A SIMULATION MODEL FOR RAINFALL INFILTRATION, DRAINAGE ANALYSIS, AND LOAD-CARRYING CAPACITY OF PAVEMENTS

Shang J. Liu

Robert L. Lytton

Texas Transportation Institute

Texas A&M University System

August 1983

ABSTRACT

The rate of deterioration of pavements nationwide has reached significant and, in some cases, alarming proportions. One of the major causes of deterioration is the effect of water in pavements. Traffic loads act on water trapped in base courses and subgrades to cause rutting, pumping, alligator cracking, and other major forms of pavement distress. The proper drainage of base courses can prolong, and in some cases, double the life of a pavement.

This report presents a method of computing the amount of rain water that penetrates into a pavement through cracks and joints, and subsequently the rate of drainage out of the base course into the subgrade and into lateral drainage. The method presented is a major advance over methods that have been used previously for the same purpose.

The method consists of five parts: (1) estimation of the amount of rainfall that falls each day on a pavement; (2) the infiltration of water through the cracks and joints in the pavement; (3) computing the simultaneous drainage of water into the subgrade and into lateral drains; (4) the dry and wet probabilities of a pavement; and (5) effect of water saturation on load-carrying capacity of base course and subgrade.

A gamma distribution is employed for describing the probability density function for the quantity of rain that

falls and a Markov chain model is applied for estimating the probabilities of wet and dry days.

Infiltration of water into the pavement cracks and joints uses either Ridgeway's rate of infiltration of water through cracks and joints, which was determined in the laboratory, or the regression equations of Dempsey and Robnett which were developed from field measurements, in estimating the amount of free water entering the pavement base course.

A new method has been developed for computing the drainage of the pavement base and subgrade. Models employing a parabolic phreatic surface and allowing drainage through a permeable subgrade are developed, which generally give better agreement with field data from observations on full scale pavements than the classical model described by Casagrande and Shannon. That model assumes a straight line phreatic surface and an impermeable subgrade.

A recurrence relation for computing probabilities associated with the Markov chain model for dry and wet days, incorporated with the gamma distribution, and the analysis of infiltration of water into the pavement and subsequent drainage is applied to estimate the dry and wet probabilities of the base courses.

The systematic prediction of the degree of free water saturation in the base courses each day is performed by combining into the analysis of the distribution of rainfall amount, the probabilities of wet and dry days, infiltration of water into the pavement, the drainage time of the base courses, and dry and wet probabilities of the weather and pavement sublayers.

The effect of saturation on the resilient modulus of the base course and the subgrade are calculated using relations presented by Haynes and Yoder, and Thompson and Robnett, and these may be used in the prediction of critical stresses and strains in a pavement to determine the amount of traffic it can be expected to carry throughout its useful life.

ACKNOWLEDGEMENTS

This research report has been funded by the Federal Highway Administration and a subcontract from the University of Illinois at Urbana. The authors gratefully acknowledge the support received from these sources.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented within. The contents do not necessarily reflect the official views of policies of the Federal Highway Administration. This report does not constitute a standard, a specification or regulation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

Pavement engineers and road builders have been aware for a long time that excess water remaining in base courses and subgrades will accelerate the deterioration and destruction of pavements. As the water content of base courses and subgrades increases, there is a significant reduction in load bearing capacity and modulus and an acceleration of unsatisfactory pavement performance, as manifested in premature rutting, cracking, faulting, pumping, increasing roughness, disintegration of stabilized materials, and a relatively rapid decrease in the level of serviceability. In estimating the long-term performance of pavements and in designing pavements to endure the effects of the local climate, it is essential to be able to estimate the effect of rainfall on the modulus of the base course and subgrade. This paper describes a comprehensive means of making such estimates and gives the results of example calculations.

This subject of base course drainage has received considerable attention over the last three decades. In 1951, Casagrande and Shannon (1) developed models for drainage analysis and made field observations on several airfields in the United States to determine the environmental conditions under which base courses may become saturated. Most of the observations were limited to two principal causes for the saturation of base courses: frost action and infiltration through the surface course. At six airfields, in Maine, Wisconsin, Michigan, North Dakota, and South Dakota, detailed observations were made, by Casagrande and Shannon (1), of groundwater levels in the subgrade in the base course beneath both concrete and bituminous pavements. The discharge through the base-course drainage pipes was also monitored at those fields. Based on their observations, they concluded that during the thawing period, ice segregation in a subgrade may be the cause of saturation of an overlying, free-draining base. It was also concluded that infiltration of surface water through pavement cracks, or joints, may cause saturation of a free-draining base overlying a relatively impervious subgrade. Other causes for the saturation of bases may be inundation of the pavement in an area that might be subject to flooding during certain times of the year, or where the natural water table may rise above the bottom of the base course.

One cause of excess moisture content in the pavement, mainly due to climatic conditions, is rainfall infiltration through cracks and joints. Methods for estimating the amount of rainfall and subsequent water infiltration through cracks and joints have been developed by Cedergren (2) and Markow (3), both of whom mention the lack of adequate field observation data on this subject. Markow simulated pavement performance under various moisture conditions by incorporating the amount of unsealed cracking in the pavement surface, the seasonal rainfall, and the quality of subsurface drainage into the modeling. He also pointed out that in pavements subjected to rainfall infiltration, three periods associated with wet weather can be distinguished:

1. the time during which rain is falling, in which the pavement sublayers may or may not be saturated;
2. the time during which the sublayers are saturated or sufficiently wet to affect material properties and structural behavior; and
3. the time during which any residual water not sufficient to affect pavement behavior is drained off.

Nevertheless, in Markow's model, in order to simplify the derivation of the models, only the second period above was considered, i.e., the period during which the pavement is significantly wet or saturated to effect material properties and structural behavior. The model is used in the EAROMAR system, which is a simulation model of freeway performance used by the Federal Highway Administration in conducting economic analyses of various strategies of roadway and pavement reconstruction, rehabilitation, and maintenance. As a conservative estimate, during the time required to drain 80% of the water from a saturated sublayer, the sublayer modulus was considered to be reduced in value by 50%.

As used to estimate the change of the elastic modulus of base course materials due to water entering the base course through cracks and joints in the pavements, the EAROMAR equation is

$$t_{wet} = (\gamma_{season}/i_{avg})[1-\exp(-9c)]t_{drain} \qquad (1\text{-}1)$$

$$c = (1/5280)\{[(L_c+A_c)/W_{lane}]+[(SH \times W_{wet})/2W_{lane}N_{lane}]+(J \times W_{wet})\} \qquad (1\text{-}2)$$

$$F_{red} = (t_{season}-0.5t_{wet})/t_{season} \qquad (1\text{-}3)$$

where t_{wet} = duration of pavement wetness in days during which structural response is assumed to be affected;

γ_{season} = seasonal rainfall in inches input by the user;

i_{avg} = daily rainfall intensity, assumed to equal 0.5 in (12.7 mm);

c = fraction of pavement area having cracks or open (unsealed) joints;

t_{drain} = time in days to drain the saturated pavement sublayers;

L_c, A_c, SH, J = quantities of damage components per lane mile computed by pavement simulation models within EAROMAR; L_c, SH, and J are the linear feet per lane mile of longitudinal cracks, lane-shoulder joints, and transverse joints; A_c is the area of alligator cracking in square feet per lane mile;

W_{lane}, N_{lane} = width of lane in feet and number of lanes in roadway, respectively, as input by user;

W_{wet} = width of subsurface zone wetted by open joint, assumed to be 6 ft (1.8 m);

F_{red} = reduction factor applied to moduli of granular pavement layers and to California bearing ratio (CBR) and moduli of subgrade;

t_{season} = length of season in days determined from season information input by user; and

t_{drain} is evaluated from Casagrande-Shannon's drainage model (1) to be approximately

$$t_{drain} = 2.5nL^2 \exp(-2S')/KH \qquad (1\text{-}4)$$

where n = effective porosity of the base course,

L = the width of the base course,

K = the permeability of the base course,

H = the thickness of the base course, assumed to be 1 foot, and

S' = an approximate slope factor, assuming a cross slope of 1/2 inch per foot (0.015 ft/ft).

Equation 1-3 applies a time-average correction to the pavement materials properties. Multiplication by 0.5 in Equation 1-3 reflects the assumed loss in material strength under wet condition.

Equation 1-3 is composed of three factors: (1) the number of days in a season on which rainfall occurs, γ_{season}/i_{avg}; (2) the proportion of rainfall flowing into the base courses, 1-exp(-9c); and (3) the period of time over which the structural response is reduced to its 50% level (t_{drain}). These three factors are multiplied together in that equation and give the total amount of time (t_{wet}) when the base courses are at least 20% saturated. Briefly, the time, in days, that a base course is in such a wet situation is equal to the number of wet days in a season multiplied by the time required to drain 80% of water, where the proportion of infiltration is taken into consideration. The following assumptions are implied.

1. The amount of water inflow into the base courses is a negative exponential function of rainfall quantity. This equation is derived from the data provided by Cedergren (2).
2. The length of the wet period, t_{wet}, is linearly related to the time required to drain 80% of the water from the sublayer.
3. The drainage analysis is approximately based on Casagrande and Shannon's model (1). (See Chapter 4).

4. Every rainy day has the same effect on a base course.
5. Dry days are subsequent to wet days which are equally spaced in time.
6. The degree of 80% drainage is a critical point for the elastic moduli of the base courses. Before 80% of drainage is completed, the moduli are reduced to 50%. After 80% of the water has drained out of the base course, there is no effect on the elasticity of the base course.

Nevertheless, certain modifications to Markow's model should be made for a more realistic and more theoretically correct approach, especially when Assumptions 3 to 6 are considered.

For lateral free drainage, in the Casagrande-Shannon model of base-course drainage (1), the analysis which has been commonly applied, a linear free water surface is assumed. This assumption is not consistent with the theoretical approach derived by Polubarinova-Kochina (4), which suggests that a parabolic phreatic surface would yield more realistic results for drainage calculations. Also a permeable subgrade, which in fact exists in the pavement structure is not taken into account by the Casagrande-Shannon model.

So far as the rainfall period and probability are concerned, Markow's model does not consider the distribution of rainfall amount and does not consider wet and dry day probabilities adequately, i.e., not every rainy day would saturate the base course and dry days following each rainy day do not divide the weather sequence realistically. In addition, in evaluating the deterioration of pavements, it is more realistic to allow the elastic moduli of the base course and subgrade to vary continuously with water content, than to assume simply that up to 80% drainage the base course modulus is half of its dry value, which is done in Markow's model.

In this report, a stochastic model is used for a systematic analysis of rainfall infiltration, drainage, and estimation of the material properties of base course and subgrade. The report describes a model consisting of five main parts: (1) estimation of the amount of rainfall that falls each day on a pavement; (2) the infiltration of water through the cracks and joints in the pavement; (3) computation of the simultaneous drainage of water into the subgrade and into the lateral drains; (4) dry and wet probabilities of the weather and pavement sublayers; and (5) the effect of water saturation on the load-carrying capacity of base courses and subgrades. Ground water sources and the side infiltration from the pavement shoulders are not considered in this report.

CHAPTER 2 MODELS OF RAINFALL DISTRIBUTION AND FREQUENCY ANALYSIS

In order to estimate the quantity of rainfall that falls on a specific pavement and eventually enters the cracks and joints of that pavement, it is necessary to establish three items of information concerning the local rainfall patterns.

1. The quantity of rain that falls in a given rainfall. The total quantity in each rainfall varies from one rainfall to the next but historical records show that the quantity follows a probability density function.
2. The intensity and duration of each rainfall.
3. The random occurrence of sequences of wet and dry days.

The methods that are used in estimating these quantities are described in the following subsections.

2.1 PROBABILITY MODEL OF QUANTITY OF RAINFALL

Applications of new techniques such as stochastic processes, time series analysis, probabilistic methods, systems engineering, and decision analysis, have been propounded and developed as mathematical and statistical methods in hydrology and water resources engineering through the past few decades.

Many climatologists and statisticians have been engaged in the systematic accumulation of various climatic data and weather records for a long period and analytical distribution models which fit the observed distributions well were proposed.

Several theoretical probability distribution models of the total quantity of precipitation in a single rainfall have been presented in statistical climatology (5). These include the Gamma, hypergamma, lognormal, normal, kappa types, Pareto, one-sided normal as well as the queuing process modeling. However, some of them are applied to fit specific situations. For example, the lognormal distribution model is often used for the amount of precipitation for short time intervals caused by such factors as cumulus clouds or weather modification experiments. Some of these model types are rather complex and are of more theoretical interest than they are for useful applications; for example, the hypergamma distribution proposed by Suzuki in 1964 (6) fits in this category.

The Gamma distribution has a long history of being used as a suitable theoretical model for frequency distributions of precipitation (7). Due to the fact that it has been well accepted as a general model as well as a fairly practical method, the Gamma distribution is selected to represent the distribution of the quantity of rainfall.

The mathematical expression and the estimation of parameters are listed in the Appendix A.

2.2 MODELS OF INTENSITY AND DURATION OF RAINFALL

Hydraulic engineers are concerned mainly with the analysis of annual rainfall and runoff records for trends and cycles. Most records of rainfall and runoff can be generalized with fair success as arithmetrically normal series and somewhat better as geometrically normal series (8).

Storms and floods vary spatially and temporally in magnitude and are often characterized through their peak discharges. Moreover, the frequency of occurrence, the maximum stage reached, the volume of flood water, the area inundated and the duration of floods are of importance to civil engineers when planning and designing roads, buildings and structures.

The rainfall intensity-duration-return period equation (9,10) has often been expressed by formulas such as

$$i = \frac{c}{t_R + b} \tag{2-1}$$

and

$$i = \frac{k t_p^{\,x}}{t_R^{\,n}} \tag{2-2}$$

where t_R = the effective rainfall duration in minutes,

t_p = the recurrence interval in years,

i = the maximum rainfall intensity in inches per hour during the effective rainfall duration, and

c,b,k,x,n = functions of the locality, for example, it was found that in the eastern United States, n averaged about 0.75 and that x and k were about 0.25 and 0.30, respectively (9,11).

In order to apply the infiltration rate of free water infiltrating into the base course from Ridgeway's model, which will be described in Chapter Three, the relation between the rainfall duration and the quantity of rainfall should be constructed.

The unit hydrograph is a hydrograph with a volume of one inch of runoff resulting from a rainstorm of specified duration and areal pattern. Most of the storms of like duration and pattern are assumed to have the same shape which is similar to the Gumbel distribution. The Gumbel distribution, which is referred to as a double-exponential distribution function, is frequently used as a model for the estimation of floods in extreme value theory (5). The difference of curve shape between the Gumbel function and normal distribution is that the former is skewed to the right and the latter is symmetric (Figure 1). Nevertheless, because of the advantage of using a standard normal curve, a well-known distribution and all the characteristics provided, the normal distribution is used instead of the Gumbel distribution as a starting point for deriving the equation of the relationship between rainfall duration, t_R, and the quantity, R (Figure 1). Moreover, the deviation between these two functions is fairly small for practical purposes.

The equation relating the duration of rainfall and its quantity is derived as (Appendix A-2)

$$t_R = \left(\frac{1.65R}{kt_p^{\ x}}\right)^{\frac{1}{1-n}} \qquad (2\text{-}3)$$

2.3 FREQUENCY MODELS OF RAINFALL - MARKOV CHAIN METHOD FOR ESTIMATING DRY AND WET PROBABILITIES

Several methods of estimating the probability distributions of the lengths of sequences of dry days and of wet days on which the quantity of precipitation is greater than 0.01 inch have been used in a variety of weather-related research fields.

Gabriel and Neumann (12) studied the time sequence of weather situations which may be classified into either dry

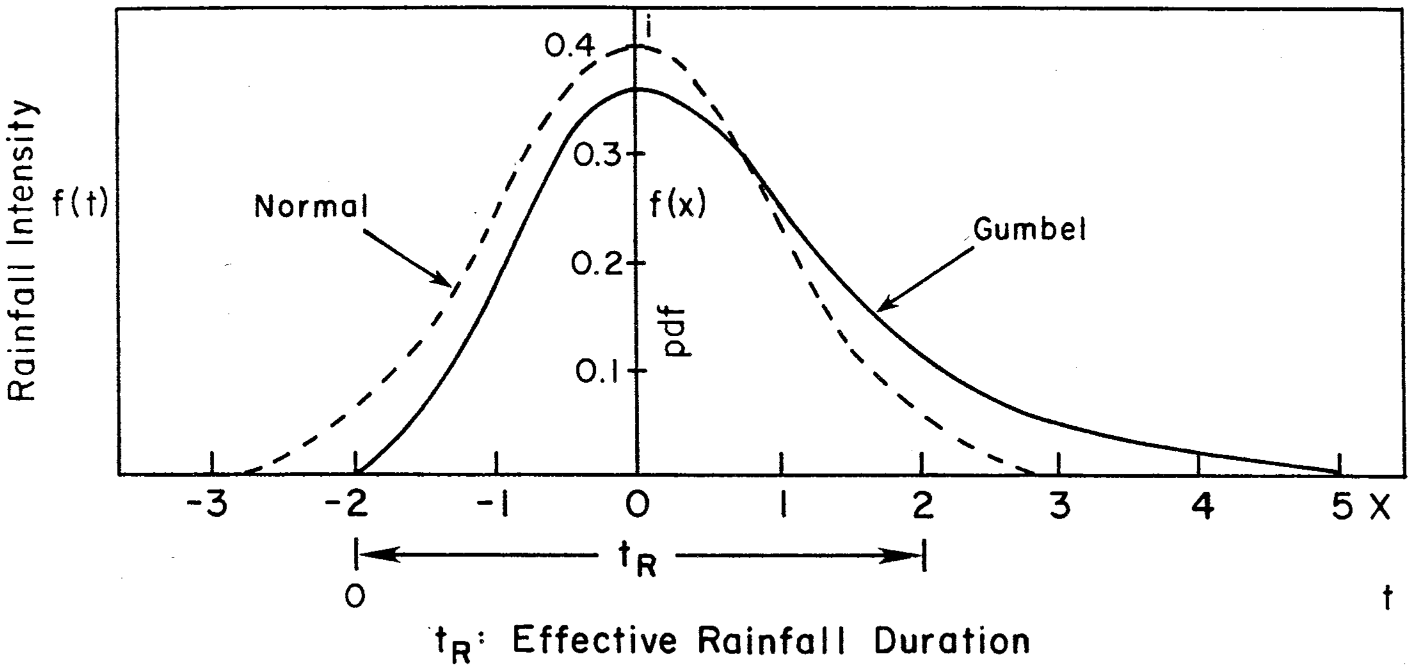


FIGURE 1. Comparison of Normal and Gumbel Distributions (5)

or wet days. They derived the probability distribution for the length of a weather cycle and proposed a probability model in the form of a Markov process of order one.

Several related models have been proposed, e.g. higher orders of Markov chain exponential model (7). However, the Markov process has been regarded as the basic general method. In order to simplify the modeling, the first order Markov chain model was selected as an estimation of the rainfall occurrence probability.

The Markov chain method is one of the techniques of modeling random processes which evolve through time in a manner that is not completely predictable. The Markov process is a stochastic system for which the occurrence of a future state depends on the immediately preceding state and only on it. This characteristic is also called the Markovian property.

A transition probability matrix, $[p_{ij}(t)]$, generated from the Markov chain method is used for predicting weather sequences; where p_{ij} represents the probability that the Markovian system is in state j at the time t given that it was in state i at time Ø. Therefore, the probability of having a dry day at time t when time Ø is a wet or dry day or vice versa, can be calculated from the Markov chain method.

Associated with the Markov chain model, a recurrence relation for computing the probabilities of dry and wet days was applied by Katz (13). Application of Katz's equations to the Markov chain model results in finding the probability of having certain number of wet or dry days during a specific period. In this simulation model, emphasis is put on estimating the probabilities of having certain consecutive dry days for draining the corresponding amount of water out of a base course, which is illustrated in Section 6.2. The Markov chain model and Katz's equations are formulated and delineated in Appendix A-3.

An example of the probabilities of having k wet days in 5 consecutive days is listed in Table 1. Based on the data of May, 1970 from the Houston Intercontinental Airport, the probability of having 5 consecutive dry days is 0.264, that of having one wet day is 0.301, of having two wet days is 0.236, etc.

In summary, the Gamma distribution is employed for the rainfall quantity probability density function, the Markov chain and Katz's recursive model are applied to evaluate the probabilities of having dry and wet days, and Equation 2-3 is used to estimate the duration of rainfall. The Gamma distribution leads to an estimate of the distribution of the amount of rainfall which falls on a pavement. Estimation of rainfall duration is used for evaluating the total amount of precipitation that infiltrates into the base, and the Markov chain method and Katz's recursive model are adopted for computing the probabilities of having dry periods during

TABLE 1. KATZ'S MODEL FOR COMPUTING THE WET PROBABILITIES ASSOCIATED WITH MARKOV CHAIN MODEL

(DATA FROM HOUSTON INTERCONTINENTAL AIRPORT FOR MAY, 1970)

N	k	$W_0(k;5)$	$W_1(k;5)$	$W(k;5)$
5	0	0.290	0.199	0.264
5	1	0.305	0.290	0.301
5	2	0.228	0.257	0.236
5	3	0.121	0.161	0.133
5	4	0.045	0.072	0.053
5	5	0.010	0.021	0.013

$P_0=0.71$ $P_{00}=0.78$ $P_{01}=0.22$ $P_{10}=0.54$ $P_{11}=0.46$

N = Number of consecutive days

k = Number of wet days

W_0 = Wet probabilities when zeroth day is dry

W_1 = Wet probabilities when zeroth day is wet

W = Probability of having k wet days in 5 consecutive days

P_{ij} = Transitional Probabilities from Markov Chain Model

P_0 = Initial wet probability

which a pavement can drain out all of the excess water. These results are used for further analysis, as described subsequently.

CHAPTER 3 INFILTRATION OF WATER INTO A PAVEMENT THROUGH CRACKS AND JOINTS

Studies have indicated that the performance life of pavements can be extended by improved protection from water infiltration and drainage of the structural section. Moisture control in pavement systems can be classified as the prevention of water infiltration and the drainage system design. Ridgeway (14), Ring (15), Woodstrom (16), Barksdale and Hicks (17), and Dempsey *et al* (18) all conducted studies on the problem of water entering pavements through cracks and joints. Darter and Barenberg (19) as well as Dempsey and Robnett (20) reported that the appropriate sealing of joints and cracks can help pavement performance by reducing water-related distress due to water infiltration.

Ridgeway (14), Barksdale and Hicks (17), and Dempsey and Robnett (20) conducted research in determining the amount of water entering pavement structures. In this report, Ridgeway's laboratory studies and Dempsey and Robnett's field observations are selected as the basis for the analytical model presented herein.

3.1 LABORATORY STUDIES

Ridgeway (14) made measurements in Connecticut of free water infiltration rates on portland cement concrete and bituminous concrete pavements using several methods. He proposed that the amount of water entering the pavement structure through the cracks or joints depends on (1) the water carrying capacity of the crack or joint; (2) the amount of cracking present; (3) the area that will drain to each crack or joint; and (4) the rainfall intensity and duration.

In Ridgeway's laboratory results, he presented the infiltration tests on bituminous concrete pavements and portland cement concrete pavements, as well as the design criteria for drainage. He also concluded that:

(1) The cracks and joints of pavements are the main path for free water, because both portland cement concrete and asphalt concrete used in a pavement surface are virtually impermeable;

(2) The design of a pavement structure should include means for the removal of water flowing through the pavement surface;

(3) Rainfall duration is more important than rainfall intensity in determining the amount of free water that will enter the pavement structure; and

(4) An infiltration rate of 0.1 ft^3 per hour per linear foot of crack (100 $cm^3/hr/cm$) can be used for design purposes.

In the analysis, the following average infiltration rates are chosen for cracks in bituminous concrete pavement, 100 cm^3/hr/cm of crack (0.11 ft^3/hr/ft or 2.64 ft^3/day/ft), and for cracks and joints in portland cement concrete pavements, 28 cm^3/hr/cm of crack or joint (0.03 ft^3/hr/ft or 0.72 ft^3/day/ft).

As Ridgeway (14) indicated in one of his conclusions, the duration of rainfall is even more important than the intensity of rainfall in estimating the amount of free water entering the pavement system. The calculation of rainfall duration is formulated in Equation 2-3, and the appropriate derivations are listed in Appendix A-2.

3.2 FIELD OBSERVATIONS

Dempsey and Robnett (20) conducted a study to determine the influence of precipitation, joints, and sealing on pavement drainage for concrete in Georgia and Illinois. Subsurface drains were installed and all drainage outflows were measured with specially designed flowmeters. The rainfall data were obtained from the nearby weather stations.

From their field observations, they used regression analysis to determine the relationship between the amount of precipitation and the outflow volumes. They concluded that (1) significant relationships were found between precipitation and drainage flow; (2) drainage flow is influenced by pavement types; (3) edge-joint sealing, in most cases, significantly reduced drainage outflow; (4) no measurable drainage outflow occurred in some test sections when all joints and cracks were sealed.

The regression equations are obtained from their field studies for both sealed and unsealed conditions in the test area. In order to make a conservative evaluation of infiltration through cracks and joints, the highest regression coefficient from one of the linear regression equations, which is measured under the unsealed condition, is chosen. The resulting equation is,

$$PO = 0.48PV + 0.32 \quad (3\text{-}1)$$

where PO = Pipe outflow volume (m^3) and

PV = Precipitation volume (m^3)

Nonetheless, Dempsey and Robnett (20) pointed out that the infiltration rates predicted by their regression analyses were considerably less than those estimated using Ridgeway's laboratory tests. In the simulation model in this report, Ridgeway's model is furnished as an analytical tool if data on the length of cracks and joints are provided by a user. If no data for cracks and joints is provided, the alternative is to use Dempsey and Robnett's model to estimate the free water amount for the pavements where the cracks and joints are not sealed.

3.3 LOW PERMEABILITY BASE COURSES

The preceding analyses of base drainage assume that the free water penetrates into the base course instantaneously, which will be an inadequate assumption for water infiltrating into a very low permeability base course. A low permeability base, dependent on the characteristics of the soil properties, generally has differential permeabilities in horizontal and vertical directions. In addition to that, the drying process relies on the rate of evaporation of water through cracks and joints both when the water is stored in cracks and when the water is in the base. The amount of evaporated water from cracks and joints can be estimated by the local evaporation rate, and the water evaporated from the base can be determined by solving the diffusion equation. The process of rainfall infiltration into the base and drying out is shown in Figure 2. However, for a conservative estimate, the amount of evaporated water from cracks and joints is considered zero, which is applied in the following analysis as well as in the computer programming.

3.3.1 Water Entry into Low Permeability Bases

Free water flows into the cracks and joints of the pavement then penetration into the base course is assumed to diffuse with an elliptical wetting front. The elliptical shape is caused by the difference in the coefficients of permeability in the vertical and horizontal flow directions, which is normally the result of compaction. It is usually easier for water to flow horizontally than vertically through a soil.

1. Dry Period

2. Rain Falls

3. and 6. Penetration of Rainfall into Base Course and Evaporation (EV) from Cracks/Joints

4. Evaporation from Bases

5. Rain Falls Before Base is dry

6. Repeat Stage 3

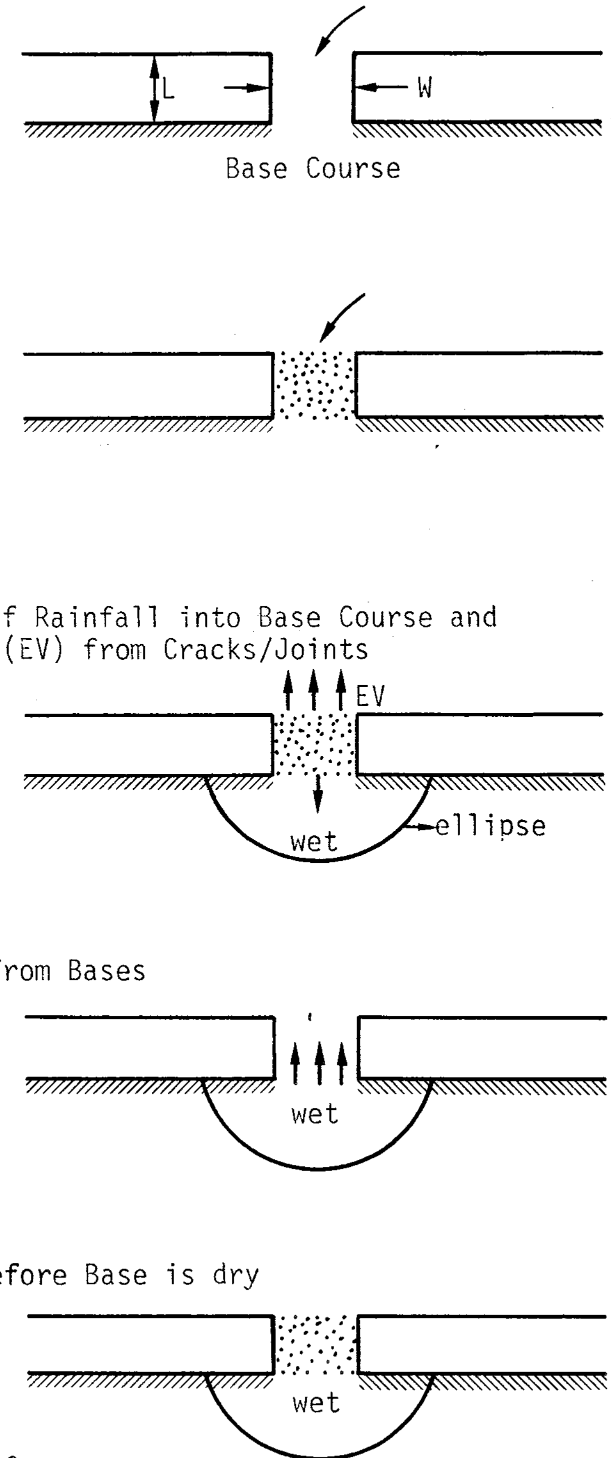


FIGURE 2. Rainfall Infiltration and Evaporation through Cracks and Joints in a Low Permeability Base

The wetting front of water in the horizontal direction and the vertical direction are (Appendix D-1):

$$x_0 = w \frac{2d\ell}{\pi} \frac{kh}{kv} \quad \text{, and} \tag{3-2}$$

$$y_0 = w \frac{2d\ell}{\pi} \frac{kv}{kh} \tag{3-3}$$

where x_0 = the x-coordinate of the wetting front in the horizontal direction,

y_0 = the y-coordinate of the wetting front in the vertical direction,

kh = the horizontal coefficient of permeability,

kv = the vertical coefficient of permeability,

w = the width of cracks or joints, and

ℓ = the depth of cracks or joints.

3.3.2 Water Evaporation from the Base Course

Water evaporation from a soil sample, i.e., the diffusion of moisture through a soil, proceeds from a state of low suction to a state of high suction. The differential equation governing the suction distribution in the soil sample is termed the diffusion equation. The rate of water evaporation from a soil can be determined by obtaining the solution from the Diffusion Equation and making the solution fit the appropriate boundary and initial conditions for this partial differential equation.

The general form of the diffusion equation is (21),

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 y}{\partial z^2} + \frac{f(x,y,z,t)}{ku} = \frac{1}{k}\frac{\partial u}{\partial t} \qquad (3\text{-}4)$$

where u = total suction expressed as a pF,

ku = the unsaturated coefficient of permeability,

k = diffusion coefficient,

t = time, and

x,y,z = the directional coordinates.

The analytical solution utilized in this report is only one dimensional and no sink or source is considered. That is to say, the equation is simplified to be

$$\frac{\partial^2 u}{\partial y^2} = \frac{1}{k}\frac{\partial u}{\partial t} \qquad (3\text{-}5)$$

As an initial condition of this problem, it is assumed that suction is constant throughout the soil. The boundary conditions used are to have evaporation into the atmosphere from the open end of a sealed sample. The determination of water evaporated from the base is outlined in Appendix D-2.

An example result is listed in Appendix E-2, where the computer program and output are employed to illustrate the water infiltration and evaporation through the cracks or joints of a low permeability base course.

CHAPTER 4 DRAINAGE OF WATER OUT OF BASE COURSES

Excess water in the base course and subgrade significantly influences the performance of pavements. The design of highway subdrainage requires a proper analysis of the drainage characteristics of base course and subgrade as indicated in Figure 3.

