1. Investigation of the permanence and movement of calcium and sodium chlorides in the Joint Highway Research Project's Test Road No. 2. (In this case the base course consisted of a graded mix containing 88.5 per cent pit-run gravel and 11.5 per cent sandy clay in the six-inch base course, and the study included a comparison of chemical movement in the unpaved road with that under a bituminous surface.)
2. Investigation of the permanence and movement of these chemicals in sections of Indiana State Roads 62 and 161.
3. A study of cation movements in highway bases and sub-grades.
4. A laboratory study of chemical migration.
5. A study of the effect of small additions of either calcium or sodium chlorides on frost action in fine-grained soils. (The amounts of chemical added vary from 0.33 per cent to 2.00 per cent in the present study.)

DRAINAGE OF HIGHWAY SUBGRADES

G. W. McAlpin,
Research Assistant, Joint Highway Research Project,
Purdue University

Land drainage, like many other branches of engineering, can be traced to remote antiquity. The use of simple ditches as a part of agricultural development is reported as far back as 400 B. C., when the Egyptians employed such methods along the Nile Valley. Later reports show that the Romans used a type of closed conduit three feet deep and filled to half its depth with pebbles, stones, and brush. The remainder of the drain was back-filled with the excavated soil.

During the seventeenth century the population of Europe had increased to the point where additional arable land and more intense cultivation of existing farms became an economic necessity. As a result of this necessity, land drainage was begun on a large scale. The practices developed during this period contributed greatly to the present knowledge concerning this subject.

The first tile drain in the United States was laid on the farm of John Johnston of Geneva, New York, in 1835. Since this time, agricultural development has employed the use of drains extensively to increase the productivity of the soil and to reclaim swamp lands. The United States Census Bureau (1929-1930) reports that 44,523,685 acres of farm land have been provided with drainage facilities.

The necessity for adequate drainage systems in the construction of highways has been recognized by engineers since the earliest days of road building. The familiar saying, "The three essentials of a good highway are drainage, Drainage, and DRAINAGE", is a true expression of the importance accredited this factor. The problems encountered on today's highway are somewhat different from those of the past; in order to provide for heavier and faster traffic and to insure greater safety, it is now necessary to reduce the grades, to straighten the alignment, to modify the crown, and, in most cases, to eliminate deep side ditches completely. These requirements mean the building of roads through locations that may not be altogether ideal. That is, it is often necessary to locate the roadway on undesirable soils that might have been detoured in the past, and to make cuts which expose fresh soil to the erosion forces of nature as well as unbalance the forces of stability that have existed for many years. It has been the engineer's job to improve the design of his drainage systems so that they will eliminate or control the undesirable factors arising from these new requirements.

The earliest drainage systems were designed for the purpose of removing the water that fell upon the surface of the roadway. While this is still a problem on today's highways, of more importance is the control of subsurface water. The problems encountered in the placement of drains to care for such water are rather complicated and can best be studied by examining the properties of the influencing factors: namely, the soil, the water in the soil, and the laws governing the action of this water.

BASIC CONSIDERATIONS

SOIL

Great advancement has been made in recent years in the practice of drainage by the realization that soils differ greatly and that these differences affect the design of drainage systems. The development of the technique for making soil profiles and the adoption of standard identification tests to aid in the interpretation of these profiles have furthered this advancement.

While considerable knowledge has been acquired concerning the properties of soils, there is still a great deal to be learned. It is known that, in general, sands are stable under all moisture contents and that they may be easily drained. It is also known that the strength of clays decreases rapidly with an increase in the moisture content and that such soils have a low permeability and cannot be easily drained. However, the properties of soils lying between these two extreme types, chiefly the silts and silty clays, are not so well known. In addition, it is the soils in this range that are most commonly encountered in nature. A decision as to the need of drains in such soils can be governed only by the good judgment and experience of the engineer.

Points to be considered in making such a decision are: the type of soil as shown by the test constants, the depth and slope of the ground water table, the density of the soil, from which the amount of void spaces and the possible maximum water content can be determined, and the water content of the soil. It should be remembered when studying the soil conditions at a certain location that failures usually occur in the spring of the year when the most adverse conditions prevail, and for this reason allowances should be made and the design based upon the soil characteristics that will exist during this critical period.

