STATE OF DELAWARE

DELAWARE GEOLOGICAL SURVEY

Bulletin No. 1

GROUND-WATER PROBLEMS IN HIGHWAY CONSTRUCTION AND MAINTENANCE

by

WILLIAM C. RASMUSSEN
Geologist
United States Geological Survey

and

LEON B. HAIGLER
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United States Geological Survey

PREPARED BY THE
UNITED STATES GEOLOGICAL SURVEY
IN COOPERATION WITH THE
DELAWARE STATE HIGHWAY DEPARTMENT
AGRICULTURAL EXTENSION SERVICE
AND EXPERIMENT STATION
AND THE
DELAWARE GEOLOGICAL SURVEY

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January 20, 1953

The Honorable J. Caleb Boggs
Governor of the State of Delaware
Dover, Delaware

Dear Sir:

I have the honor to submit to you the accompanying report on geologic problems related to highway engineering prepared as a cooperative effort by the State Highway Department, the United States Geological Survey, and the Agricultural Extension Division of the University of Delaware.

Very respectfully yours,

John A. Perkins

PREFACE

Growing interest in the geology of Delaware and its practical applications to problems of highway engineering and water supply manifested itself in December 1949, when the State entered into a cooperative agreement with the United States Geological Survey. At that time the State was represented by the University of Delaware's Agricultural Extension Service and Experiment Station and by the State Highway Department. In July 1951, the General Assembly created the Delaware Geological Survey which continued the cooperation with the Ground Water Branch of the United States Geological Survey. Although nearly all the investigations discussed in this paper were completed before the Delaware Geological Survey began its operations, the Survey is happy to publish it as its Bulletin Number 1.

JOHAN J. GROOT
State Geologist

ABSTRACT

This report discusses the occurrence of ground water in relation to certain problems in highway construction and maintenance. These problems are: the subdrainage of roads; quicksand; the arrest of soil creep in road cuts; the construction of lower and larger culverts necessitated by the farm-drainage program; the prevention of failure of bridge abutments and retaining walls; and the water-cement ratio of sub-water-table concrete. Although the highway problems and suggested solutions are of general interest, they are considered with special reference to the State of Delaware, in relation to the geology of that State.

The new technique of soil stabilization by electroosmosis is reviewed in the hope that it might find application here in road work and pile setting. Field application by the Germans and Russians is reviewed.

INTRODUCTION

Purpose and Scope

The relation of ground-water occurrence to certain problems in highway construction and maintenance have been investigated in the State of Delaware. The State Highway Department is one of the State agencies cooperating with the United States Geological Survey. As a part of that cooperation, problems of difficult subdrainage, soil creep, and settling of grade or structure in certain localities were referred to the authors and were investigated in the field.

Applications of Geology and Hydrology to Road Engineering

In recent months, much interest has been stimulated in the geological and ground-water approach to problems in highway engineering, as shown by papers by Sinnott (1951), Cleaves (1951), Parrott (1951), Stokstad (1951), and Horner and Dobrovolny (1951)*. Two of those papers (Sinnott; Parrott) describe the highway problems of Virginia, which has a Coastal Plain and Piedmont similar to those of Delaware.

The functions of the Geology Section of the State Highway Commission of Kansas have been described by Horner and Dobrovolny (1951, p. 1451). The functions include the following:

> "...(1) preparation of subsurface data needed for bridge design; this includes the direction and operation of drilling equipment; (2) engineering geological surveys of road locations and classification of materials for excavation; (3) study and report on ground water as needed to determine location and kind of underdrains required in a given geological setting; (4) from time to time condition surveys, material surveys, and other surveys requested, which originate in any one of the other departments."

*See bibliography, p. 24

Investigation in Delaware in Relation to the Geology and Roads of the State

The two physiographic provinces in Delaware, the Piedmont and the Coastal Plain, are delineated in figure 1. These provinces are separated by the Fall Line, a narrow zone, where the waters of the major rivers of the Atlantic Coast drop in falls and rapids from the hills onto the Coastal Plain in their course to the sea. This lines passes through Philadelphia, Pa., Wilmington and Newark, Del., Baltimore, Md., Washington, D. C., and Richmond, Va. Across this line there is a gradual but observable change in topography, from predominance of hills on the west to a predominance of plain on the east. This change is due to differences in the underlying rock, and to the erosion and deposition that have affected each province.

In Delaware, the Piedmont province lies north and west of this line. It comprises the Great Circle area of Delaware, about one-twentieth of the total area of the State. The Coastal Plain province lies south and east of the Fall Line and comprises the remaining 95 percent of the surface area of the State. The Piedmont province is composed of the erosional foothills of the Appalachian Mountains, whereas the Coastal Plain province is the remaining part of the depositional apron or fan of sediments at the base of the mountain range.

The Piedmont countryside in Delaware is hilly and rolling, with a maxium elevation of about 440 feet above sea level, and a local relief of 100 to 300 feet from hilltops to the floors of the mature valleys. The underlying rocks are hard and crystalline, ranging from metamorphic gneiss, schist, and serpentine to igneous gabbro and granodiorite. These hard rocks are in general mantled by weathered material derived from their decomposition in place, or composed of material transported only a short distance. The unaltered rock crops out in road cuts and stream channels. The land is wooded, with occasional meadows and small cultivated fields.

The remainder of the State, composing the Coastal Plain, rarely exceeds an elevation of 80 feet, though along the Fall Line contact it attains an altitude of about 100 feet above sea level. In general this area is a flat, almost featureless plain. Tidal streams, with marginal marshes, extend back into the plain. The divide areas of the plain also contain headwater marshes. Much of the land is cultivated. The uncultivated land is in pine or oak forest, and marsh.

A few terrace remnants are represented by low stabilized dunes, and slight changes in surface gradient. The soil is in general a sandy loam. The underlying sediments are sands, silts, and clays, with a few gravel beds and shell banks.

In the Piedmont, ground water occurs in the crevices and fractures of the hard rocks, and in the pore spaces of the more loosely consolidated materials of the weathered zone. The weathered zone is usually between 5 and 50 feet in thickness. Inflow often seems to come at the contact of the weathered material and the hard rock. Yields of ground water are generally small, enough to supply domestic or farm wells, and occasionally small towns or industries, but large yields for municipalities or industries are not known. Where moderate yields as high as 50 gallons a minute are available, an extensively fractured or shear zone is indicated in the hard rock.

The older Coastal Plain sediments usually yield moderate to large quantities of ground water to properly constructed wells. Many of the water-bearing beds have an intake area for ground water at the surface along belts which trend northeast. The ground-water reservoir customarily dips to the southeast beneath confining beds of clay or shale. Wells produce water from depths between 50 and about 500 feet, and it is believed that productive wells in central and southern Delaware may eventually be drilled to depths of over a thousand feet.

The younger Coastal Plain sediments also yield moderate to large ground water supplies to properly developed wells as well as many small supplies to drive point wells. These sediments are, in general, almost flat lying terrace deposits that cover many of the older formations to depths ranging from 5 feet to possibly as much as 200 feet. Wells in these formations are commonly 50 to 90 feet deep.