4.1 CASAGRANDE AND SHANNON'S METHOD

The subject of base course drainage has received considerable attention over the last three decades. Casagrande and Shannon (1) made field observations on several airfields in the United States to determine the environmental conditions under which base courses may become saturated. They performed a simplified theoretical analysis of the base course drainage. They assumed symmetry along the axis of the pavement and the equations governing drainage for one half of the cross section of the base course layer ABCD (See Figure 4) were developed. In their analysis, the drainage process was divided into two parts. In the first part shown in Figure 4, the free surface gradually changes from position CD to CA due to free drainage through the open edge CD of the pavement. Darcy's Law and the continuity equation were satisfied to establish a relation among time, t and x(t) in terms of H, L, , k_1, and n_1 as illustrated in Figure 4. In the

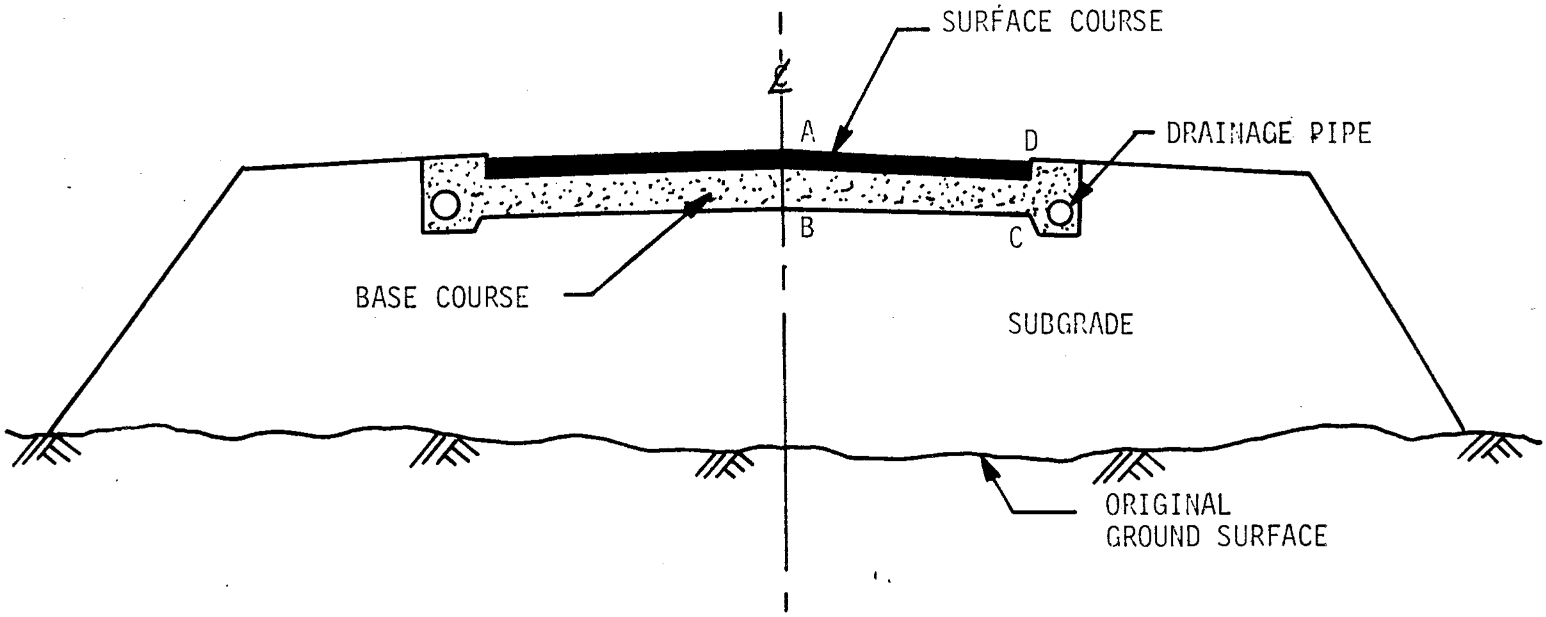
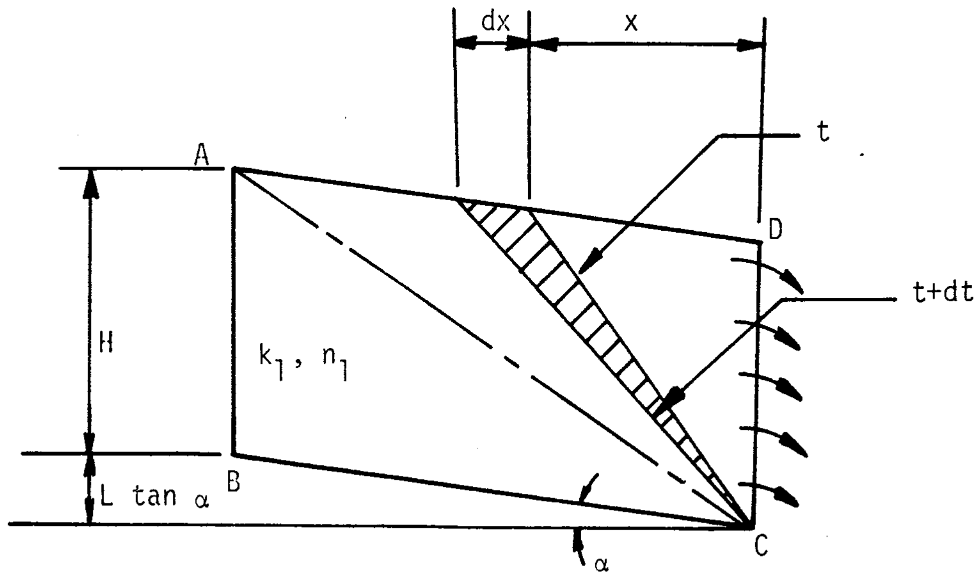
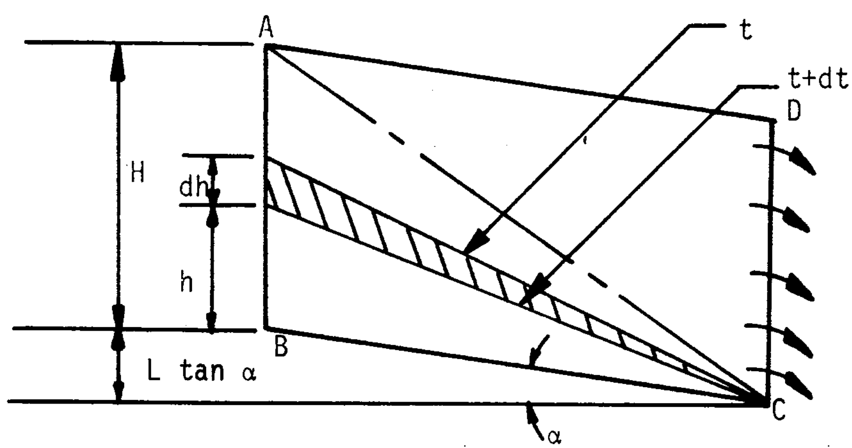


FIGURE 3. CROSS SECTION OF A PAVEMENT



STAGE 1 U ≤ 50%



STAGE 2 U ≥ 50%

FIGURE 4. CASAGRANDE-SHANNON MODEL FOR BASE COURSE DRAINAGE

second part shown in Figure 4, the free surface rotates from position CA to CB due to the loss of water through the face CD. The subgrade is assumed to be impervious through the entire flow calculation. In this part, Casagrande and Shannon (1) established a relation among t and h(t) in terms of other parameters mentioned previously. Further details of their development and the drainage equations are presented in the following section of this paper. The theoretical results were compared with field observations by Casagrande and Shannon (1) and the deviations between theory and field results are primarily due to the assumptions that the phreatic surface is a straight line and the subgrade is impervious. Later Barber and Sawyer (22) presented Casagrande and Shannon's (1) equations in the form of a dimensionless chart shown in Figure 5. Most recently Cedergren (2) and Moulton (23) have modified the original definition of the slope factor, S, as the reciprocal of the one shown in Figure 5 and have presented similar drainage charts in their work on highway subdrainage design.

Drainage of a sloping layer of base course involves unsteady flow with a phreatic surface. The assumptions by Casagrande and Shannon (1) lead to the simple model shown in Figure 4. In this model, the centerline of the base course, AB, and the bottom of the base course, BC, are considered as impervious boundaries. Free discharge is

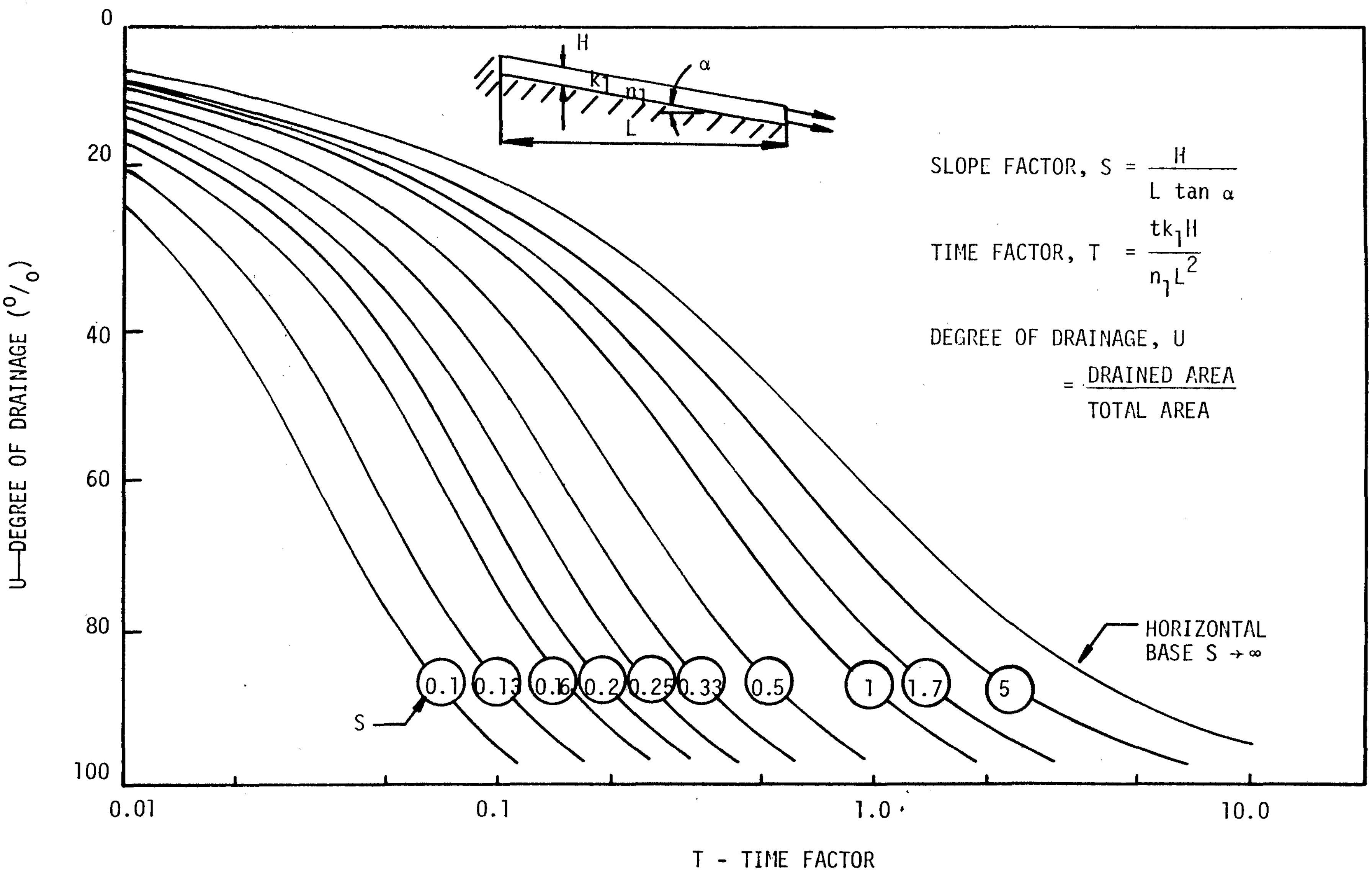


FIGURE 5. VARIATION OF DRAINAGE AREA WITH SLOPE FACTOR AND TIME FACTOR (1)

assumed along the outer edge of the base course, CD. At the beginning of drainage, the base layer is assumed saturated, and the face CD is opened instantaneously for free drainage. In the Casagrande-Shannon model, the phreatic surface is assumed as a straight line that rotates with time as illustrated in Figure 4. The problem was solved in two parts and the solutions were presented in the following dimensionless form:

(A) Horizontal Bases

<u>Stage 1</u> $0 \leq U \leq 50\%$ (4-1)

$$T = 2U^2$$

<u>Stage 2</u> $50\% \leq U < 100\%$ (4-2)

$$T = \frac{U}{2-2U}$$

(B) Sloping Bases

<u>Stage 1</u> $0 \leq U \leq 50\%$ (4-3)

$$T = 2\,US - S^2 \ln\left[\frac{S+2U}{S}\right]$$

<u>Stage 2</u> $50\% \leq U < 100\%$ (4-4)

$$T = S + S \ln\left[\frac{(2S-2US+1)}{(2-2U)(S+1)}\right] - S^2 \ln\left[\frac{S+1}{S}\right]$$

in which Degree of Drainage, $U = \frac{\text{Drained Area}}{\text{Total Area}}$

Slope Factor, $S = \frac{H}{L\tan\alpha}$

Time Factor, $T = \frac{Tk_1H}{n_1L^2}$

where H = thickness of base course,

L = half width of the pavement,

α = slope angle,

t = time,

k_1 = coefficient of permeability of base course, and

n_1 = effective porosity of base course.

The Casagrande-Shannon model has been used extensively by Barber and Sawyer (22), Cedergren (2), Markow (3), and Moulton (23), in the form of a chart shown in Figure 5. However, the theoretical analyses reported by Wallace and Leonardi (24) indicate that the phreatic surface assumes a shape closer to a parabolic rather than to a straight line. Dupuit's assumption as used in related drainage problems by Polubarinova-Kochina (4) also suggested that a parabolic phreatic surface would yield more realistic results for drainage calculations.

It was noted in the paper by Casagrande and Shannon (1) that as the slope of the pavement ($\tan \alpha$) became flatter or the depth of the base (H) became greater, the predictions differed more widely from observations. To account for this difference, Casagrande and Shannon (1) introduced a correction factor which depended upon these variables. In addition it appeared that in the actual cases reported in this paper, the base course took longer to drain than was predicted by the theory. Because the Casagrande-

Shannon theory underpredicts the amount of time that a base course is wet, which is not conservative especially in the deeper and flatter pavements, it was considered beneficial to develop a better means of analyzing the drainage from base courses.

4.2 PARABOLIC PHREATIC SURFACE METHOD WITH AN IMPERMEABLE SUBGRADE

In order to compare the effects of an assumed parabolic phreatic surface relative to the straight line assumed by Casagrande and Shannon (1), an impermeable subgrade was assumed and the resulting drainage equations were developed (24). Two separate stages were identified as shown in Figure 6 and the corresponding equations are as follows (see Appendix B):

(A) Horizontal Bases

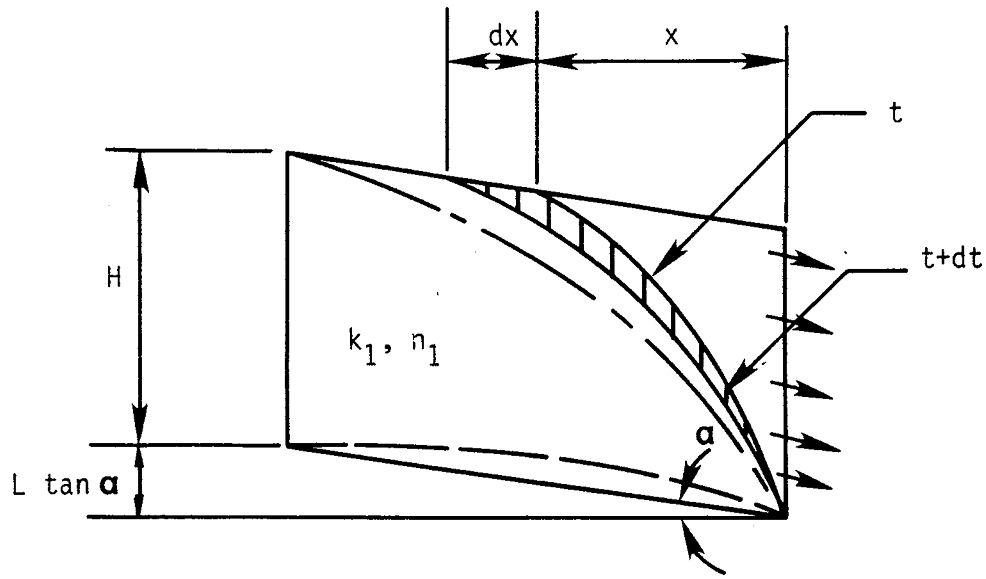
Stage 1 $$0 \le U \le \frac{1}{3} \qquad T = 3U^2 \tag{4-5}$$

Stage 2 $$\frac{1}{3} \le U < 1 \qquad T = \frac{8}{9}\left(\frac{1}{1-U}\right)-1 \tag{4-6}$$

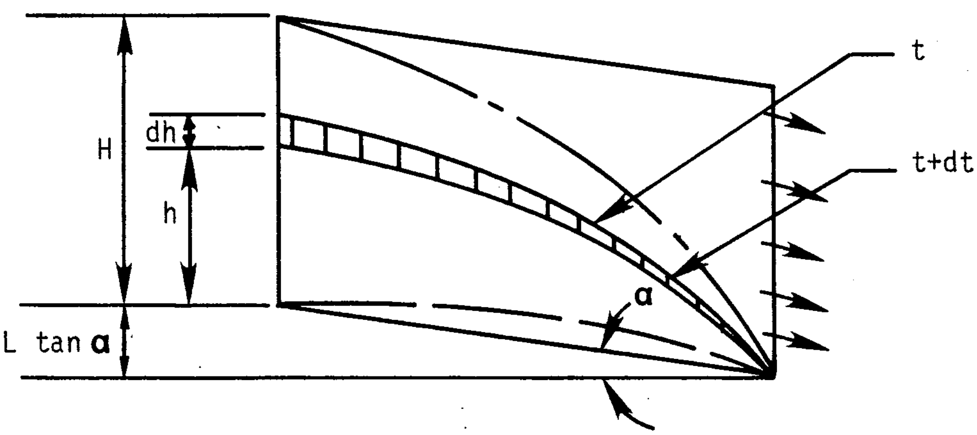
(B) Sloping Bases

Stage 1 $$0 \le U \le \frac{1}{3} \qquad T = \frac{3}{2}SU-\frac{3}{8}S^2\ln\left[\frac{S+4U}{S}\right] \tag{4-7}$$

Stage 2 $$\frac{1}{3} \le U < 1 \qquad T = \frac{S}{2}-\frac{3}{8}S^2\ln\left[\frac{3S+4}{3S}\right]+S\ln\left[\frac{9S-9SU+8}{3(1-U)(3S+4)}\right] \tag{4-8}$$



STAGE 1 $0 \leq U \leq \frac{1}{3}$



STAGE 2 $\frac{1}{3} \leq U < 1$

FIGURE 6. TTI MODEL FOR BASE COURSE DRAINAGE WITH AN IMPERMEABLE SUBGRADE

The results of these drainage equations are presented in the form of a dimensionless drainage chart in Figure 7. Also, the calculated results from the new model are compared with field data reported by Casagrande and Shannon (1) on three of their five pavement test sections in Figures 8 to 10. In the Texas Transportation Institute (TTI) model drainage proceeds slower than in the Casagrande-Shannon model, and has roughly the same shape.

The TTI model could be made to fit the field data results better if drainage were allowed to infiltrate into a permeable subgrade, thus increasing the initial degree of drainage and shortening the drainage time.

4.3 ANALYSIS OF SUBGRADE DRAINAGE

In order to study the influence of subgrade drainage on base course drainage, two models were developed. In these models the phreatic surfaces in the base course were assumed to be linear and parabolic. The two distinct stages of drainage in the first permeable subgrade model are shown in Figure 11. In this model, the properties of the subgrade are defined by the coefficient of permeability k_2, and porosity, n_2. An advancing wetting front, FC, was assumed at an unknown depth of $y_0(t)$ as shown in Figure 12. Similar to the Casagrande-Shannon model, the drainage problem begins with a saturated base-subgrade composite system and the faces EC and DC are opened instantaneously,

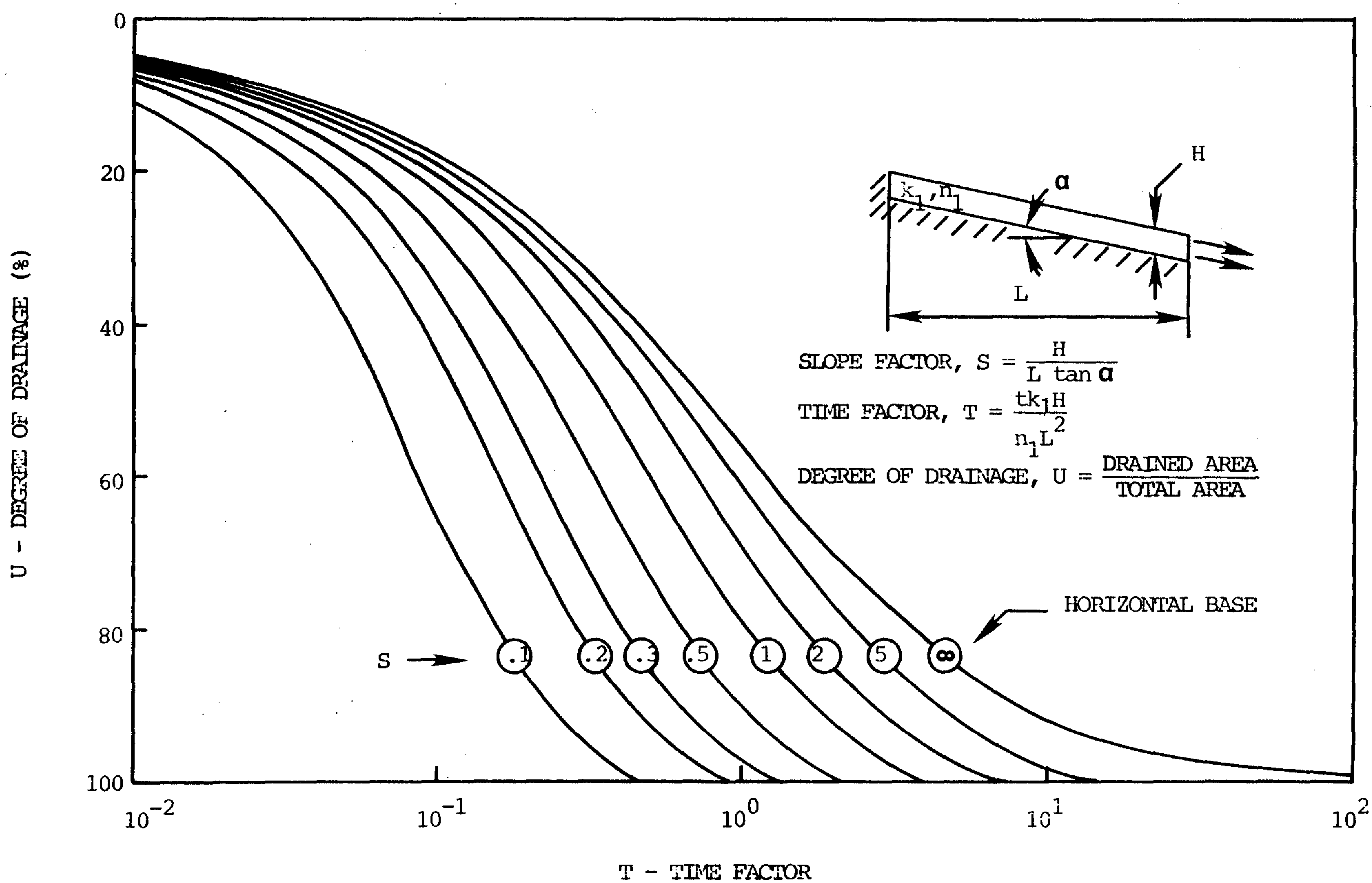


FIGURE 7. TTI DRAINAGE CHART WITH AN IMPERMEABLE SUBGRADE

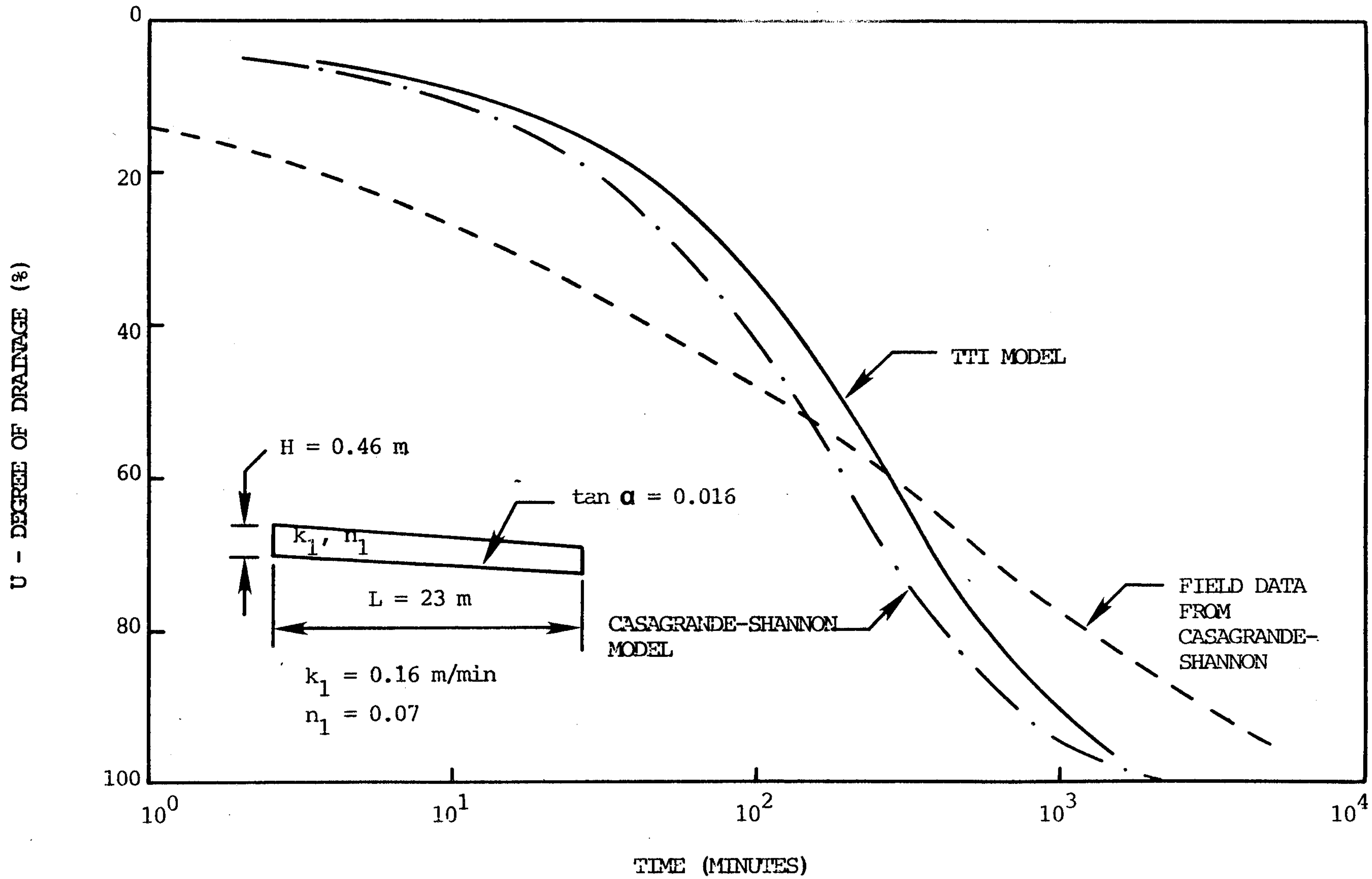


FIGURE 8. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE

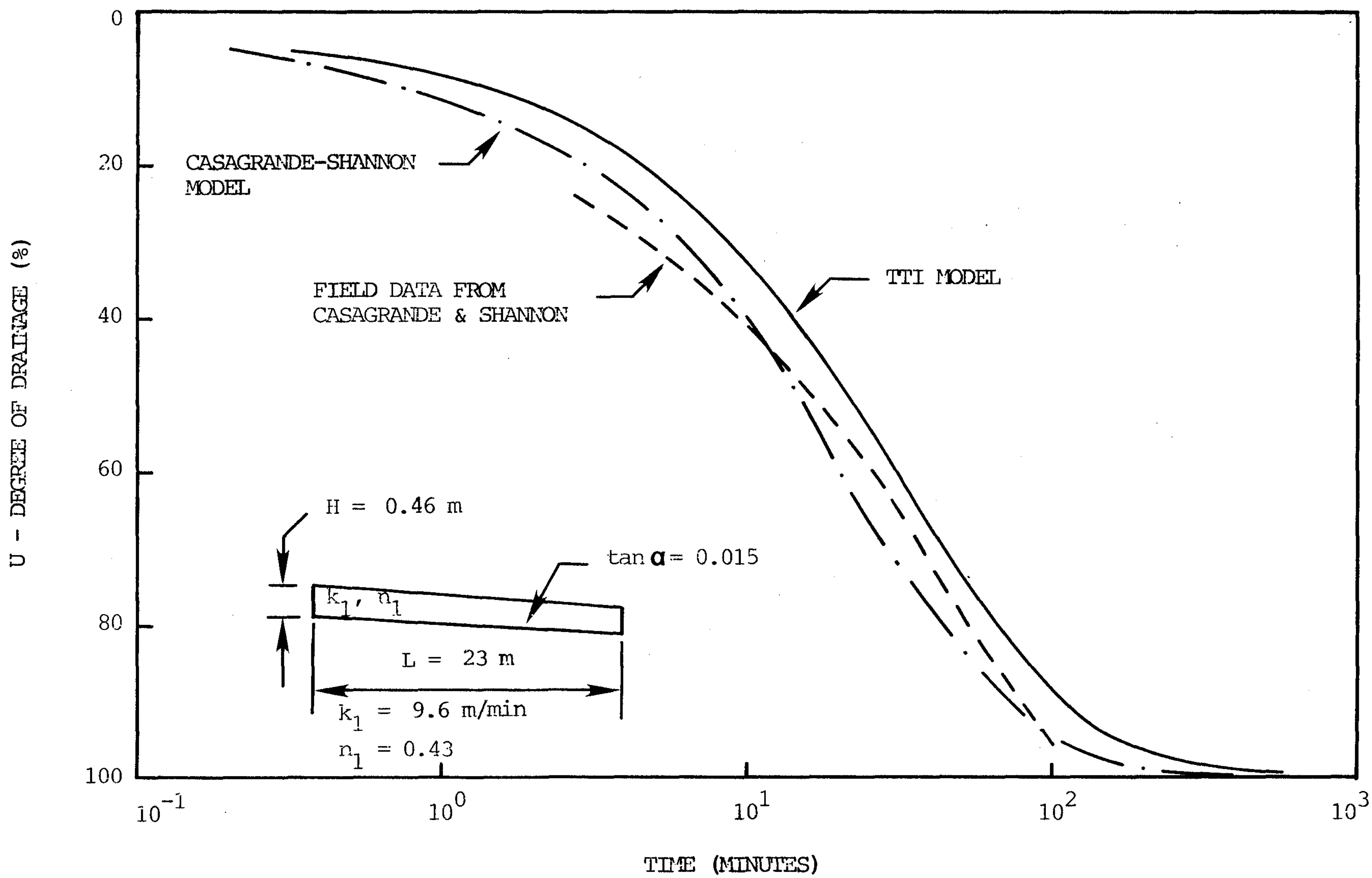


FIGURE 9. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE

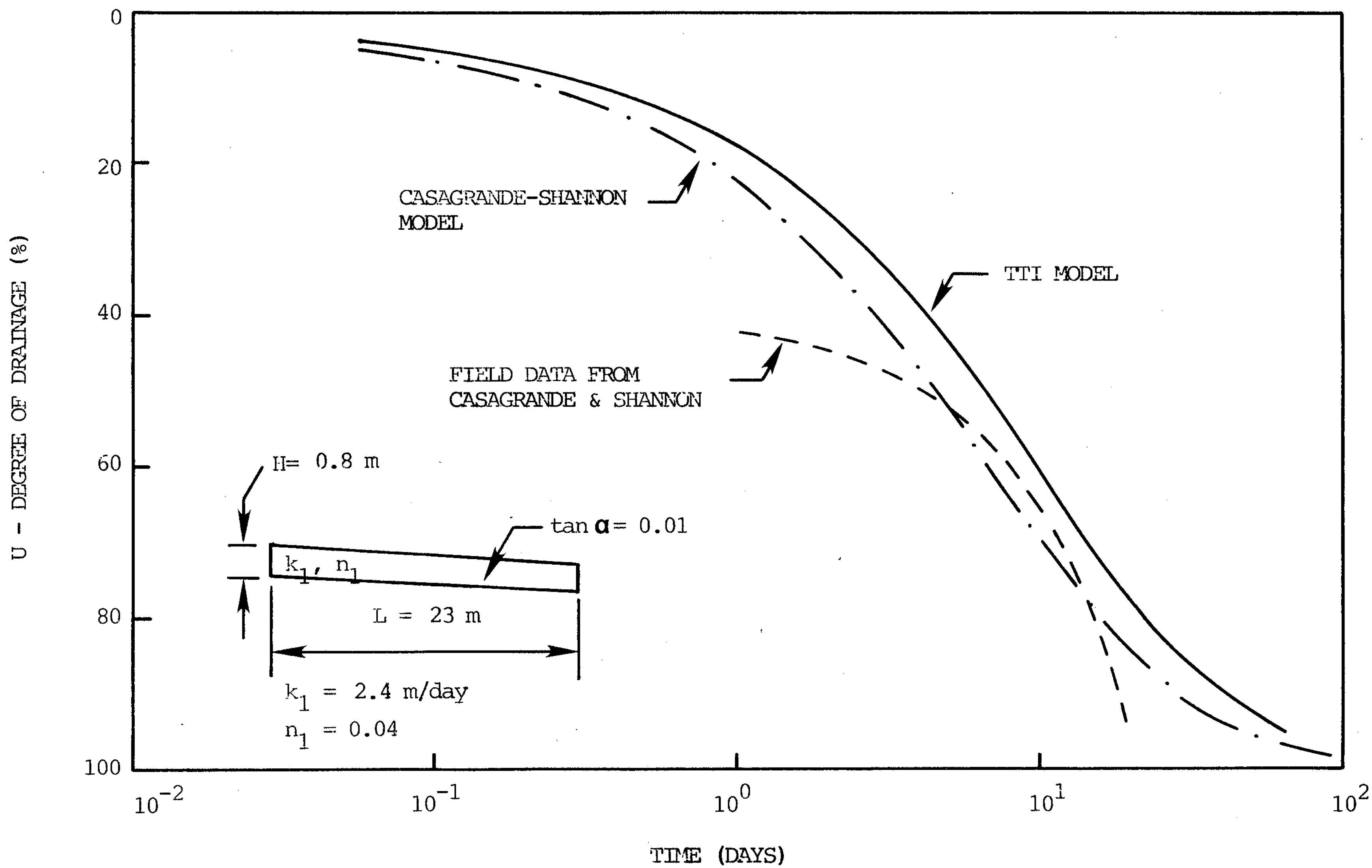
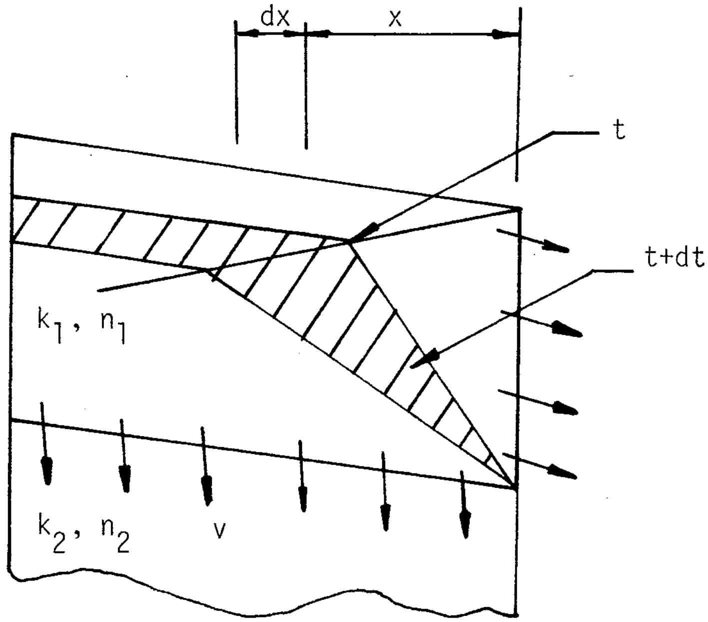
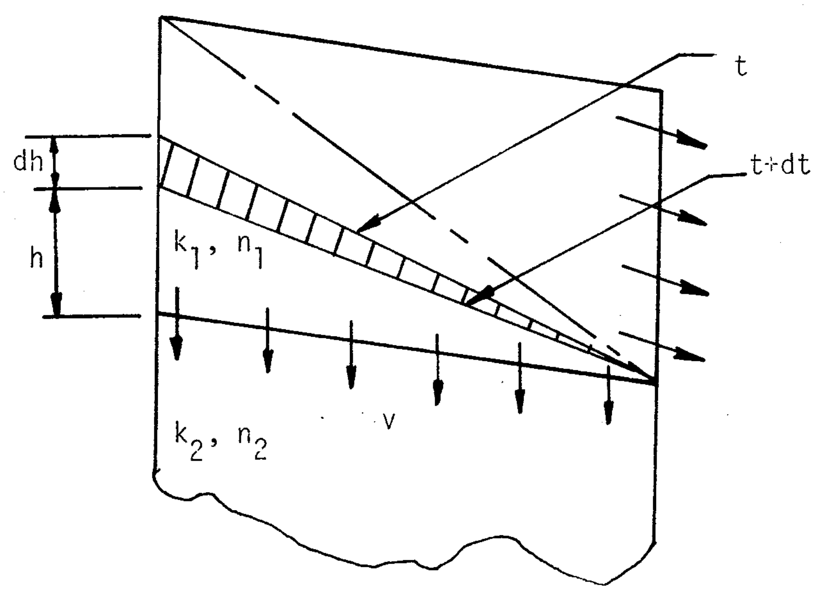


