sand and gravel showing a fair degree of stratification.

FIG. 36. PROFILE NO. 12

STATIONS CARBON COUNTY

FIG. 37. CUT NO. 14

FIG. 38. PROFILE NO. 13

FIG. 39. CUT NO. 15

Comparison of Resistivity Data to Core Boring and Field Data. This area (Figure 40) was too deep in dense wooded and rough country to attempt taking the jeep-auger-in. A skid-mounted rig was taken in to put down the three holes shown. The resistivity results were excellent. However it had the top of rock on top of a very highly weathered zone of rock which was easily removed by a shovel without blasting. Rock below the sound rock line was blasted easily.

Cost Analysis

The cost of exploration by drilling machine, as used on the Turnpike, should be compared to the cost of exploration by power auger and electrical resistivity only in a qualitative sense. The basic design of the sampling tools, operational procedure, and specific purpose of the drilling machine is considerably different than that of the power auger and resistivity machine and also, as such, is inherently slower and more expensive to use. A drill rig is a relatively heavy piece of machinery and the operational procedure requires long hours of skilled labor while a complete probing by auger or resistivity takes a matter of minutes.

A rig, with its many soil and rocks sampling devices, can be adapted to take both representative soil samples or rock cores from exact known depths. For this reason it yields the ultimate in quantity, accuracy, and completeness of data when compared to the auger and resistivity. Unlike the auger or resistivity it cannot be stopped by boulders, high water table, difficult accessibility, or extremely irregular surface or bedrock profiles. Because of its capabilities and reliability, drill rigs alone were used for the investigation of structure foundation sites on the Turnpike.

FIG. 40. CUT NO 16

There are also other reasons why the cost of drilling was higher than the cost of augering and electrical sounding, and why the cost of drilling should be used in a comparison only with great care. All drill machine work was contracted while the augering and sounding was done by Commission personnel. Contracted work always required inspection by Commission employees while in the case of the auger and resistivity, the operators did their own inspection.

Cost of Combined Soil Sampling and Rock Coring Using Contracted Drilling Machines

The cost of drilling work accomplished by diamond core drilling machines can be divided into three parts: (1) cost per foot as bid by the contractor; (2) inspection costs; and (3) hidden or indeterminate costs.

The latter includes time spent by the office of Chief Engineer in interdepartmental meetings; checking and approving the drilling contract and proposal as well as checking and accepting bids. Time spent by the legal department in reviewing and revamping legal matters in old specifications to meet the times and special conditions should also be considered. On occasions, the legal department was called upon to deal with resistant property owners and to see that damage claims against drilling companies by property owners were settled. There was some work done by the drafting and reproduction departments. The bridge department supplied a preliminary estimate of the size and number of structures. The list was used to estimate the amount of boring footage for foundation investigations. Also for the latter investigations, design firms had to prepare drawings and make field stake-outs showing the

exact location of bore holes. The utilities department obtained information and submitted drawings showing the location of all underground utilities from small city water lines to coaxial cables and cross-country high pressure oil and gasoline lines. While most of this work would have been done even if there had not been a drilling program a very small percent of the expense should be attributed to costs of drilling exploration but the exact percent or amount could never be determined.

Field work began April 1, 1954 and was essentially completed in thirteen months. Over 150 structure foundation sites, over 160 major cuts, and one 4500 foot tunnel site were bored. The drilling work was performed by three drilling companies using a total of fifteen drill rigs. Field supervision and inspection was performed by a geological engineer and five inspectors. After boring in each construction section was completed a consultant geologist compiled the logged data and wrote a report on each section. His fees were not considered to be part of the boring costs.

Because of the complex geologic structure of the coal fields in the Wyoming Valley (part of the Ridge and Valley Province) in the vicinity of Scranton, and especially because of the extensive mining operations, a coal consulting organization was employed to make an investigation, take deep borings, write a special report, and recommend the best route across the coal fields. The cost of this work and boring is not considered in this thesis.