Delaware is served by modern hard-top roads. A divided highway extends almost the full length of the State, and many lateral arteries connect with the principal communities, resorts, and farming areas. A few gravel roads are still maintained along less frequently traveled routes.

Roads in the Piedmont must be constructed by cut and fill. They follow the crests of ridges, or hug the valley walls. Moderate grades are necessary, and the roads curve with the topography. Some road cuts must be blasted, and gullies must be spanned. Ground-water problems are those of soil creep, bridge abutments, and retaining walls.

Roads in the Coastal Plain are long and straight, with occasional gentle curves, and low grades. In general, their location is controlled more by purchase of right of way than by topography. There are few cuts, but fills are frequent in marshy ground, and numerous borrow pits are opened to provide fill material. Ground-water problems are those of subdrainage, quicksand, and settlement of grade.

Cooperation and Acknowledgments

The original cooperative agreement between the State of Delaware and the Geological Survey, U. S. Department of the Interior, for the remainder of the fiscal year 1950, was signed by the Hon. Elbert N. Carvel, Governor of Delaware, on December 1, 1949. Subsequent annual agreements have been written through the Agricultural Experiment Station and the Delaware Geological Survey, of the University of Delaware. Mr. George Worrilow, of the Agricultural Experiment Station, served as cooperative official in the fiscal year 1951, and Mr. Johan J. Groot, State Geologist of Delaware, served as cooperative official in the fiscal years 1952 and 1953.

The cooperation of the soils and road engineers of the Delaware State Highway Department is gratefully acknowledged.

GROUND-WATER PROBLEMS INVOLVED IN ROAD CONSTRUCTION AND MAINTENANCE

Road Subdrainage

Where the subgrades of roads extend into a zone of saturation, either permanently or in wet weather, subdrainage of roads is necessary. Subdrainage of roads is a common practice generally done by construction of ditches. However, an unusually difficult problem was encountered on a new road between Laurel and Portsville, in Sussex County, Del. (See fig. 2). A road cut intersected a high water table perched on a substratum of clay, as shown in cross section in figure 3. The State Highway engineers placed an intercepting subdrain in a trench parallel to the road, then backfilled with sand, a construction similar to that shown in figure 4. The subdrain is open at the joints, but does not allow sufficient entryway to carry off water during periods of high infiltration.

On the basis of a study of the ground water and related geologic conditions in this area, it appears that one method of handling the excess ground water would be to increase the infiltration capacity of the subdrain. As commonly is done in vertical water wells to increase or obtain relatively large yields, a casing or pipe can be perforated or a screen used opposite the water-yielding sediments. In the case of a nearly horizontal subdrain, the perforations could be made along the entire section where the ground water is under a positive head with respect to the surface of flow in the subdrain. The open area of adequately perforated pipe would be materially greater than the open area that is possible by leaving an opening at the joints of the ordinary subdrain pipe. In areas where a single subdivision would not effectively drain a desired area, as in the vicinity of section E-F, laterals could be used to increase the area of interception; the location of the laterals would depend on ground-water conditions in the immediate vicinity.

If perforated pipe were used as a subdrain water collector and conduit, it might be desirable as a precautionary measure to use properly graded gravel for back-fill material around the pipe to reduce the chance of plugging the perforation. Above the gravel, the ordinary back-fill material could be used.

Even a subdrain as described above probably would not intercept all the ground-water underflow that would reach it. For a complete cut-off of perched ground water moving on top of a tight clay as indicated in figure 3, a cut-off wall of essentially impermeable clay might be used. For example, in figure 2, to cut off the northward underflow of ground water under the highway west from section C-D, a clay cut-off wall from land surface to the surface of the clay bed (shown in sections on fig. 3) could be used along the south side of the highway. This would intercept the underflow coming from the south. In order that the effect of the wall would not be merely to raise the water level to the land surface, the cut-off wall should be alined so that underflow would be diverted to the west, in this example. As a cut-off wall interrupts the normal ground-water flow, it commonly might be necessary to use such a wall in conjunction with a subdrain—the subdrain to be placed up gradient from the cut-off wall.

Whether a subdrain or cut-off wall or both are required in a given location depends in part upon the amount of underflow, the effective transmissibility of the sediments under the new regimen, and the extent to which the underflow is to be cut off.

There may be some danger in the use of a clay core as a ground-water dam in areas that have more frigid winters than the State of Delaware, which has an average January temperature of 34.2°F. If the clay became saturated with water, as might eventually happen because of capillary attraction, there might be danger of freezing, and frost heave.

Quicksand

Quicksand is a hazard in road construction and maintenance in sandy areas where there is sufficient spring discharge or content of thixotropic clay to make the sand quick. Because much of the surface of Delaware is sandy, a brief investigation was made to determine the extent of quicksand there.

The writers, in searching the literature, found few recent papers describing or discussing quicksand. Because much of the older, rather extensive literature on quicksand is not readily available, the writers have included a moderately detailed discussion and a number of references.

Quicksand may be defined as any sand or silt which flows, either rapidly or viscously, in response to a change in pressure. This ability to flow causes the surface of an area underlain by quicksand to have low bearing power, and most objects sink readily into the sand, which flows around and over them. If the quicksand is deep, the objects can disappear completely. Quicksand has been known to engulf horses, cattle, sheep, hogs, human beings, and even a train which jumped a bridge near Pueblo, Colo., in 1875 (Rasmussen, 1949, p. 90).

Ordinary sand is not quick. It becomes harder and drier under pressure—for example, by the step of a foot along the wet strand—and returns to its original moisture as the pressure is removed. This is the property known as dilatancy (Reynolds, 1885, 1886) and it is reported only for systems that are closely packed.

Quicksand, on the contrary, is remarkable because the surface seems fairly firm when undisturbed but becomes soft and liquid when dislocated. It is sand that has become loosely packed. Quicksands are usually fine grained, or very fine grained. Some might be better termed quicksilts. Some have rounded grains. Many have a small admixture of clay.

There are apparently two dominant causes of quicksand: upwelling water and thixotropic behavior.

The outward movement of water separating and buoying up the sand grains is considered by some to be the principal cause (Hazen, 1900; Smith, 1946, 1946a, 1947, 1947a). Fine grains are more often quick because they boil up under lower head than medium or coarser grains. Quicksand areas of this kind mark the emergence of a ground-water seep or spring, and imply a partially confined ground-water reservoir nearby, with sufficient head to keep the discharge area in a fluid condition.

In line with this idea, some soil-mechanics engineers regard quicksand as due solely to the development of a critical hydraulic gradient, independent of properties of the material (Tschebotarioff, 1951, p. 87):

> "The preceding discussion shows that any sand can become a quicksand and remain continuously in that condition as long as a flow of water and a critical hydraulic gradient have been developed and are

> maintained by pumping during inadequately planned construction operations, or by special drainage conditions, such as under improperly designed dams built on a bed of sand. Thus a quicksand is not a type of material but a condition thereof which can be prevented by appropriate measures. A special condition may arise in uncompacted, loosely deposited, fully saturated sands, the loose grain structure of which may collapse as a result of a sudden shock, so that the whole mass may be momentarily liquefied, that is, become momentarily quick, with unpleasant consequences. Some uncompacted, very fine, uniformly loose sands may be particularly susceptible to such momentary liquefaction. Shearing stresses imposed by construction operations may favor momentary liquefaction in all loose, fully saturated sands."