FIGURE 10. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE



STAGE 1



STAGE 2

FIGURE 11. PERMEABLE SUBGRADE WITH CASAGRANDE-SHANNON DRAINAGE MODEL

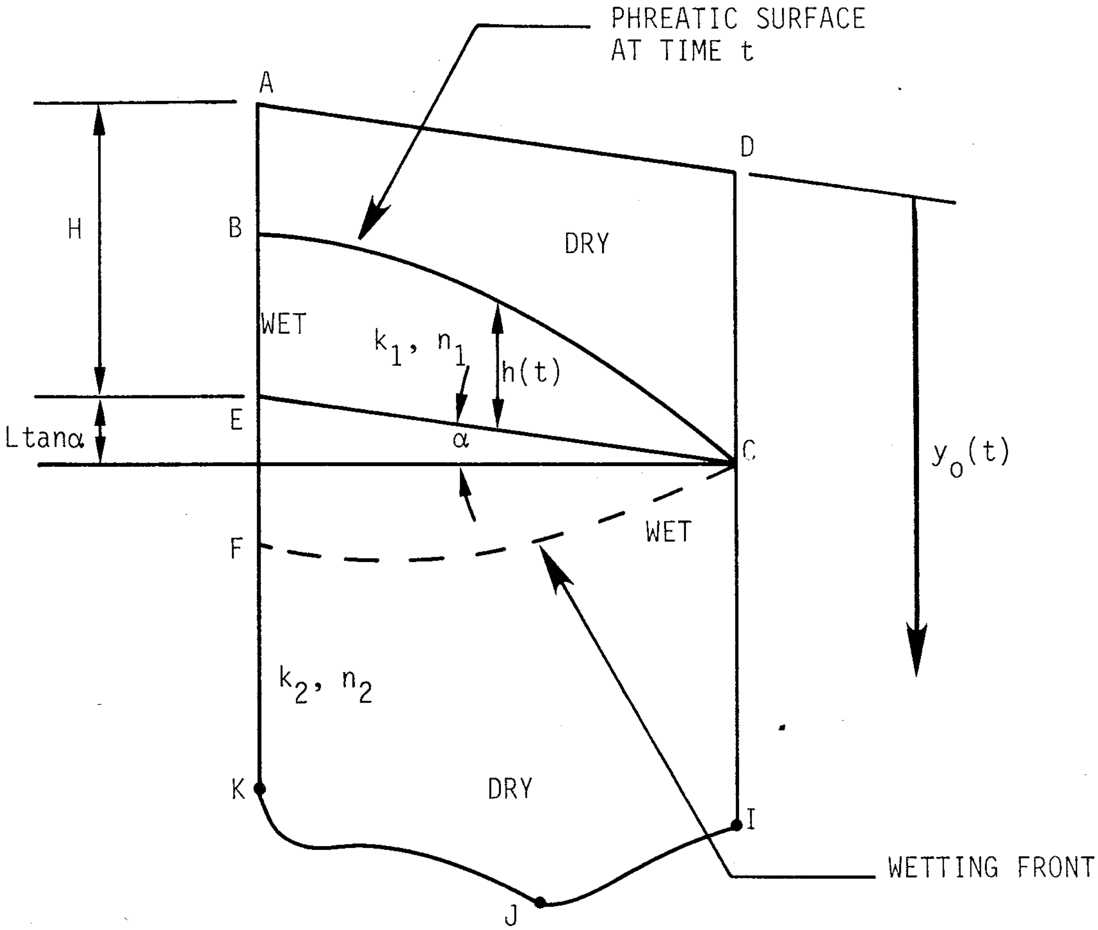


FIGURE 12. Definition Sketch For Subgrade Drainage Model

allowing free drainage. In order to keep the model simple, a one-dimensional flow into the subgrade is assumed in accordance with Polubarinova-Kochina (4). From this formulation the velocity of drainage, v, into the subgrade is given by (see Appendix C-1):

$$v = \frac{y_0(t)+h(t)-H}{\frac{h(t)}{k_1} - \frac{(y_0(t)-H)}{k_2}} \tag{4-9}$$

$$y_0(t) = H+\frac{n_1}{n_2}(H-h(t)) \tag{4-10}$$

$h(t)$ = depth of water in base course,

$y_0(t)$ = penetration of water into the subgrade,

k_1 = coefficient of permeability and porosity of the base course, and

k_2 = coefficient of permeability and porosity of the subgrade.

The modified differential equations for this model did not yield a set of dimensionless variables to permit the preparation of dimensionless drainage charts. Furthermore, the governing equations were too complex to generate any closed form solutions. A numerical integration scheme was used to solve these governing equations.

4.4 DRAINAGE WITH A PARABOLIC PHREATIC SURFACE AND A PERMEABLE SUBGRADE

The parabolic phreatic surface model, incorporated with the subgrade drainage, is used for subdrainage analysis. The derivation is listed in Appendix C-2. The model has the same two stages as were identified earlier in Figure 6 and is illustrated in Figure 13.

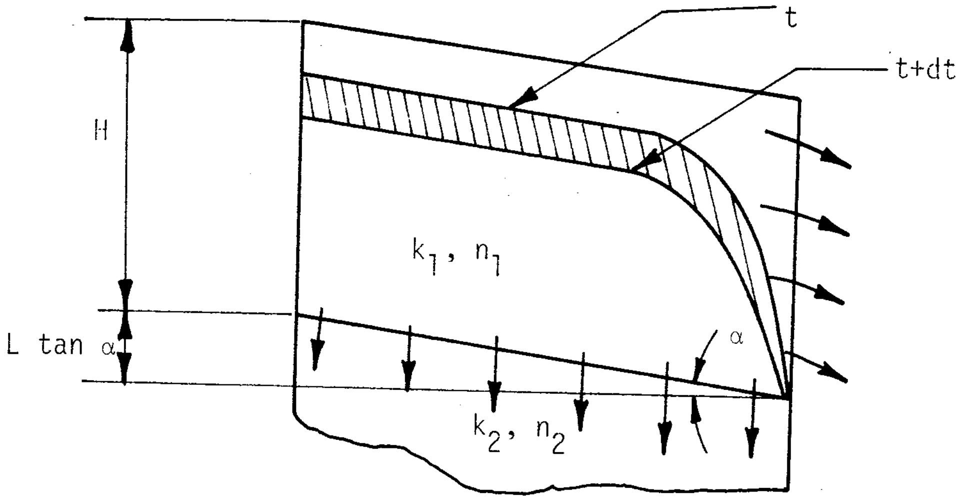
Five field cases were studied using this model and the results for two of these are shown in Figures 14 and 15. It is interesting to note in Figure 14 that the field curve follows a trend very similar to that of the two drainage curves (k_2/k_1 = K=Ø and Ø.ØØØ2) given by the present model and lies between the two theoretical curves. In this case, the permeable subgrade model with a parabolic phreatic surface yields results that compare well with field data.

In Figure 15, the parabolic model with a permeable subgrade (K = Ø.ØØØ1) is in closer agreement with the field data than the Casagrande-Shannon model.

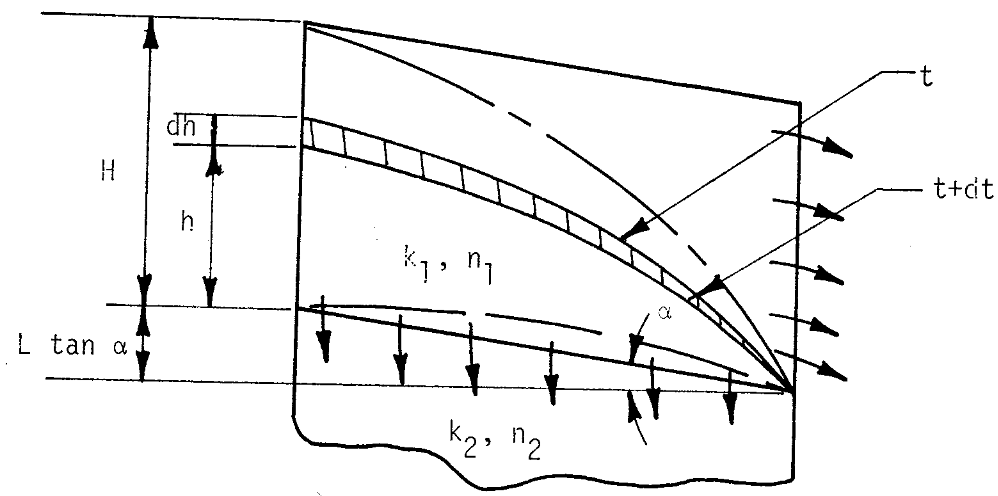
As a result of the studies reported here, the parabolic phreatic surface model with permeable subgrades was chosen for all future drainage analyses.

4.5 APPLICATION TO PAVEMENT DRAINAGE DESIGN

As an illustration of the importance of subgrade drainage, a base course Ø.8 m (2.5 ft) thick and 46 m (15Ø ft) wide with 1% cross slope is considered. The base course has its smallest particles in the medium sand range and has a coefficient of permeability, k_1 = 2.4 m/day (7.8 ft/day), and the porosity, n_1 = Ø.Ø4. It is required to



STAGE 1



STAGE 2

FIGURE 13. SUBGRADE DRAINAGE MODEL WITH PARABOLIC PHREATIC SURFACES

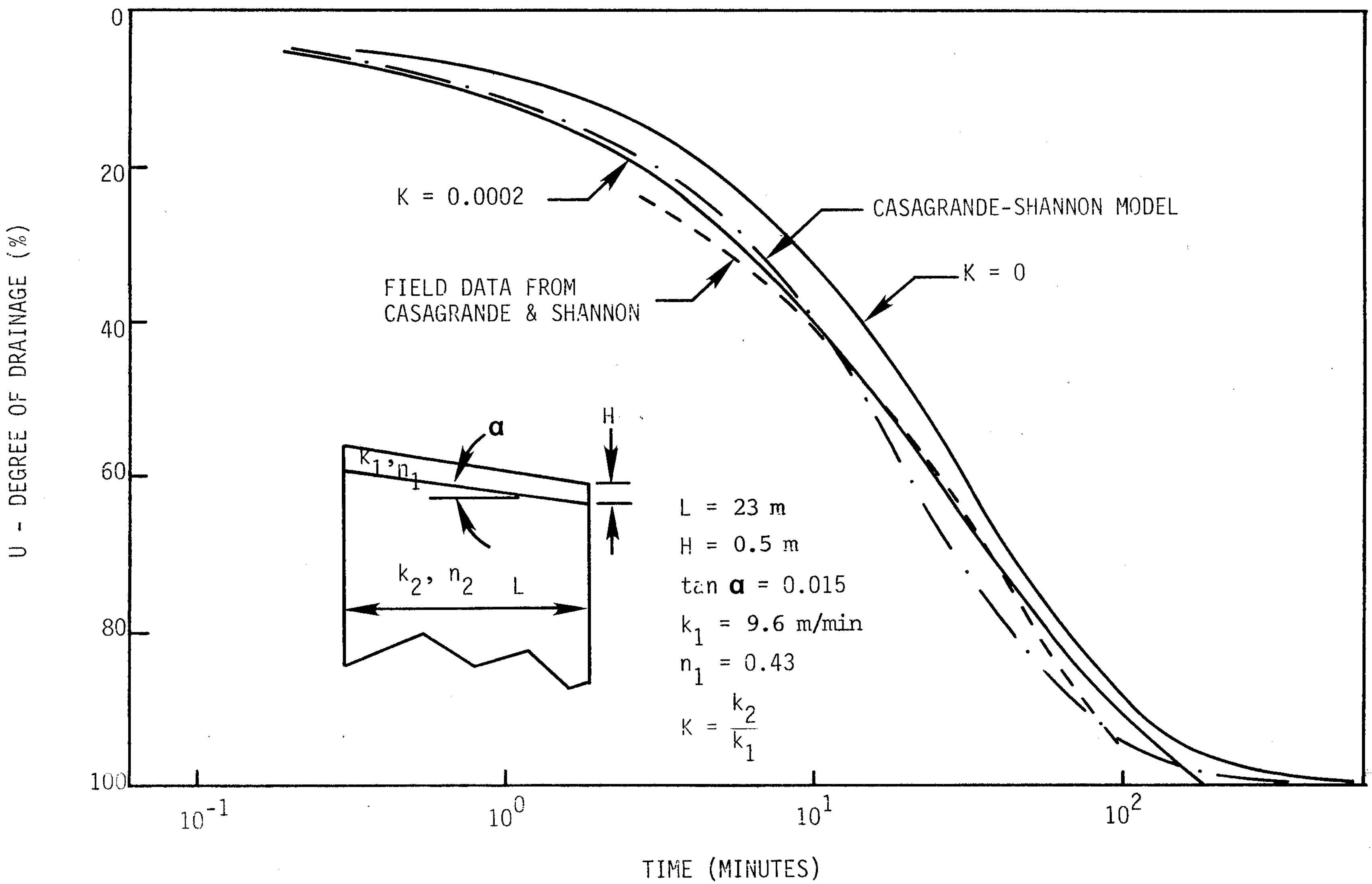


FIGURE 14. RESULTS OF TTI MODEL WITH PERMEABLE SUBGRADES

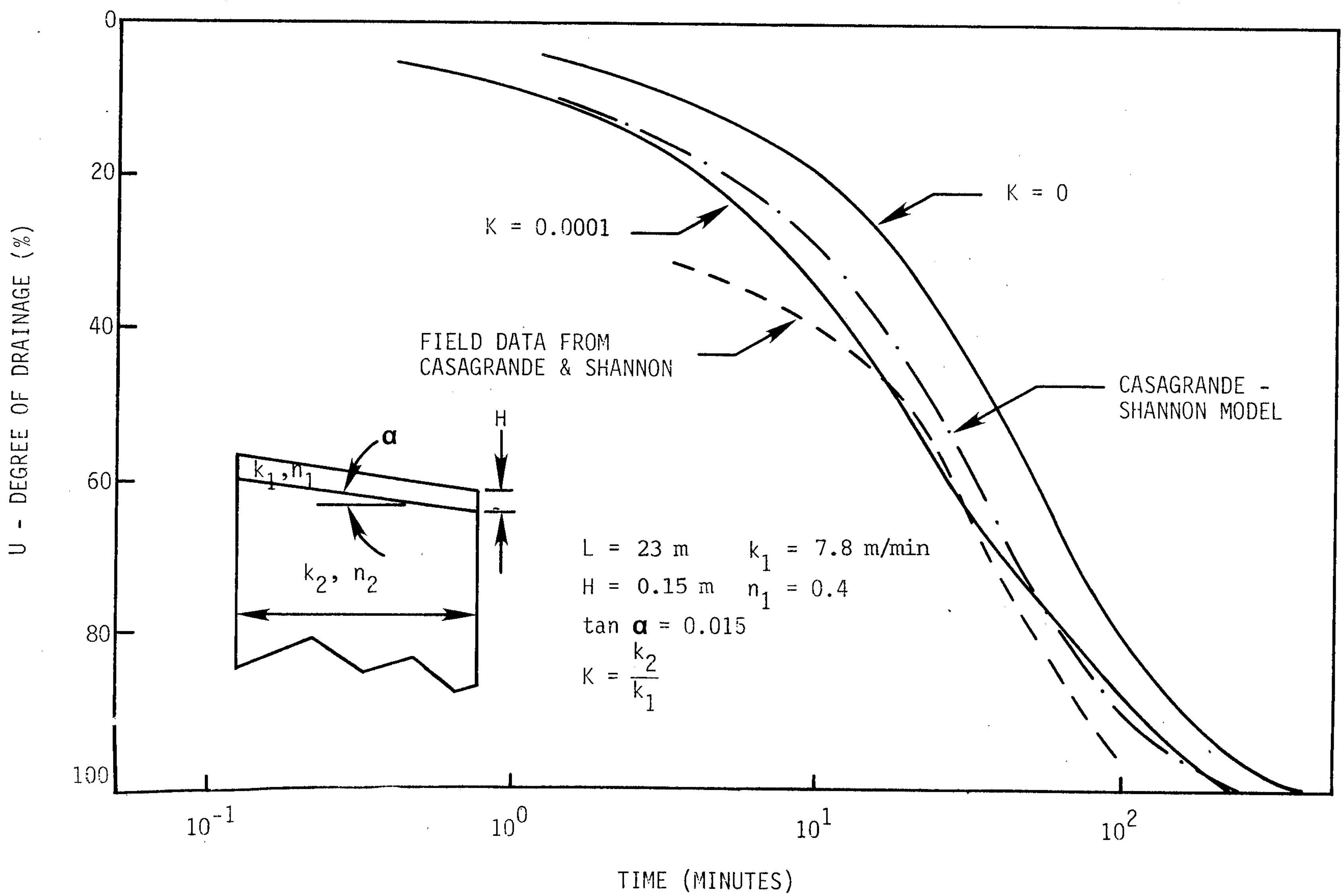


FIGURE 15. RESULTS OF TTI MODEL WITH PERMEABLE SUBGRADES

determine the drainage time for a 60% degree of drainage for a number of subgrade materials. Figure 16, for various values of subgrade permeability, the times required for 60% drainage can be obtained as follows:

a) Subgrade material is a plastic clay.

k_1 = 0.0024 m/day (0.0078 ft/day)

K = k_2/k_1

= 0.001

t = 5 days

b) Subgrade material is a glacial till.

k_1 = 0.0048 m/day (0.0156 ft/day)

K = 0.002

t = 2.5 days

c) Subgrade material is a silty sand.

k_1 = 0.24 m/day (0.78 ft/day)

K = 0.1

t = 84 minutes

It becomes clear, from the above calculations that the subgrade permeability will significantly influence pavement drainage and subdrainage design. A specific example is used here to illustrate the usefulness of the new TTI base-subgrade drainage model with the aid of Figure 16. More general pavement drainage design calculations can be performed by using the computer program "TTIDRAIN" which was used to make the calculations reported here.

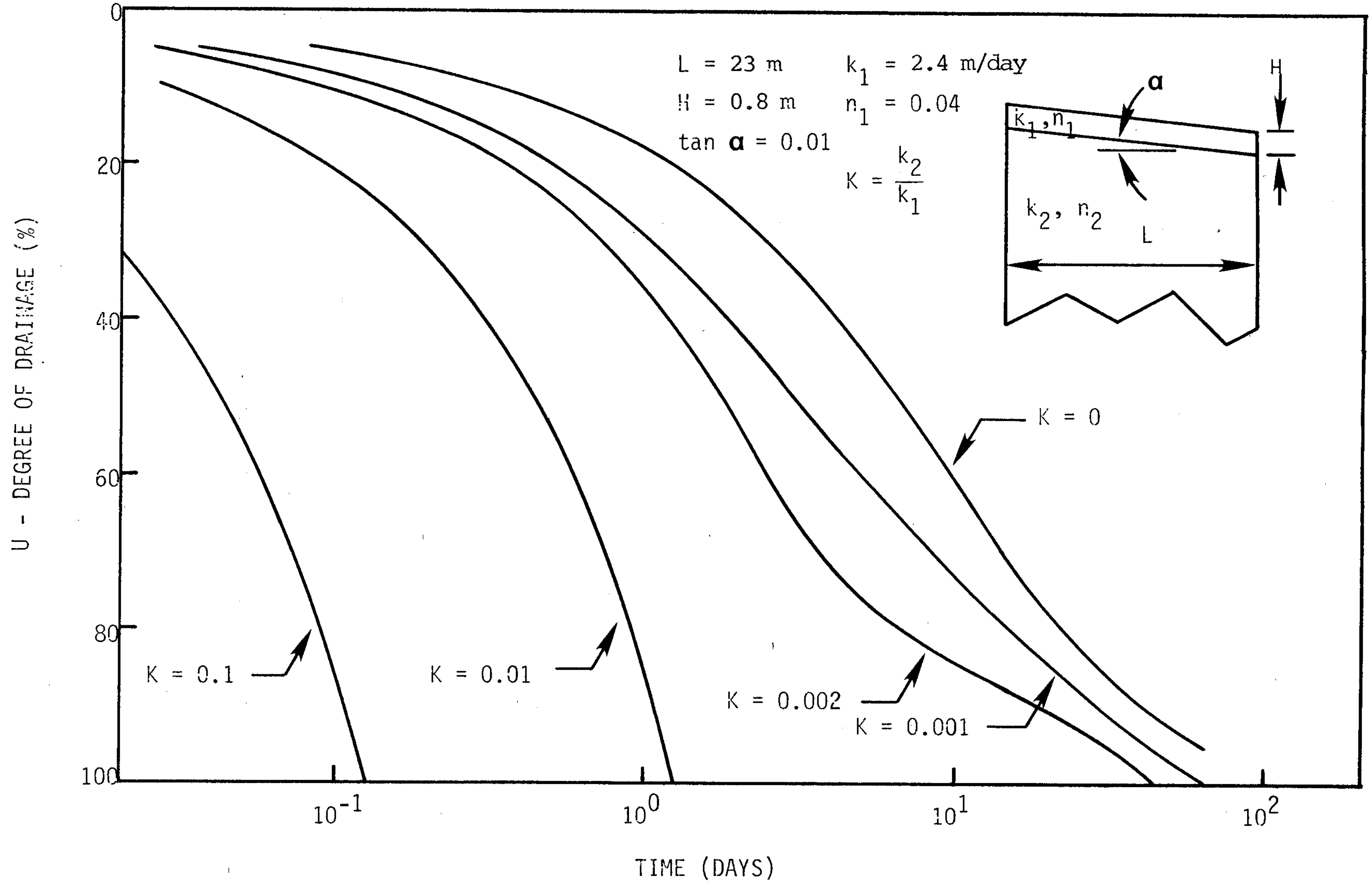


FIGURE 16. DRAINAGE CURVES FOR TTI MODEL WITH PERMEABLE SUBGRADES

4.6 ESTIMATION OF DRAINABILITY OF THE BASE COURSE AND EVALUATION OF DRAINAGE DESIGN

The material properties effect base drainage and highway performance significantly. Good quality moisture resistant materials generally reduce water damage even when a pavement is constructed in a wet climate. Likewise, poor materials will not be aided by drainage since they are incapable of removing the moisture causing the damage. The granular components of the roadbed system directly influence the water retaining capacity of the system as well as the time required for drainage. Soil texture plays an important role in the water retaining capability. Clays exhibit much stronger attraction for water than does the sand at the same water content. The higher the clay content in a soil, the more water that will be retained by that soil. The percentage of the total water that actually drains is dependent on the grain size distribution, the amount of fines, the type of minerals in the fines, and hydraulic boundary conditions. Figure 17 presents the effect of the amount and type of fines on the permeability and Table 2 indicates the relative amount of water that can be drained as it is influenced by soil texture (26). Haynes and Yoder (27) performed a laboratory investigation of the behavior of AASHO Road Test gravel and crushed stone mixtures subjected to repeated loading to examine the influence of moisture on load. They concluded that above 85% saturation the total deformation

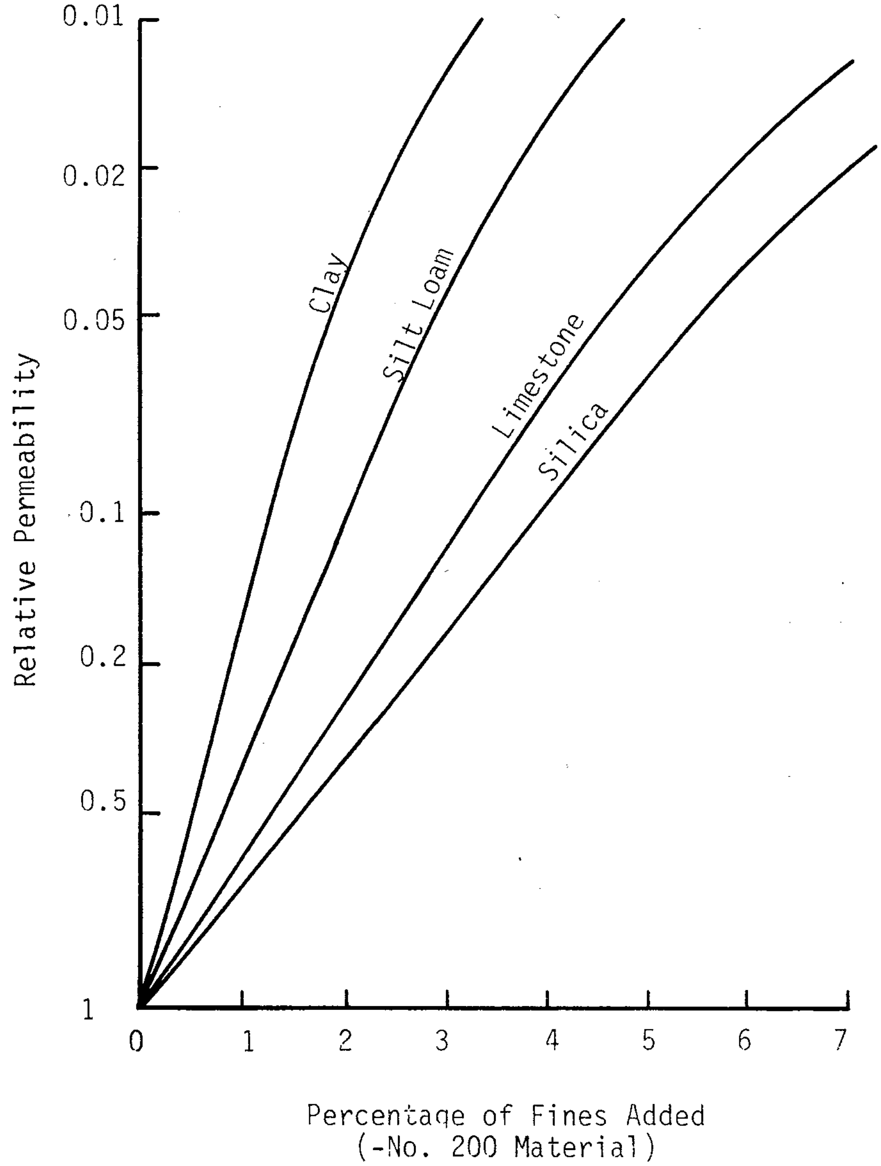


FIGURE 17. Effect of Amount and Type of Fines on the Permeability (26)

TABLE 2. Drainability (in Percentage) of Water in the Base Courses from a Saturated Sample (26)

AMOUNT OF FINES	<2.5% FINES			5% FINES			10% FINES		
TYPE OF FINES	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY
GRAVEL	70	60	40	60	40	20	40	30	10
SAND	57	50	35	50	35	15	25	18	8

* Gravel, 0% fines, 75% greater than #4: 80% water loss

* Sand, 0% fines, well graded: 65% water loss.

* Gap graded material will follow the predominant size.

increases thus accelerating fatigue damage. Research done in New Zealand (28) has shown a degree of base course saturation of 80% is sufficient to create pore water pressure build up and associated loss of stability when a pavement is subjected to repetitive traffic loadings.

The degree of drainage, U, which is employed in the previous sections of this chapter, can be readily converted to saturation using Table 2. The relationship between saturation, S_a, and the degree of drainage is

$$S_a = 1 - P.D. \times U \qquad (4\text{-}11)$$

where P.D. is a percentage indicating the amount of water that can be drained from a sample.

A drainage time of five hours to reach a saturation level of 85% is set as an acceptable material based on studies done at Georgia Tech and the University of Illinois (Figure 18). A drainage time between 5 and 10 hours is marginal and greater than 10 hours is unacceptable. A base course with granular materials that are classified as unacceptable will hold more water (26), allow excessive deformations, pumping, stripping, etc., in the pavements.

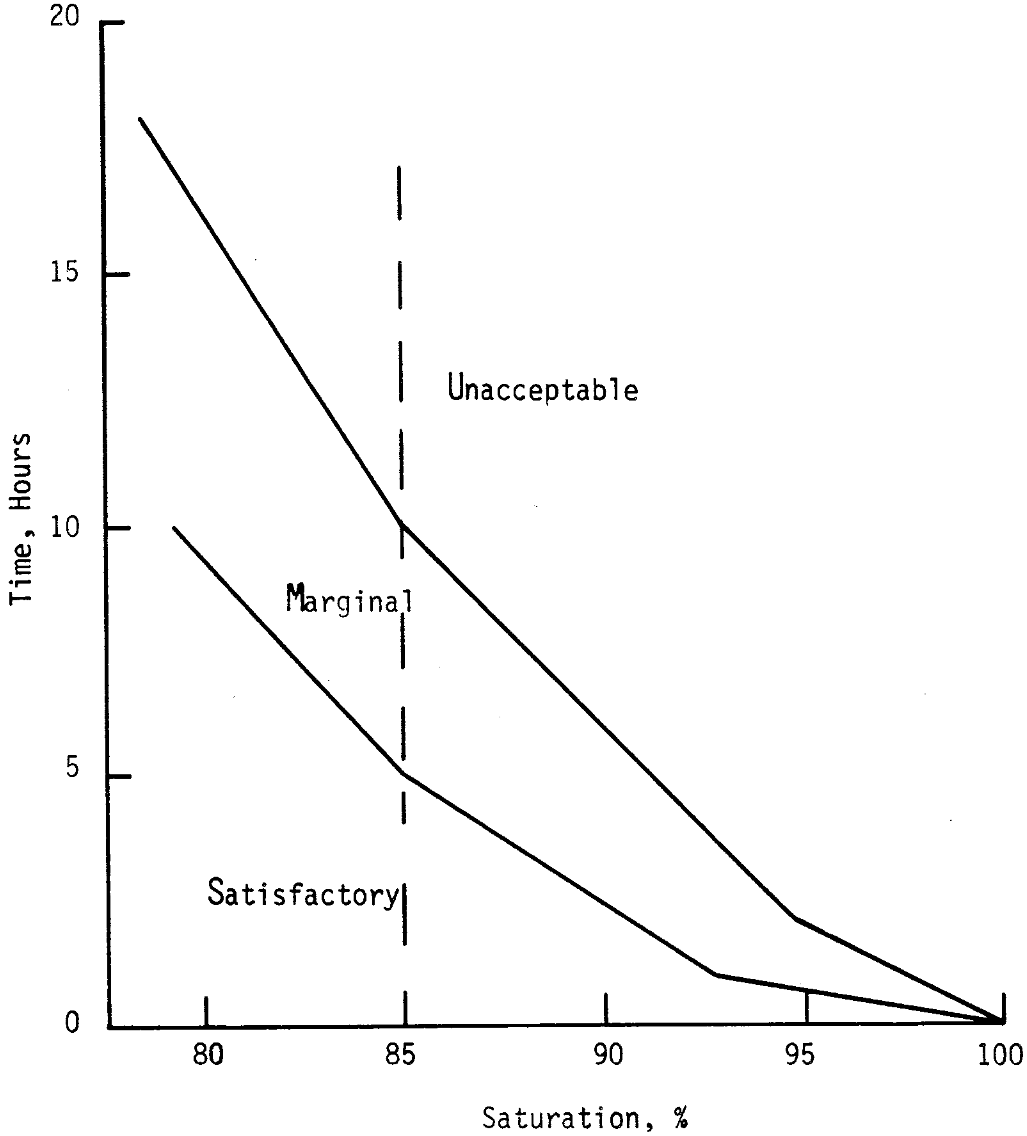


FIGURE 18. Drainage Criteria for Granular Layers (26)

CHAPTER 5 EFFECT OF SATURATION ON LOAD-CARRYING CAPACITY OF BASE COURSE AND SUBGRADE

For both highway and airfield pavements, benefits derived from proper drainage cannot be overemphasized. With excess water in a pavement structure, the damaging action of repeated traffic loads will be accelerated. Barenberg and Thompson (29) reported the results of accelerated traffic tests and showed that rates of damage when excess water was present were 100 to 200 times greater than when no excess water was present.