By far the greatest percentage of boring was combined soil sampling and rock coring. Four-inch casing was used and soil samples were either

taken every five feet or at a change of material with a two-inch split spoon by the standard penetration test method. Rock cores were 2 1/8 inches in diameter and at least five to ten feet into rock. This combined soil and rock boring is listed as Type I on Table 2. The contract prices ranged from \$4.20 a foot to \$7.90. The chart also shows how cost varied with field conditions. Site accessibility and wash water availability are big factors. Accessibility depends on the frequency and nearness of access roads, depth and denseness of woods and ruggedness of topography. Wash water availability depends primarily on the frequency and nearness of streams. Drillers usually prefer to string water hose up to several thousand feet rather than to haul water. Price is also influenced by type and depth of overburden and rock hardness.

Preliminary studies indicated that for a wide belt of limestone in the Great Valley and adjacent areas of terminal moraine and alluvium, the soils were deep and cohesive and the water table was very low. To take advantage of these soil conditions, specifications were written calling for routine soil sampling only and to stop either at refusal or at a depth designated by the engineer in charge. Since it was possible, in this material, to clean the hole by driving and pulling casing, which eliminated the use of wash water as the soil would stick in the casing, a low bid price of three dollars a foot was obtained. This method of soil sampling is listed as Type II on Table 2.

Several major river crossings were made. The price for underwater combined soil sampling and rock coring was twelve dollars a foot. The method is listed as Type III on Table 2.

For exploration of the tunnel through Blue Mountain, a group of vertical holes were put through the two talus zones into bedrock. Two

Contracted Costs of Soil Sampling & Rock Coring by Drilling Machines-(1954-1955)							
Type of Sampling	Type I Type II Type III Type IV	Hole advanced by chopping bit and wash water. 4" casing and 2" split spoon driven by 250 lb. and 140 lb. hammers free falling 30". Samples taken every 5' and/or change of soil. 2-1/8" cores taken at least 5 to 10' into rock. Soil sampling alone and as above but hole advanced by driving & pulling casing in cohesive soil. Same as type I but usually done under water from a raft or barge. Horizontal rock coring. Cores 2 1/8" to 1" diameter. 2 holes each averaging 1657' long.					
Item	Footage	Type	Kind of Rock & Soil Sampled	Topography & Field Conditions	Mile Post Location	Unit Price	Total Price
1	15,069.8	I	Shale, sandstone, limestone, dolomite, askose, baked shale, hornfels, diabase, granite gneiss and slate. Residual soils of these; clayey & granular drift, & clayey alluvium	Moderate hilly, gently rolling & flat, access roads and streams frequent. Triassic lowlands & Great Valley	0-50	4.20	63,293.16
2	3,578.6	II	Mainly residual shale & limestone soil and some moraine, till & alluvium mostly clayey.	Gently rolling and flat. Mostly open fields. Roads & streams frequent	0-50	3.00	10,735.80
3	7,152.8	I	Mainly sandstones with conglomerate, shale, & coal. Residual soils & glacial sand & gravel	Sharply hilly (100' relief) streams abundant. Roads ample. Glac. Allegheny	100-110	5.70	41,125.44 354.48 Lump Sum
4	13,426.8	I	Mainly sandstones with shale & conglom. also siltstone, slate, chert and coal. Residual soils & glacial sand, gravel & boulder outwash in aggraded valleys	Sharply hilly to low mts. nearly all wooded and often boulder strewn. Access roads scarce streams abundant. Ridge and Valley & Glaciated Allegheny Section	52-110	7.90	106,071.72
5	228.7	I	Shale, sandstone, siltstone & coal. Residual soil & some glacial outwash; sand, gravel and boulders.	Sites easily accessible by road. Water not over 10' deep. Current moderate. Rock shallow	55-56 73 100	12.00	2,720.40
TUNNEL AT BLUE MOUNTAIN							
6	2,463.6	I	Vertical holes primarily in shale, sandstone siltstone and quartzite. Residual soil and talus.	Moderately sloping mt. side. Access road previous built. Water had to be hauled in.	50.5-51.5	7.90	19,462.44
7	3,314.0	IV	Horizontal holes in sandstone, quartzitic sandstone, conglomerate, quartzite, siltstone and shale	Same as above but plenty of water from the core hole	50-52	12.00	39,768.00
8	Lump sum for Mobilizing and Demobilizing Plant and Equipment at Tunnel Site						2,000.00
Total	45,234.3					Total	285,531.44