WATER IN SOILS

There are three forms in which water may exist in soils: (1) Hygroscopic moisture, or that which condenses from the atmosphere on the surface of the soil particles when the soil is allowed to become air dry. (2) Capillary or film water, or that which is held against gravity by the surface tension of the films of water surrounding the soil particles. (3) Gravitational water, or that which is free to move through the soil under the influence of gravity. To explain further the meaning of these three forms of soil moisture, they will be discussed separately.

Hygroscopic Moisture. The quantity of hygroscopic moisture within a mass of soil varies directly as the surface area of the soil grains and the relative humidity of the atmosphere and inversely as the temperature of the air surrounding the soil. The moisture retained in the soil in this form is of interest only from a laboratory standpoint and does not enter into field considerations.

Capillary Water. Capillary water is that water above the free water surface which is held in the interstices between the soil grains by surface tension. While water held in the soil in this form is known to be an important factor in many subgrade problems, its greatest harmfulness generally occurs in relation to frost action. The factors governing the occurrence of such water in soils can best be explained by an illustration.

If one end of a small glass tube is immersed in water, the water within the tube will rise to an elevation higher than that on the outside. This phenomena is due to the affinity of the molecules of the glass and those of the water. The height to which the water will rise is dependent upon the magnitude of this affinity, the surface tension of the water, and the diameter of the tube. For soils, the first two of these factors may be considered constant; and it can be shown that the height of rise is expressed by the formula, $h = \frac{0.3}{d}$, where (d) is the diameter of the capillary tubes expressed in centimeters. From this it is seen that clays which have very small openings between the soil grains will have a much higher height of capillary rise than sands whose openings are comparatively large. However, for fine-grained soils such as clay, the height of capillary rise as expressed by this formula is probably far in excess of that possible under field conditions. Professor C. F. Tolman[1] states, "The majority of modern authorities give the maximum capillary lift as 10 ± feet." The properties and characteristics of this type of water are undoubtedly of great importance in highway constructions and should be the subject of an extensive program of research.

Gravitational Water. As its name implies, gravitational water is that which is free to obey the laws of gravity. If a saturated soil is allowed to drain, the water which flows out is the gravitational water; the hygroscopic and capillary water remain in the soil mass. This type of water is the one of most interest to the highway engineer because it introduces problems with respect to stability which involve both static and dynamic forces. This paper discusses the results of experiments aimed at a better understanding of the action of drainage installation in reducing or controlling the area affected by this gravitational water.

THEORY OF FLOW

The laws governing the flow of water through soil are expressed by the same general equations as those developed in hydrodynamics for the motion of viscous fluids in ordinary free vessels. Although many simplifications can be made in these equations by considering the fluid water incompressible and the velocity of flow as being so small that inertia forces may be neglected, the mathematical difficulties of applying these equations to the flow through soils are, for practical purposes, insurmountable. A thorough treatment of these general equations and the simplifications introduced in the solution of problems involving the flow of water through soil is given by M. Muskat in his book "The Flow of Homogenous Fluids Through Porous Media."

For the purpose of this paper it is sufficient to say that the flow of water through soils is laminar or streamline in all cases, with the possible exception of large gravel. That is, adjacent particles of water flow along in paths that are parallel. This flow adjusts itself to the boundary conditions and the forces to which it is subjected by a particular problem. As mathematical solutions of such problems are usually extremely difficult and in many cases impossible, graphical means or model studies are usually employed.

---

[1] *Ground Water*, by C. F. Tolman, McGraw-Hill Book Co., 1937.

The discussion which follows describes the procedure used in this investigation for determining by the use of sand models the path followed by the water as it flows through the soil toward a highway drain.

DRAINAGE INVESTIGATIONS BY THE JOINT HIGHWAY RESEARCH PROJECT

In organizing a working plan for the investigation of problems relating to the drainage of highway subgrades, it was first necessary to decide just what these problems were. For this purpose the subject was divided into four parts, each of which is a complete investigation within itself. These are: (1) the distribution and magnitude of the stresses transmitted to the subgrade through the road surface, (2) the relationship between the moisture content of a soil and its strength, (3) the permeability of different soil types, and (4) the determination of the most effective depth and location of subdrains. The nature and purpose of these investigations will be somewhat expanded below.

1. The determination of the distribution and magnitude of the stresses transmitted to the subgrade through the road surface. This problem is being investigated by Mr. F. J. Woodsmall by the use of photoelastic methods on gelatin models.