A contrary viewpoint of quicksand considers that a sediment can maintain a loose jellylike condition even when there is no appreciable water head to buoy up the grains. This phenomenon was named "thixotropic behaviour" by Freundlich and Juliusberger (1935). They say (p. 770):

> "It would be easy enough to distinguish between these two possibilities: if quicksand is thixotropic, small samples of the sand investigated in a test-tube would still behave like the bulk of the sand in its natural surroundings; this would not be the case if the mobile state of the quicksand were caused by streaming water."

A quicksand in the marsh on the John Hammond farm near Fieldsboro, Del., was so covered with vegetation that a man could walk on it, as on a quagmire (June 1952). A sample of the sand taken to the laboratory appeared distinctly thixotropic when a small amount of water was added to it and the matte of roots removed. This sand had a high content of organic matter and clay (estimated to be 20 percent).

It appears that, even with a thixotropic sand, there must be enough seepage water to maintain it at a sufficiently high moisture content to be quick. When the clayey sand dries, as through the process of evapotranspiration, it becomes firm. The hydrophilic (water-loving) clay particles coat the grains of sand, which, when wet, provide a highly lubricated, loosely packed system.

Recent study of the clay minerals has shown that water, initially adsorbed on the basal surfaces of the particles, is made up of a loosely packed hexagonal net of water molecules which exhibit a tetrahedral distribution of charges. This water develops a definite structural configuration and therefore nonliquid properties.

Grim (1951, p. 11) says:

> "The concept of oriented water on clay mineral surfaces probably can be applied to certain fine silt-sized particles. It provides an explanation for the fact, not always recognized, that some materials composed almost entirely of fine silt-sized particles are very sensitive—that is, they may show considerable rigidity and strength under certain conditions, such as compaction load, but no rigidity (actually becoming fluid) under a slight change of conditions. In such materials the bond between the silt particles is probably oriented water holding the particles firmly in place. So long as the water molecules are oriented the material has strength, but the sudden application of stress or a very slight increase in the amount of water can abruptly cause the water to lose its orientation and break the bond. The material therefore quickly passes from a rigid to a fluid condition."

Moist fine powders (0.001 to 0.01 mm. in diameter), such as bentonite and fine volcanic ash, will flow on shaking but return to a firm, pastelike condition when at rest.

Inquiry of persons familiar with rural conditions and of local road, town, and drainage engineers disclosed only 11 localities of quicksand in the State (see fig. 1). Three of these areas are beach sites, two are marsh sites, one is a group of ponds, three are creek bottoms, and two are dug wells. Investigation indicated that all these areas are of small extent.

The quicksand along the beach is most apparent immediately after a storm, when the beach deposits are shifted and new areas of ground-water discharge are exposed. The rainfall from the storm contributes recharge which, in the highly permeable deposits, increases the seepage almost immediately, and makes some sand areas quick. The shoreline roads are not affected, in general, because they are constructed back on the more stable portion of the shore, away from destructive influence of wind and wave, and of ground-water sapping.

The quicksand of the marsh areas represents the emergence of springs and also, usually, the presence of thixotropic mixtures. The higher head of water is furnished by the water table of nearby higher land, 5 feet or more above the marsh. The quick area may be almost barren of vegetation, or it may lie beneath a dense mat. The marsh mat acts as a confining layer over the rest of the quagmire, forcing the discharge of underground water to become concentrated within a small area. In road construction, the extensive fill required in building across a marsh usually quells any spring areas beneath the right of way, and their discharge is diverted to other outlets in the adjacent marsh.

A group of quicksand ponds were located southwest of Townsend in the plain that forms the divide of the Delmarva Peninsula. The ponds are scattered at elevations of 60 to 70 feet above sea level, with gently rising higher ground only 10 feet or so above them. Possibly an impervious silt or clay, lying at shallow depth, has perched the water table in this area, and caused the surficial soil and sand to become waterlogged. Proper subdrainage, as discussed in the preceeding section, should take care of such areas as these in road construction.

The three areas of quicksand in creek bottoms are in the vicinity of Newark, Del., in the sandy alluvium of creeks which drain the Piedmont. The relief is 50 to 100 feet in this area, and the water table lies in the weathered mantle rocks and in the fissures and fractures of the parent crystalline rocks. In general there is a water head of 30 to 80 feet above the valley bottoms, which provides the source for many small seeps and springs. This water head is probably responsible for the quicksand alluvium. The quicksand on the Van Scoy land near Newark was of very small extent, in the stream bottom itself, and was only about 2 feet thick. Such quicksand as this along proposed rights of way probably can be stabilized by fill, or a route may be chosen that bypasses the trouble spots.

Quicksand was reported in two dug wells, one in the Townsend area and the other in the Cheswold area. In each case the quicksand was encountered at a depth of 7 to 8 feet and the wells could not be finished because of it.

These 11 small localities of quicksand in Delaware probably represent only a few of the occurrences, but even if there are many times this number their aggregate extent and troublesomeness is small. Personal danger from quicksand is practically unknown to the people of Delaware.

Three separate reconnaissance trips made during the winter and spring of 1951-52 failed to disclose any extensive occurences of quicksand in Delaware. It may be concluded that the phenomenon occurs only on a small scale, and only sporadically during wet periods.

The reasons for this are apparent when one considers the occurrence of ground water in Delaware. In general, the soil is so permeable that seeps occur along the full length of most of the watercourses, and not enough pressure is built up at any one point to create sand boils. In the coastal plain, the relief is generally so gentle that the water head is low.

Although many of the sands of Delaware appear to possess enough admixture of clay to be thixotropic, they generally are not supplied with enough moisture to retain a quick condition for very long; when encountered, quicksand can be overcome by means of standard fill and drainage practices.

Soil Creep

A third problem involving ground water is soil creep, as shown by the cut along the Hockessin Road near Yorklyn, Del. (for location, see fig. 1). Here the road was cut on the side of a hill of weathered gneiss, schist, and pegmatite. Ordinarily these weathered rocks when dry would be stable at the angle of the cut. However, the cut intersected the water table and springs were formed. The weathered rocks, saturated with water, were not stable at the slope of the cut and slumped to a lower angle of repose. A collector system of drain pipes was installed and when last inspected was removing water fast enough to stabilize the slope. In the event of renewed soil creep, under the conditions outlined, additional collector pipes could be installed. Where it is desirable to have collector pipes of high efficiency, properly perforated pipes or screens can be used.

Road Drainage as Affected by the Farm-Drainage Program

Much of the coastal plain of Delaware consists of low, wet, swampy or overflowed lands, particularly in the lower two counties, and particularly also during the winter and spring of each year. The area requiring drainage is shown in figure 5. Drainage of these lands has been a rewarding practice, because the soil is commonly higher in organic matter and potentially richer than the soils of of the better-drained lands of the State.