Table 2 Contracted Costs of Soil Sampling & Rock Coring by Drilling Machines-(1954-1955)

horizontal holes, averaging 1700 feet each were drilled 100 to 300 feet above the tunnel grade. It was possible to do this as the rock dip was about 50° and previous studies had indicated the strata uniform enough to project the data obtained to the tunnel grade. It was necessary to put the holes this high above grade as a solid rock face was required to properly start the holes for the purpose of obtaining accurate alignment. An accurate aim was necessary because it was specified that the borings stay within a cylindrical space of 100 foot diameter. The vertical holes, at \$7.90 a foot, are classified as Type I and the horizontal holes, costing \$12 a foot for 2 1/8 cores, are classified as Type IV.

On Table 3 the costs of field supervision and inspection are shown. One month's salary of the geological engineer, previous to the start of field work, is included to cover time spent in collecting data, making a fact-finding study, going over the line in the field, preparing an estimate of boring footage, preparation of specifications and proposals, assembling inspectors and obtaining cars and light field equipment for them.

In the field each inspector usually had two or three rigs to observe. Since rig assembly and disassembly, and moving to a new sit, required near or more than half the time of a complete boring operation, it was generally possible for each inspector to inspect the more critical work at each rig. Because of the rush, each inspector mailed a pencil copy of his field log the same day the hole was completed directly to the design engineer. A checked and typed log followed shortly thereafter.

The other items on the list are self-explanatory. The total cost of field supervision was \$31,520 and the total footage bored was 45,243 feet. Thus the cost of inspection per foot was very close to \$.70.

Table 3

Diamond Drill Core Boring and Soil Sampling

Field Inspection and Supervision Costs

(April 1, 1954 to April 31, 1955)

	Costs
1. Salaries and expenses	
Geological engineer and 5 inspectors'	\$18,579.00
Two clerks @ 1/3 time	2,500.00
2. Transportation	
Operation and maintenance of 6 cars	3,238.00
Depreciation of 6 very old cars	1,200.00
3. Overhead (20% of total of all other items)	5,253.00
4. Special field and office supplies	
(Rules, hand levels, core logs, maps, etc.)	500.00
5. Core storage - 10 tarpaulins	250.00
	<hr/>
	\$31,520.00

- - - - -

For purposes of future planning and cost estimating it can be figured that the combined cost of inspection and indeterminate costs (or organizing costs) will be a minimum of about \$1 a foot.

Cost of Electrical Resistivity

The electrical resistivity program for the turnpike studied was conducted over a seven months period between January 1, 1954 and July 31, 1954. About 85 percent of the cut areas lying along a center line distance of 110 miles were sounded. The resistivity unit used was the Gish Rooney alternating current type and the field procedure employed the Wenner electrode configuration. Resistivity tests were taken at every 100 feet along center line or at every survey station in the cut areas.

Depth measurements were made at intervals of 1½ feet to a depth of 12 feet and then at three foot intervals for the remaining depth. Total depth of measurement was usually 1½ times the depth of cut except in excessively deep cuts where it was fairly certain that rock was shallow.

In contrast to the operation of seismic equipment in the field, the operation of electrical resistivity equipment does not require that the party chief have formal training in its use, the party chief of an electrical crew need only have a high school education and about one week of training in the operation of the resistivity unit. The Turnpike crew consisted of a party chief, and five other men classified as rod-men or chairmen. One of these five served as a note keeper and the other four moved and drove each of the four horseshoe-peg-like electrodes a few inches into the ground for each reading.

Though it is very easy to make all the necessary computations with a slide rule in the field, the raw data were brought to the office, where computations were made on a computing machine. Graphs were drawn, and preliminary interpretations made before the data was mailed to the consulting geophysicist for a final and official interpretation.