2. The relationship between the moisture content of a soil and its strength. Data concerning this relationship are being obtained by Mr. L. E. Gregg in his work with the tri-axial compression studies. It is hoped that by combining the results of this study and those from the stress-distribution investigation it will be possible to ascertain whether or not a soil actually needs to be drained; that is, will the moisture content of the soil ever become so high that its strength will be decreased to the point where it can no longer support the loads to which it is subjected?

3. The permeability of different types of soil. This investigation is being carried on in part by Mr. W. J. Kay, and includes the testing of different types of soils to determine their permeability. It is known that the coarse materials such as sands can be easily drained and that it is much more difficult to drain the fine-grained soils such as clay whose permeability is very low. Somewhere between these two extreme types lies a range of soils in which the value of drainage is doubtful. It is the ultimate object of this project to obtain data concerning the permeability of the soils in this range.

4. The determination of the most effective location of subdrains: This investigation is being carried on by the writer by the use of sand models. The results obtained are discussed in the following pages.

Investigation of Flow by Sand Models

Sand models were used in this investigation to determine the path followed by water as it flows through the soil toward a highway drain. By this method it was possible to obtain results that show a comparison of the effectiveness of drains located at different positions below the road surface.

The frame of the model was so constructed as to confine the flow to a single plane: that is, the length and height were large and the thickness was comparatively small. The sand was confined between a piece of 5/8″ plywood and a sheet of 1/4″ plate glass which were spaced 1/2″ apart by placing sponge rubber along the bottom and the sides. By the use of clamps, the glass and plywood were drawn together and the rubber compressed to form a watertight container. The drain consisted of a piece of brass, 30-mesh screen bent into cylindrical form. Holes were bored in the plywood at the location at which it was desired to place the drain. At the edge of the model an inlet for the water and an overflow pipe to maintain a constant head of water were provided. In preparing the model for a test, the container was filled to half its depth with water and the Ottawa sand poured in. This procedure was adopted to prevent air from filling the interstices between the sand grains. The drain, which had been closed during the placement of the sand, was then opened. The elevation of the water at the edge of the model was held constant throughout the test by the overflow pipe previously mentioned. After allowing the water to run for approximately ten minutes to give it time to adjust itself to the flow conditions, dye was inserted at a point along the vertical at the edge of the model. The path followed by the water as it flowed through the sand toward the drain was traced by the dye.

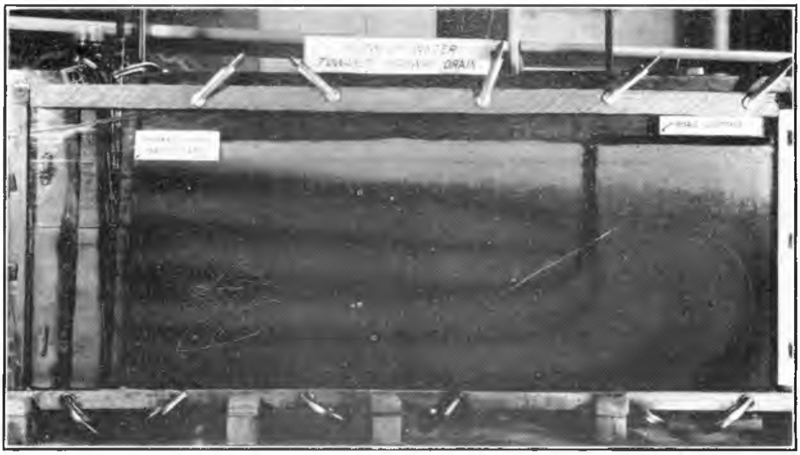

Fig. 1. Photograph of sand model used in determining flow lines of ground water towards subdrain at edge of pavement.

The different conditions investigated are described separately, and the results obtained for each case are shown by the figures. A model scale of one inch equals one foot was used for each of these conditions.

Case 1. The model was constructed to represent a typical cross-section in which the terrain is flat and the ground-water table located at approximately one foot below the ground surface. In such a case the problem is to lower the water table so that the moisture content of the soil beneath the roadway will be reduced and controlled. The right-hand edge of the model was taken as the centerline of the roadway. A 20-foot pavement was used. The drain was located 7 feet below the edge of the pavement and consisted of an 8-inch perforated pipe placed in a one-foot-wide trench and backfilled with coarse material. The ground-water level was maintained constant at the left side of the model at one foot below the elevation of the road surface. The photograph (Fig. 1) shows the lines traced by the dye as it moved through the sand toward the drain. While not shown in the figure, the free water surface beneath the centerline of the roadway was at a depth of approximately 4½ feet.