In the early years, drainage was undertaken chiefly on a small scale by individual owners. In recent years, drainage has become a large-scale program, involving entire drainage basins, and requiring the cooperation of many farmers, chiefly with Federal-State aid. The U. S. Soil Conservation Service began its enlarged program in Delaware in 1944, and expanded it so that in Sussex County alone 1,662,401 linear feet of drains, requiring movement of 1,813,111 cubic yards of earth, had been installed through 1951, and ditching was going forward at the rate of 425,000 linear feet a year (Annual Report, 1951, Soil Conservation District of Sussex County, Del.).

In accomplishing this drainage, the system in use from 1944 to 1949 required the construction of gentle V-notched ditches, 12 to 18 inches deep, and 100 feet apart in the headwaters, which connected with more widely spaced, deeper drains farther down. In order to farm greater areas with machinery, the prevailing (1952) practice is to construct a large V-shaped ditch, 3 to 4 feet deep, every 300 to 400 feet which connects with transverse ditches, and thence to natural drainageways.

Because Kent and Sussex Counties are well served by roads, this program of farm drainage has necessitated the installation of many new culverts, the lowering or enlargement of others, and the replacement and building of some small bridges. The locations of some of these are shown on the map, figure 1.

The chief problem has been the lowering of existing culverts, for the drainage program establishes a lower ditch, canal, or stream grade which often crosses the right of way of a road 3 to 4 feet below the previous grade.

A secondary problem has been the silting up of the culverts as a result of accelerated erosion engendered by lowered grade and by introduction of new land to cultivation. Many of the culverts have had to be replaced by larger ones which could be cleaned more easily.

Still a third problem results from the new hydrologic regimen established on the drainage basin. The increased number of widely ramified channels permit surface runoff to "flash" more rapidly during a storm. However, the total storm runoff may be reduced because more storage space is provided between the surface and the lowered water table. Thus ground-water flow to streams may be sustained for hours and even days after the storm.

Although the change in the hydrologic balance is not clear, it is obvious that total runoff will increase. Because most culverts are designed to take care of the estimated capacity flood, and because a drained area will discharge more rapidly than the previous undrained area, larger culverts, have, in general, had to be supplied. An exception to this rule has occurred where one large culvert has been replaced by several smaller ones, which now drain the same land with more ditches, and whose aggregate capacity is greater than the capacity of the previous single culvert.

The new drainage regimen undoubtedly decreases evapotranspiration, by lowering the water table. Drains designed to meet the extreme condition of high water table during the spring of the year may cause overdrainage during the summer growing season. Ferris (1949, p. 263) says:

> "Through the summer and fall seasons such overdrainage may deplete the regional ground-water body to such an extent that the capillary zone is drawn beyond the reach of the plant rootlets and large soil-moisture deficiencies may develop. This practice may account for the large loss of top soil evidenced in some overdrained muckland areas. It would seem reasonable that in some areas drainage ditches should be blocked and the water should be used for irrigation in the season of low water table."

This latter recommendation, if followed, would create complications in the impact of storm runoff upon culverts, requiring careful regulation so that temporary blocks or dams did not burst and impose unusual flood conditions on the road conduits.

The equation of the hydrologic cycle may be written:

$$P = R + E + \Delta S$$

in which
- P is precipitation
- R is runoff (surface and ground-water)
- E is evapotranspiration, and
- ΔS is change in storage (surface water, soil moisture, and ground water).

The balance of this equation may be considered altered by the farm-drainage program by an increase in R, a decrease in E, and greater fluctuations, both positive and negative, in ΔS.

Water that is economically recoverable by the works of man, and that is allowed to pass to waste through lack of development, represents a potential source for expansion of industry and agriculture. Here, water that was formerly wasted by evaporation and transpiration (and perhaps also some water that was transpired by useful vegetation in the summer), is converted to runoff, and carried off to the sea without use. This is done, of course, because the high water table prevents man from working the land in wet seasons, so that the water becomes a nuisance and must be eliminated.

Bridge Abutments and Retaining Walls

Bridge abutments in Delaware are almost invariably placed at the end of a filled grade, across the low, broad valley of a stream, so that the only problem is that of assuring adequate settlement of the grade. However, in moderately hilly areas, such as are found in the Piedmont, it is sometimes necessary to construct the abutment at a cut. Where a cut intersects the water table, the abutment or retaining wall may dam the ground water, causing the water table to rise and the ground-water head to increase. During wet weather the resulting unbalanced pressure may cause the wall to crack or fail. Freezing weather that occurs at times when the water table is high may hasten failure by the force of ice wedges in cracks.

Small discharge pipes placed through the concerte wall allow the water to percolate out and relieve the pent-up pressure (see fig. 6). To reduce the chances for such pipes to clog and fail to function, the end of the pipe, which is extended through the wall into the backfill, might be fitted with a sandpoint well screen instead of being left open. Drainage would be further assisted by a permeable fill of sand and crushed rock between the abutment and the rock face. Lateral discharge pipes, emptying beyond the wing wall, would provide an additional avenue of drainage.

Sub-Water-Table Concrete Foundations

It is well known that the water-cement ratio in fresh concrete should be kept low when the set is to take place under water. The same requirement applies if the set is to take place below the water table. The accompanying table shows the water-cement ratio as recommended by the Corps of Engineers for various structures and conditions of exposure. The left column of conditions would be applicable to most conditions of concrete set below the water table.

In pouring concrete below the water table during freezing weather, there is less danger of obtaining an incomplete set than there is at the surface, for at such times the ground temperature is higher than the air temperature.

WATER-CEMENT RATIO FOR SUB-WATER-TABLE CONCRETE FOUNDATIONS

(Corps of Engineers, Reference Data, War Dept. Field Manual 5-35, p. 220, 1944. Reproduced by permission of the Department of the Army.)

Type of structure	Standards of measurement	Condition of exposure or wear		
		Subject to severe wear or weather conditions, alternate freezing and thawing, exposure to sea water or weak chemical solutions, etc.	Subject to moderate wear or weather conditions; or for watertight concrete.	Protected from wear and weather; not subject to moisture, alternate freezing and thawing, nor to corrosive ground waters, etc.
Heavily stressed concrete. Structural members and protective structures.	(1) $\frac{W}{C}$	5½	6	6½
	(2) SPC	3,750	3,400	3,000
	(3) HE	4,500	4,000	3,750
Moderately stressed structures. Pavements, basement floors, retaining walls, etc.	(1) $\frac{W}{C}$	6	6½	7¼
	(2) SPC	3,000	3,000	2,500
	(3) HE	4,000	3,750	3,200
Mass concrete heavy walls, piers, foundations, dams, etc.	(1) $\frac{W}{C}$	6½	7¼	8
	(2) SPC	3,000	2,500	2,000
	(3) HE	3,750	3,200	2,700

(1) Maximum water-cement ratio $\frac{(W)}{(C)}$ in gallons per sack of cement.

(2) 28-day compressive breaking strength in pounds per square inch using standard portland cement (SPC).

(3) 28-day compressive breaking strength in pounds per square inch using high early strength cement (HE).