For most of the program, daily operation was from a centrally located field office so that "portal to portal" operations were somewhat time-consuming. Also involved in this "portal to portal" time was a smaller amount of "walk-in" time which was required for the crew to walk from the corps bus through woods or over rough terrain to the particular cut area. However the number and length of hikes was kept to a minimum by using large scale photogrammetric maps (1 inch equals 200 feet and with five foot contour intervals) which showed the easiest

walking routes and the numerous logging and mining roads, State Park roads, fire lanes, trails, and wide clearings for cross-country pipe lines.

Listed below are conditions that helped to keep the exploration work ahead of schedule and made it possible to maintain a 40-hour working week:

1. Use of a full crew of six. This increased the man-hours and helped to keep production near normal at all times.
2. Overgrown center line areas had been previously brushed or cleared by surveyors. Thus it was possible for the crew to move faster and to string wires to the electrodes more quickly.
3. The instrument man had had considerable experience and was very capable and extremely fast in manipulating and reading the controls and dials on the resistivity machine.
4. Weather conditions during the seven months were favorable so that little time was lost due to inclement weather. For a total of several weeks with snow lying on the ground six to twelve inches deep, work continued at about three-quarter speed.
5. Raw data was processed in the office using all the conveniences of an engineering office.
6. The crew was young, energetic, and morale was high at all times.

Table 4 shows a breakdown of all the resistivity costs into eleven different items. The tabulation is arranged with the largest expenses at the top. As indicated, certain costs are "exact" figures and the others are accurate estimates. Of the exact figures, three of the four are considered very accurate, but item one, crew salaries, could be as

much as three to five percent in error due to rotation of personnel, with slightly different salaries. Since the salary differences were so slight, and the situation compensating, it is felt that the figure can be called exact for the purpose of this thesis. Adding these figures and comparing this total to the over-all total, shows that the exact figures compose 70 percent of all the costs. Thus it is felt that final answers, the cost per foot and the cost per complete resistivity sounding, are essentially accurate and may be used in future planning.

Final cost of the seven months project was \$22,908.00. Total footage depth sounded was 67,090 linear feet giving a cost of 34.2 cents per foot. The number of stations or sites sounded was 1852 and the cost per station, with an average depth of 36.2 feet, came to \$12.36. This cost included the interpretation of the resistivity logs and graphs by a qualified geophysicist as to the depth of bedrock.

Of the \$22,908 total cost, crew salaries and expenses were \$14,438 or 63 percent of the total project cost. The crew received partial expenses, \$75 a month, for the first $3\frac{1}{2}$ months because of excessive scattering of work.

The second largest single item appearing on the list is overhead. It was computed as 20 percent of the total of all other items. Overhead includes office rental, heat, light, telephone, janitor service, payroll and personnel bookkeeping, etc.

The original cost of resistivity equipment, the machine proper, battery box, electrodes and connecting wire on aluminum reels, is relatively low. Depreciation, maintenance and parts are very low. The Turnpike apparatus, Gish-Rooney alternating current type, was purchased in

Table 4
Electrical Resistivity Costs

Gish Rooney Alternating Current Type of Instrument
Six Man Crew for a Seven Months Period
(January 1, 1954 to July 31, 1954)

Items	Costs	Part of Total Cost	Exact (✓) Estimated (x)
Crew salaries	\$12,600.00	55.1%	✓
Overhead expenses (20% of total of all other items)	3,818.00	16.7%	x
Crew expenses for 3.5 months	1,837.50	8.0%	✓
Two office clerks for 1/3 time	1,288.00	5.6%	x
Ass't geological engr. at 1/6 time	1,000.00	4.4%	x
Corp bus operation and maintenance	849.25	3.7%	✓
Consulting geophysicist fees and expenses	765.25	3.3%	✓
Corp bus depreciation	400.00	1.7%	x
Resistivity unit depreciation and insurance	200.00	0.9%	x
Office supplies, blue prints, forms, mail	100.00	0.4%	x
Resistivity parts and repairs	50.00	0.2%	x
	<u>\$22,908.00</u>	<u>100. %</u>	<u>✓ = 70.1%</u> <u>x = 29.9%</u>

Total number of resistivity stations sounded - - - - - 1852
Total depth of all resistivity stations sounded - - - - 67,090 ft.
Average sounding depth for each resistivity station $\frac{67,090}{1852} = 36.2$ ft.