Most pavement design methods use strength tests made on base course and subgrade samples that are in a nearly saturated condition. This has been standard practice for many years due to the fact that the soil moisture content is usually quite high under a pavement even under desert conditions.

5.1 EFFECT OF SATURATION ON BASE COURSE PROPERTIES

Moynahan and Sternbert (30) studied the effect of the gradation and direction of flow within a densely graded base course material and found that there was little effect on the drainage characteristics caused by the direction of flow; however, fines content was found to be a much more significant factor in determining the rate of highway subdrainage.

As mentioned in Chapter 4, Haynes and Yoder (27) performed a laboratory investigation of the behavior of the AASHO Road Test gravel and crushed stone mixtures subjected to repeated loading. A series of repeated triaxial tests were performed on the crushed stone and gravel base course materials. Their studies indicated that the degree of saturation level was closely related to the material strength of the base course (Figure 19), especially above 85% saturation.

In the simulation model presented here, the moduli of different base course materials must be furnished. The base moduli in Table 3 were measured by a wave propagation method at the TTI Pavement Test Facility (31) and are provided as default values to the simulation model. In simulating the influence of degree of saturation on the base moduli, Figure 19 is applied to determine the ratio of elastic moduli affected (27). A linear relationship is used to convert the rate of deflection change to the rate of elastic modulus change, at different saturation levels. In the range of degree of saturation from 0 to 60%, the elastic moduli are assumed to be constant. Between 60% and 85% saturated the slope between deflection measurements and saturation levels is 0.24. At degrees of saturation greater than 85%, the slope is 3.5. To estimate the average base modulus during any specific season, the cumulative probabilities of each

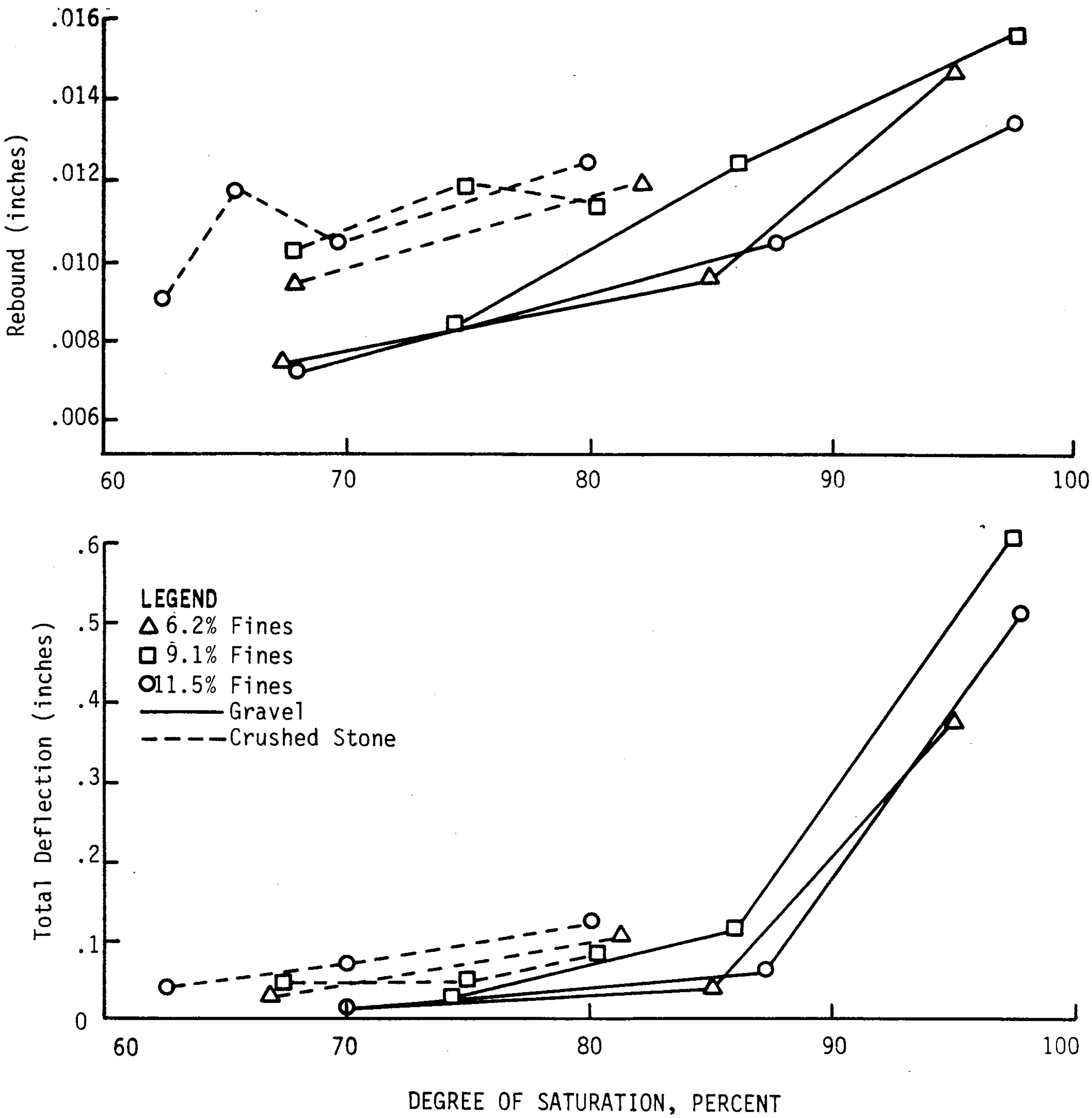


FIGURE 19. Effect of the Degrees of Saturation on the Repeated-Load Deformation Properties of the AASHO Granular Materials (27)

TABLE 3. Calculated Elastic Moduli for Materials in the TTI Pavement Test Facility (31)

Materials	Unit Weight, lb/ft^3	Poisson's Ratio	Calculated Elastic Modulus lb/in^2
1. Crushed Limestone + 4% Cement	140	0.45	425,300
2. Crushed Limestone + 2% Lime	140	0.45	236,300
3. Crushed Limestone	135	0.45	209,300
4. Gravel	135	0.47	64,600
5. Sand Clay	125	0.47	29,800
6. Embankment - Compacted Plastic Clay	120	0.48	17,100
7. Subgrade			15,000
8. Asphalt Concrete			500,000

section of the elastic modulus as well as the dry and wet probabilities of the base course (see Chapter 6) are incorporated into the model.

5.2 EFFECT OF SATURATION ON SUBGRADE PROPERTIES

The moisture content of subgrades are significantly affected by the location of the water table. If the water table is very close to the surface, within a depth of 20 feet, the major factor influencing moisture is the water table itself. However, when the water table is lower than 20 feet (32), the moisture content is determined primarily by the seasonal variation of rainfall. In this report, the location of the water table is not taken into account.

The subgrade soil support is a major concern in the design thickness of a flexible pavement. Thompson and Robnett (33) conducted research toward identifying and quantifying the soil properties that control the resilient behavior of Illinois soils. In their paper, they concluded that the degree of saturation is a factor that reflects the combined effects of density and moisture content. The simple correlation analyses indicated a highly significant relation between the resilient modulus and the degree of saturation of the subgrade. A set of regression equations were developed for various soil classification groups (Table 4). The equations developed can be used to predict the resilient moduli of different soil groups. The regression

TABLE 4. Regression Coefficients for the Effect of Degree of Saturation on Elastic Moduli of Subgrade Soils (33)

Group	Horizons	a Kips per square inch	b
(a) AASHO			
A-7-5	ABC BC	39.83 27.54	0.453 0.266
A-4	ABC BC	17.33 16.76	0.158 0.146
A-7-6	ABC BC	31.22 24.65	0.294 0.196
A-6	ABC BC	36.15 35.67	0.362 0.354
(b) Unified			
CL, ML-CL	ABC BC	31.89 32.13	0.312 0.311
CH	ABC BC	21.93 23.02	0.151 0.161
ML, MH	ABC BC	31.39 29.01	0.331 0.284

Equation: $E_s = a - bS_a$

E_s is in kips per square inch; S_a is degree of Saturation as a percentage coefficient b is indicative of moisture sensitivity.

The depth of the base course and subgrade is assumed to be 70 inches in order to evaluate the degree of saturation in the subgrade. The average wetting front of water penetrated from base into subgrade is calculated by estimating the proportions of water in the base flowing into the subgrade from the TTI drainage model (see Chapter 4)(25). The average subgrade modulus is determined by the average rainfall during that season that will infiltrate into the subgrade from the base.

The subgrade modulus is calculated by (31)

$$E_s = \frac{E_1 d_1^{\,3} + E_2 d_2^{\,3}}{d^3} \tag{5-1}$$

where

E_s = calculated total subgrade modulus,

d = depth of subgrade,

E_1 = subgrade modulus under 100% saturated condition, which is evaluated from Thompson and Robnett equations (33),

d_1 = average depth of water penetrating into subgrade from the base course,

E_2 = subgrade modulus under dry condition, and

d_2 = average depth of dry portion of the subgrade.

CHAPTER 6 SYNTHESIS OF THE METHODS OF RAINFALL INFILTRATION, DRAINAGE, AND LOAD-CARRYING CAPACITY OF A PAVEMENT

The following models are presented to serve as analytical procedures of rainfall infiltration, drainage analysis, and load-carrying capacities of base courses and subgrades.

1. The Gamma distribution (7) for the rainfall amount distribution.
2. Dempsey and Robnett's (20) regression equations, as well as Ridgeway's (14) laboratory results from which an estimation of the amount of rainfall which, in turn, permits an estimate of the duration of the rainfall, for infiltration analysis.
3. The TTI drainage model (25), the parabolic phreatic surface with subgrade drainage, as developed for base course and subgrade drainage analysis.
4. Markov Chain Model (7,12) and Katz's recurrence equations (13) for the calculation of dry and wet probabilities of the weather and the base course.
5. Evaluation of base course (26) and subgrade moduli (31,33) as they are affected by moisture contents in the materials.

A conceptual flow chart is drawn for a comprehensive and clear profile of the entire model in Figure 20, and a synthesis of the various models mentioned above into a systematic analysis of rainfall infiltration and drainage analysis of a pavement is sketched in Figure 21.

6.1 CONCEPTUAL FLOW CHART FOR RAINFALL, INFILTRATION AND DRAINAGE ANALYSIS

The local rainfall frequency during a period of time is used to predict the chances of local climate being wet and dry by Markov chain model. The rainfall amount of every rainy day during the same period are for estimating the parameters of a Gamma distribution, which is applied as a probability density function of rainfall quantity.

The amount of water penetration into the base through cracks and joints are estimated either by Ridgeway's laboratory results or by Dempsey-Robnett's regression equation, which depend on whether the data of cracks and joints are provided.

Drainage analysis is based on the TTI model, which determines the time required for water to flow out a base course through the edge and subgrade. In the meantime, the base drainage design is evaluated on the soil properties of that base.

Then Katz's recurrence equations (13), which are associated with Markov chain model, incorporated with the gamma distribution, the infiltration of water into the base

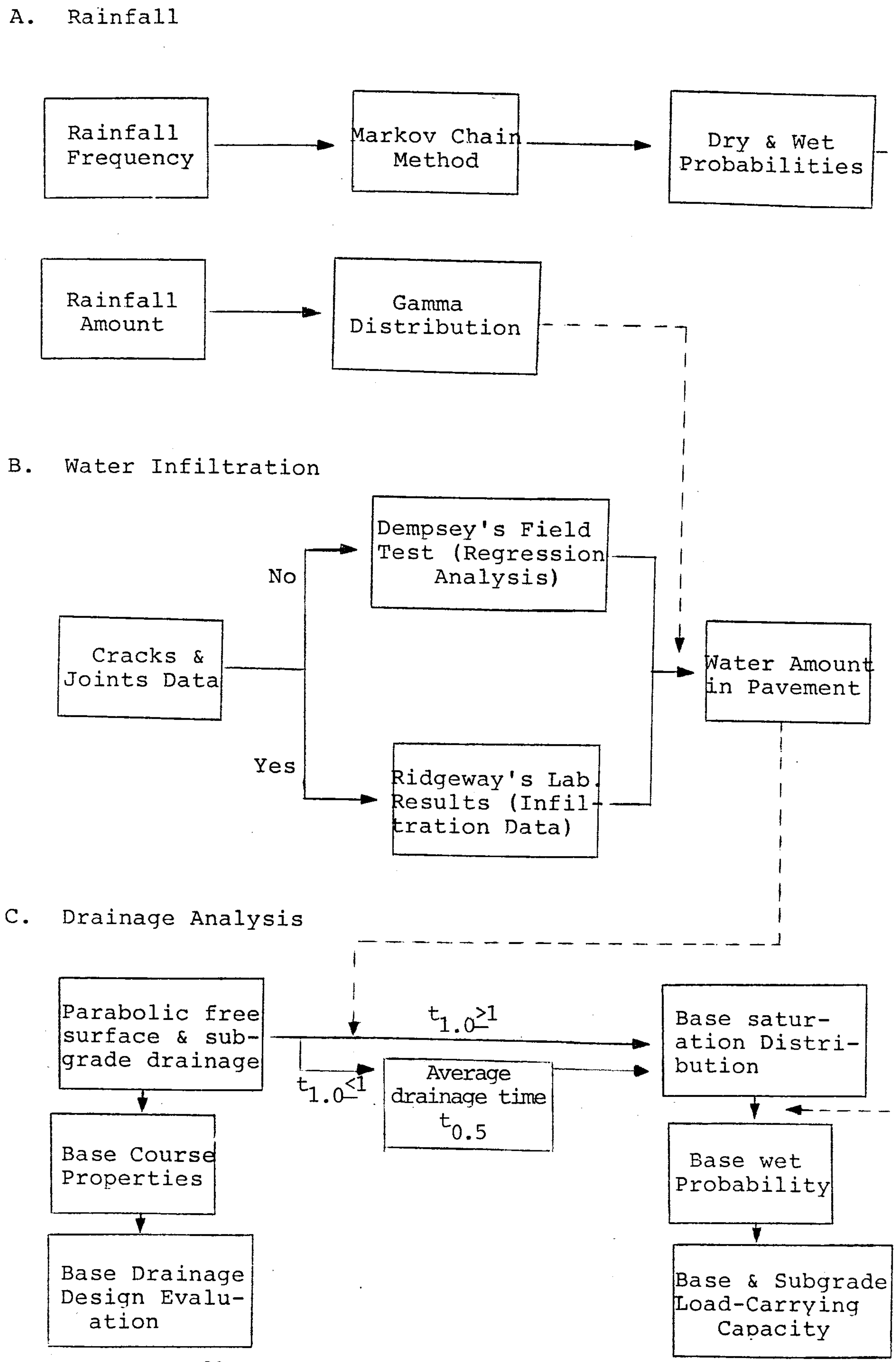


FIGURE 20. Flow Chart for Conceptual Model of Rainfall Infiltration and Drainage Analysis of Pavements

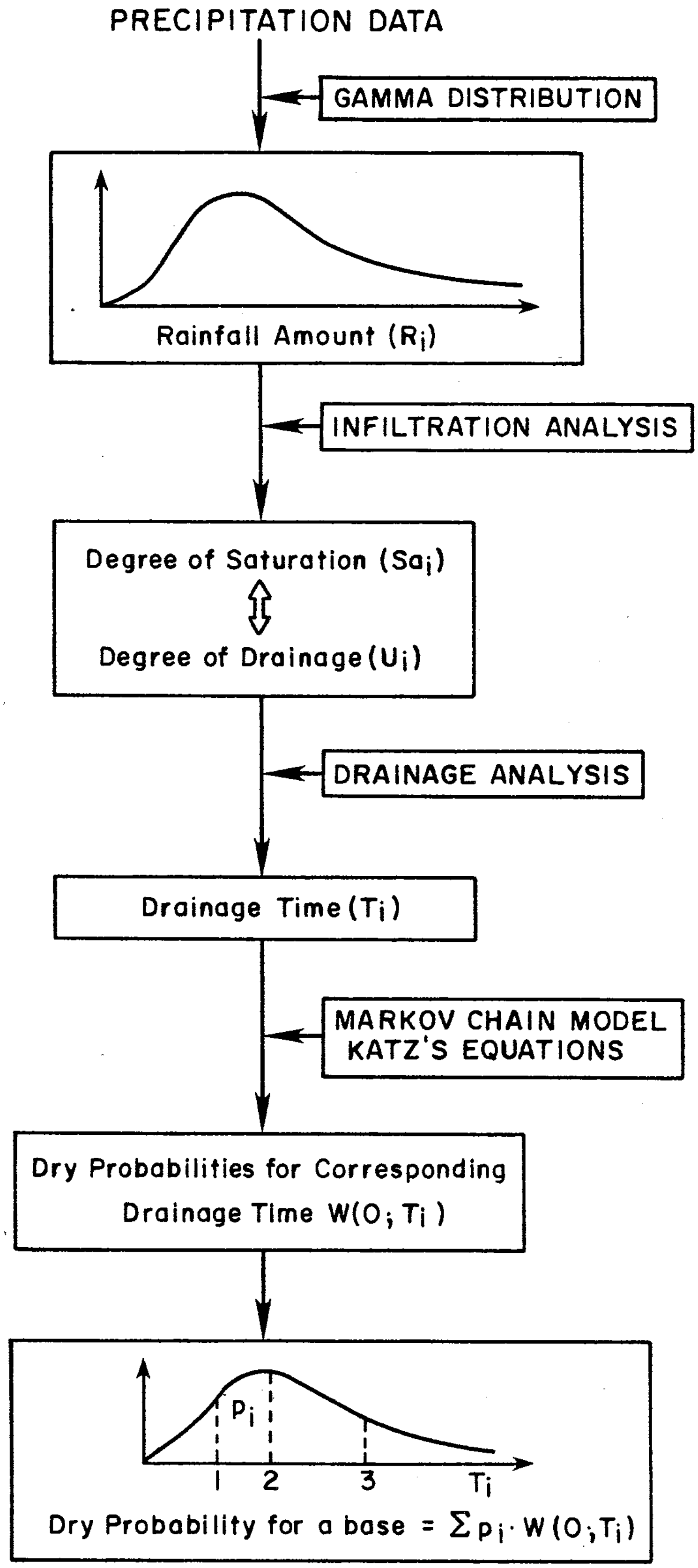


FIGURE 21. Synthesis of Models Used in Systematic Analysis of Rainfall Infiltration and Drainage Analysis of a Pavement

course and drainage analysis, are applied to estimate the probability of a base course remaining dry or wet. After taking the climatic condition, water penetration and drainage design of a base course into consideration, the distribution of various saturation levels in a base and a subgrade is then used for predicting the load carrying capacity of a pavement.

6.2 SYNTHESIS OF THE METHODS OF RAINFALL MODEL, INFILTRATION AND DRAINAGE ANALYSIS

Figure 20 indicates that a gamma distribution is used to fit the quantity of rainfall distribution, and the rate of infiltration of rainfall into a pavement is estimated using Ridgeway's (14) laboratory tests. The model for the estimation of the duration of rainfall provides the calculation of the amount of water and the degree of saturation in a base course. If the data on cracks and joints are not available, Dempsey and Robnett's (20) regression equation is used.

The computation of the time required to drain all excess water out of base courses uses the TTI drainage model. This model furnishes the relationship between drainage time and degree of drainage. The degree of drainage directly corresponds to the degree of saturation which is related to the gamma distribution and to the rainfall infiltration analysis. That is to say, the probability of having a particular amount of rainfall is given by the gamma distribution, is converted into the degree of saturation with the aid of infiltration analysis, and the degree of saturation is used to estimate the time required for draining excess water out of the base courses with the TTI drainage model.

As a result, the amount of rainfall is transformed into the corresponding drainage time in terms of days. This transformation is not linear due to the fact that the drainage curves of the TTI model are approximately a reverse S shape (see Chapter 4), while the conversions of the amount of rainfall into a degree of saturation and further into a degree of drainage are linearly correlated. In spite of this nonlinear relation between the amount of rainfall and the drainage time, the gamma distribution is used to estimate the probability of requiring a given amount of time in days to drain out a specified amount of water that infiltrates. This estimate of the probabilities of having a specific required drainage time is found by integrating the areas under the Gamma distribution curve between Ø to 1, 1 to 2, 2 to 3 days, etc.

Once those probabilities of requiring drainage periods (dry periods) of a specific length in order to remove water from a base course down to a specified level of water saturation are known, the probabilities of having consecutive dry days during which the drainage can occur can be computed by the Markov chain method and Katz's recurrence equations. The multiplication of the probability of a required drainage period and the corresponding probability of actually having that dry period gives the probability of a base course being dry at the specified saturation level.

$$BC_{dry} = P_i \times W(\emptyset;T_i) \quad \text{for } t_{1.0}>1 \qquad (6\text{-}1)$$

where

BC = the probability of a base course being dry,

P_i = the cumulative probability of required drainage time from i-1 days to i days, which is corresponds to a certain degree of water saturation,

$W(\emptyset;T_i)$ = the probability of T_i consecutive dry days from Katz's model (13), and

$t_{1.0}$ = the time, in days, required to drain 100% of free water from a base course.

While for $t_{1.\emptyset}<1$, i.e., all the free water can be drained from a base course within one day, the following equation is applied

$$BC_{dry} = 1-(P_{wet})^{t_{\emptyset.5}} \quad \text{for } t_{1.0}\leq 1 \qquad (6\text{-}2)$$

where

BC_{dry} and $t_{1.\emptyset}$ defined as in Equation 6-1.

P_{wet} = the probability of wet days in the season concerned, and

$t_{0.5}$ = the time, in days, required to drain 50% of free water from a base course, which is considered as the average draining time.

Equation 6-2 is substituted for Equation 6-1 whenever it takes less than one day to drain all free water from a base course after it is fully saturated by rainfall. This is due to the fact that Katz's model is incorporated in Equation 6-1 in calculating the probabilities of consecutive dry days, and it is only on a daily basis, which is considered inadequate for estimating the dry probability for a base course when all the free water is drained within 24 hours. For example, there is no difference in estimating the probability of one base course being dry which takes one hour to drain 100% of the free water and the same probability of another base course which takes 24 hours to reach a dry state.

Two assumptions are made for Equations 6-1 and 6-2,

(1) Entrance of free water from rainfall into the pavement is instantaneous,

(2) No two raining periods occur on any single dry day when $t_{1.0}$ is less than one day.

In summary, as a result of these calculations, the probability of having a dry base under local weather conditions may be evaluated by Equations 6-1 for $t_{1.0}>1$ and Equation 6-2 for $t_{0.1}\leq 1$, respectively.

The average base course modulus for a pavement is computed by incorporating into the analysis the wet conditions in a base due to the precipitation, the material strength of the base course affected by different saturation levels, and the dry-wet probabilities of that base course.

Since the rainfall amount is converted into the saturation level, the corresponding material strength may be calculated by using Haynes and Yoder's (27) laboratory test results. The average base modulus under wet conditions can thus be estimated by finding the average for the gamma distribution. Furthermore, because the probability of having a wet base is known as mentioned above, and because the base course material maintains its full modulus under dry conditions, consequently the average base course modulus may be computed.

A series of sample calculations from the computer program are listed in Tables 5-9. The rainfall data is for Houston Intercontinental Airport for May 1970, and a pavement structure is assumed for illustration. The pavement is 100 feet wide on one side, the base course is 6 inches thick, and the subgrade is permeable. Table 5 shows the degree of drainage and the draining time under the given base materials by using the TTI drainage model. The evaluation of a drainage design (26) is presented in Table 6.

Based on the weather data and pavement structure, the drainage time, degree of drainage and corresponding probabilities are calculated in Table 7. Table 8 gives the characteristics of gamma distribution and related material properties under local rainfall conditions, and Table 9 shows the rainfall effect on the base and subgrade moduli.

TABLE 5. TTI DRAINAGE MODEL FOR AN ANALYSIS OF A HOUSTON PAVEMENT

Problem Number 1 -- Analysis of Houston Pavement in May 1970.

System Analysis of Rainfall Infiltration and Drainage

Length	Height	Slope%	Perm.1	Perm.2	Poro.1	Poro.2
50.00	0.50	1.50	10.00000	0.00100	0.2000	0.0500

(1, 2 stand for base course and subgrade, respectively)

Note: The following analysis is based on parabolic phreatic surface plus subgrade drainage

Drainage %	Hours
5.0	0.202E 00
10.0	0.760E 00
15.0	0.165E 01
20.0	0.282E 01
25.0	0.426E 01
30.0	0.595E 01
35.0	0.788E 01
40.0	0.101E 02
45.0	0.125E 02
50.0	0.151E 02
55.0	0.198E 02
60.0	0.256E 02
65.0	0.323E 02
70.0	0.403E 02
75.0	0.499E 02
80.0	0.620E 02
85.0	0.779E 02
90.0	0.100E 03
95.0	0.137E 03
100.0	0.187E 03

TABLE 6. TTI DRAINAGE MODEL FOR EVALUATION OF A DRAINAGE DESIGN OF A HOUSTON PAVEMENT

Evaluation of Drainage Design

Water Drained Percentage Due to Gravel	=	80.00
Percentage of Gravel in the Sample	=	70.00
Water Drained Percentage Due to Sand	=	65.00
Percentage of Sand in the Sample	=	30.00
Percentage of Water Will be Drained	=	75.50
Critical Drainage Degree (85% Saturation)	=	19.87
Draining Time for 85% Saturation (Hours)	=	2.79

This Drainage Design is Satisfactory

TABLE 7. MARKOV CHAIN MODEL AND KATZ'S RECURRENCE EQUATIONS FOR DRY PROBABILITIES VERSUS A DRAINAGE CURVE OF A HOUSTON PAVEMENT

Time (days)	Drainage (%)	Prob (Consecutive Dry Days)
1	58.72	0.710
2	74.08	0.554
3	83.32	0.432
4	89.17	0.338
5	98.02	0.264
6	95.57	0.206
7	97.30	0.161
8	100.00	0.125

TABLE 8. Stochastic Models for a System Analysis of Rainfall Infiltration and Drainage Analysis of a Houston Pavement

Parameters of Gamma Distribution and Markov Chain Model		
Rainfall Average Per Wet Day (inches)	=	1.649
Variance of Rainfall Amount	=	2.341
Alpha of Gamma Distribution	=	1.161
Beta of Gamma Distribution	=	0.704
Lamda of Dry Days (Markov Process)	=	0.409
Lamda of Wet Days (Markov Process)	=	1.000
Sum of Lamda of Dry and Wet Days	=	1.409
Probability of Dry Days	=	0.710
Probability of Wet Days	=	0.290
Water Carrying Capacity of Base (sq. ft.)	=	5.000
Average Degree of Drainage per hour (%)	=	3.303
Overall Probability of Saturated Base	=	0.225
Dry Probability of Base Course	=	0.517
Wet Probability of Base Course	=	0.483

(The analysis for water entering pavement is based on Dempsey's Infiltration Equation.)

TABLE 8. Stochastic Models for a System Analysis of Rainfall Infiltration and Drainage Analysis of a Houston Pavement (cont'd)

Probability Distribution of Modulus of Base Course

Saturation Level (%)	10	20	30	40	50	60	70	80	90	100
Water in Base (sq.ft.)	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
Rainfall Qt. (inches)	0.19	0.44	0.69	0.94	1.19	1.44	1.69	1.94	2.19	2.44
Rain Duration (hours)	0.00	0.06	0.35	1.21	3.09	6.62	12.54	21.76	35.31	54.37
Base Moduli (ksi)	64.60	64.60	64.60	64.60	64.60	64.60	29.36	19.00	5.07	2.14
Ratio of Dry Modulus	1.00	1.00	1.00	1.00	1.00	1.00	0.45	0.29	0.08	0.03
Subgrade Moduli (ksi)	29.61	27.99	26.36	24.69	22.97	20.05	16.70	12.75	7.68	1.52
Probability Density	0.48	0.46	0.41	0.37	0.32	0.27	0.24	0.20	0.17	0.15
Probability	0.08	0.12	0.11	0.10	0.09	0.07	0.06	0.05	0.05	0.04
Cumulative Probability	0.08	0.20	0.31	0.41	0.50	0.57	0.63	0.69	0.74	0.78

TABLE 9. EVALUATION OF RAINFALL EFFECT ON PAVEMENT PERFORMANCE OF A HOUSTON PAVEMENT

Distribution Characteristics of Rainfall Effect

Average Free Water in Base	(Sq Feet)	=	1.07
Duration of Average Rainfall Amount	(Hours)	=	0.08
Average Rainfall Amount Per Day	(Inches)	=	0.479
Average Base Course Modulus in Wet State	(ksi)	=	41.45
Average Base Course Modulus	(ksi)	=	53.41
Average Subgrade Modulus	(ksi)	=	27.30

6.3 DATA REQUIRED FOR ANALYSIS AND SAMPLE RESULTS

The following data should be provided by the users of the computer program listed in Appendix V that has been written to make these calculations. Default values for certain of the parameters are incorporated in the program.

(A) Simulation Model (see Appendix E-3)

(1) Field data for the base course and subgrade, which include: the half width, height, slope (%), as well as coefficients of permeability and porosity of base course and subgrade, respectively.

(2) Evaluation of base drainage design, input the percentage of fines (e.g., <2.5%, 5%, 10%), types of fines (e.g., inert filler, silt, clay) and percentage of gravel and sand in the base (see Table 2).

(3) Pavement structure and materials data, which include the total area of cracks and joints, the pavement type (Portland cement concrete or asphalt concrete), base materials (Table 3), the soil type and horizon of subgrades (Table 4), and total length surveyed.

(4) Climatic data, which include: intended evaluation period, rainfall amount of every rainy day (precipitation ≥ 0.01 inch) during that season, and the sequential number of wet and dry days.

(5) The weather parameters which depend on the

locality, k, x, n and shape factor (SF) in Chapter 2. The default values for these parameters in order are Ø.3, Ø.25, Ø.75 and 1.65, respectively.

The printout of the program mainly consists of four parts.

(1) Drainage analysis with TTI drainage model,

(2) Evaluation of the drainage design, the output evaluates the drainage design to be one of the three categories: unacceptable, marginal, and satisfactory;

(3) Parameters of the climate, the alpha (α) and beta (β) of the Gamma distribution, the wet and dry probabilities of the weather and the base course from the Markov chain model and Katz's recurrence equations,

(4) The probability density distribution and averages of the base course and subgrade moduli due to the distribution of saturation levels.

(B) Low Permeability Base Courses Model.

(1) Input the data of each crack width and depth, the coefficients of horizontal and vertical permeability, respectively, porosity of the base course and the capillary head in order to estimate the rate and depth of water penetration into the base course.

(2) The suction of atmosphere, the initial suction of

base course, diffusion coefficient, ratio of water content and suction and evaporation constant to calculate the rate and the amount of water evaporated from the base course.

The output gives:

(1) The horizontal and vertical distances which water flows at different times and the depth of water remaining in the crack.

(2) The distribution of suction at different times and different soil depths.

(3) The amount of water evaporated from the base course at different times.

6.4 AN EXAMPLE OF SYSTEMATIC ANALYSIS OF RAINFALL INFILTRATION, DRAINAGE, AND LOAD-CARRYING CAPACITY OF PAVEMENTS

The following conclusions result from a case study of the effects of rainfall amount and subgrade drainage on the load-carrying capacity of a pavement. It is assumed that a base course is 70% gravel, 30% sand, 100 feet wide, 6 inches deep, 1.5% slope, the coefficient of permeability of the base course is 10 feet per hour, and the porosity is 0.1, and the subgrade is assumed to be impermeable. The drainage design used is considered marginally acceptable in terms of the drainage time of 6.35 hours required to reach a less than 85% saturation level in the base.

In two climatic regions this same design for a base course is used. Abilene and Houston, Texas, represent low and high rainfall areas, respectively. Daily rainfall data from 1970 were entered into the simulation model to compare the results for these cities. The results (Figure 22) show that the precipitation quantity affects the elastic moduli of the base course. If the water in the base course can drain into the subgrade with a permeability of 0.01 ft/hour and a porosity for freely draining water of 0.01 in a higher rainfall area, i.e. Houston, the load-carrying capacity can be improved significantly.