SOIL STABILIZATION BY ELECTROOSMOSIS

Theory

Electroosmosis is the process of movement of a fluid through a semipermeable membrane as a result of application of a direct electric current. Figure 7 illustrates U-tube, with a semipermeable clay diaphragm at the base of the U (Vey, 1948). When an electromotive force is impressed between two electrodes on opposite sides of the diaphragm, fluid moves through the clay from the positive to the negative side.

This method is used practically by means of a filter well, which serves as a negative electrode, and a pipe driven into the ground some distance away, which serves as a positive electrode. A current is impressed between the electrodes, establishing an electric field within the ground. This field causes ground water to move, if the soil is sufficiently fine, from the region of the positive to the negative electrode. The discharge of the filter well is thereby increased by a substantial amount (see fig. 8).

The following brief explanation of the phenomenon is quoted in translation from the German because it is particularly clear (Schaad and Haefeli, 1946):

> "The physical phenomenon of electroosmosis depends upon the contact electricity of two adjoining media. It is known that at the contact surface of two different materials there is an electric potential difference by which the material with the higher dielectric constant becomes charged positively relative to the other. *** At the interface of the fluid and the capillary wall an attraction of the electrons of both materials takes place through electrostatic forces resulting in the aforesaid potential difference. This is designated as electrokinetic particle potential. The inner layer acts as a condenser with a double coating of electric charges. If an electric current is now applied at the ends of the capillary by means of electrodes, the charged fluid particles will be put in motion under the effect of the electric field forces. For instance, the water particles are driven generally from the positive to the negative electrode, because water has a high dielectric constant and as a rule becomes charged positively relative to other materials. Similarly, this motion occurs in interconnected capillary systems, and consequently also in porous formations. Therefore, it can be applied to electrodrainage or, in general, to the moving of a liquid through fine-grained porous masses. From a technical point of view, many applications may be considered, such as drainage, injection, impregnations, and acceleration of settlement by removal of water."

The British (MacLean and Rolfe, 1945) investigated electroosmosis during the war, and gave the following conclusions: When large current densities are employed, considerable heating takes place at the anode. The temperature gradients thus produced increase the ease of water movement. The weight of water expelled at the cathode is proportional to the quantity of electricity (in coulombs) passed between the electrodes through the soil until the soil dries out at the anode. A linear relation exists between the "clay" content of the soil and the quantity of electricity required to expel a given weight of water.

This phenomenon was used on a practical basis independently by the Germans and the Russians in World War II to remove water from soils so as to assist consolidation and stabilization. Fortunately, the method can be used to arrest road failure or pile settling without closing the roadway for repairs. To illustrate its application the following synopsis is presented.

The Germans employed electroosmosis to stabilize the subgrade of a double-track railway at Salzgitter (Markwick and Dobson, 1947). It was planned to make a cut 20 feet deep, but when the silty soil was opened it was found impossible to excavate with a mechanical shovel, for the slopes were not stable. Two lines of well points, 10 in each line, 32½ feet (10 meters) between lines, were sunk at 32½ foot intervals, along a 292.5-foot-long section. The wells were of 4-inch perforated pipe set in 10-inch holes, and sand and gravel was packed outside the pipes. The wells were 24 feet deep and were used as negative electrodes, each well receiving 25 amperes of current. Ninety volts was applied to the entire system. One-inch gas pipes driven opposite the wells to the same depth between the two lines of well points were used as positive electrodes. One small centrifugal pump was connected to every two or three well points. From an initial moisture content ranging from 20 to 24 percent, moisture was reduced by electroosmosis to 14 to 17 percent. When the soil dried out, it was excavated with a face shovel to a slope of 1:1. A blanket of sand was applied as a filter medium and retaining slope, and drains were laid in ditches on both sides. Costs were assessed as 0.6 reichsmark per cubic meter (about 12 cents a cubic yard). For bridge abutments, to which the process was later applied, the cost was about 30 cents a cubic yard.

The Germans applied the process on a large scale to the construction of a U-boat pen at Trondheim, Norway. An earlier pen had been severely damaged by earth movements, causing double-skin sheet piling to become distorted and the bottom formations to rise. The wells were similar to those at Salzgitter but ringed the excavation, which was to cover an area 550 by 330 feet to a depth of 40 feet. In the salty soil, 40 volts between electrodes was sufficient; the current consumption averaged 20 to 30 amperes a well. Before passing the current, yields ranging from 0.25 gallon to 11 gallons an hour were obtained from the individual wells. After the application of current, the flow per well increased after about a day to 2½ to 105 gallons an hour. Each well was furnished with a small electrically driven plunger pump. In dry weather 28,000 gallons a day was obtained, but this increased to 47,000 gallons a day during the autumn rains. The sides and bottom of the excavation were concreted and no further trouble occurred. The cost was about 6 cents a cubic yard for the material unwatered. The anodes were partly destroyed by corrosion, which, of course was accelerated by electrolysis.

Whereas the Germans applied electroosmosis to semipermeable sandy silts and loams, the Russians developed the process for heavy clays of low permeability. Their costs, therefore, were much higher, being between $4 and $19 a cubic yard, but these costs were reported to be far lower than those of chemical or mechanical stabilization (Sokoloff, 1947, p. 822).

The Russians investigated the theory involved, which dates back to Helmholtz in 1879, made a scientific laboratory investigation, and then made several successful applications in the field (Rzhanitzin, 1941). The density and bearing strength of clayey soils were increased by using copper cathodes and aluminum

anodes spaced 19.5 to 39 inches (0.5 to 1 meter) apart, and applying 30 to 200 kilowatt-hours of direct current, at 20 to 97 volts per yard (22 to 100 volts per meter) and not more than 16.7 amperes per square yard (20 amperes per square meter).

The Moscow canalization agency desired to dig a collector drain on the left bank of the Iausa River. A trench was dug to the water table, 26.2 feet (8 meters) below the land surface, and a protective screen was installed. As the trench was being dug below ground-water level, the clay was loosened and tended to "float." Despite intense excavation, the trench could not be sunk to the intended level; indeed, a hydrostatic mud level was established that could not be lowered. Electrodes were then placed at the sides of the trench, which was 39 inches (1 meter) wide, and driven to the required depth, about 11 feet (3.5 meters). Initially, power of 62 kilowatts was supplied at 120 volts intermittently for 8 days. Then the distance between the electrodes was reduced to 19½ inches (0.5 meter) and 60 volts was applied at a total power consumption of 1.75 kilowatt-hours per cubic foot (62 kw-hours per cubic meter). The ground was stabilized, the moisture content being reduced from the original 53 percent to 20 percent. The "float", transformed into a dense clayey mass, was removed with spades and the walls were timbered. The necessary apparatus was portable and simple.

A laboratory investigation in Russia was made of the electroosmotic process to increase the carrying strength of piles. If the piles are made to serve as electrodes, the electric current may produce a stabilized pediment at the foot of every pile. Model aluminum piles 40 centimeters long and 34 millimeters in diameter were sunk into soft clayey ground under their own weight, and their carrying strength, in grams per square centimeter of surface area, was determined in relation to the expenditure of power. The optimum for both electrodes was 1.25 watt-hours per square centimeter of area, and stabilization at the anode was superior to that at the cathode. A decrease in carrying strength after attainment of the optimum may be related to drying and cracking of the clay near the electrode.