Cost of electrical resistivity per foot $\frac{\$22,908}{67,090 \text{ ft}} = \0.342 *

Cost of electrical resistivity per station sounding (using an
average depth of 36.2 feet) = \$12.36 *

* This cost includes the resistivity logs and graphs and the interpretation of this data, by a qualified geophysicist, as to the depth of bedrock.

1951 at a cost of \$1850 and shortly thereafter the price increased \$500. After studies on the Delaware River and Northeastern Extensions, the main unit showed very little wear and functioned perfectly. Large copper clamps which were used to connect the wires to electrodes were probably the most expensive repair items required. Infrequently the heads of the soft electrodes, even with shoes of harder metal for caps, became badly frayed and had to be replaced. Other than the resoldering of a few wires broken loose in the processes of cleaning commutators and connections, and repairs of leather carrying-straps, repair costs were essentially negligible. Thus the upkeep on electrical resistivity apparatus is very low and if used carefully in the field and stored properly when not in use, the equipment should last indefinitely and always have a high resale value.

Other cost items listed in Table 4 are self-explanatory.

The following, concerning the cost of resistivity surveys, is quoted from Barnes (1) on Cost of Resistivity in Michigan:

5. Cost of surveys: Next to the value of information obtained, the cost of surveys is probably the second important item of consideration. Costs will vary depending upon the size of the project and the type of information desired. Single soundings will necessarily cost much more than production surveys pro-rated for single soundings. An analysis of the surveys conducted by the Michigan State Highway Department for the year 1952 is given below.

Number of soundings made	800
Number of miles represented	15
Lineal feet of sounding depth	24000
Average depth of sounding, in feet	30
Cost per lineal foot of depth, in cents	70

(The cost item above includes labor, rental and incidentals for the index and confirmation borings made with a mobile continuous flight auger unit.)

Unfortunately Barnes has not given the cost of augering per lineal foot so that the cost per foot of resistivity alone on the Michigan project cannot be compared directly to the cost on the Turnpike project. However, resistivity costs even including the cost of a presumably small number of auger borings used as a guide are nominal.

Cost of Augering

The Geology and Soils Department of the Pennsylvania Turnpike Commission first used a small power auger for subsurface exploration in 1952 on the Delaware River Extension. Since the feasibility of its use and the value of the data to be obtained were unknown, a relatively small and inexpensive auger was purchased. It was a small four-inch continuous flight machine mounted on the rear of a three-quarter ton Willies Overland Truck (see Figure 4). Rotary motion was supplied to the auger through a power-take-off. Vertical motion was supplied by means of a hydraulic ram, the pump of which also operated from the truck engine.

With a fairly good idea of the capabilities of the auger and considering the many miles of what now appeared to be favorable soil and rock conditions on the Northeastern Extension, plans were made for its extensive use on this road. Here the auger was used mostly in the exploration of cut areas and to lessening degrees in fill and borrow areas with a very small amount for structure foundation investigation. The greater majority of the drilling was performed on the southern half of the Turnpike right-of-way in the Triassic Lowlands, Reading Prong and the Great Valley. Flatter terrain, more open fields, less dense woods,

and deeper overburden made this southern half of the line more suitable for both truck and auger.

Cost per foot of power augering for a large exploration program, as determined for the work on this extension, might be slightly on the high side for the following reasons. A three-man crew was used instead of a two-man crew because of the pressure to complete the job in a short time and the inexperience of the crew. High priority design sections and various small rush problems were scattered over the entire length of center line. Running the auger from the truck's engine by a power-take-off proved to be mechanically inadequate for the required very hard and continuous operation. While the auger machine itself did remarkably well, it too, however, suffered a few mechanical failures and delays for repairs.