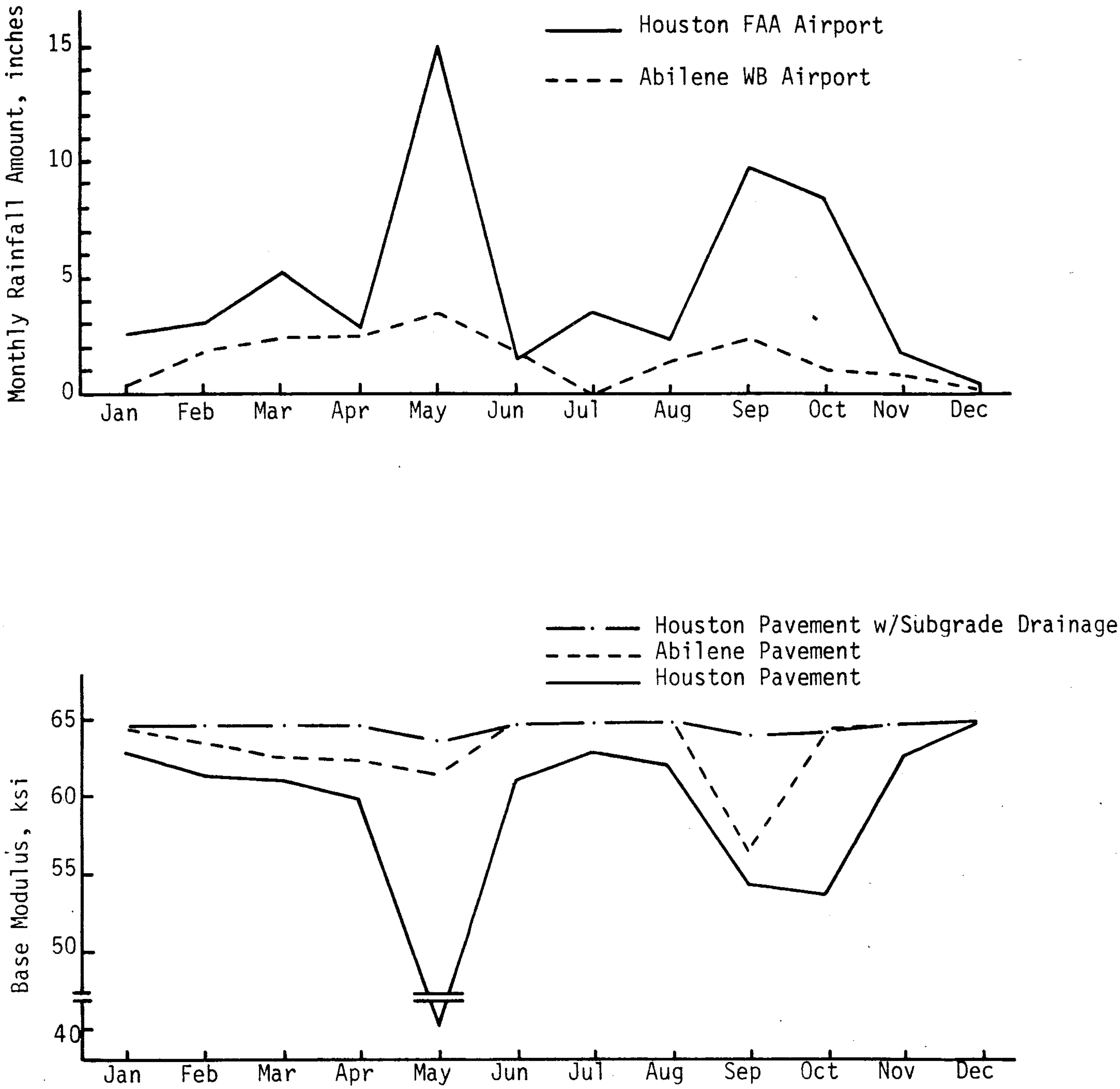


FIGURE 22. Effects of Rainfall Amount and Subgrade Drainage on Load-Carrying Capacity of Pavements

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

A systematic analysis is constructed which incorporates a probability distribution of the amount of rainfall, the probabilities of dry and wet days, water infiltration into pavements, drainage analysis of pavements, and load-carrying capacities of base courses and subgrades. The simulation model presented herein is a major advance over other methods that have been used previously for the same purpose.

The new method has been developed for computing the drainage of the pavement base and subgrade models using a parabolic phreatic surface and allowing drainage through a permeable subgrade. A model of water penetration into low permeable base courses is also constructed.

This comprehensive analysis of the effect of rainfall on pavement structures, is recommended as an effective approach to evaluate design criteria for pavement and overlay construction and to estimate future environmental effects on pavements.

REFERENCES

1. Casagrande, A. and Shannon, W. L., "Base Course Drainage for Airport Pavement", Proceedings of the American Society of Civil Engineers, Vol. 77, June, 1951.

2. Cedegren, H. R., "Drainage of Highway and Airfield Pavements", Wiley, New York, 1974.

3. Markow, M. J., "Simulating Pavement Performance Under Various Moisture Conditions", TRB, Transportation Research Record, 849, 1982, pp. 24-29.

4. Polubarinova-Kochina, P. Ya., "Theory of Ground Water Movement", Translated by J. M. Roger De Wiest, Princeton University Press, New Jersey, 1962.

5. Kottegoda, K. T., "Stochastic Water Resources Technology", Wiley, New York, 1980.

6. Suzuki, E., "Hyper-Gamma Distribution and Its Fitting to Rainfall Data", Papers in Met. and Geoph., 15, 1964, pp. 31-35.

7. Suzuki, E., "A Summarized Review of Theoretical Distributions Fitted to Climatic Factors and Markov Chain Models of Weather Sequences, with Some Examples", Statistical Climatology, Elsevier, Amsterdam, Netherlands, 1980, pp. 1-20.

8. Fair, G. M., Geyer, J. C., and Okum, D. A., "Water and Wastewater Engineering", Vol. 1, Water Supply and Wastewater Removal. Wiley, New York, 1966.

9. Linsley, R. K., Jr. and Franzini, J. B., "Elements of Hydraulic Engineering", McGraw-Hill, New York, 1955.

10. Kazmann, R. G., "Modern Hydrology", Harper and Row, New York, 1965.

11. Am. Soc. Civ. Eng., "Hydrology Handbook", Manual of Engineering Practice, No. 28, 1949.

12. Gabriel, K. R. and Neumann, J., "A Markov Chain Model for Daily Rainfall Occurrence at Tel Aviv", Quart. J. Roy. Met. Soc. 88, 1962, pp. 90-95.

13. Katz, R. W., Computing Probabilities Associated with the Markov Chain Model for Precipitation. Journal of Applied Meteorology 13, 1974, pp. 953-954.

14. Ridgeway, H. H., "Infiltration of Water Through the Pavement Surface", TRB, Transportation Research Record 616, 1976, pp. 98-100.

15. Ring, G. W., "Drainage of Concrete Pavement Structures", Proceedings of International Conference on Concrete Pavement Design, Purdue University, West Lafayette, Indiana, 1977.

16. Woodstrom, J. H., "Improved Base Design for Portland Cement Concrete Pavements", Proceedings of International Conference on Concrete Pavement Design, Purdue University, West Lafayette, Indiana, 1977.

17. Barksdale, R. D. and Hicks, R. G., "Drainage Considerations to Minimize Distress at the Pavement-Shoulder Joint", Proceedings of International Conference on Concrete Pavement Design, Purdue University, West Lafayette, Indiana, 1977.

18. Dempsey, B. J., Darter, M. I., and Carpenter, S. H., "Improving Subdrainage and Shoulders of Existing Pavement-State-Of-The-Art", University of Illinois, Urbana, Interim Report, 1977.

19. Darter, M. I. and Barenberg, E. J., "Zero-Maintenance Pavements: Results of Field Studies on Performance Requirements and Capabilities of Conventional Pavement Systems", FHWA Report, FHWA-RD-76-105, 1976.

20. Dempsey, B. J. and Robnett, Q. L., "Influence of Precipitation, Joints, and Sealing on Pavement Drainage", TRB, Transportation Research Record 705, 1979, pp. 13-23.

21. Mitchell, P. W., "The Structural Analysis of Footings on Expansive Soil", K. W. G. Smith & Associates Research Report No. 1, Adelaide, Australia, 1980.

22. Barber, E. S. and Sawyer, C. L., "Highway Subdrainage", Public Roads, Vol. 26, No. 12, 1952.

23. Moulton, L. K., "Highway Subdrainage Design", FHWA Report, FHWA-TS-80-224, 1980.

24. Wallace, K. and Leonardi, F., "Theoretical Analyses of Pavement Edge Infiltration and Drainage", James Cook University, Australia, Department of Civil Engineering, Research Report 6, 1975.

25. Liu, S. J., Jeyapalan, J. K, and Lytton, R. L., "Characteristics of Base and Subgrade Drainage of Pavements", Sixty-Second Annual Transportation Research Board Meeting, 1983.

26. Carpenter, S. H., Darter, M. I., and Dempsey, B. J., "A Pavement Moisture Accelerated Distress (MAD) Identification System, Vol. 2, FHWA Report, FHWA-RD-81-080, 1981.

27. Haynes, J. A. and Yoder, E. J., "Effects of Repeated Loadings on Gravel and Crushed Stone Base Materials in the AASHO Road Test", Highway Research Record 19, 1963, pp. 82-96.

28. Martin, G. R. and Toan, D. V., "Effect of Base Course Saturation on Pavement", Proceedings of Roading Symposium, Vol. 2, 1971, pp. 486-491.

29. Barenberg, E. J. and Thompson, O. O., "Behavior and Performance of Flexible Pavements Evaluated in the University of Illinois Pavement Test Track", Highway Engineering Series No. 36, Illinois Cooperative Highway Research Program Series No. 108, 1970.

30. Moynahan, T. J., Jr. and Sternberg, Y. M., "Effects on Highway Subdrainage of Gradation and Direction of Flow Within a Densely Graded Base Course Material", TRB, Transportation Research Record 497, 1974, pp. 50-59.

31. Lytton, R. L. and Michalak, C. H., "Flexible Pavement Deflection Equation Using Elastic Moduli and Field Measurements", Research Report No. 207-7F, Texas Transportation Institute, Texas A&M University, College Station, Texas, August, 1979.

32. Yoder, E. J. and Witczak, M. W., "Principles of Pavement Design", 2nd ed., Wiley, New York, 1975.

33. Thompson, M. R. and Robnett, Q. L., "Resilient Properties of Subgrade Soils", Transportation Engineering Journal, ASCE, 1979, pp. 71-89.

34. Taha, H. A., "Operations Research 2nd ed.", MacMillian, New York, 1976.

APPENDIX A

Rainfall Amount Distribution, Rainfall Duration and Markov Chain Model

A-1. RAINFALL AMOUNT DISTRIBUTION

Among the theoretical distribution models of precipitation, the Gamma distribution has a long history as a suitable model for frequency distributions of precipitation. The probability density function of the Gamma distribution is:

$$f(R;\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} e^{-\beta R} R^{\alpha-1} \quad , \quad R \geq 0 \qquad \text{(A-1)}$$

$$0 \quad , \quad R<0$$

where

R = precipitation amount and

$\Gamma(\alpha)$ = Gamma function where (n+1)=n! n=Ø, 1, 2, ---.

The parameters and may be estimated by the moments method:

$$\alpha = \bar{R}^2/S^2 \qquad \bar{R} = \text{mean} = \Sigma Ri/n \qquad \text{(A-2)}$$

$$\beta = \bar{R}/S^2 \qquad S^2 = \text{variance} = \sum^{n}(Ri-\bar{R})^2/n \qquad \text{(A-3)}$$

A-2. RAINFALL DURATION

In Ridgeway's laboratory tests (14), he concluded that rainfall duration is more important than rainfall intensity in determining the amount of free water that will enter the pavement structure. The relation between rainfall intensity, i, and duration, t_R, has often been expressed in the intensity-duration-recurrence period equation, (9)

$$i = \frac{ktp^x}{t_R^n} \qquad \text{(A-4)}$$

where

t_R is the effective rainfall duration in minutes,

t_p is the recurrence interval in years,

i is the maximum rainfall intensity, inches per hour, during the effective rainfall duration, and

k, x, and n are constants which depend on the locality.

For instance, in the eastern United States, n averages about 0.75 and x and k are about 0.25 and 0.30, respectively. It is assumed that the relation between rainfall intensity and time is a Gaussian curve (Figure 1).

Using the standard normal distribution, a rainfall duration, t_R, was chosen from -1.96 to 1.96 which made the area under the curve to be 0.95. Furthermore, i corresponds to Ø.3989 in the standard normal distribution curve. Therefore, the ratio between the product $(t_R)i$ and the total amount of rainfall during effective duration, R, is

$$\frac{(t_R)i}{R} = \frac{t_R x i}{0.95} = \frac{3.92 \times 0.3989}{0.95} = 1.65 \qquad \text{(A-5)}$$

which is called the shape factor (SF).

The next step is to derive the formula for rainfall amount, R, and effective rainfall duration, t_R, from the intensity-duration-recurrence equation:

$$R = \frac{t_R i}{SF}$$

$$= (t_R)(kt_p^{\ x})/(t_R^{\ n})(SF)$$

$$= kt_R^{\ (1-n)} t_p^{\ x}/(SF) \qquad \text{(A-6)}$$

$$\text{Thus, } t_R = \left[\frac{R(SF)}{kt_p^{\ x}}\right]^{\frac{1}{1-n}} \qquad \text{(A-7)}$$

The constant for shape factor (SF) could be determined and entered by the user (for example, 1.Ø for uniform distribution and 1.5 for parabolic curves).

In the computer programs, the users are allowed to choose the constants n, x, k, and shape factor. In the meantime, the default numbers have been set up to be Ø.75, Ø.25, Ø.3Ø, and 1.65, respectively.

A-3. Markov Chain Model for a Time Sequence of Weather Observation

A transition probability matrix generated from the Markov chain method for predicting weather sequences is represented by four elements, represented by the probabilities given in the matrix below. The matrix is known as a "transition" matrix.

$$P(t) = [p_{ij}(t)] = \begin{bmatrix} p_{00}(t) & p_{01}(t) \\ p_{10}(t) & p_{11}(t) \end{bmatrix} \qquad \text{(A-8)}$$

where p_{ij} represents the probability that the Markovian system is in state j at the time t given that it was in state i at time 0; the subscript 0 stands for dry, and a subscript of 1 for wet. Thus $p_{10}(t)$ represents the probability of having a dry day at time t when time 0 is a wet day, and other elements of this matrix can be illustrated in a similar manner.

The transition probability matrix of the Markov chain model is derived from the assumption that the sequence of events, i.e., wet and dry days, is a negative exponential distribution.

$$f(x) = \lambda e^{-\lambda x} \qquad x > 0, \quad > 0, \text{ and}$$

$$x = \text{wet or dry days} \tag{A-9}$$

The variable λ is the reciprocal of the average dry or wet days per period,

$$\lambda_d = \frac{1}{\bar{x}_{dry}} \quad \text{and} \quad \lambda_w = \frac{1}{\bar{x}_{wet}} \tag{A-10}$$

where

$\bar{x}_{dry}$ = the average number of dry days in a given period

$\bar{x}_{wet}$ = the average number of wet days in that same period.

So that the transition matrix is derived as (34)

$$p(t) = \frac{1}{\lambda_w+\lambda_d} \begin{bmatrix} \lambda_w+\lambda_d \; e^{-(\lambda_w+\lambda_d)t} & \lambda_d[1-e^{-(\lambda_w+\lambda_d)t}] \\ \lambda_w[1-e^{-(\lambda_w+\lambda_d)t}] & \lambda_d+\lambda_w e^{-(\lambda_w+\lambda_d)t} \end{bmatrix} \tag{A-11}$$

Associated with the Markov chain model given above is a recurrence relation for computing the probabilities of dry and wet days which was applied by Katz (13).

$$\begin{bmatrix} W_0(k;N) \\ W_1(k;N) \end{bmatrix} = \underbrace{\begin{bmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{bmatrix}}_{\text{Transition Matrix}} \times \begin{bmatrix} W_0(k;N-1) \\ W_1(k-1;N-1) \end{bmatrix} \tag{A-12}$$

where

$W_0(k;N)$ = the probability of k wet days during N consecutive days when the zero-th day is dry (the subscript Ø stands for the zero-th day equals dry and the subscript 1 stands for the zero-th day equals wet, and the transition matrix is derived from the Markov chain method (Equation A-11). Since the recurrence relation is on a daily basis, the time t is set at 1 day in the transition matrix. Also, the probability of occurrence of a given number of wet days in a period of time is formulated as (13)

$$W(k;N) = (1-p_0)W_0(k;N) + p_0 W_1(k;N) \qquad \text{(A-13)}$$

where

$W(k;N)$ = the probability of having k wet days during N consecutive days

$p_\emptyset$ = initial probability of having a wet day.

Application of Katz's equations to the Markov chain model results in finding the probability of having k wet days out of N consecutive days. In order to have exactly k wet days out of N, either (1) the first day is dry and exactly k of the remaining N-1 days are wet, i.e., $W_\emptyset(k;N-1)$, or (2) the first day is wet and exactly k-1 of the remaining N-1 days are wet, i.e., $W_1(k-1;N-1)$ (Figure 23). Suppose that the zero-th day is dry, then the probability of the first day being dry is $p_{\emptyset\emptyset}$ and the probability for the first day being wet if $p_{\emptyset 1}$. Therefore, when the zero-th day is dry, the probability of exactly k wet days out of N consecutive days is the

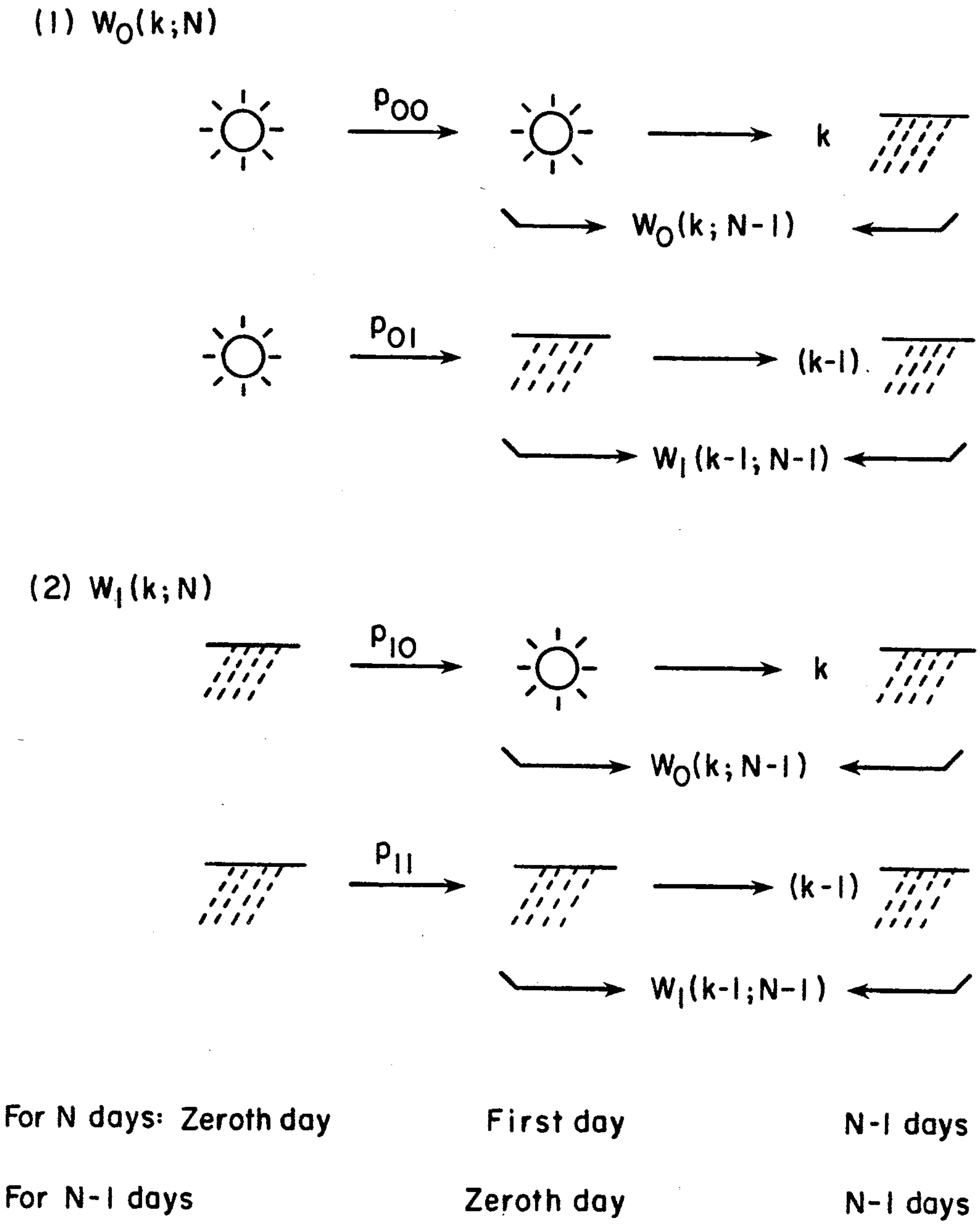


FIGURE 23. Definition Sketch of Katz Model

probability of the first day remaining dry from zero-th day ($p_{\emptyset\emptyset}$) multiplied by the probability of having k wet days of the remaining N-1 days, $W_{\emptyset}(k;N-1)$, plus the probability of changing from a dry zero-th day to a wet first day ($p_{\emptyset 1}$) multiplied by the probability of having k-1 wet days in the remaining N-1 days, $W_1(k-1;N-1)$; so that

$$W_0(k;N) = p_{00}W_0(k;N-1) + p_{01}W_1(k-1;N-1) \qquad \text{(A-14)}$$

Similarly, if the zero-th day is wet, the probability of k wet days out of a sequence of N days is

$$W_1(k;N) = p_{10}W_0(k;N-1) + p_{11}W_1(k-1;N-1) \qquad \text{(A-15)}$$

Equation A-12 is simply a matrix form of Equations A-14 and A-15. The total probability of having k wet days out of N consecutive days is further dependent on the initial probability of having a wet day ($p_{\emptyset}$ of Equation A-13).

APPENDIX B

Parabolic Phreatic Surface Drain Models
for Base Courses with Impermeable Subgrades

B-1. Analysis of Horizontal Bases with Impervious Subgrades

The shape of free water surface is to reamin a parabola that changes with time throughout the analysis. Two separate stages are identified and illustrated in Figure 24; ABCD is the boundary of one-side base and point B is the origin of this system.

$$y = \sqrt{ax} \tag{B-1}$$

$$a = \frac{H^2}{x_1}$$

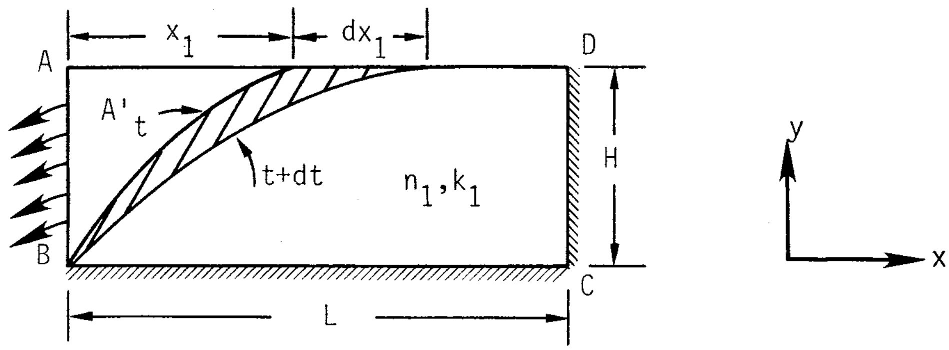
$$\text{Drained Area} = A' = \frac{Hx_1}{3} \tag{B-2}$$

The rate of water amount (q) change is

$$dq = n_1 \cdot \frac{dA}{dx_1} \cdot dx_1 = \frac{n_1 H}{3} dx_1 \tag{B-3}$$

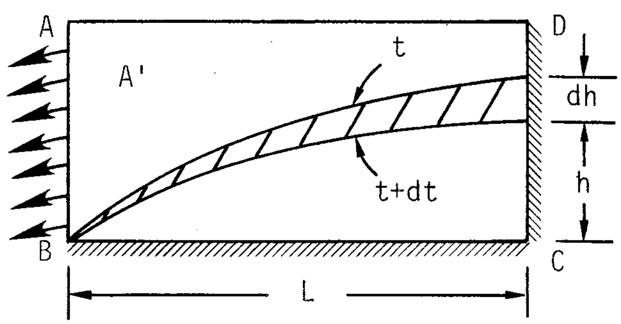
The flow from time t to t+dt is computed by means of Darcy's law and Dupuit's assumption. The hydraulic gradient, i, is $\frac{dy}{dx}$, and the average flow area per unit of width is y;

$$\frac{dq(x)}{dt} = k_1 iy = k_1 \cdot \frac{dy}{dx} \cdot y = \frac{k_1}{2x_1} H^2 \tag{B-4}$$



Stage I. $0 \leq U \leq \frac{1}{3}$

U = Degree of Drainage.
n_1 = Effective porosity of the base course.
k_1 = Coefficient of permeability of the base course.
t = Time.



Stage II. $\frac{1}{3} \leq U < 1$

FIGURE 24. Stages of Parabolic Phreatic Surface in a Horizontal Base

Combining Equations B-3 and B-4, a differential equation can be derived, the solution of which leads to

$$t = \frac{1}{3}\,\frac{n_1 x_1^{\;2}}{k_1 H} \qquad \text{(B-5)}$$

Two dimensionless quantities, introduced by Casagrande and Shannon (2), are called the degree of drainage (U) and the time factor (T), respectively:

$$U = \frac{\text{Drained Area}}{\text{Total Area}} \qquad \text{(B-6)}$$

$$T = \frac{t k_1 H}{n_1 L^2} \qquad \text{(B-7)}$$

Incorporating T and U ($U = \frac{x_1}{3L}$) into Equation B-5 gives

$$T = 3U^2 \quad T = 3U^2 \qquad \text{(B-8)}$$

which is valid for $0 \leq U \leq \frac{1}{3}$ of horizontal bases.

The second part, Stage 2, of the drainage process, where the variable parabola has a constant base length L and a variable height, h, (Figure 24) is developed in a manner similar to the development of Stage 1.

$$A' = HL - \frac{2}{3}hL \qquad \text{(B-9)}$$

$$dq = -\frac{2}{3}\, n_1 L dh \qquad \text{(B-10)}$$

$$\frac{dq}{dt} = \frac{k_1}{2L}\, h^2 \qquad \text{(B-11)}$$

Combining Equations B-1Ø and B-11,

$$\int_{t_H}^{t_h} dt = \frac{-4}{3} \int_H^h \frac{n_1}{k_1 h^2} dh \qquad \text{(B-12)}$$

where t_h and t_H are the elapsed time for the free surface to hit H and h, respectively. Also

$$t_h - t_H = \frac{4}{3} \frac{n_1 L^2}{k_1} \left(\frac{1}{h} - \frac{1}{H}\right) \qquad \text{(B-13)}$$

where t_H is the time when the free water surface reaches the full base length (L) in Stage 1. Therefore,

$$t_H = \frac{1}{3} \frac{n_1 L^2}{k_1 H} \text{ , and}$$

$$t_h = \frac{n_1 L^2}{k_1} \left(\frac{4}{3h} - \frac{1}{H}\right) \qquad \text{(B-14)}$$

The final solution can be expressed by incorporating the dimensionless quantities T and U:

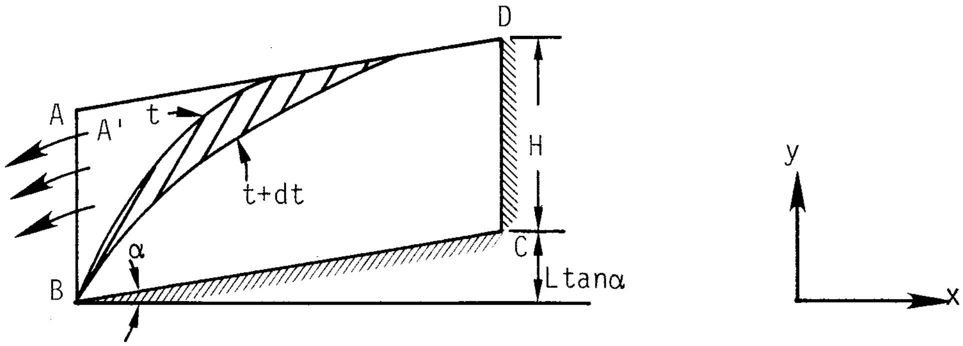
$$U = 1 - \frac{2h}{3H} \text{ , and}$$

$$T = \frac{8}{9(1-U)} - 1 \qquad \text{(B-15)}$$

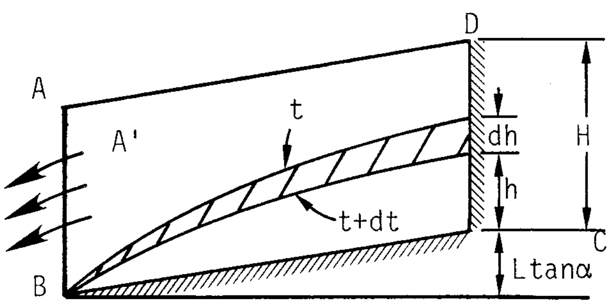
which are valid for $\frac{1}{3} \leq U < 1$ of horizontal bases.

B-2. Analysis of Sloping Bases with Impervious Subgrades

Previously, the authors made an attempt to have the phreatic surface parabola oriented with respect to the horizontal axis, which forced a limitation of the model. The limitation is that it cannot then be used to analyze pavement sections with a slope factor, S, less than 1, corresponding to base courses with high slopes (tan α) or large widths (L), or shallow depths of base courses (H). This is due to the fact that when $S<1$, the parabolic phreatic surface may rise above the top of the base course giving a physically impossible negative degree of drainage. Thus in the following development, the parabolic free water surface is described with respect to the lower boundary of the base course rather than the horizontal axis. Two stages are identified as shown in Figure 25, where ABCD is the boundary of one-side base and point B is the origin of this system.



Stage 1. $0 \leq U \leq \frac{1}{3}$



Stage 2. $\frac{1}{3} \leq U < 1$

FIGURE 25. Stages of Parabolic Phreatic Surface in a sloping Base

$$y = \sqrt{ax} + x \tan \alpha$$

$$a = \frac{H^2}{x_1}$$

$$y = \frac{H}{\sqrt{x_1}} \sqrt{x} + x \tan \alpha$$

Drained Area

$$A' = (H + x_1 \tan \alpha) x_1 - \frac{x_1^2}{2} \tan \alpha$$

$$- \int_0^{x_1} \left(\sqrt{\frac{H^2}{x_1}} \sqrt{x} + x \tan \alpha \right) dx$$

$$= \frac{H}{3} x_1 \quad \text{(B-16)}$$

$$dq = n_1 \frac{dA'}{dx_1} \cdot dx_1 = \frac{n_1 H}{3} dx_1 \quad \text{(B-17)}$$

Darcy's law $\frac{dq}{dt} = k_1 i\ y$

Therefore, $dq(x) = k_1 \cdot (y - x \tan \alpha) \cdot \frac{dy}{dx} dt$

$$= k_1 \left(\frac{H^2}{2x_1} + \frac{H \sqrt{x} \tan \alpha}{\sqrt{x_1}} \right) \quad \text{(B-18)}$$

The average rate of flow can be expressed by

$$\frac{dq}{dt} = \frac{k_1}{x_1} \int_0^{x_1} dq(x) dx$$

$$= k_1 \left(\frac{H^2}{2x_1} + \frac{2}{3} H \tan \alpha \right) \quad \text{(B-19)}$$

From Equations B-17 and B-18

$$\int_0^t dt = \int_0^{x_1} \frac{2n_1 x_1}{k_1 (3H + 4x_1 \tan \alpha)} dx_1$$

$$t = \frac{2n_1}{k_1} \left[\frac{x_1}{4\tan\alpha} - \frac{H}{16\tan^2\alpha} \ln \left(\frac{3H + 4x_1 \tan\alpha}{3H} \right) \right] \quad \text{(B-20)}$$

Let $T = t \dfrac{k_1 H}{n_1 L^2}$

Since $U = \frac{x_1}{3L}$ and $S = \frac{H}{L\tan\alpha}$

$$T_I = \frac{3}{2} SU - \frac{3}{8} S^2 \ln\left(1 + \frac{4U}{S}\right) \qquad \text{(B-21)}$$

which is valid for $0 \leq U \leq \frac{1}{3}$ of sloping bases

Stage 2:

$$y = \sqrt{ax} + x \tan \alpha$$

$$a = \frac{h^2}{L}$$

$$y = \frac{h\sqrt{x}}{\sqrt{L}} + x \tan \alpha$$

Drained Area

$$A' = (H + L \tan \alpha)\, L - \frac{1}{2} L^2 \tan \alpha - \int_0^L \left(\frac{h\sqrt{x}}{\sqrt{L}} + x\tan\alpha\right) dx$$

$$= HL - \frac{2}{3} hL \qquad \text{(B-22)}$$

$$dq = n_1 \frac{dA'}{dh} dh = -\frac{2}{3} n_1 L dh \qquad \text{(B-23)}$$

Using Darcy's law,

$$dq(x) = k_1 (y - x\tan\alpha) \frac{dy}{dx} dt$$

$$= k_1 \left(\frac{h^2}{2L} + \frac{h\tan\alpha}{\sqrt{L}} \sqrt{x}\right) \qquad \text{(B-24)}$$

$$\frac{dq}{dt} = \frac{1}{L} \int_0^L dq(x)\, dx$$

$$= k_1 \left(\frac{h^2}{2L} + \frac{2}{3} h \tan \alpha\right) \qquad \text{(B-25)}$$

From Equations B-23 and B-24

$$\int_{t_H}^{t_h} dt = \int_H^h \frac{-4\ L^2 n_1 dh}{k_1(3h^2+4hL\tan\alpha)}$$

$$\Delta t = t_h - t_H = \frac{n_1 L^2}{k_1 L\tan\alpha}\left[\ln\left(\frac{\frac{H}{h}}{\frac{3H+4L\tan\alpha}{3h+4L\tan\alpha}}\right)\right] \qquad \text{(B-26)}$$

Let $U = \dfrac{HL-\frac{2}{3}\,hL}{HL} = 1 - \dfrac{2}{3}\,\dfrac{h}{H}$

$$\Delta T = \Delta t\ \frac{k_1 H}{n_1 L^2}$$

$$= S\ \ln\left[\frac{9S-9US+8}{3(1-U)(3S+4)}\right] \qquad \text{(B-27)}$$

when x_1 reaches L in Stage 1, $U = \frac{1}{3}$

Maximum $T_I = \dfrac{S}{2} - \dfrac{3}{8}\,S^2\ \ln\left(\dfrac{3S+4}{3S}\right)$

$T_{II} = T_I\text{maximum} + \Delta T$

$$= \frac{S}{2} - \frac{3}{8}\,S^2\ \ln\left(\frac{3S+4}{3S}\right) + S\ \ln\left[\frac{9S-9US+8}{3(1-U)(3S+4)}\right] \qquad \text{(B-28)}$$

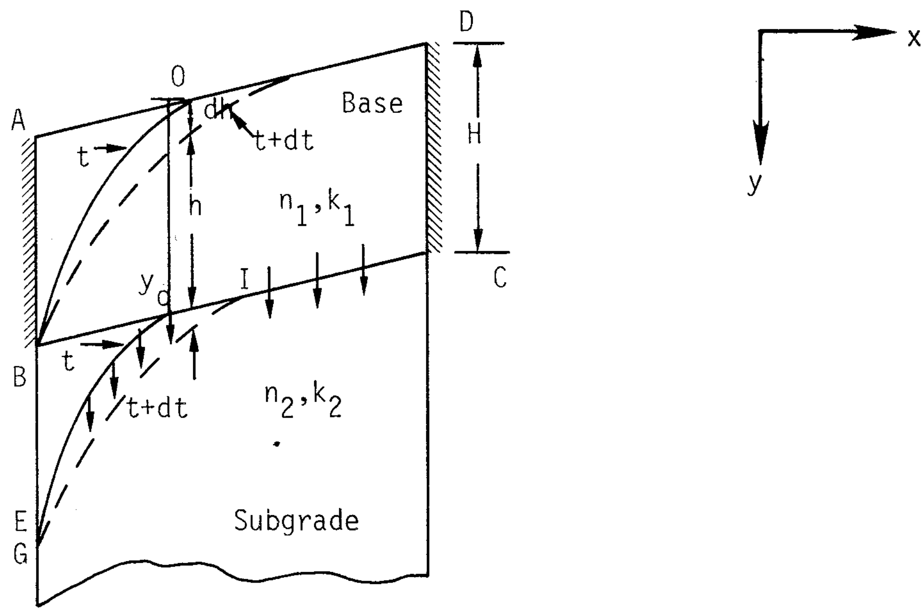
APPENDIX C

Parabolic Phreatic Surface Drain Models for Base Courses with Subgrade Drainage

The influence of subgrade drainage is discussed in this appendix. In Part C-1 (Figure 26), velocity of water penetration into the subgrade without side flow from the base course is evaluated. In Part C-2 (Figure 27), differential equations for both base and subgrade drainage are derived. In Figures 26 and 27, ABCD is the boundary of a one-side base course. Beneath the boundary BC is the subgrade into which water will penetrate. Different shapes of the wetting front in the subgrade are caused by the effect of side drainage from the base course. The wetting front in Part C-1 is parallel to the phreatic surface of the base, when there is no water flow through the base boundary. The wetting front in the subgrade of Part B will eventually reflect the image of phreatic surface in the base. It is due to the fact that the parabolic shape is created by base-edge flow and the rest of the water drained is significantly affected by infiltration into the subgrade.