The use of electroosmosis to prevent frost heave was also investigated, using calcium and sodium chloride as electrolytes (Solntzev, 1951).

This resume of the process and uses of electroosmosis is given to point out the need for study of the process as a potential means of overcoming unfavorable geologic and ground-water conditions in highway construction and maintenance. Development of suitable apparatus would be an excellent program for joint experimentation by soils and road engineers and ground-water hydrologists.

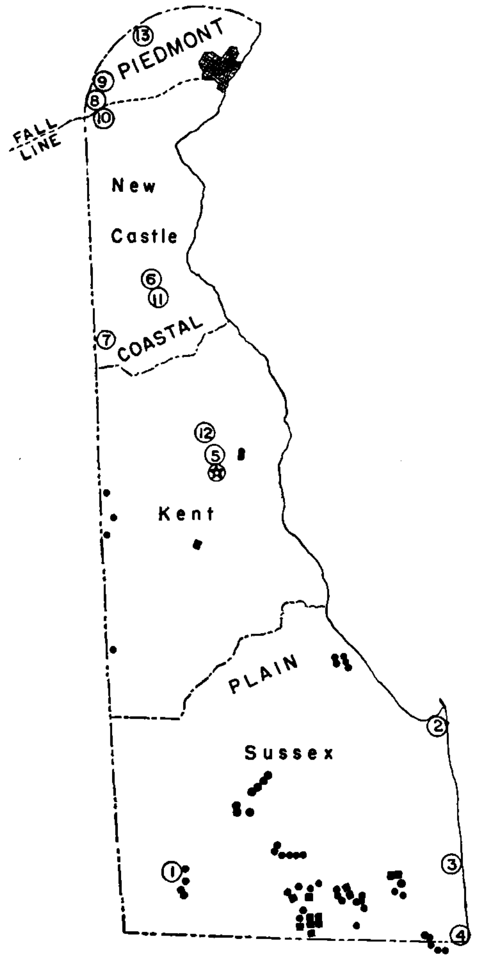

Figure 1.—Map of the State of Delaware, showing the physiographic provinces and the localities discussed.

1. Subdrainage of road between Laurel and Portsville. 2. Quicksand on beach near Lewes. 3. Quicksand on beach near Bethany Beach. 4. Quicksand on beach of Fenwick Island. 5. Quicksand in marsh on St. Jones River. 6. Quicksand in marsh on Hammond Farm near Fieldsboro. 7. Quicksand in marsh ponds near Townsend. 8. Quicksand in creek near Van Scoy home, 2 mi. NW of Newark. 9. Quicksand in creek 1½ mi. NNW of Newark. 10. Quicksand in creek near Chrysler plant, Newark. 11. Quicksand in well near Fieldsboro. 12. Quicksand in well at Marker's Hatchery, near Dover. 13. Soil creep between Yorklyn and Hockessin.

A black circle indicates a culvert replaced, or added, as a result of the farm drainage program. A square indicates a bridge replaced, or added, as a result of the farm drainage program.

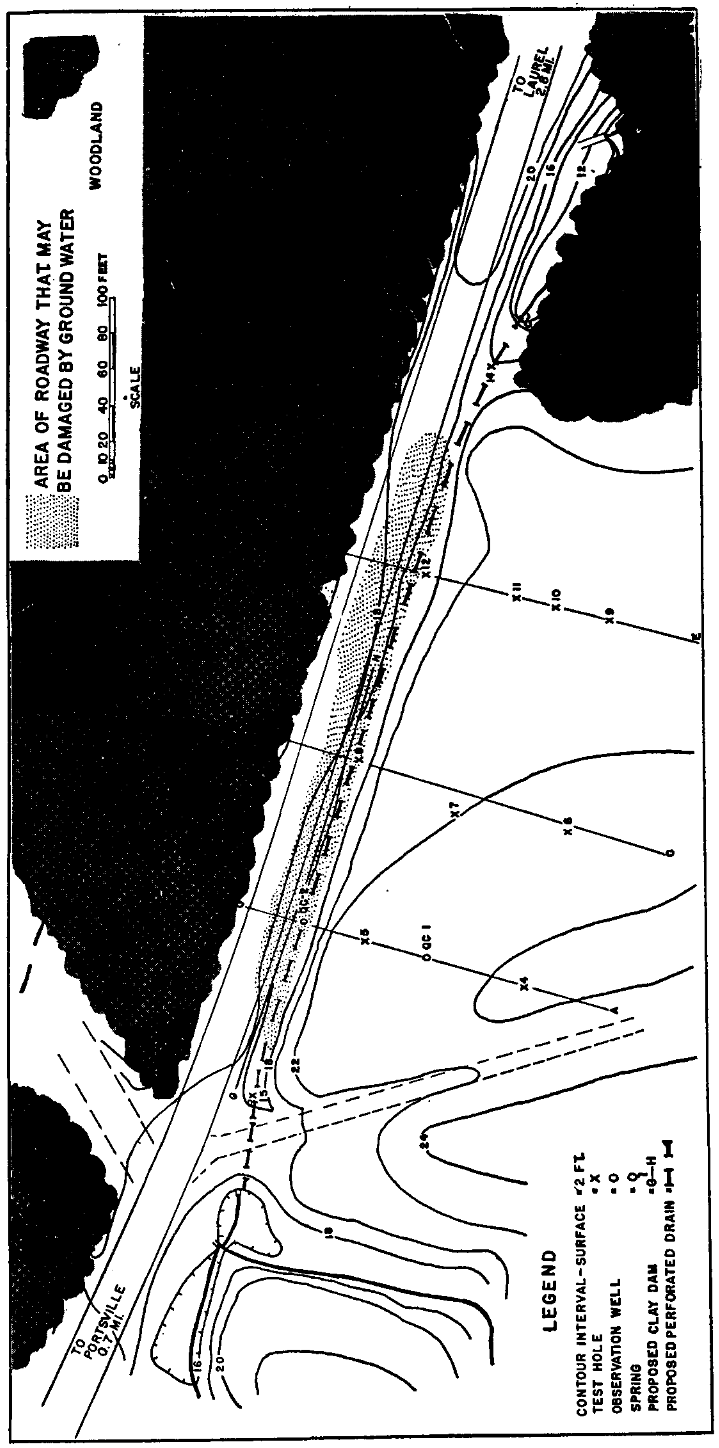

Figure 2.—Map of subdrainage problem, roadway near Portsville, between Laurel and Bethel, Sussex County, Del.