In Table 5 costs of the augering program are shown in an itemized form. It can be seen that salaries and expenses of personnel took nearly 61 percent of the total cost. By far the largest individual amount is crew salaries and expenses and it was fortunate that it was possible to get the most accurate data on the largest item. Salary and expenses of the soils engineer and the clerk were estimated by estimating the percent time spent on work connected with the field augering phase.

Overhead includes office rental, heat, light, telephone, janitor service, payroll and personnel bookkeeping, etc. It was computed by totaling all the other items and then taking 20 percent of this total. As the crew was small and in the field the majority of the time, it is felt that 20 percent might be slightly on the conservative side.

Table 5

Costs of Power Augering

Four-Inch Continuous Flight Auger—Jeep Truck Mounted
 Three Man Crew for Twelve Months Period
 (March 1, 1954 to February 28, 1955)

Items	Costs	Part of Total Cost	Exact (✓) Estimated (x)
Salaries and expenses of personnel:			
a) Crew	10,951	46.5%	✓
b) Soils Engineer	2,250	9.6%	x
c) Clerk	1,104	4.7%	x
Overhead expenses (20% of the total of all other items)	3,924	16.7%	x
Trucks and auger:			
a) Depreciation	2,500	10.6%	x
b) Operation and maintenance (includes truck parts)	1,594	6.8%	✓
c) Auger parts	573	2.4%	✓
Transportation on the job:			
a) Crew	300	1.3%	x
b) Soils Engineer	250	1.0%	x
Supplies			
a) Sacks, tare can, etc.	100	0.4%	x
	<u>23,546</u>	<u>100. %</u>	<u>✓ = 55.7%</u> <u>x = 44.3%</u>

Total number of soil and moisture samples taken - - - - - 935
 Total footage augered - - - - - 11443
 Total number of holes augered - - - - - 967
 Average depth of auger hole - - - - - 11.83'

Cost of power augering per foot $\frac{23,546}{11,443 \text{ ft}} = \2.05 per foot^*

Cost of power augering per 11.83' hole $\frac{23,546}{967} = \$24.35 \text{ per hole}^*$

* This cost includes a log showing a visual description of the type and depth of each different soil and/or loose rock encountered. It also shows the depth of refusal, and the depth of free water if encountered. It includes an average of one 10-pound bag sample and one moisture sample per hole.

The original cost of the auger was \$3,400, and the four-year old jeep truck was valued at \$300. Considering that the auger and trucks were used nearly two years on the Delaware River Extension before a year of extremely hard use on the Northeastern Extension, a depreciation figure of \$2,500 is fair and reasonable. Accurate data on operation and maintenance of the trucks and auger was supplied by the Motor Vehicle Department.

It was the general procedure of the auger crew to leave the truck and auger in the field near the site under study. Transportation to and from the central field office was usually provided by one of the core boring inspectors working in the vicinity. So even though transportation costs were practically nil, one-half the cost of operation for an inspector's car for one year was used. This amounted to \$300. The partial of the Soils Engineer's transportation costs was estimated at \$250.

Over the entire line the total recorded effective footage augered was 11,443 feet. When it was known that penetration was stopped by a boulder and one or more other holes were drilled only a few feet away, only the deepest hole was logged and the depth called the effective footage. The number of effective holes drilled was 967, making the average hole depth approximately 12 feet.

Soil samples taken were for identification and classification and/or Proctor Compaction Tests. With each of these larger samples a smaller moisture sample was usually taken. The total number of samples taken, not counting the moisture samples, was 935 or an average of about one per 12 foot hole. Actually, however, one hole might have yielded several

samples while an adjacent hole showing the same material and stratification would not be sampled. The following computed costs of augering quite naturally did not include the cost of laboratory soil tests.

They do, however, include a soils log giving a visual description and identification of the soils and loose rock encountered; depth of refusal, which proved to have considerable meaning in some cases; and the depth of the free ground water level if encountered.

With a total cost of \$23,546, a total footage of 11,443, and a total number of holes of 967, the final results of the cost analysis of this large-scale power augering program are as follows: Cost per foot \$2.05 and cost per average 12-foot hole \$24.35. It should be emphasized again that the program was extensive and the cost per foot cannot be pro-rated for individual borings or small jobs.