Case 2. This model treated the same problem as that outlined in Case 1. The terrain was flat; the ground-water table was one foot below the surface of the roadway. However, in this case the material above the drain was the same as the surrounding soil. Fig. 2 is a sketch showing the results obtained from this model. The line of wetted sand can be seen in this figure and is approximately 6 feet below the road surface at the centerline. This line represents the top of the zone of capillary saturation and not the surface of free water.

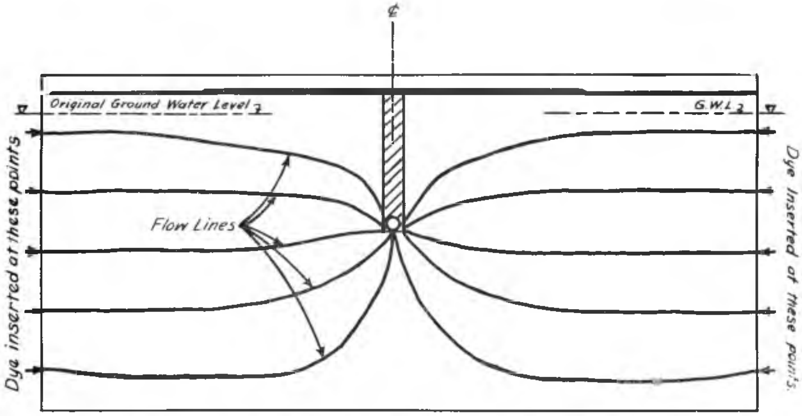

Fig. 2. Drain at centerline of roadway. Flat terrain—high ground-water table. Eight-inch perforated pipe—backfill same as surrounding soil. Bottom of pipe is 6 feet below ground-water level.

While the thickness of the zone of capillary saturation varies for different types of soils, the surface of the free water will theoretically assume the same shape and height regardless of the soil type.

Case 3. The model for this case was designed to investigate the effect of a single drain placed at the centerline of the roadway. The terrain, as in Cases 1 and 2, was flat and the ground water table one foot beneath the surface. The drain was placed 7 feet below the road surface and backfilled with coarse material. The ground-water elevation was maintained constant at both ends of the model. Water flowed from both sides toward the drain. The flow lines traced by the dye are shown in Fig. 3. It will be noted that at the edge of the pavement the ground water elevation was lowered about 1½ feet.

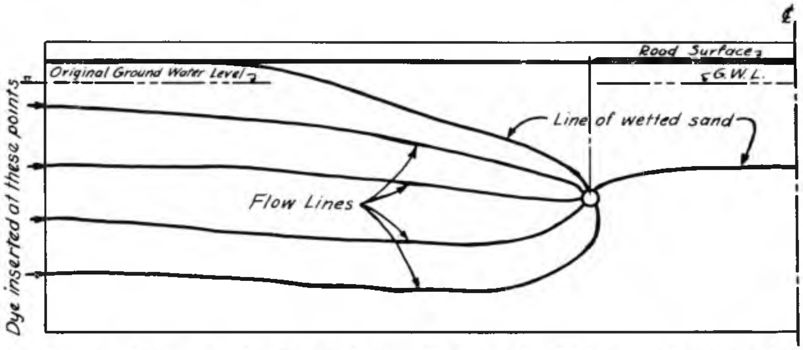

Fig. 3. Drain at edge of roadway. Flat terrain—high ground-water table. Eight-inch perforated pipe below edge of roadway. Backfill same as surrounding soil. Bottom of drain 5½ feet below ground-water level.