C-1. WATER PENETRATION INTO THE SUBGRADE FROM A BASE COURSE

The phreatic surface of water which is affected by lateral drain might be assumed to have any kind of shape.



n = porosity
k = permeability
t = time

FIGURE 26. Water Penetration into a Subgrade without Lateral Drainage

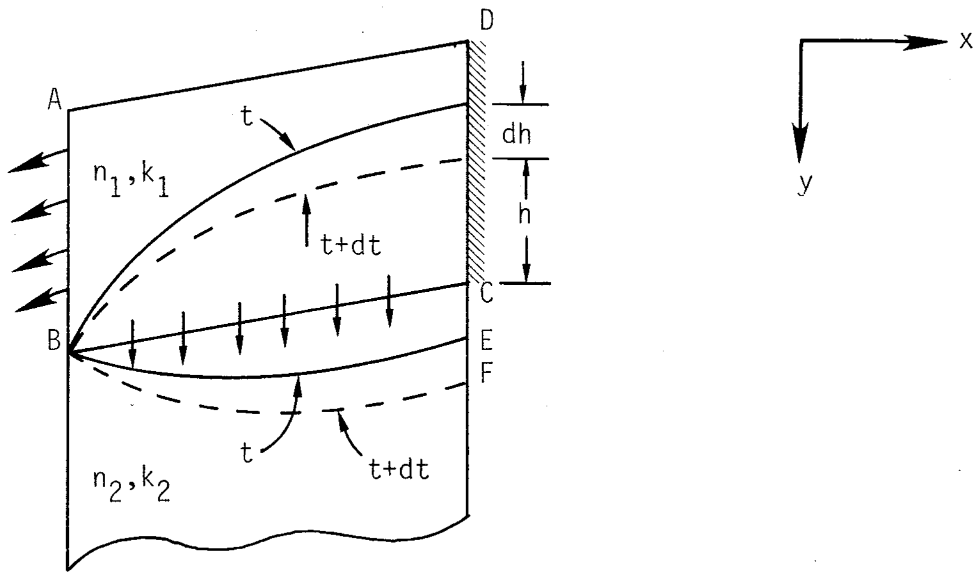


FIGURE 27. Water Penetration into a Subgrade with Lateral Drainage

The parabola drawn here is only to be consistent with the previous derivations. The datum is located at point Ø in Figure 26.

The velocity of water is generally defined as

$$V = \frac{d\phi}{dy} = -k \frac{dh}{dy} \qquad (C-1)$$

$$h = \frac{P}{\gamma_w} - y \qquad (C-2)$$

$$\phi = vy + c \qquad (C-3)$$

where v is the velocity,

ϕ is the velocity potential,

h is the total head of water,

k is the coefficient of permeability,

γ_w is the unit weight of water,

P is the pressure of water, and

c is a constant.

The velocity potential of the base course and the subgrade are ϕ_1, and ϕ_2, respectively. Applying Equations C-1 to C-3 we achieve

$$\phi_1 = -k_1 \left(\frac{P_1}{\gamma_w} - y\right), \quad v_1 = \frac{d\phi_1}{dy} \quad \phi_1 = v_1 y + c_1 \qquad (C-4)$$

$$\phi_2 = -k_2 \left(\frac{P_2}{\gamma_w} - y\right), \quad v_2 = \frac{d\phi_2}{dy} \quad \phi_2 = v_2 y + c_2 \qquad (C-5)$$

The subscript 1 stands for the parameters of the base course and 2 for those of the subgrade. At the interface of the base course and the subgrade (line BC), y=H,

$v_1 = v_2 = v$, and thus

$\frac{\phi_1}{k_1} = \frac{\phi_2}{k_2}$, and

$$\frac{vH + c_1}{k_1} = \frac{vH + c_2}{k_2} \tag{C-6}$$

In order to solve for C_1 and C_2 in terms of the parameters which we have been using, two points y=H-h and $y=y_\emptyset$ (the wetting front) are chosen.

at y=H-h, P=0

$\phi_1 = -k_1(-y) = k_1 y = k_1(H-h) = v_1(H-h)+c_1$, so that

$$c_1 = (H-h)(k_1-v_1). \tag{C-7}$$

at $y=y_0$, P=0

$\phi_2 = v_2 y_0 + c_2 = k_2 y_0$, so that

$$c_2 = (k_2-v_2)y_0. \tag{C-8}$$

Substituting Equations C-7 and C-8 into Equation C-6, we find the velocity that water penetrates from the base course into the subgrade:

$$\frac{vH+(H-h)(k_1-v)}{k_1} = \frac{vH+(k_2-v)y_0}{k_2} \quad \text{and}$$

$$v = \frac{y_0 - H+h}{\frac{h}{k_1} + \frac{y_0-H}{k_2}} \tag{C-9}$$

Furthermore, the wetting front $y_\emptyset$ must be determined.

Since $v = n_2 \frac{dy_0}{dt} = -n_1 \frac{dh}{dt}$ and

$n_2 \int_N^{y_0} dy_0 = -n_1 \int_N^{h} dh$, we have

$$y_0 = H + \frac{n_1}{n_2}(H-h) \tag{C-10}$$

which is consistent with the principle of conservation of mass. Therefore, the velocity of water penetrating into the subgrade from the base course is

$$v = \frac{\frac{n_1}{n_2}(H-h) + h}{\frac{h}{k_1} + \frac{\frac{n_1}{n_2}(H-h)}{k_2}} \tag{C-11}$$

C-2. Parabolic Phreatic Surface with Subgrade Drainage

Through the derivations in Appendix B, as well as in this Appendix, we are aware that the height from base course boundary to the water surface h (Figure 25) is dependent on the drainage through the edge line of the base course, to which we have referenced the parabolic shape. Therefore, the height is a function of both time and the horizontal coordinate, x.

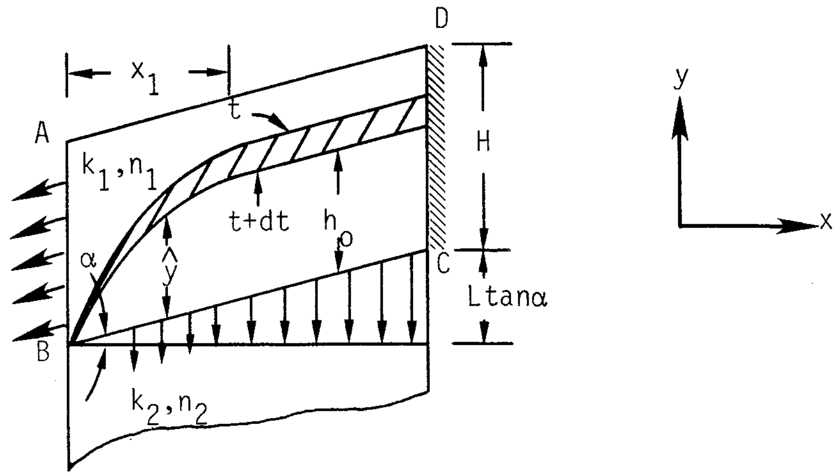
Incorporating the lateral and subgrade drainage, the model is sketched as Figure 28. Point B is the datum.

In Stage 1, the free water surface is parabolic from the origin to x_1. From x_1 to L, since the lateral drain has no effect on drainage at time t, the phreatic surface is parallel to base course lower and upper boundaries through the subgrade drainage only. In Stage 2, once the effect of water draining out from the edge line reaches the width length, L, the whole free water surface becomes a parabolic shape.

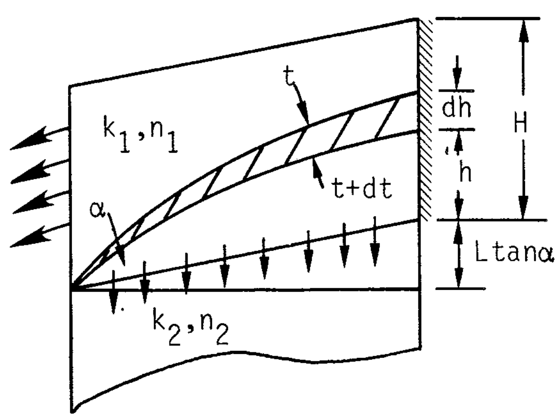
Again, by employing the same techniques used in deriving the previous equations, the geometry and the rate of the water quantity draining out are

$$\text{Stage 1} \quad dq_x = k_1 \left(\frac{h_o^2}{2x_1} + \frac{2}{3} h_o \tan \alpha\right) dt \qquad \text{(C-12)}$$

$$\text{Stage 2} \quad dq_x = k_1 \left(\frac{h^2}{2L} + \frac{2}{3} h \tan \alpha\right) dt \qquad \text{(C-13)}$$



Stage 1



Stage 2

FIGURE 28. Stages of Parabolic Phreatic Surface with both Lateral and Subgrade Drainage for a Sloping Base

The water quantity flowing through subgrade is

$$dq_y = n_2 dy_0 \, dx$$
$$= v \, dx \, dt$$

In Stage 1,

(a) from origin to x_1,

$$y = \sqrt{ax} + x\tan\alpha \quad \text{for parabolic free surface}$$

on Figure 28

$$\hat{y} = y - x\tan\alpha = \frac{h_0}{\sqrt{x_1}} \sqrt{x} \qquad \text{(C -14)}$$

$$dq_y(0-x_1) = v \, dx \, dt$$
$$= k_2 \frac{\hat{y}\,(1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H}{\hat{y}\,(\frac{k_2}{k_1} - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H} \, dxdt \qquad \text{(C -15a)}$$

(b) from x_1 to L

$$dq_y(x_1-L) = \frac{h_0\,(1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H}{h_0\,(\frac{k_2}{k_1} - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H} \, dxdt \,. \qquad \text{(C-15b)}$$

Therefore, total $\frac{dq_y}{dt}$

$$= \frac{1}{L} \Bigg[k_2 \int_0^{x_1} \frac{\hat{y}\,(1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H}{\hat{y}\,(\frac{k_2}{k_1} - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H} \, dx$$

$$+ \frac{h_0\,(1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H}{h_0\,(\frac{k_2}{k_1} - \frac{n_1}{n_2}) + \frac{n_1}{n_2}H} (L-x_1) \Bigg] \qquad \text{(C -16)}$$

In Stage 2,

$$\hat{y} = \frac{h}{\sqrt{L}} \sqrt{x}$$

$$\text{Total } \frac{dq_y}{dt} = k_2 \int_0^L \frac{\frac{h}{\sqrt{L}} \sqrt{x} \left(1-\frac{n_1}{n_2}\right) + \frac{n_1}{n_2}H}{\frac{h}{\sqrt{L}} \sqrt{x} \left(\frac{k_2}{k_1}-\frac{n_1}{n_2}\right) + \frac{n_1}{n_2}H} dx \quad \text{(C-17)}$$

Similar to the derivation in Appendix I, to combine the rate of water flow, edge and subgrade drain, and the rate of drained area change, differential equations for Stages 1 and 2 can be constructed.

$$dq = dq_x + dq_y$$

Stage 1

dq_x = Equation C-12

dq_y = Equation C-15

Runge - Kutta's numerical method is applied to solve this differential equation.

Stage 2

dq_x = Equation C -13

dq_y = Equation C -17

Simpson's Rule is applied for numerical integration here.

APPENDIX D

ENTRY AND EVAPORATION OF WATER IN A LOW PERMEABILITY BASE COURSE

D-1. WATER ENTRY INTO BASE COURSES OF LOW PERMEABILITY

Free water, mainly due to the rainfall, flows into cracks and joints of the pavement then penetrates into the base course. The water infiltration into a low-permeability base course is diffused elliptically. The elliptical shape is caused by the difference in the coefficients of permeability in the vertical and the horizontal directions, which is a result of the soil particles lying horizontally thus making it easier for water to flow horizontally than vertically.

The origin of this system is the point Ø of Figure 29, a point lying in the plane of the bottom. The two sides of the crack are symmetric about a vertical plane through Ø.

The rate of change of water amount in Area ABCD

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad \text{(D-1)}$$

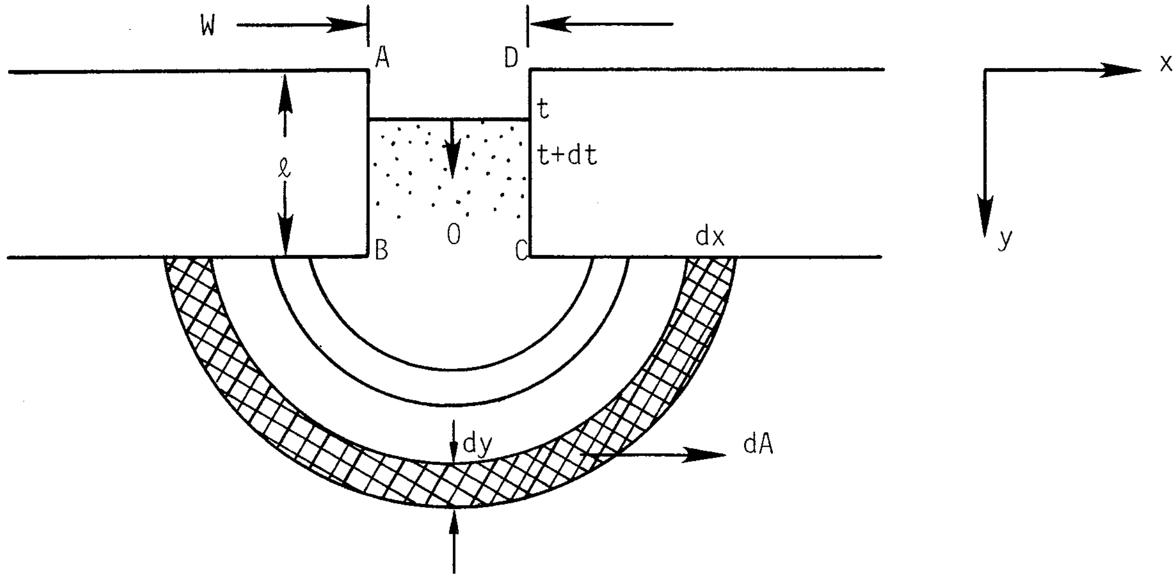
$$\frac{x^2}{(a+dx)^2} + \frac{y^2}{(b+dy)^2} = 1 \qquad \text{(D-2)}$$

The rate of change of water amount in Area ABCD

$$dq = wd\ell = dA$$

$$dA = \frac{\pi}{2}ab - \frac{\pi(a+dx)(b+dy)}{2} = \frac{\pi}{2}b(dx) + \frac{\pi}{2}a(dy) \qquad \text{(D-3)}$$

where a and b are constants for the major and the minor axes



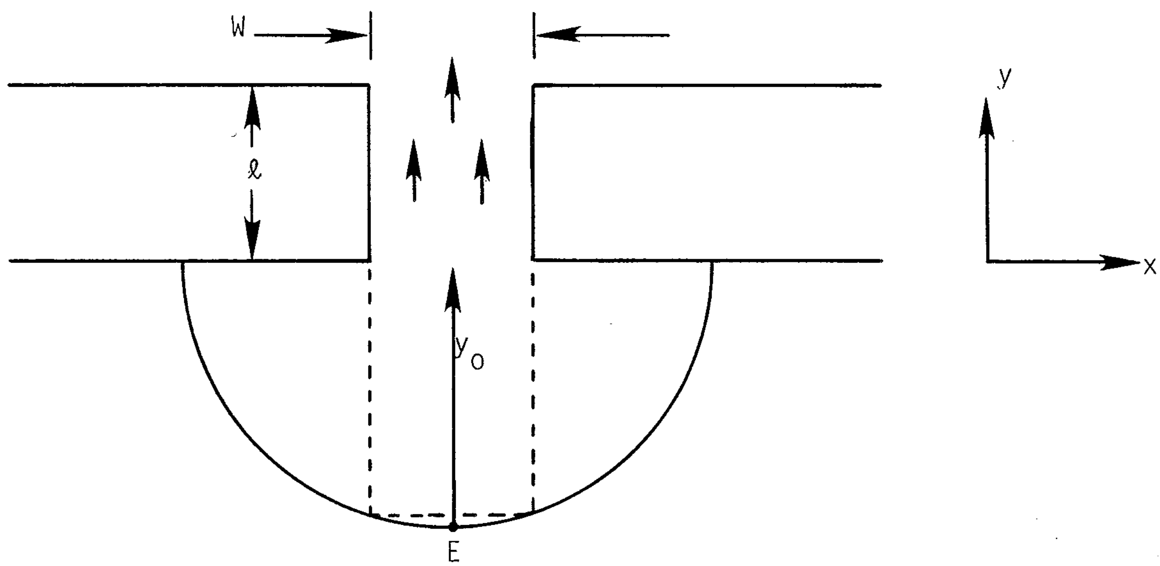


FIGURE 29. The Elliptical Shape of Water Penetration and the Evaporation in a Low Permeability Base Course

of the ellipse. By the continuity equation,

$$\frac{dq}{dt} = w\left(\frac{d\ell}{dt}\right) = \frac{dA}{dt} = \frac{\pi}{2}b\left(\frac{dx}{dt}\right) + \frac{\pi}{2}a\left(\frac{dy}{dt}\right) \qquad \text{(D-4)}$$

$\frac{dx}{dt}$ is the rate of horizontal flow and

$\frac{dy}{dt}$ is the rate of vertical flow, a, b are constants.

$$v_y = \frac{dy}{dt} = \frac{-k_v}{n}\frac{\partial h}{\partial y} = \frac{-k_v}{n}\frac{\partial}{\partial y}\left(\frac{P}{\gamma} - y\right) \qquad \text{(D-5)}$$

where v_y is the vertical velocity,

h is the total head,

k_v is the vertical coefficient of permeability,

n is the effective porosity in base course,

P is the water pressure, and

γ is the unit weight of water.

Assume h is a linear function of the depth y, then

$$h = a_1 y + c_1$$

at $y=0$, $h=\ell=c_1$

and $y=y_0$, $h=a_1 y_0+\ell$

where $y_\emptyset$ is the wetting front in the vertical direction.

Since $h = -y_0-h_k$,

$$a_1 = \frac{-y_0-h_k-\ell}{y_0} \qquad \text{(D-6)}$$

where h_k is the capillary head.

Thus

$$h = \frac{-(y_0+h_k+\ell)}{y_0} \quad y + \ell \tag{D-7}$$

$$\frac{dh}{dy} = \frac{-(y_0+h_k+\ell)}{y_0} \tag{D-8}$$

From Eq. D-1

$$\frac{dy}{dt} = \frac{-k_v}{n}\frac{dh}{dy} = \frac{-k_v}{n} \quad \frac{(y_0+h_k+\ell)}{y_0}$$

therefore,

$$\frac{y_0}{y_0+h_k+\ell}\, dy_0 = \frac{k_v}{n}\, dt \tag{D-9}$$

$$v_x = \frac{dx}{dt} = \frac{-k_h}{n}\frac{dh}{dx} \tag{D-10}$$

Assume $h = a_2x + c_2$

$x = 0$ $\qquad\qquad h = \ell = c_2$

and $x = x_0$ $\qquad\qquad h = ax_0 + \ell = -h_k$

where x_0 is the wetting front in horizontal direction.

Therefore,

$$a_2 = \frac{-\ell - h_k}{x_0} \tag{D-11}$$

$$\frac{dx}{dt} = \frac{k_h}{n} \frac{(\ell + h_k)}{x_0} \tag{D-12}$$

therefore,

$$\frac{x_0^2}{2} = \frac{k_h}{n}[\ell + h_k]t \tag{D-13}$$

From Eq.D-5and since $x_0 = a$, $y_0 = b$,

$$\frac{dq}{dt} = w \frac{d\ell}{dt} = \frac{\pi}{2}\left[\frac{y_0}{x_0} \frac{k_h}{n} (\ell + h_k) + \frac{x_0}{y_0} \frac{k_v}{n} (y_0 + \ell + h_k)\right] \tag{D-14}$$

This differential equation is accompanied by the initial conditions

$$\frac{x_0(0)}{y_0(0)} = \frac{k_h}{k_v} \tag{D-15}$$

$$w d\ell = \frac{\pi}{2} x_0 y_o$$

$$= \frac{\pi}{2} x_0^2(0) \frac{k_v}{k_h} \tag{D-16}$$

therefore, $x_0 = \sqrt{w \frac{2d\ell}{\pi} \frac{k_h}{k_v}}$ (D-17)

$$y_0 = \sqrt{w \frac{2d\ell}{\pi} \frac{k_v}{k_h}} \tag{D-18}$$

The following numerical procedures are used to solve the differential equations of water penetration into a base of low permeability.

(1) Use Euler's method to achieve the solution of vertical wetting front, y_0, at different time in Equation D-9. Equation D-18 is applied as the initial condition for y_0.

(2) Incorporate time t to calculate $x_0(t)$ of Equation D-13.

(3) Evalute $\Delta \ell$ from the Equation D-14.

(4) Compute the water quantity, in terms of length, left in the cracks or joints.

D-2. Water Evaporation from a base of low permeability.

Diffusion Equation: $\frac{\partial u}{\partial t} = \kappa \frac{\partial^2 u}{\partial y^2}$ (D-19)

Initial Condition: $u(y,0) = u_0$ (D-20)

Boundary Conditions: $\frac{\partial u(0,t)}{\partial x} = 0$ (D-21)

$$\frac{\partial u(y_0,t)}{\partial x} = -\beta\{u(y_0,t)-h_0\} \quad \text{(D-22)}$$

The point E of Figure 29 is the origin of that system. It is located at the wetting front of water penetration into the base.

The solution is (21):

$$u = u_a + \sum_{n=1}^{\infty} A_n \exp\left(\frac{-y_n^2 t\kappa}{y_0^2}\right) \cos\left(y_n \frac{x}{y_0}\right) \quad \text{(D-23)}$$

where $A_n = \frac{2(u_0-u_a)\sin y_n}{y_n+\sin y_n \cos y_n}$ (D-24)

y_n = solution of $\cot y = \frac{y}{\beta y_0}$

u_a = suction of atmosphere,

u_0 = original suction throughout soil,

y_0 = wetting front of water penetration,

β = evaporation constant, and

κ = diffusion coefficient.

The amount of water evaporated from the base, Δw, is determined by integration of suction loss times the rate of moisture change with respect to suction;

$$\Delta w = \int_0^{y_0} \Delta u(y,t_f) \left[\frac{\partial \theta}{\partial u}\right] dy, \quad \text{(D-25)}$$

where

$$\Delta u(y,t_f) = u(y,0)-u(y,t_f)$$
$$= u_0-u(y,t_f), \text{ and} \qquad \text{(D-26)}$$

t_f is the time when evaporation stops.

The slope of $[\frac{\partial\theta}{\partial u}]$ (Figure 30) is a soil property that must be read in for calculation. It is assumed that there is no hysteresis.

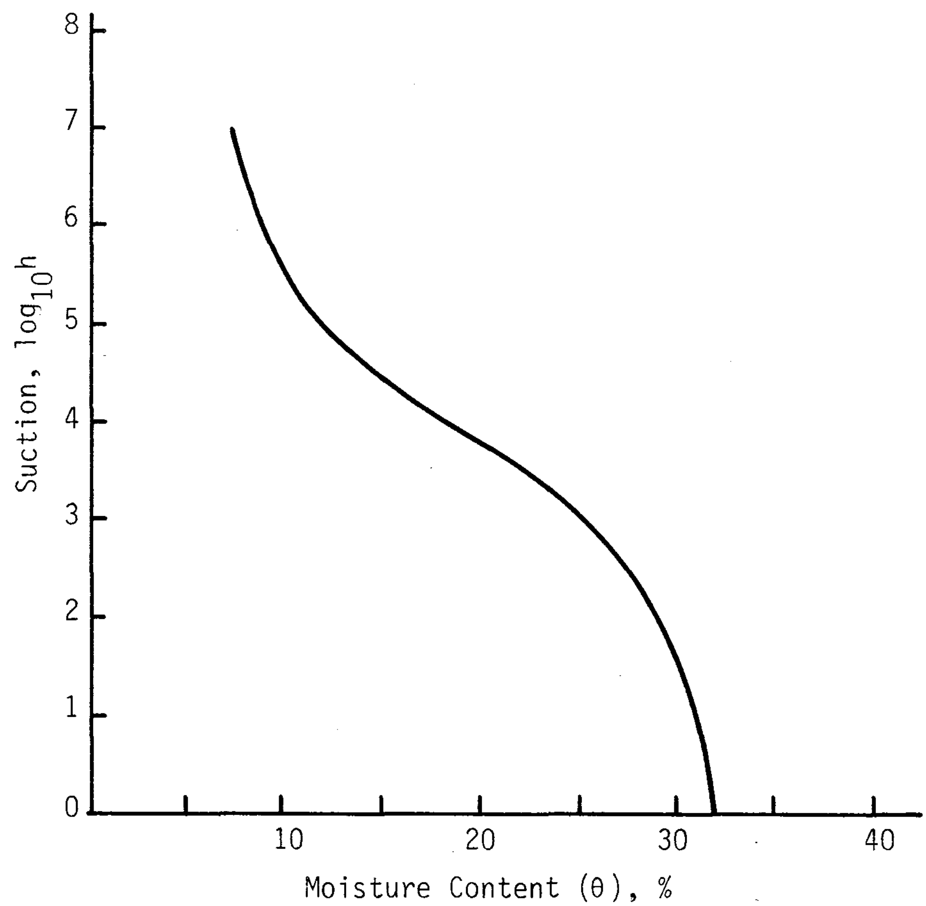


FIGURE 30. Relationship between Suction (Water Potential) and Moisture Content in Soil.

APPENDIX E

FLOW CHART, COMPUTER PROGRAMMING, AND USER'S GUIDE

This computer program for the simulation model of rainfall infiltration and drainage analysis is constructed mainly in five parts:

(1) Drainage calculation by using the TTI model.

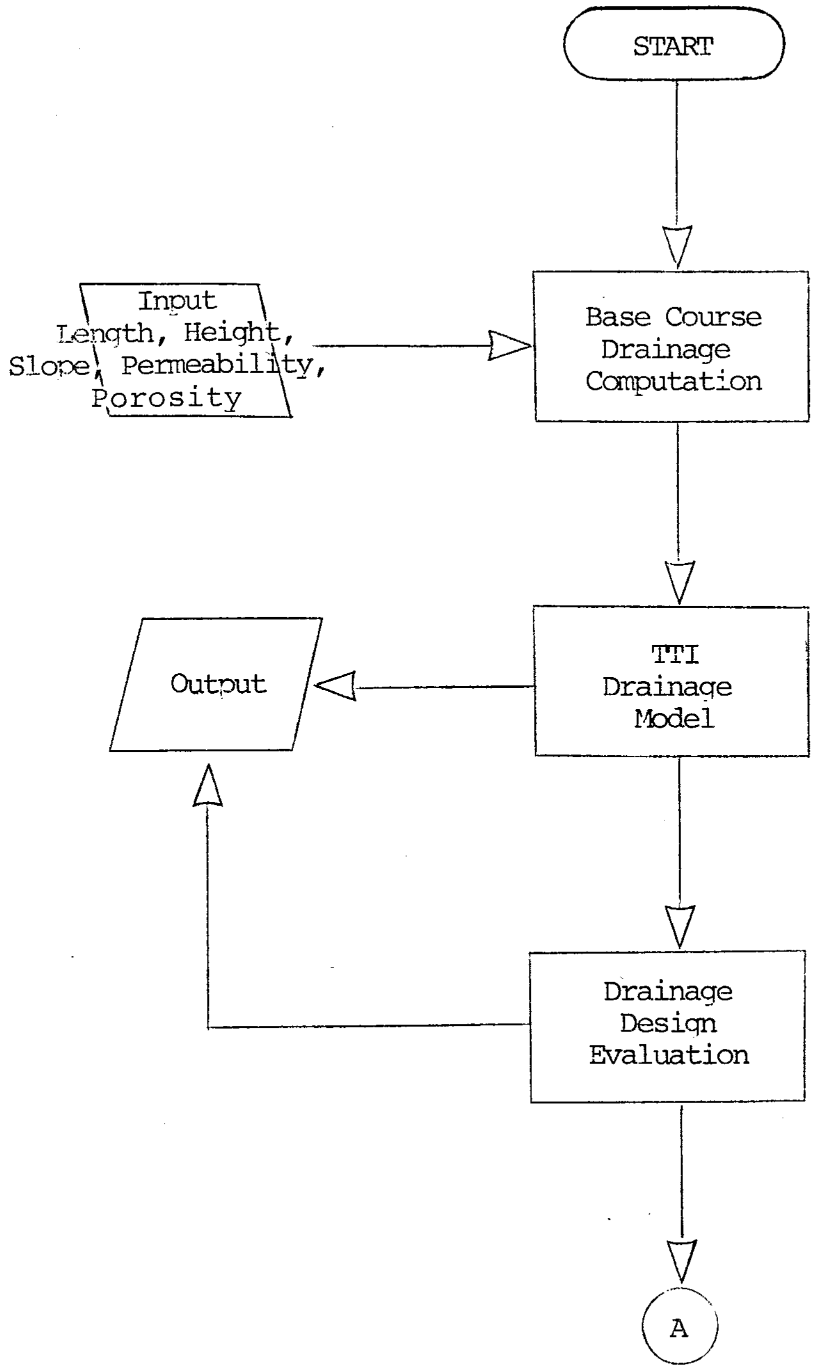
(2) Drainage design evaluation.

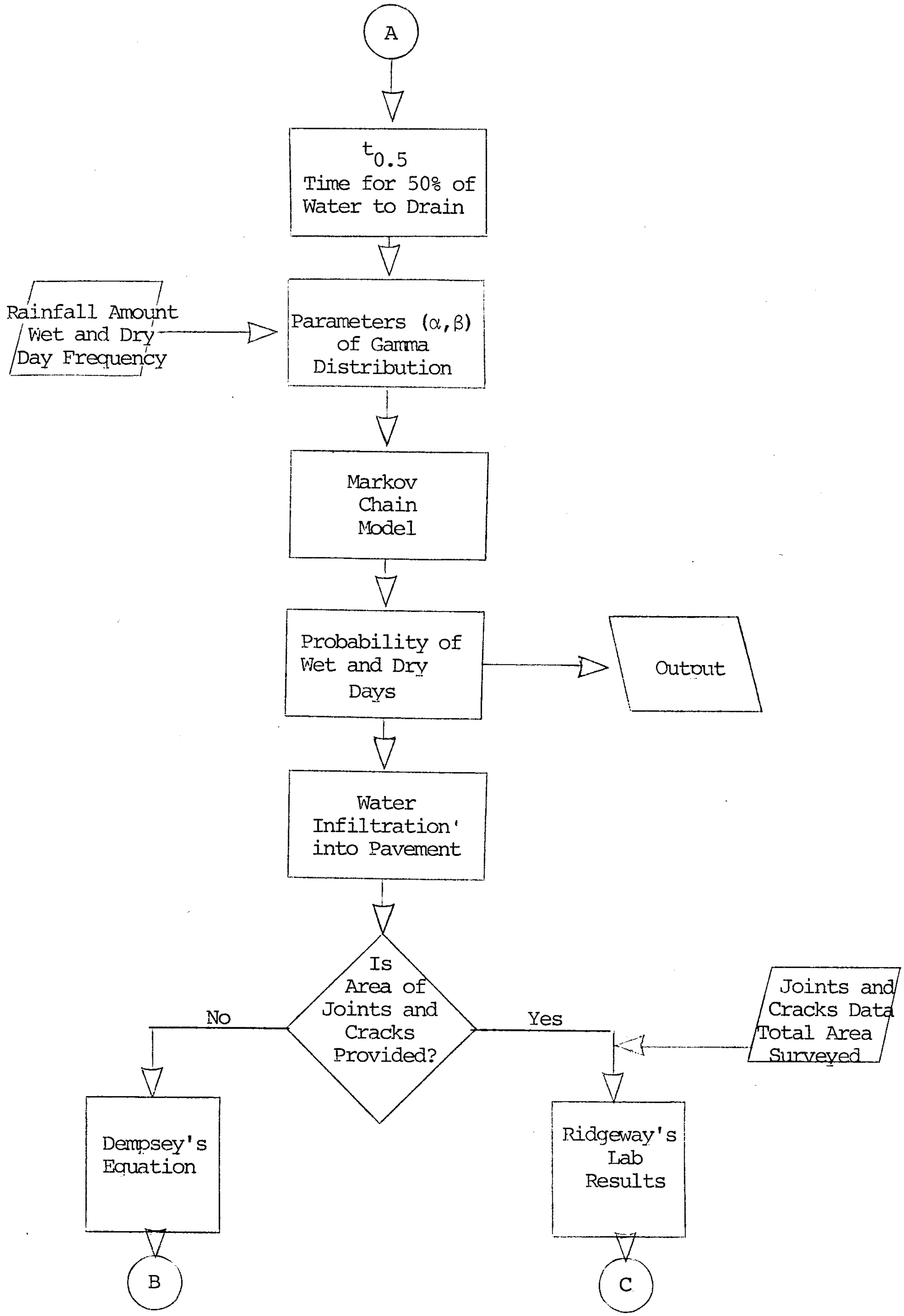
(3) Estimation of parameters of Gamma distribution for rainfall amount, calculation of rainfall duration.