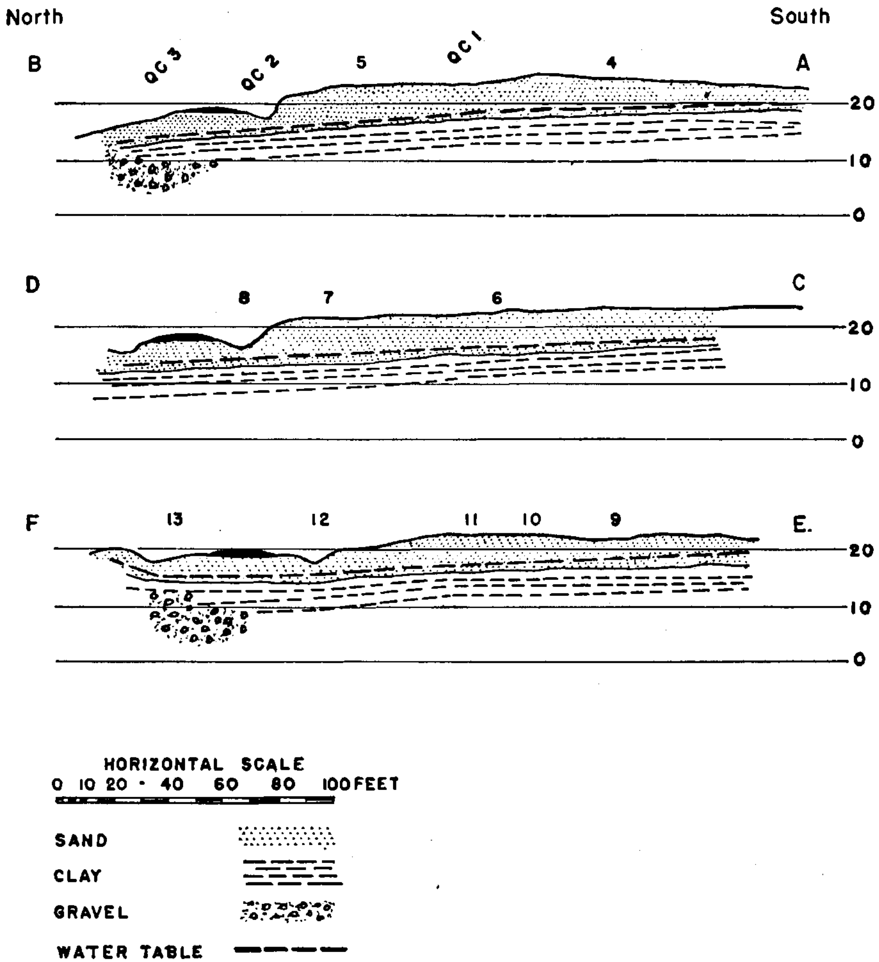

Figure 3.—Cross sections showing high water table beneath road shown in figure 2.

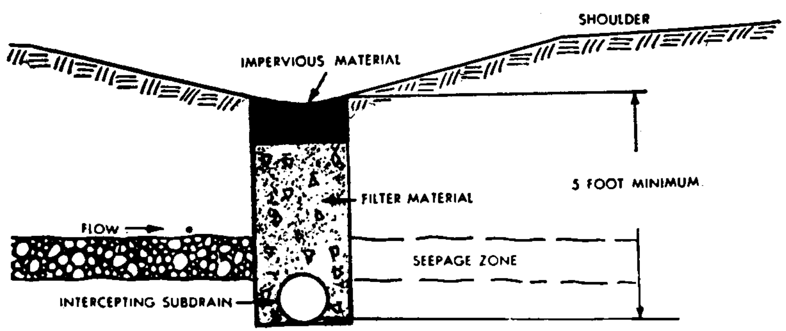

Figure 4.—Intercepting subdrain for a roadway (Aviation Engineers, War Dept. Tech. Manual 5-255, fig. 49, p. 125, 1944. Reproduced by permission of the Dept. of the Army.)

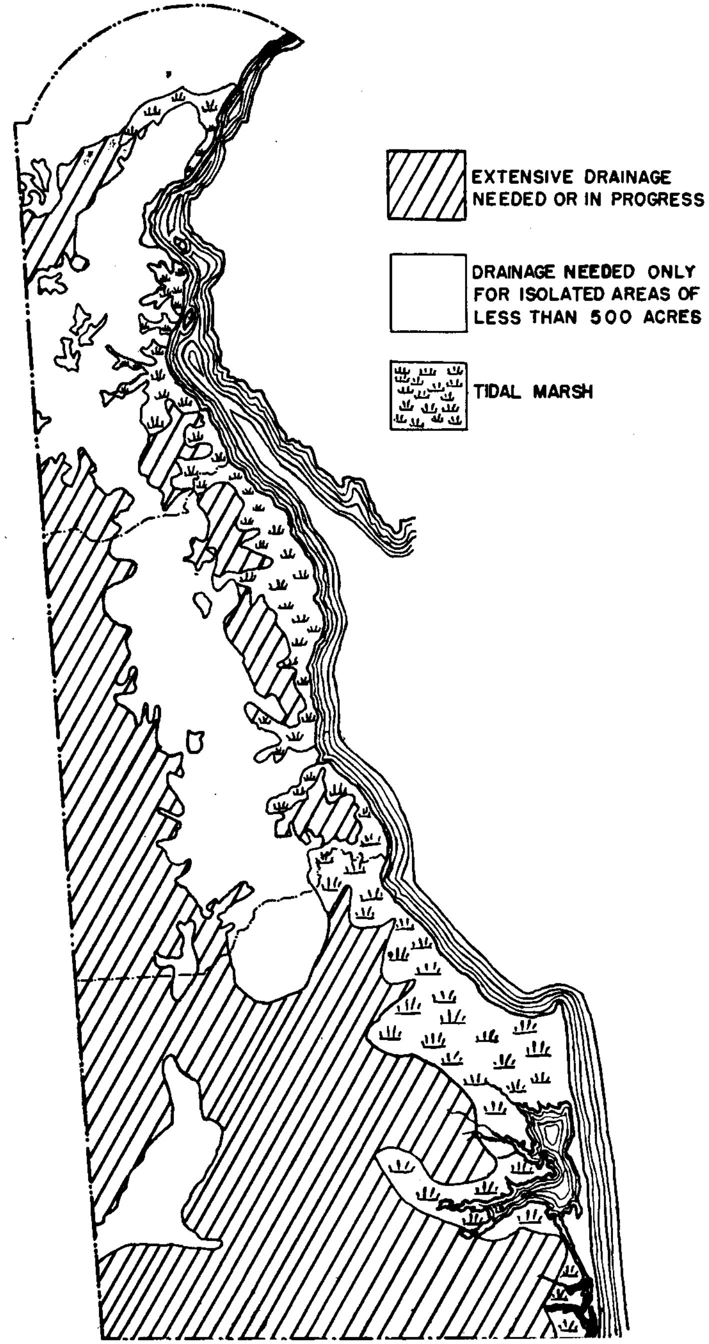

Figure 5.—Areas requiring draining in Delaware. (After E. H. Talbert, Soil Conservation Service, U. S. Dept. Agr., Georgetown, Del.)