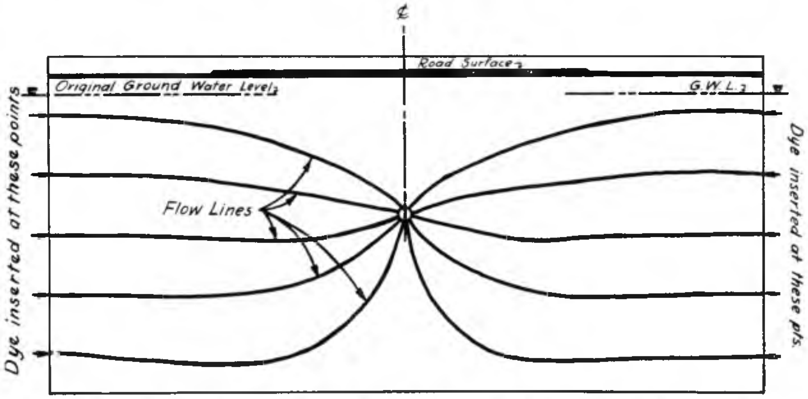

Fig. 4. Drain at centerline of roadway. Flat terrain—high ground-water table. Eight-inch perforated pipe laid in 1-foot wide trench. Backfilled with coarse material (all retained on No. 10 sieve). Bottom of pipe is 6 feet below ground-water level.

Case 4. This model differed from that used in Case 3 only in that the backfill material was the same as the surrounding soil. The drain was again placed 7 feet below the road surface. It will be noted in Fig. 4 that the flow lines around the immediate vicinity of the drain are somewhat lower than for Case 3. Under the edge of the pavement, however, the amount of drawdown for the two cases is approximately the same—1½ feet.

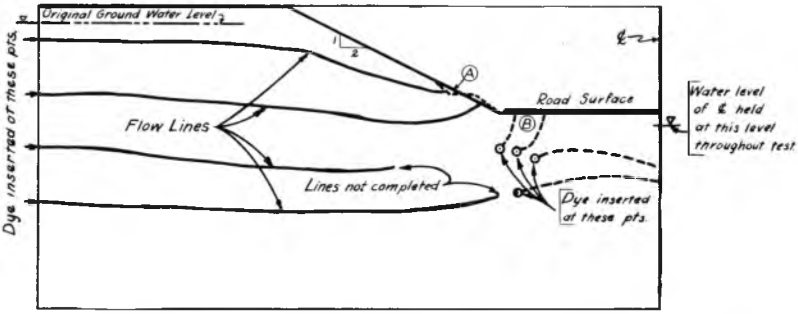

Fig. 5. Cut section—no drain. Water level on left was maintained at 5 feet above the roadway. Water level on right was maintained at 1 foot below the roadway. Uppermost flow line intersected the slope at A. Flow coming up under the roadway at B.

Case 5. This case consisted of a cut section in which the original ground-water level was high. The slope of the cut was one on two. The model was designed for the purpose of investigating the conditions of flow when there was no drain. It was necessary to assume that the elevation of the water table under the centerline of the roadway would be at a depth of one foot below the surface. This was accomplished by having an overflow pipe at this point in order that the water could leave the model. Fig. 5 shows the results obtained. It is interesting to note that the two uppermost flow lines intersect the slope of the cut and that the soil at these points of intersection was "fluffed" away. This checks very closely the condition occurring in the field. Another observation of interest is the direction of flow at point (B) as shown in the figure. Here the flow is almost vertical and comes up under the pavement. In such a condition the subgrade is not only subjected to an excessive amount of water but also to the dynamic force of the flowing water. In some soils this force may be of such a magnitude as to cause the material to act as a "quicksand" and become very unstable. This effect is often noticed in the construction of cuts through silty soils.

Case 6. The effect of placing a drain at the toe of the slope described in Case 5 was investigated. The bottom of the drain was 3½ feet below the road surface, and the trench in which it was placed was backfilled with coarse material. The road surface was 5 feet below the original ground-water elevation.

Fig. 6 shows the results obtained by this model. The drain affected the uppermost flow line, and prevented it from intersecting the face of the cut as in Case 5. From observations it was noted that about one foot of material under the road was above the free water zone.