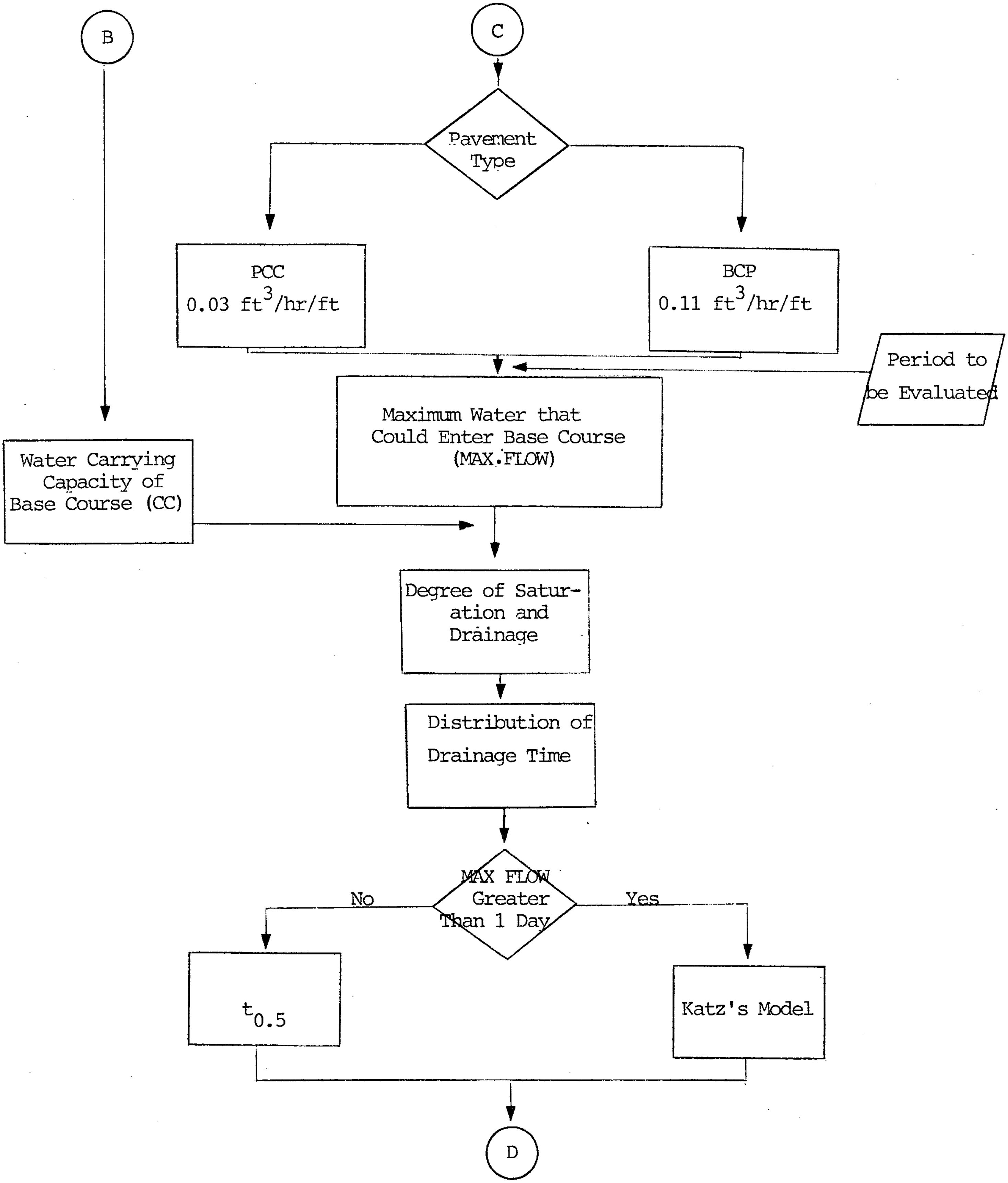
(4) Dry and wet probabilities of the weather and the base course from the Markov chain model and Katz's recurrence equations.

(5) Estimation of elastic moduli of base course and subgrade.

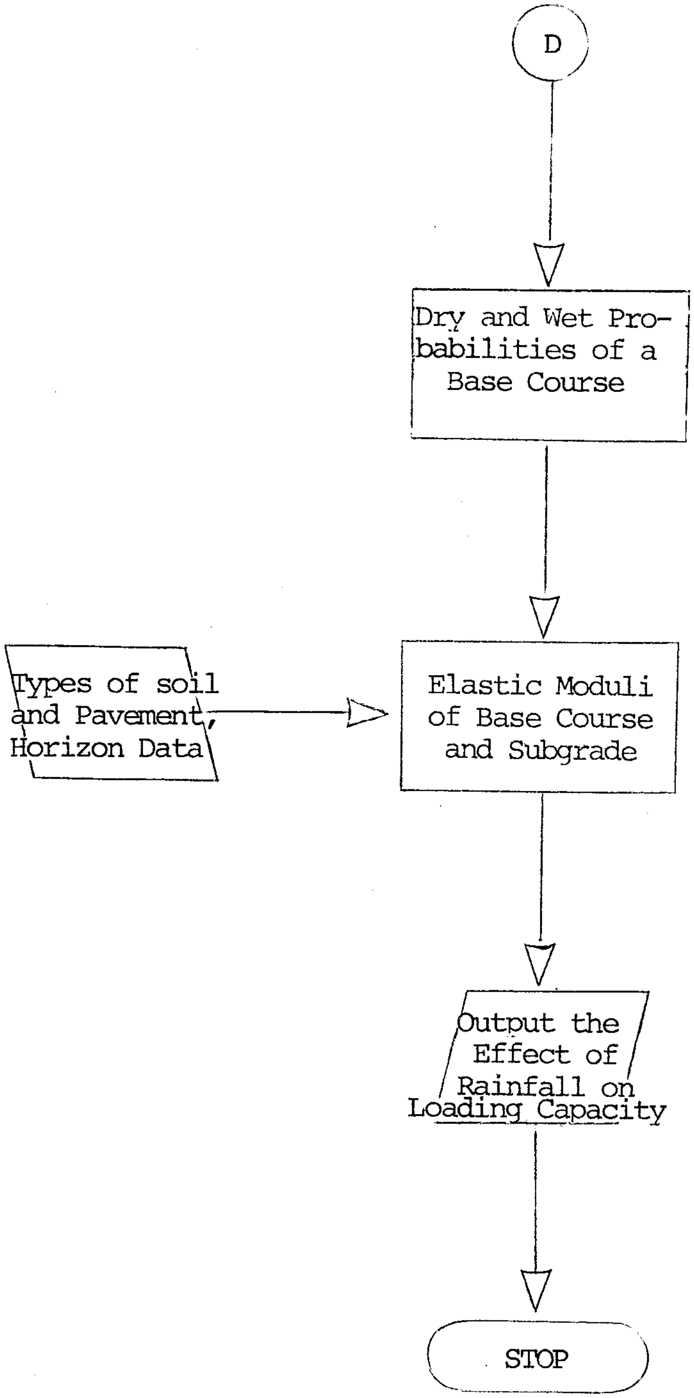
E-1. FLOW CHART FOR COMPUTER PROGRAMMING




A
$t_{0.5}$ Time for 50% of Water to Drain
Rainfall Amount Wet and Dry Day Frequency
Parameters (α,β) of Gamma Distribution
Markov Chain Model
Probability of Wet and Dry Days
Output
Water Infiltration into Pavement
Is Area of Joints and Cracks Provided?
No
Yes
Joints and Cracks Data Total Area Surveyed
Dempsey's Equation
Ridgeway's Lab Results
B
C



B
C
Pavement Type
PCC
0.03 ft3/hr/ft
BCP
0.11 ft3/hr/ft
Period to be Evaluated
Maximum Water that Could Enter Base Course (MAX.FLOW)
Water Carrying Capacity of Base Course (CC)
Degree of Saturation and Drainage
Distribution of Drainage Time
MAX FLOW Greater Than 1 Day
No
Yes
t0.5
Katz's Model
D


D
Dry and Wet Probabilities of a Base Course
Types of soil and Pavement, Horizon Data
Elastic Moduli of Base Course and Subgrade
Output the Effect of Rainfall on Loading Capacity
STOP