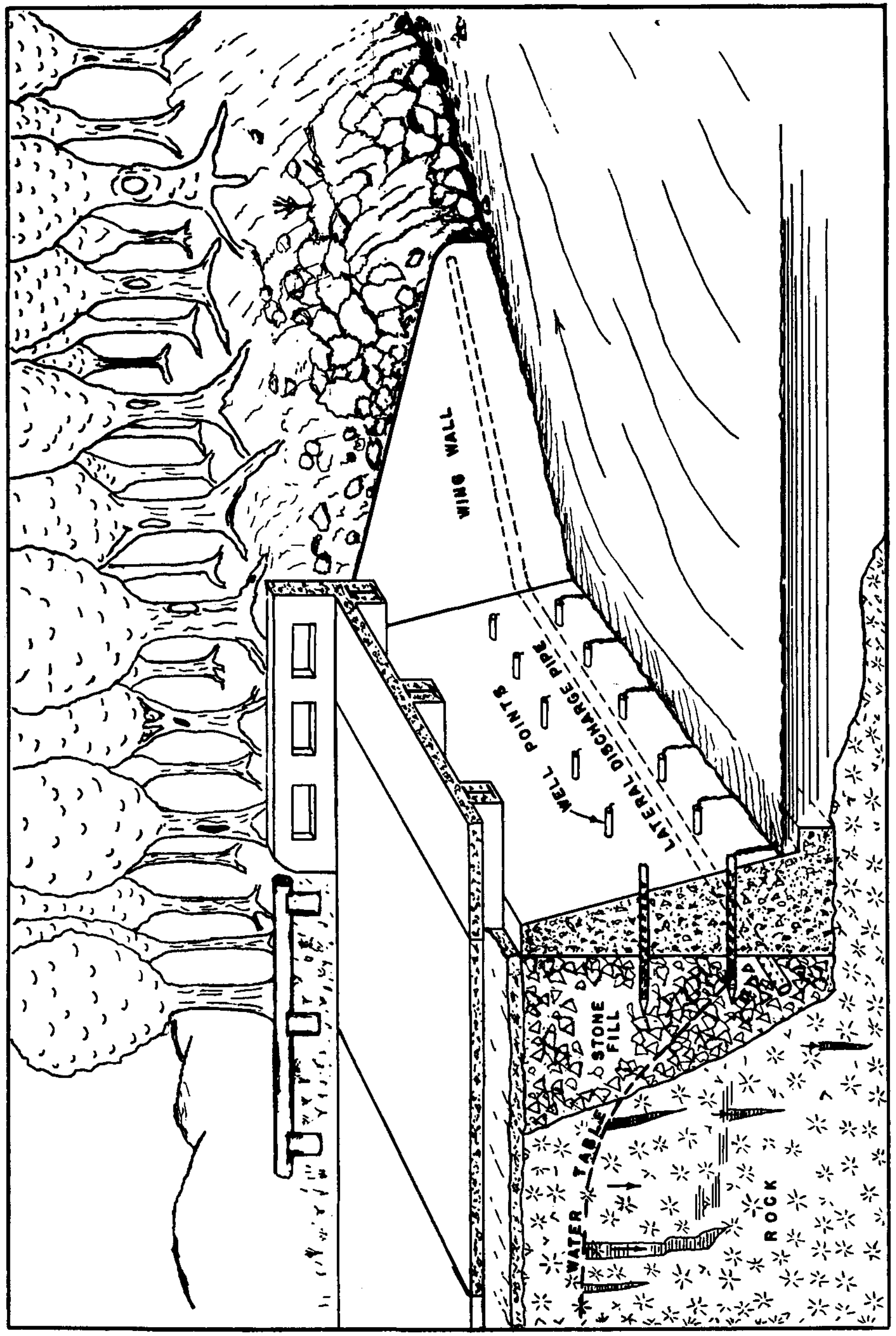

Figure 6.—Diagram of a bridge abutment with porous fill and screened drain pipes designed to relieve the water pressure and to prevent the abutment from acting as a ground-water dam.

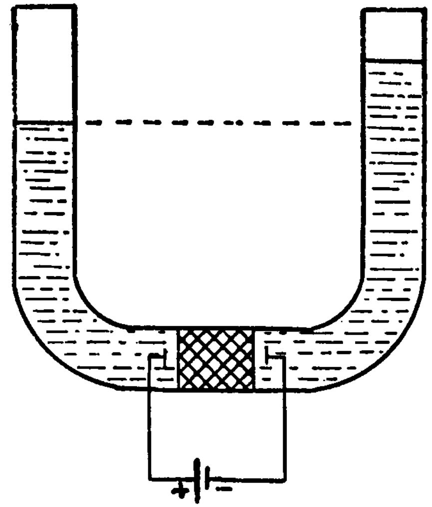

Figure 7.—Electroosmosis through a clay diaphragm in a U-tube. (Adapted from Vey, 1948.)

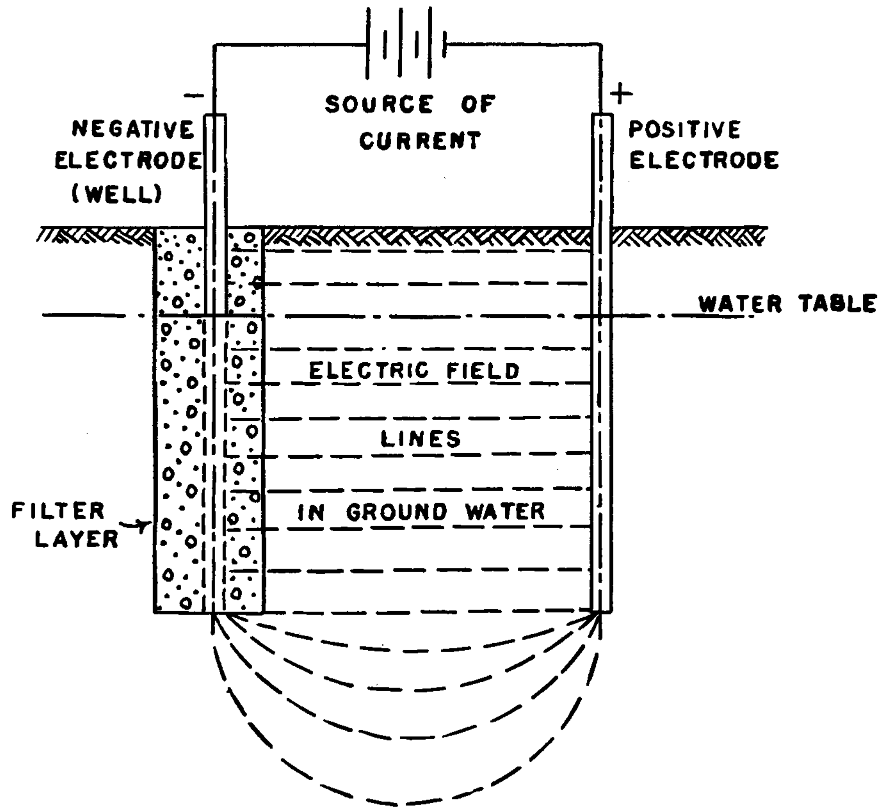

Figure 8.—Schematic diagram of a drainage well, supplied with water by electroosmosis.

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