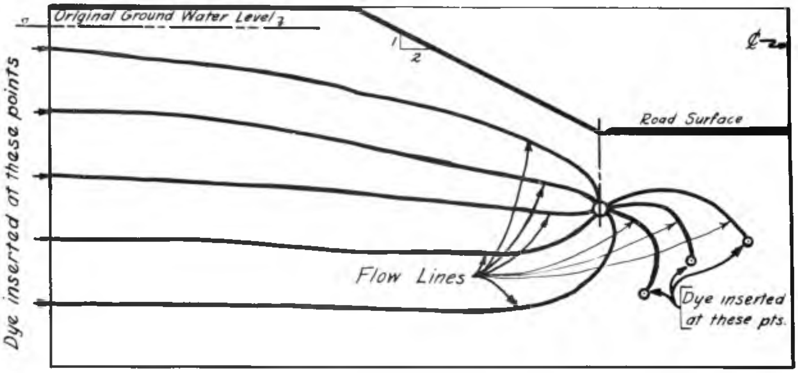

Fig. 6. Cut section—drain below toe of slope. Eight-inch perforated pipe—backfill same as surrounding soil. Bottom of pipe is 3½ feet below toe of slope. Road surface is 5 feet below original ground-water level.

Case 7. This case differs from Case 6 only in that the backfill material above the drain was the same as the surrounding soil. The uppermost flow line is farther inside the slope than Case 6 (about 2 feet against 1½ feet). The depth to the free water surface beneath the pavement was about 2 feet. It should be noted (Fig. 7) that the water beneath the pavement also flows toward the drain and does not tend to come to the surface as in Case 5. As mentioned previously, such installations as described in this Case 7 may not be suitable if conditions are such that seepage planes and water-bearing strata need to be intersected.

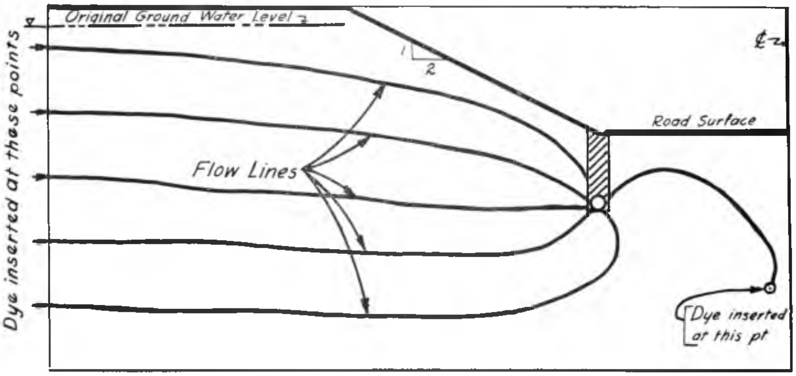

Fig. 7. Cut section—drain below toe of slope. Eight-inch perforated pipe laid in 1-foot wide trench. Backfilled with coarse material. (All retained on No. 10 sieve.) Bottom of pipe 3½ feet below toe of slope. Road surface 5 feet below original ground-water level.

DISCUSSION OF RESULTS

Under the conditions specified in these model studies it appears that the placement of a coarse backfill over the drain is of little advantage. In fact, the draw-down of the groundwater table seems to be more complete in the cases where the material directly over the drain is the same as the surrounding soil. This statement is made as an observation from the models and may not under all conditions be the most advantageous for actual practice. In a field installation the soil may not be homogeneous, and a large percentage of the total quantity of water entering the drain may be flowing through the more pervious portions of the soil mass. In such a case the porous backfill will act as an interception medium which will conduct the water to the drain and would probably be more efficient than a drain backfilled with native material.

The models showed that a drain placed at each side of the pavement is more effective than placing a single drain beneath the centerline of the roadway. A field condition in which the soil is composed of alternate layers of pervious and impervious material would increase the advantage of the two drains. However, if for reasons of economy only one drain is to be used, then the most effective location is at the centerline, since two drains are not twice as effective as one drain.

The models of the cross-section of a cut section show clearly the advantage of placing a drain at the toe of the slope. In the case where no drain was provided, the water outcropped on the face. Such seepage, as the model shows, causes the soil to "sluff" away. In the field, such conditions would increase maintenance cost and, unless checked, might endanger the entire slope. The placement of a drain at the toe of the slope draws the free water within the soil mass so that it no longer intersects the slope. The elimination of the upper flow of water beneath the pavement is also very important.

While many of the observations made on the models to date are too general to have any direct application, it is believed that they, supplemented by the results of models to be run in the future, will present a visual solution of basic typical problems.

TRAFFIC PAINT STUDIES

W. H. Goetz,
Research Chemist, Joint Highway Research Project,
Purdue University

In 1911 Mr. Edward Hines, then Road Commissioner of Wayne County, Michigan, originated the painted centerline for