E-2. COMPUTER PROGRAMS AND SAMPLE RESULTS

(a) Simulation Model for Rainfall Infiltration and Drainage Analysis of Pavement

```
C
C**********************************************************************
C*                                                                    *
C*                  TEXAS TRANSPORTATION INSTITUTE                    *
C*                                                                    *
C*                                                                    *
C*    SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND PAVEMENT DRAINAGE  *
C*                                                                    *
C*                           AUGUST,1983                              *
C*                                                                    *
C**********************************************************************
C
C**********************************************************************
C*                                                                    *
C*                                                                    *
C*                BASE AND SUBGRADE DRAINAGE MODELS                   *
C*                                                                    *
C*         PARABOLIC FREE SURFACE PLUS SUBGRADE DRAINAGE              *
C*                                                                    *
C*                                                                    *
C**********************************************************************
C
      IMPLICIT REAL(J-Z)
      INTEGER N,NA,NB,NC
      EXTERNAL DUMMYF,GAMDIS
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      COMMON  /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
      COMMON /TNUM/ INABT
      DIMENSION UAREA(120,10)
      DIMENSION LOGTIM(120,10)
      DIMENSION ITITLE(18)
      DATA UDRAN/0.5/
C
C UDRAN : 50 PERCENT DRAINAGE
C INDS  : NUMBER OF DATA SET
C NA    : NO. OF SECTORS IN RUNGE-KUTTA METHOD FOR CASE 1
C NB    : NO. OF SECTORS IN DIVIDING HEIGHT FOR CASE 2
C N     : NO. OF SECTORS IN SIMPSON'S RULE
C INABT : SUM OF NA AND NB
C LA    : LENGTH OF BASE (FEET)
C HE    : HEIGHT OF BASE (FEET)
C TAPER : SLOPE RATIO OR THE VALUE OF TANGENT ALPHA (IN PERCENT)
C K1    : PERMEABILITY OF BASE COURSE (FEET PER HOUR)
C K2    : PERMEABILITY OF SUBGRADE (FEET PER HOUR)
C N1    : POROSITY OF BASE COURSE
C N2    : POROSITY OF SUBGRADE
C TA    : SLOPE RATIO (IN DECIMAL POINTS),TAPER/100.
C
C INEED : 0     DRAINAGE ANALYSIS ONLY
C         1     DRAINAGE ANALYSIS AND EVALUATION OF DRAINAGE DESIGN
C         2     SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINAGE
C
      NA=30
      NB=30
      INT=NA+NB
      INABT=INT
      N=10
      DO 300 INDS=1,10
```

```
C
C     INPUT THE DATA
C
       READ(5,55555,END=99999) IPROB,INEED,ITITLE
55555 FORMAT(I5,I3,18A4)
      WRITE(6,55556) IPROB,ITITLE
55556 FORMAT(1H1,2(/),5X,'PROBLEM NUMBER',I5,2X,18A4)
      IF(INEED.EQ.0) WRITE(6,55557)
      IF(INEED.EQ.1) WRITE(6,55558)
      IF(INEED.EQ.2) WRITE(6,55559)
55557 FORMAT(3(/),5X,'DRAINGE ANALYSIS USING TTI DRAINAGE MODEL')
55558 FORMAT(3(/),5X,'DRAINAGE ANALYSIS AND DESIGN EVALUATION')
55559 FORMAT(3(/),5X,'SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAIN
     AGE')
      IA=INDS
      READ(5,15)LA,HE,TAPER,K1,K2,N1,N2
   15 FORMAT(7(F10.0))
      TA=TAPER/100.
C
C     HORIZONTAL BASE COURSE
C
      IF(TA.LE.0.) TA=0.1E-06
      IF(N2.LE.0.) CALL PORO2
C
C     IF N1 EQUALS TO N2 AND K1 EQUALS K2 WHICH IMPLIES BASE COURSE IS
C     INFINITIVELY DEEP AND THE PROGRAM WILL NOT WORK
C
      IF(N1.EQ.N2.AND.K2.EQ.K1) K2=K2*1.0001
      WRITE(6,25)
   25 FORMAT(3(/),5X,'LENGTH',4X,'HEIGHT',4X,'SLOPE%',
     +4X,'PERM.1',4X,'PERM.2',4X,'PORO.1',4X,'PORO.2')
      WRITE(6,55)LA,HE,TAPER,K1,K2,N1,N2
   55 FORMAT(1X,3(F10.2),2(F10.5),2(F10.4))
      TWETA=LA*HE
      S=HE/(LA*TA)
      WRITE(6,35)S
   35 FORMAT(//,5X,'SLOPE FACTOR=',F6.3//)
      WRITE(6,255)
  255 FORMAT(5X,'NOTE: THE FOLLOWING ANALYSIS IS BASED ON PARABOLIC SHAP
     +E PLUS SUBGRADE DRAINAGE')
C
C RUNGE-KUTTA METHOD FOR PARABOLIC(DQX) AND HORIZONTAL(DQY) EQUATION OF CA
C
      WRITE(6,115)
  115 FORMAT(6(/), 5X,'HEAD ON X COOR.',' HT.(SUB.DRAIN ONLY)'
     1,8X,'AVG. HEIGHT.',7X,'TIME(STAGE 1)',7X,'DRAINAGE DEG.'//)
      TIME=0.
      XM=0.
      AK1=0.
      DELT=LA/NA
      CASE=1.
      DO 700 I2=1,NA
      TIME2=TIME+AK1
      XM=XM+DELT
      NUM=2.
      CALL SUBHT(TIME2,HSUB2)
      HSUBB=HSUB2
      CALL CONSFC(XM,A)
      DTDX=DUMMYF(XM)
      AK2=DTDX*DELT
```

```
      TIME=TIME+(AK1+AK2)/2.
      NUM=1.
      CALL SUBHT(TIME,HSUB1)
      HSUBA=HSUB1
      CALL CONSFC(XM,A)
      DTDX=DUMMYF(XM)
      AK1=DTDX*DELT
      WET1=(HE-HSUBA)*LA+HSUBA*XM/3.
      UE1=WET1/TWETA
      HAVG1=(TWETA-WET1)/LA
      IF(HSUBA.LE.0.OR.HSUBA.LE.HAVG1) HSUBA=HAVG1
      WRITE(6,135)XM,HSUBA,HAVG1,TIME,UE1
  135 FORMAT(5(E20.4))
      XTIME(I2,IA)=TIME
      YAREA(I2,IA)=UE1
  700 CONTINUE
C
C USE SIMPSON'S RULE IN CALCULATING TIME FOR CASE 2
C HSUBA(MAXIMUM HEIGHT IN CASE 2),XM(TOTAL LENGTH IN CASE 1)
C AND TIME(MAXIMUM TIME IN CASE 1) WERE ALL RESERVED FROM UPPER DO LOOP
C
      WRITE(6,45)
   45 FORMAT(1H1,6(/), 5X,'HEAD ON Y COOR.',' HT.(SUB.DRAIN ONLY)',
     +8X,'AVG. HEIGHT',7X,'TIME(STAGE 2)',7X,'DRAINAGE DEG.'//)
      CASE=2.
      HMAX=HSUBA
      HMAX2=HMAX
      DELTH=HMAX/NB
      DO 800 I3=1,NB
          HMIN=HMAX2-DELTH*I3
      I5=I3+NA
          IF(I3.EQ.NB.OR.HMIN.LE.0.) HMIN=HMAX*0.5
          CALL CONSFC(XM,HMIN)
          CALL SIMPSN(AREA,DUMMYF,HMIN,HMAX,N)
          TIME=TIME+AREA
          CALL SUBHT(TIME,HTSU)
          WET2=TWETA-2.*HMIN*LA/3.
          UE2=WET2/TWETA
          HAVG2=(TWETA-WET2)/LA
           IF(HTSU.LE.0.OR.HTSU.LE.HAVG2) HTSU=HAVG2
          WRITE(6,135)HMIN,HTSU,HAVG2,TIME,UE2
      XTIME(I5,IA)=TIME
      YAREA(I5,IA)=UE2
      UAREA(I5,IA)=YAREA(I5,IA)*100.
          HMAX=HMIN
      IF(I3.EQ.NB) TIMAX(IA)=TIME
      IF(I3.EQ.NB) UEMAX(IA)=UE2
  800 CONTINUE
      IMAXD=TIMAX(IA)/24.+0.5
      CALL INPOLA(TDRAN,UDRAN,IA,LOGTIM)
      IF(INEED.NE.0)
     1CALL JUDGE(IA,INT,ITYPFI,IQFINE,GRAVPC,SANDPC)
      IF(INEED.EQ.2) CALL RAIN(TDRAN,IMAXD)
  300 CONTINUE
99999 WRITE(6,125)
  125 FORMAT(1H1)
      STOP
      END
C
C
```

```
C***********************************************************************
C*                                                                     *
C*  VARIOUS CONSTANTS EMPLOYED IN EQUATIONS                            *
C*                                                                     *
C*  XM: MAXIMUM HORIZONTAL DISTANCE IN CASE 1;                         *
C*  HMIN: MINIMUM VALUE OF HEIGHT                                      *
C*                                                                     *
C***********************************************************************
C
      SUBROUTINE CONSFC(XM,HMIN)
      IMPLICIT REAL(J-Z)
      INTEGER N,NA,NB,NC,NJONT,NLANE
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      IF(NUM.EQ.1.) HSUB=HSUBA
      IF(NUM.EQ.2.) HSUB=HSUBB
          IF(CASE.EQ.2.) HSUB=HMIN
          IF(CASE.EQ.2.) XM=LA
      A1=HSUB/SQRT(XM)
      B1=A1*(1.-N1/N2)
      B2=A1*(K2/K1-N1/N2)
      C1=N1*HE/N2
      G1=B1/B2
      G2=C1*(1.-G1)/B2
      G3=C1*G2
      R1=G3/B2
      RETURN
      END
C
C
C***********************************************************************
C*                                                                     *
C*  CALCULATE DRAINAGE AREA CORRESPONDING TO DESIRED NUMBER OF DRY DAYS*
C*  YAREA,XTIME,TIMAX,UEMAX ARE THE SAME AS PREVIOUSLY DEFINED         *
C*  IDRY : NUMBER OF DRY DAYS ;                                        *
C*  YDRAN: DRAINING AREA (IN %) COMPUTED BY INTRAPOLATION ;            *
C*                                                                     *
C***********************************************************************
C*
C*
      SUBROUTINE DRYDAY(IMAXD,YDRAN,WPROB)
      COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
      COMMON /TNUM/ INABT
      DIMENSION YDRAN(100),WPROB(50,50)
      IA=INDS
      DO 6000 I=1,100
      IDRY=I
         DO 6100 I2=1,100
         IF(I2.EQ.INABT) GO TO 6222
         IF(XTIME(I2,IA).GT.IDRY*24.) GO TO 6111
 6100    CONTINUE
 6111 I1=I2-1
      IF(I1.LE.0) GO TO 6001
      REGCOE=(YAREA(I2,IA)-YAREA(I1,IA))/(XTIME(I2,IA)-XTIME(I1,IA))
      CONCOE=YAREA(I2,IA)-REGCOE*XTIME(I2,IA)
      YDRAN(IDRY)=(CONCOE+REGCOE*IDRY*24.)*100.
      GO TO 6000
 6001 YDRAN(IDRY)=100.*YAREA(I2,IA)*IDRY*24./XTIME(I2,IA)
 6000 CONTINUE
 6222 IF(IMAXD.LE.0) RETURN
```

```
      IMAXD=IDRY
      IF(IMAXD.GE.39) IMAXD=39
      YDRAN(IMAXD)=100.
      WRITE(6,6005)
 6005 FORMAT(1H1,5(/),T34,'PROBLEM NO.',5X,'TIME(DAYS)',4X,'DRAINAGE(%)'
     2,2X,'PROB(CONSECUTIVE DRY DAYS)',5(/))
      IN=1
      DO 6600 I=1,IMAXD
      IN=IN+1
      WRITE(6,6010)IA,I,YDRAN(I),WPROB(1,IN)
 6010 FORMAT(T30,I15,I15,F15.2,20X,F8.3,5(/))
 6600 CONTINUE
      RETURN
      END
C
C
C*********************************************************************
C*                                                                   *
C*  ROUTINE FOR COMPUTING ALL THE FUNCTIONS                          *
C*                                                                   *
C*  X: MAXIMUM X VALUE FOR CASE 1;  X=LA FOR CASE 2;                 *
C*     MINIMUM X VALUE FOR CASE 3;                                   *
C*                                                                   *
C*********************************************************************
C
C
      FUNCTION DUMMYF(X)
      IMPLICIT REAL(J-Z)
      INTEGER N,NA,NB,NC,NJONT,NLANE
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      IF(NUM.EQ.1.) HSUB=HSUBA
      IF(NUM.EQ.2.) HSUB=HSUBB
           IF(CASE.EQ.2.) AE=X
           IF(CASE.EQ.2.) X=LA
           IF(CASE.EQ.2.) HSUB=AE
        HED=HSUB
      IF(N2.GT.0.1E-05.AND.K2.NE.0.) GO TO 5555
      DUM3=0.
      GO TO 6666
 5555 FAC1=G1*X+2.*G2*SQRT(X)
      FAC2=2*R1*ALOG(ABS((B2*SQRT(X)+C1)/C1))
      FACR=FAC1-FAC2
      IF(N2.LE.0.1E-05) DQY=0.
      IF(N2.GT.0.1E-05)DQY=(HSUB*(1.-N1/N2)+C1)/(HSUB*(K2/K1-N1/N2)+C1)
      DUM3=6.*K2*X*((LA-X)*DQY+FACR)/LA
 6666 CONTINUE
      IF(CASE.EQ.1.) DUM1=2.*N1*HSUB*X
      IF(CASE.EQ.2.) DUM1=4.*N1*LA**2
      DUM2=K1*(3.*HSUB**2+4.*HSUB*X*TA)
      DUMMYF=DUM1/(DUM2+DUM3)
          IF(CASE.EQ.2.) X=AE
          IF(CASE.EQ.2.) HSUB=HED
      RETURN
      END
C
C
C*********************************************************************
C*                                                                   *
C*  EVALUATE THE MODULI OF BASE AND SUBGRADE BY DISTRIBUTION         *
```

```
C*  OF MATERIAL SATURATION FROM THE RAINFALL                                *
C*                                                                          *
C*  ALPHA,BETA: PARAMETERS OF GAMMA DISTRIBUTION                            *
C*  PWET,PDRY : PROBABILITY OF WET AND DRY DAYS IN STEADY STATE             *
C*  HALFT     : TIME OF 50% DRAINAGE(HOUR);                                 *
C*                                                                          *
C*                                                                          *
C***************************************************************************
C
C
      SUBROUTINE FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE,
     2ASOIL,BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPROB,IMAXD)
C
C   GAMDIS: GAMMA DISTRIBUTION AS A FUNCTION
C   AINTER,BSLOPE: INTERCEPT AND SLOPE OF THE LINEAR FUNCTION OF BASE COUR
C                        MODULUS VS. WATER SATURATION DEGREE
C   EMPDF : PROBABILITY DENSITY FUNCTION OF BASE COURSE MODULUS IN WET STA
C   PAVE  : INFILTRATION RATE OF PCC(1) OR BCP(2),UNIT=FT**3/(HOUR*FT)
C   FLOAVG: INFILTRATION RATE SELECTED ACCORDING TO PAVEMENT TYPE
C   PVA,PVB:THE INTERCEPT AND SLOPE OF REGRESSION EQUATION IN DEMPSEY'S TE
C   PX    : SPECIFIC RAINFALL AMOUNT
C   CFHALF: THE AVERAGE DEGREE OF FREE WATER DRAINAGE PER HOUR
C   DEFL  : DEFLECTION OF BASE MATERIALS (INCHES)
C   DERATE: RATIO OF BASE MODULUS OF ELASTICITY
C   BCMAT : BASE MODULI OF ELASTICITY (KSI)
C   BCRATE: SLOPE OF DEFLECTION CHANGE WITH RESPECT TO DEGREE OF SATURATIO
C   TURNPT: 1. DEFLECTION OF DRY BASE MATERIAL
C           2. DEFLECTION OF 85% SATURATION LEVEL
C
      REAL LA,K1,K2,N1,N2
      EXTERNAL GAMDIS
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE
      COMMON  /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
      COMMON /TNUM/ INABT
      COMMON /SGWET1/ SGWET(100),SGDRY(100),SGW(100),SGD(100)
      COMMON /NOGAMA/ NUMWET,AVGAMT,TOTSUM
      DIMENSION EMPDF(100),SGEM(100),AINTER(2,9),BSLOPE(2,9)
      DIMENSION PAVE(2),SOIL(9),HORIZ(2),PTYPE(2),FREE(100)
      DIMENSION PX(100),DURAT(100),SECT(20),CDF(20),IIA(100)
      DIMENSION DEFL(100),DERATE(100),BCRATE(2),BCMAT(6),TURNPT(2),
     2BCEM(100)
      DIMENSION FREE2(100),DURATB(100),PXB(100),SECTB(50)
      DIMENSION YDRAN(100),WPROB(50,50)
      INTEGER PTYPE/'PCC','BCP'/
      DATA PAVE/0.03,0.11/
      DATA PVA,PVB/0.32,0.48/
      DATA    BCMAT/425.3,236.3,209.3,64.6,29.8,17.1/
      DATA BCRATE/0.24,3.5/,TURNPT/0.02,0.08/
      REAL*8 SOIL/'A-7-5','A-4','A-7-6','A-6','CL','ML-CL',
     2'CH','ML','MH'/,ASOIL
      INTEGER HORIZ/'ABC','BC'/,BHORIZ
      DATA AINTER/39.83,27.54,17.33,16.76,31.22,24.65,36.15,35.67,
     2            31.89,32.13,31.89,32.13,21.93,23.02,31.39,29.01,
     3            31.39,29.01/
      DATA BSLOPE/0.453,0.266,0.158,0.146,0.294,0.196,0.362,0.354,
     2            0.312,0.311,0.312,0.311,0.151,0.161,0.331,0.284,
     3            0.331,0.284/
       IF(IMAXD.GE.39) IMAXD=39
```

```
      IF(ITYPE.EQ.PTYPE(1)) FLOAVG=PAVE(1)
      IF(ITYPE.EQ.PTYPE(2)) FLOAVG=PAVE(2)
      DO 7100 I=1,9
         IF(ASOIL.NE.SOIL(I)) GO TO 7100
         INDEXB=I
         GO TO 7555
 7100 CONTINUE
 7555 IF(BHORIZ.EQ.HORIZ(1)) INDEXA=1
      IF(BHORIZ.EQ.HORIZ(2)) INDEXA=2
C
C   FLOWMX: THE MAXIMUM AMOUNT WHICH WATER WOULD ENTER THE PAVEMENT
C   CC     : CARRYING CAPACITY OF WATER IN BASE COURSE (N1*L*H)
C
      CC=N1*LA*HE
      CFHALF=(0.5/HALFT)*100.
C
C  DISTRIBUTION OF PAVEMENT MODULI AND DRY, WET PROBABILITIES
C
C   FREE  : AMOUNT OF FREE WATER IN PAVEMENT(FEET**2)
C   DURAT : DURATION OF SPECIFIC RAINFALL AMOUNT(HOURS)
C   ITEST : 1 USING RIDGEWAY'S EQUATION; 2 USING DEMPSEY'S FOR NO CRACKS
C           DATA AND WHEN RIDGEWAY'S METHOD TURNS OUT TO BE UNREASONABLE
C
      IF(NUMWET-1)33333,22222,11111
11111 PX1=0.
      K=0
      CDFSUM=0.
      DO 7000 I=5,100,5
      FREE(I)=CC*I*0.01
C
C   SGWET : WET DEPTH OF SUBGRADE
C   SGDRY : DRY DEPTH OF SUBGRADE
C   SGW   : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (E1**3)
C   SGD   : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE
C   SGEM  : SUBGRADE MODULUS
C
      SGW(I)=(AINTER(INDEXA,INDEXB)-BSLOPE(INDEXA,INDEXB)*100.)
     2       *(SGWET(I)**3)
      IF(SGW(I).LE.0.) SGW(I)=0.
      SGD(I)=AINTER(INDEXA,INDEXB)*(SGDRY(I)**3)
      SGEM(I)=(SGW(I)+SGD(I))/((5.83333-HE)**3)
      IF(SGEM(I).LE.0.) SGEM(I)=0.
      IF(CRKJON.EQ.0.) GO TO 7777
      ITEST=1
      DURAT(I)=(FREE(I)*FTLONG)/(CRKJON*FLOAVG)
      PX(I)=(60.*DURAT(I))**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE
      RIDGE=BETA*PX(I)
      IF(RIDGE.GE.174.) GO TO 7777
      GO TO 7788
 7777 ITEST=2
      PX(I)=((FREE(I)*FTLONG*0.02832-PVA)/(PVB*0.02832*FTLONG*LA))*12.
      IF(PX(I).LE.0.) PX(I)=0.
      DURAT(I)=((PX(I)*SHAPE)/(CONST*(YEAR**RECPOW)))**(1./(1.-DURPOW))
     2 /60.
 7788 PX2=PX(I)
      EMPDF(I)=GAMDIS(PX2,ALPHA,BETA)
      IF(I.GT.85) GO TO 7755
      IF(I.LE.60) GO TO 7744
        DEFL(I)=TURNPT(1)+BCRATE(1)*0.01*(I-60)
      DERATE(I)=TURNPT(1)/DEFL(I)
```

```
        BCEM(I)=BCMAT(IBC)*DERATE(I)
      GO TO 7766
 7744 BCEM(I)=BCMAT(IBC)
      DERATE(I)=1.0
      GO TO 7766
 7755   DEFL(I)=TURNPT(2)+BCRATE(2)*0.01*(I-85)
      DERATE(I)=TURNPT(1)/DEFL(I)
        BCEM(I)=BCMAT(IBC)*DERATE(I)
 7766 IIB=I/10*10
      IF(IIB.NE.I) GO TO 7000
      CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA)
      K=K+1
      IF(SECTOR.LE.0.) SECTOR=0.
      IF(SECTOR.GT.1.0) SECTOR=1.0
      SECT(K)=SECTOR
      CDFSUM=CDFSUM+SECT(K)
      IF(CDFSUM.GE.1.0) CDFSUM=1.0
      CDF(K)=CDFSUM
      PX1=PX2
 7000 CONTINUE
C
C   CALCULATE THE PART WHICH IS BEYOND THE FIELD CAPACITY IN GAMMA DISTRIB
C   PX2 IS THE MAXIMUM INFILTRATION AMOUNT AFTER THE ABOVE LOOP
C
      TAILPT=1.0-CDFSUM
C
C   THE DRY AND WET PAOBABILITIES OF THE PAVEMENT
C
C   PAVDRY: THE DRY PROBABILITY OF PAVEMENT
C   PAVWET: THE WET PROBABILITY OF PAVEMENT
C
      IF(TIMAX(INDS)/24.LT.1.) GO TO 8833
      PX1=0.
      K=0
      DO 8000 I=1,IMAXD
      FREE2(I)=CC*0.01*YDRAN(I)
      IF(CRKJON.EQ.0.) GO TO 8777
      ITEST=1
      DURATB(I)=(FREE2(I)*FTLONG)/(CRKJON*FLOAVG)
      PXB(I)=(60.*DURATB(I))**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE
      RIDGE=BETA*PXB(I)
      IF(RIDGE.GE.174.) GO TO 8777
      GO TO 8788
 8777 ITEST=2
      PXB(I)=((FREE2(I)*FTLONG*0.02832-PVA)/(PVB*0.02832*FTLONG*LA))*12.
      IF(PXB(I).LE.0.) PXB(I)=0.
      DURATB(I)=((PXB(I)*SHAPE)/(CONST*(YEAR**RECPOW)))
     2**(1./(1.-DURPOW))/60.
 8788 PX2=PXB(I)
      CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA)
      K=K+1
      IF(SECTOR.LE.0.) SECTOR=0.
      IF(SECTOR.GT.1.0) SECTOR=1.0
      SECTB(K)=SECTOR
      PX1=PX2
 8000 CONTINUE
      PAVDRY=0.
      IN=1
      DO 8100 K=1,IMAXD
      IN=IN+1
```

```
      PAVDRY=PAVDRY+SECTB(K)*WPROB(1,IN)
 8100 CONTINUE
      PAVDRY=PAVDRY+WPROB(1,IN)*TAILPT
      GO TO 8844
 8833 DHALF=HALFT/24.
      PAVDRY=1.-PWET*DHALF
 8844 PAVWET=1.-PAVDRY
C
C
C   CALCULATE THE PROBABILITIES OF SATURATION LEVELS:
C      SECT1: 0-60%;    SECT2: 60-85%;    SECT3: 85-100%
C
C
      CALL SIMP2(SECT1,GAMDIS,0.,PX(60),60,ALPHA,BETA)
      IF(SECT1.GE.1.0) SECT1=1.0
      CALL SIMP2(SECT2,GAMDIS,PX(60),PX(85),60,ALPHA,BETA)
      CALL SIMP2(SECT3,GAMDIS,PX(85),PX(100),60,ALPHA,BETA)
      SECT3=SECT3+TAILPT
C
      GO TO 44444
C  NUMBER OF RAINFALL QUANTITY EQUALS TO 0 OR 1 (NO GAMMA DISTRIBUTION)
C
C  YRAIN1: DRAINAGE LEVEL OF ONE RAINY DAY (IN DECIMAL POINT)
C  TRAIN1: TIME FOR THE CORRESPONDING DRAINAGE LEVEL OF ONE RAINY DAY
C
22222 ITEST=1
      IF(CRKJON.EQ.0.) GO TO 9191
      AVGDUR=(AVGRAS*0.08333*LA*FTLONG)/(CRKJON*FLOAVG)
      AVGFLO=(60.*AVGDUR)**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE
      GO TO 9292
 9191 ITEST=2
      AVGDUR=(SHAPE*AVGRAS/(CONST*(YEAR**RECPOW)))**(1./(1.-DURPOW))/60.
      AVGFLO=(PVB*AVGRAS*0.08333*FTLONG*LA*0.02832+PVA)/(0.02832*FTLONG)
 9292 YRAIN1=AVGFLO/CC
C
C  FIND THE CORRESPONDING TIME FOR DEGREE OF DRAINAGE
C
         DO 9900 I2=2,100
         IF(I2.EQ.INABT) GO TO 9922
         IF(YAREA(I2,INDS).GE.YRAIN1) GO TO 9911
 9900    CONTINUE
 9911 I1=I2-1
      REGCOE=(XTIME(I2,INDS)-XTIME(I1,INDS))/
     2        (YAREA(I2,INDS)-YAREA(I1,INDS))
      CONCOE=XTIME(I2,INDS)-REGCOE*YAREA(I2,INDS)
      TRAIN1=CONCOE+REGCOE*YRAIN1
      GO TO 9933
 9922 TRAIN1=TIMAX(INDS)
 9933 PAVWET=TRAIN1/(TOTSUM*24.)
      PAVDRY=1.-PAVWET
      IF(YRAIN1-0.85) 9944,9944,9955
 9944 SECT3=0.
      GO TO 9966
 9955 SECT3=XTIME(103,INDS)/TOTSUM
 9966 IF(YRAIN1-60.)9988,9988,9977
 9977 SECT2=(XTIME(108,INDS)-XTIME(103,INDS))/TOTSUM
      GO TO 9999
 9988 SECT2=0.
 9999 SECT1=1.-SECT2-SECT3
44444 DEFL(73)=TURNPT(1)+BCRATE(1)*0.125
```

```
      DERATE(73)=TURNPT(1)/DEFL(73)
      DEFL(93)=TURNPT(2)+BCRATE(2)*0.075
      DERATE(93)=TURNPT(1)/DEFL(93)
      AVBCEM=BCMAT(IBC)*(1.*SECT1+DERATE(73)*SECT2+DERATE(93)*SECT3)
      GEBCEM=AVBCEM*PAVWET+BCMAT(IBC)*PAVDRY
C
C   AVERAGE RAINFALL DURATION AND BASE COURSE MODULUS
C
C   AVGDUR: DURATION CORRESPONDING TO THE AVERAGE RAINFALL AMOUNT
C   AVGFLO: FREE WATER IN PAVEMENT DUE TO AVERAGE RAINFALL AMOUNT
C   GESGEM: TOTAL AVERAGE OF SUBGRADE MODULI
C   AVBCEM: AVERAGE BASE MODULI IN WET STATE
C   GEBCEM: TOTAL AVERAGE OF BASE MODULI
C
      AVGDUR=(SHAPE*AVGRAS/(CONST*(YEAR**RECPOW)))**(1./(1.-DURPOW))/60.
      IF(ITEST.EQ.2) GO TO 8888
      AVGFLO=FLOAVG*AVGDUR*CRKJON/FTLONG
      GO TO 8899
 8888 AVGFLO=(PVB*AVGRAS*0.08333*FTLONG*LA*0.02832+PVA)/(0.02832*FTLONG)
 8899 IF(AVGFLO.GE.CC) AVGFLO=CC
C
C   CALCULATE SUBGRADE MODULI
C
       EXACT2=AVGFLO/CC
         DO 9100 I2=1,100
       IF(EXACT2.GE.1.) GO TO 9222
       IF(YAREA(I2,INDS).GT.EXACT2) GO TO 9111
 9100    CONTINUE
 9111  I1=I2-1
      IF(I1.LE.0) GO TO 9001
       REGCOE=(XTIME(I2,INDS)-XTIME(I1,INDS))/
     2 (YAREA(I2,INDS)-YAREA(I1,INDS))
       INCEPT=XTIME(I2,INDS)-REGCOE*YAREA(I2,INDS)
       TSGAVW=INCEPT+REGCOE*EXACT2
      GO TO 9333
 9001 TSGAVW=XTIME(1,INDS)*EXACT2/YAREA(1,INDS)
      GO TO 9333
 9222 TSGAVW=TIMAX(INDS)
 9333 CALL SUBHT(TSGAVW,HSUBEM)
C
C    SGWETD: AVERAGE WET DEPTH OF SUBGRADE DURING THE SEASON
C    SGDRYD: AVERAGE DRY DEPTH OF SUBGRADE
C    SG1   : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (E1**3)
C    SG2   : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE
C
      SGWETD=(HE-HSUBEM)*N1/N2
      IF(SGWETD.LE.0.OR.K2.EQ.0.) SGWETD=0.
      SGDRYD=5.83333-HE-SGWETD
      SG1=(AINTER(INDEXA,INDEXB)-BSLOPE(INDEXA,INDEXB)*100.)*(SGWETD**3)
      IF(SG1.LE.0.) SG1=0.
      SG2=AINTER(INDEXA,INDEXB)*(SGDRYD**3)
      GESGEM=(SG1+SG2)/((5.83333-HE)**3)
C
      IF(NUMWET.LE.1) GO TO 55555
      WRITE(6,735)CC,CFHALF,TAILPT,PAVDRY,PAVWET
  735 FORMAT(3(/),T40,'WATER CARRYING CAPACITY OF BASE(SQ.FT)=',F10.3,/,
     2            T40,'AVERAGE DEGREE OF DRAINAGE PER HOUR   =',F10.3,/,
     3            T40,'OVERALL PROBABILITYT OF SATURATED BASE=',F10.3,/,
     4          //,T40,'DRY PROBABILITY OF BASE COURSE        =',F10.3,/,
     5            T40,'WET PROBABILITY OF BASE COURSE        =',F10.3)
```

```
      IF(ITEST.EQ.2)   WRITE(6,745)
  745 FORMAT(//,T30,'(THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED
     2ON DEMPSEY¢S FIELD EQUATION)')
      IF(ITEST.EQ.1)   WRITE(6,755)
  755 FORMAT(//,T30,'(THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED
     2ON RIDGEWAY¢S LAB EQUATION)')
      WRITE(6,705)
  705 FORMAT(//,T35,'**********PROBABILITY DISTRIBUTION OF MODULUS OF BA
     2SE COURSE**********',///)
        DO 7200 I=1,10
 7200   IIA(I)=I*10
         WRITE(6,715)(IIA(I),I=1,10),(FREE(I),I=10,100,10),
     2                 (PX(I),I=10,100,10),(DURAT(I),I=10,100,10),
     3                 (BCEM(I),I=10,100,10),(DERATE(I),I=10,100,10),
     4                 (SGEM(I),I=10,100,10),(EMPDF(I),I=10,100,10),
     5                 (SECT(K),K=1,10),(CDF(K),K=1,10)
  715    FORMAT(T25,'SATURATION LEVEL (%)',10I7,//,
     1            T25,'WATER IN BASE(SQ.FT)',10F7.2,//,
     2            T25,'RAINFALL QT.(INCHES)',10F7.2,//,
     3            T25,'RAIN DURATION(HOURS)',10F7.2,//,
     4            T25,'BASE MODULI    (KSI)',10F7.2,//,
     5            T25,'RATIO OF DRY MODULUS',10F7.2,//,
     6            T25,'SUBGRADE MODULI(KSI)',10F7.2,//,
     7            T25,'PROBABILITY  DENSITY',10F7.2,//,
     8            T25,'         PROBABILITY',10F7.2,//,
     9            T25,'CUMULATIVE     PROB.',10F7.2)
      WRITE(6,775)AVGFLO,AVGDUR,AVGRAS,AVBCEM,GEBCEM,GESGEM
  775 FORMAT(//,T40,'***** DISTRIBUTION CHARACTERISTICS OF RAINFALL EFFE
     2CT *****',
     3//,T30,'AVERAGE FREE WATER IN BASE           (SQ.FEET)=',F10.2,
     4//,T30,'DURATION OF AVERAGE RAINFALL AMOUNT   (HOURS)=',F10.3,
     5//,T30,'AVERAGE RAINFALL AMOUNT PER DAY      (INCHES)=',F10.3,
     6//,T30,'AVERAGE BASE COURSE MODULUS IN WET STATE(KSI)=',F10.2,
     7//,T30,'AVERAGE BASE COURSE MODULUS               (KSI)=',F10.2,
     8//,T30,'AVERAGE SUBGRADE MODULUS                  (KSI)=',F10.2)
      RETURN
C
C  A SEASON IS COMPLETE DRY
C
33333 PAVDRY=1.
      PAVWET=0.
      AVGRAS=0.
      AVGDUR=0.
      AVGFLO=0.
      AVBCEM=BCMAT(IBC)
      GEBCEM=AVBCEM
      AVSGEM=AINTER(INDEXA,INDEXB)
      GESGEM=AINTER(INDEXA,INDEXB)
C
C  PRINTOUT FOR ONLY ONE RAINY DAY OR A COMPLETE DRY SEASON
C
55555 WRITE(6,785)
  785 FORMAT(3(/),T40,'****************************************',/,
     2            //,T10,'NO GAMMA DISTRIBUTION IS APPLIED TO THIS ANALYSI
     3S DUE TO ONLY ONE OR NO RAINFALL QUANTITY IS FOUND',//)
      IF(ITEST.EQ.2)   WRITE(6,745)
      IF(ITEST.EQ.1)   WRITE(6,755)
      WRITE(6,765)PAVDRY,PAVWET,
     2             AVGFLO,AVGDUR,AVGRAS,AVBCEM,GEBCEM,GESGEM
  765 FORMAT(
```

```
     2//,T30,'DRY PROBABILITY OF BASE COURSE                    =',F10.3,
     3//,T30,'WET PROBABILITY OF BASE COURSE                    =',F10.3,
     4//,T30,'AVERAGE FREE WATER IN BASE           (SQ.FEET)=',F10.2,
     5//,T30,'DURATION OF AVERAGE RAINFALL AMOUNT   (HOURS)=',F10.3,
     6//,T30,'AVERAGE RAINFALL AMOUNT PER DAY      (INCHES)=',F10.3,
     7//,T30,'AVERAGE BASE COURSE MODULUS IN WET STATE(KSI)=',F10.2,
     8//,T30,'AVERAGE BASE COURSE MODULUS               (KSI)=',F10.2,
     9//,T30,'AVERAGE SUBGRADE MODULUS                  (KSI)=',F10.2)
      RETURN
      END
C
C
C************************************************************************
C*                                                                      *
C*  COMPUTING PROBABILITIES OF CONSECUTIVE DRY DAYS BY KATZ'S METHOD    *
C*                                                                      *
C************************************************************************
C
C
      SUBROUTINE KATZ(IMAXD,W)
      DIMENSION WZERO(50,50),WONE(50,50),W(50,50)
      COMMON /DRYWET/ TLAMDA,DRYLAM,WETLAM,PWET
C   KATZ'S METHOD TO COMPUTE THE DISTRIBUTION OF WET AND DRY DAYS
C   IN CERTAIN PERIOD, WHICH IS ASSOCIATED WITH MARKOV CHAIN MODEL
C   WZERO(I,J): THE PROBABILITY OF I-10 WET DAYS IN J CONSECUTIVE DAYS
C                 WHEN THE ZEROTH DAY IS DRY
C   WONE (I,J): THE PROBABILITY OF I-10 WET DAYS IN J CONSECUTIVE DAYS
C                 WHEN THE ZEROTH DAY IS WET
C   MAXWET: TIME REQUIRED TO DRAIN OUT 99% WATER IN THE PAVEMENT
C
      IF(TLAMDA.GE.174.)    EXPCON=0.
      IF(TLAMDA.LT.174.)    EXPCON=EXP(-TLAMDA)
      P00=(WETLAM+DRYLAM*EXPCON)/TLAMDA
      P01=DRYLAM*(1.-EXPCON)/TLAMDA
      P10=WETLAM*(1.-EXPCON)/TLAMDA
      P11=(DRYLAM+WETLAM*EXPCON)/TLAMDA
      WRITE(6,45) P00,P01,P10,P11
   45 FORMAT(5(/),T30,'********** TRANSITION PROBABILITY MATRIX ********
     2**',3(/),T40,'P00=',F5.3,10X,'P01=',F5.3,//,
     3        T40,'P10=',F5.3,10X,'P11=',F5.3)
C     WZERO(10,11)=P00
C     WZERO(11,11)=P01
C     WONE(10,11)=P10
C     WONE(11,11)=P11
      WZERO(10,10)=1.
      WONE(10,10)=1.
       IF(IMAXD.GE.39) IMAXD=39
      MXWTP1=IMAXD+1
      DO 200 NJ=2,MXWTP1
      DO 100 K=1,NJ
         NJ10=NJ+10
         K10=K+10
         NJ9=NJ10-1
         NJ8=NJ9-1
         K9=K10-1
         K8=K9-1
C   WONE(-1;N-1)=0.
         WONE(9,NJ8)=0.
C   WZERO(N;N-1)=0.
         WZERO(NJ9,NJ8)=0.
```

```
         WZERO(K9,NJ9)=P00*WZERO(K9,NJ8)+P01*WONE(K8,NJ8)
         WONE(K9,NJ9)=P10*WZERO(K9,NJ8)+P11*WONE(K8,NJ8)
         W(K9,NJ9)=(1.-PWET)*WZERO(K9,NJ9)+PWET*WONE(K9,NJ9)
  100 CONTINUE
  200 CONTINUE
C
C
C   CONVERT THE I+10 SEQUENCE TO LOWER SERIES STARTING FROM 1
C   WHICH STANDS FOR DRY DAY, 2 FOR 1 WET DAY.......
C
C
      DO 500 I=1,MXWTP1
      DO 500 J=1,I
        I10=I+9
        J10=J+9
        WONE(J,I)=WONE(J10,I10)
        WZERO(J,I)=WZERO(J10,I10)
        IF(I.GT.1)W(J,I)=W(J10,I10)
  500 CONTINUE
C
C
C     WRITE(6,35)
C  35 FORMAT(1H1,5X,'********** PROBABILITIES OF K WET DAYS IN COSECUTIV
C    2E N DAYS **********',5(/),T40,45('-'),//,T40,4X,'N',4X,'K',
C    +3X,'W0(K;N)',3X,'W1(K;N)',4X,'W(K;N)')
C     DC 400 J2=1,IMAXD
C        J3=J2+1
C         WRITE(6,25)
C  25     FORMAT(//,T40,45('-'),//)
C     DO 300 I2=1,J3
C        J210=J2+1
C        I29=I2
C        I1=I2-1
C        WRITE(6,15)J2,I1,WZERO(I29,J210),WONE(I29,J210),
C    2              W(I29,J210)
C  15    FORMAT(T40,I5,I5,3F10.3)
C 300 CONTINUE
C 400 CONTINUE
      RETURN
      END
C
C
C***********************************************************************
C*                                                                     *
C*  CALCULATE THE DESIRED DRAINING AREA BY INTRAPOLATION               *
C*                                                                     *
C*  XTIME: TIME ( X COORDINATE ) ;                                     *
C*  YAREA: DRAINING AREA ( Y COORDINATE ) ;                            *
C*  TDRAN: TIME OF 50 PERCENT DRAINAGE;                                *
C*  UDRAN: 50 PERCENT DRAINAGE;                                        *
C*  TIMAX: MAXIMUM VALUE FOR TIME;                                     *
C*  UEMAX: MAXIMUM VALUE FOR DRAINAGE;                                 *
C*                                                                     *
C***********************************************************************
C
      SUBROUTINE INPOLA(TDRAN,UDRAN,IA,LOGTIM)
      IMPLICIT REAL(J-Z)
      COMMON  /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
      COMMON /TNUM/ INABT
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
```

```
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      COMMON /SGWET1/ SGWET(100),SGDRY(100),SGW(100),SGD(100)
      DIMENSION LOGTIM(120,10),YAPER(120,10)
      DATA IPT/20/
      REAL INCEPT
C
C   SGEMT : TOTAL SUBGRADE MODULUS
C   SGWET : WET DEPTH OF SUBGRADE
C   SGDRY : DRY DEPTH OF SUBGRADE
C   SGDEP : DEPTH OF SUBGRADE (TOTAL DEPTH OF BASE AND SUBGRADE IS 70IN)
C
      IA=INDS
       DO 1000 I=1,IPT
       EXACT=1.0*I/IPT
      IX=100*I/IPT
      SGDEP=5.83333-HE
         DO 1100 I2=1,100
         IF(I2.EQ.INABT) GO TO 2222
         IF(YAREA(I2,IA).GT.EXACT) GO TO 1111
 1100    CONTINUE
 1111  I1=I2-1
      IF(I1.LE.0) GO TO 1001
       REGCOE=(XTIME(I2,IA)-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA))
       INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA)
       I100=I+100
       XTIME(I100,IA)=INCEPT+REGCOE*EXACT
       YAREA(I100,IA)=EXACT
      CALL SUBHT(XTIME(I100,IA),HSUBX)
      SGWET(IX)=(HE-HSUBX)*N1/N2
      IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
      IF(SGWET(IX).LE.0.OR.K2.EQ.0.) SGWET(IX)=0.
      SGDRY(IX)=5.83333-HE-SGWET(IX)
       IF(IFIX(100*EXACT).EQ.IFIX(100*UDRAN)) TDRAN=XTIME(I100,IA)
      GO TO 1000
 1001 I100=I+100
      XTIME(I100,IA)=XTIME(I2,IA)*EXACT/YAREA(I2,IA)
      YAREA(I100,IA)=EXACT
      CALL SUBHT(XTIME(I100,IA),HSUBX)
      SGWET(IX)=(HE-HSUBX)*N1/N2
      IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
      IF(SGWET(IX).LE.0.OR.K2.EQ.0.) SGWET(IX)=0.
      SGDRY(IX)=5.83333-HE-SGWET(IX)
 1000  CONTINUE
 2222 IMAX=I100+1
      XTIME(IMAX,IA)=TIMAX(IA)
      YAREA(IMAX,IA)=UEMAX(IA)
      CALL SUBHT(XTIME(IMAX,IA),HSUBX)
      SGWET(IX)=(HE-HSUBX)*N1/N2
      IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
      IF(SGWET(IX).LE.0.OR.K2.EQ.0.) SGWET(IX)=0.
      SGDRY(IX)=5.83333-HE-SGWET(IX)
      WRITE(6,2)
    2 FORMAT(1H1,5(/),T30,'DRAINAGE%',11X,'TIME',5X,'PROBLEM NO.')
         DO 1200 I7=101,IMAX
               YAPER(I7,IA)=YAREA(I7,IA)*100.
 1200    CONTINUE
        DO 1600 IB=1,20
        IB100=IB+100
         WRITE(6,305)YAPER(IB100,IA),XTIME(IB100,IA),IA
  305    FORMAT(T30,F9.1,5X,E10.3,I15)
```

```
 1600 CONTINUE
      RETURN
      END
C
C
C*********************************************************************
C*                                                                   *
C*  EVALUATION OF THE DRAINAGE DESIGN FOR GRANULAR LAYERS            *
C*                                                                   *
C*  85% SATURATION ;                                                 *
C*                      SATISFACTORY: LESS THAN 5 HOURS              *
C*                      MARGINAL    : 5 TO 10 HOURS                  *
C*                      UNACCEPTABLE: GREATER THAN 10 HOURS          *
C*                                                                   *
C*  PERIND: PERCENTAGE INDEX, THE PERCENTAGES OF WATER               *
C*                                 CAN BE DRAINED IN A SATURATED SAMPLE  *
C*  IQFINE: CATEGORY OF FINES AMOUNT (1. 0%, 2. 2.5%, 3. 5%, 4. 10%) *
C*  ITYPFI: TYPE OF FINES (1. INERT FILLER, 2. SILT, 3. CLAY)        *
C*  UCRIT : DEGREE OF DRAINAGE CORRESPONDING TO 85% SATURATION       *
C*  TCRIT : TIME (HOUR) CORRESPONDING TO 85% SATURATION              *
C*  GRAVPC: PERCENTAGE OF GRAVEL IN THE SAMPLE                       *
C*  SANDPC: PERCENTAGE OF SAND   IN THE SAMPLE                       *
C*                                                                   *
C*********************************************************************
C
C
      SUBROUTINE JUDGE(IA,INT,ITYPFI,IQFINE,GRAVPC,SANDPC)
      COMMON  /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
      DIMENSION GRAVEL(3,4),SAND(3,4)
      REAL INCEPT
      DATA GRAVEL/3*80.,70.,60.,40.,60.,40.,20.,40.,30.,10./
      DATA SAND  /3*65.,57.,50.,35.,50.,35.,15.,25.,18.,8./
      READ(5,345)ITYPFI,IQFINE,GRAVPC,SANDPC
  345 FORMAT(2I5,2F10.0)
      PERIND=(GRAVPC*GRAVEL(ITYPFI,IQFINE)+SANDPC*SAND(ITYPFI,IQFINE))
     1*0.01
      UCRIT=15./PERIND
      UCRPER=100.*UCRIT
      DO 400 I2=1,INT
        IF(YAREA(I2,IA).LT.UCRIT) GO TO 400
        I1=I2-1
        REGCOE=(XTIME(I2,IA)-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA))
        INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA)
        TCRIT=INCEPT+REGCOE*UCRIT
        IF(YAREA(I2,IA).GE.UCRIT) GO TO 4411
  400 CONTINUE
 4411 WRITE(6,415)GRAVEL(ITYPFI,IQFINE),GRAVPC,SAND(ITYPFI,IQFINE),
     1 SANDPC,PERIND
  415 FORMAT(5(/),T30,'******** EVALUATION OF DRAIANGE DESIGN ********',
     1//,T30,'WATER DRAINED PERCENTAGE DUE TO GRAVEL    =',F11.2,
     2/, T30,'PERCENTAGE  OF GRAVEL IN THE SAMPLE       =',F11.2,
     3/, T30,'WATER DRAINED PERCENTAGE DUE TO SAND      =',F11.2,
     4/, T30,'PERCENTAGE  OF SAND IN THE SAMPLE         =',F11.2,
     5/, T30,'PERCENTAGE  OF WATER WILL BE DRAINED      =',F11.2,3(/))
      IF(UCRIT.GE.1.) GO TO 4444
      WRITE(6,425)UCRPER,TCRIT
  425 FORMAT(
     1/,T30,'CRITICAL DRAINAGE DEGREE (85% SATURATION)=',F11.2,
     2/,T30,'DRAINING TIME FOR 85% SATURATION (HOURS) =',F11.2,3(/))
      IF(TCRIT.GT.10.) WRITE(6,1115)
```

```
 1115 FORMAT(//,T30,'$$$$ THIS DRAINAGE DESIGN IS NOT ACCEPTABLE $$$$')
      IF(TCRIT.GE.5.AND.TCRIT.LE.10.) WRITE(6,1125)
 1125 FORMAT(//,T30,'$$$$ THIS DRAINAGE DESIGN IS IN THE MARGINALLY ACCE
     2PTABLE REGION $$$$')
      IF(TCRIT.LT.5.) WRITE(6,1135)
 1135 FORMAT(//,T30,'$$$$ THIS DRAINAGE DESIGN IS SATISFACTORY $$$$')
      GO TO 4455
 4444 WRITE(6,1145)
 1145 FORMAT(//,T40,'!!!! THIS DRAINAGE DESIGN WILL NOT ALLOW THE SATURA
     2TION LEVEL REACH OR LOWER THAN 85% !!!!')
 4455 RETURN
      END
C
C
C*******************************************************************
C*                                                                 *
C*  COMPUTE THE N2 VIA KNOWN K1,K2,N1 WITH NEWTON-RAPHSON'S METHOD *
C*                                                                 *
C*       EQUATION:   K*(1-N)**2/(N**3) = CONSTANT                  *
C*                   K: PERMEABILITY;    N: POROSITY               *
C*                                                                 *
C*******************************************************************
C
      SUBROUTINE PORO2
      IMPLICIT REAL(J-Z)
      INTEGER N,NA,NB,NC,NJONT,NLANE
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      DATA EPSI/0.1E-03/
      DELK=0.10
      IF(K2.LE.K1) GO TO 455
      N2=N1
      GO TO 999
  455   IF(K2.GT.0.) GO TO 555
        N2=0.1E-05
        GO TO 999
  555   AFCTR=((1.-N1)**2)*K1/(K2*(N1**3))
        K=K2*0.1/K1
        FOFK1=AFCTR*K**3-K**2+2.*K-1.
  204   KN=K+DELK
        FOFKN=AFCTR*KN**3-KN**2+2.*KN-1.
        IF(FOFK1*FOFKN)206,205,207
  205   CONTINUE
        IF(FOFK1.EQ.0.) N2=K
        IF(FOFKN.EQ.0.) N2=KN
        RETURN
  207   K=KN
        FOFK1=FOFKN
        GO TO 204
  206   N21=KN
  208   FOFN=AFCTR*N21**3-N21**2+2.*N21-1.
        DFDN=3.*AFCTR*N21**2-2.*N21+2.
        N2=N21-FOFN/DFDN
        IF(ABS(N2-N21)-EPSI)210,210,209
  209   N21=N2
        GO TO 208
  210   FOFN2=AFCTR*N2**3-N2**2+2.*N2-1.
  999 RETURN
      END
C
```

```
C
C*********************************************************************
C*                                                                   *
C*  PRECIPITATION AS WELL AS DRY AND WET SEQUENCE                    *
C*                                                                   *
C*  GAMMA DISTRIBUTION FOR RAINFALL AMOUNT                           *
C*  MARKOV CHAIN MODEL FOR DRY AND WET SEQUENCE                      *
C*                                                                   *
C*  READ THE RAINFALL AMOUNT AS WELL AS DRY AND WET SEQUENCE DATA IN  *
C*  INPUT MATERIAL PROPERTIES AND CHARACTERISTICS OF BASE AND SUBGRADE *
C*  COMPUTE THE ALPHA AND BETA OF GAMMA DISTRIBUTION                 *
C*                                                                   *
C*  HALFT: TIME FOR 50% DRAINAGE(HOUR)                               *
C*                                                                   *
C*********************************************************************
C
C
      SUBROUTINE RAIN(HALFT,IMAXD)
      IMPLICIT INTEGER (I-N)
      DIMENSION ITITL2(20)
      DIMENSION AMT(5,300),SUM(10),NUM(10),YDRAN(100),WPROB(50,50)
      COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE
      COMMON /DRYWET/ TLAMDA,DRYLAM,WETLAM,PWET
      COMMON  /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
      COMMON /NOGAMA/ NUMWET,AVGAMT,TOTSUM
C
C   READ THE RAINFALL AMOUNT DATA IN AND COUNT THE NUMBER OF WET DAYS
C
C   AMT(1): THE RAINFALL AMOUNT DURING THE PERIOD IS CONCERNED (IN INCHES)
C   AMT(2): THE SEQUENCE OF DRY DAYS
C   AMT(3): THE SEQUENCE OF WET DAYS
C   ITYPE : TYPE OF PAVEMENT, EITHER PCC OR BCP
C   ASOIL : SOIL TYPES CLASSIFIED BY 'AASHTO' OR 'UNIFIED'.
C   BHORIZ: HORIZON (ABC OR BC).  P.86,ASCE TRANS.ENGR.J.,JAN,1979
C   IBC   : INDEX OF BASE MATERIALS
C   CRKJON: THE LENGTH OF CRACKS AND JOINTS(IN FEET)  FROM FIELD SURVEY
C   FTLONG: THE TOTAL LENGTH SURVEYED FOR CRACKS AND JOINTS
C   YEAR  : THE EVALUED PERIOD IN YEARS
C   CONST : CONSTANT 'K' FOR INTENSITY-DURATION-RECURRENCE EQUATION
C                   DEFAULT = 0.3
C   RECPOW: POWER OF RECURRENCE INTERNAL( PERIOD EVALUATED )
C                 DEFAULT = 0.25
C   DURPOW: POWER OF RAINFALL DURATION
C                 DEFAULT = 0.75
C   SHAPE : THE CONSTANT DUE TO CURVE SHAPE OF RAINFALL INTENSITY VS. PERI
C                 DEFAULT = 1.65 (GAUSSIAN CURVE)
C
      REAL*8 ASOIL
      INTEGER BHORIZ
C
C   INPUT MATERIAL PROPERTIES OF BAE AND SUBGRADE
C
      READ(5,445)IBC,ITYPE,ASOIL,BHORIZ
  445 FORMAT(I4,A4,A8,A4)
      READ(5,485)CRKJON,FTLONG
  485 FORMAT(2F10.0)
      READ(5,475)YEAR,CONST,RECPOW,DURPOW,SHAPE
  475 FORMAT(5F10.2)
      IF(CONST.EQ.0.) CONST=0.3
      IF(RECPOW.EQ.0.) RECPOW=0.25
```

```
         IF(DURPOW.EQ.0.) DURPOW=0.75
         IF(SHAPE.EQ.0.) SHAPE=1.65
         WRITE(6,955)
     955 FORMAT(1H1,T30,'***** PAVEMENT TYPES DATA AND PERIOD *****'///,1X,
        2T20,'PVMT TYPE ',5X,'SOIL CLASS',5X,' HORIZON',6X,'  CRK.JT. FT.',
        35X,'  SURVEYED FT',5X,' PERIOD(YEAR)',//)
         WRITE(6,965)ITYPE,ASOIL,BHORIZ,CRKJON,FTLONG,YEAR
     965 FORMAT(T20,A10,7X,A8,11X,A4,2(5X,F13.1),5X,F13.0,//)
         WRITE(6,455)
     455 FORMAT(T30,'*****CHARACTERISTICS OF RAINFALL INTENSITY-DURATION-RE
        2CURRENCE EQUATION*****',//,T30,
        3'K(I-D-R EQ)','   REC. POWER','   DUR. POWER',
        4'  CURVE SHAPE',//)
         WRITE(6,465)CONST,RECPOW,DURPOW,SHAPE
     465 FORMAT(T30,4F13.2)
C
C  READ IN RAINFALL DATA. ISEQ: 1,RAINFALL AMOUNT EACH RAINY DAY;
C                               2,SEQUENCE OF DRY DAYS FREQUENCY
C                               3,SEQUENCE OF WET DAYS FREQUENCY
C
         READ(5,985) IRAIN
     985 FORMAT(I3)
         DO 77777 ITIME=1,IRAIN
         READ(5,405) ITITL2
     405 FORMAT(20A4)
         WRITE(6,495) ITITL2
     495 FORMAT(1H1,T30,20A4)
         DO 500 ISEQ=1,3
         NUM(ISEQ)=0
            DO 100 L=1,20
            INT=(L-1)*16+1
            IEN=(L-1)*16+16
            READ(5,415) (AMT(ISEQ,I),I=INT,IEN)
     415    FORMAT(16F5.0)
                DO 200 I=INT,IEN
                IF(AMT(ISEQ,I).EQ.0.) GO TO 500
     200        NUM(ISEQ)=I
     100    CONTINUE
     500 CONTINUE
         DO 800 IJ=1,3
         K=NUM(IJ)
         IF(K.EQ.0) K=1
           IF(IJ.EQ.1) WRITE(6,915) NUM(1)
           IF(IJ.EQ.2) WRITE(6,925) NUM(2)
     995   FORMAT(T40,16I5)
           IF(IJ.EQ.3) WRITE(6,935) NUM(3)
     905   FORMAT(T40,16F5.2)
     915   FORMAT(//,T40,'***** RAINFALL AMOUNT DATA*****',//,
        2         T40,'NO. OF COUNTS =',I5,//)
     925   FORMAT(//,T40,'***** SEQUENCE OF DRY DAYS *****'//,
        2         T40,'NO. OF COUNTS =',I5,//)
     935   FORMAT(//,T40,'***** SEQUENCE OF WET DAYS *****',//,
        2         T40,'NO. OF COUNTS =',I5,//)
           IF(IJ.NE.1) WRITE(6,995)(IFIX(AMT(IJ,I)),I=1,K)
C    TOTSUM: TOTAL NUMBER OF DAYS IN A PERIOD
C    TOTNUM: TOTAL NUMBER OF COUNTS FROM DRY AND WET DAYS' SEQUENCE
           IF(IJ.EQ.1) WRITE(6,905)(AMT(IJ,I),I=1,K)
     800 CONTINUE
C
C   THE AVERAGE AND VARIANCE
```

```
C
      DO 600 IB=1,3
        SUM(IB)=0.
        IVALUE=NUM(IB)
        IF(IVALUE.EQ.0) IVALUE=1
         DO 300 J=1,IVALUE
         SUM(IB)=SUM(IB)+AMT(IB,J)
  300    CONTINUE
  600 CONTINUE
      NUMWET=NUM(1)
      IF(NUMWET.EQ.0) GO TO 333
      AVGAMT=SUM(1)/NUM(1)
      GO TO 444
  333 AVGAMT=0.
  444 TOTNUM=NUM(2)+NUM(3)
      TOTSUM=SUM(2)+SUM(3)
      AVGRAS=SUM(1)/TOTSUM
      IF(NUMWET.LE.1) GO TO 888
      DRYLAM=TOTNUM/SUM(2)
      WETLAM=TOTNUM/SUM(3)
      TLAMDA=DRYLAM+WETLAM
      PWET=DRYLAM/TLAMDA
      PDRY=WETLAM/TLAMDA
C
C   AVGAMT: AVERAGE OF RAINFALL AMOUNT PER RAINY DAY
C   AVGRAS: AVERAGE OF RAINFALL AMOUNT PER DAY
C   WETLAM: RECIPROCAL OF THE AVERAGE OF WET DAYS
C   DRYLAM: RECIPROCAL OF THE AVERAGE OF DRY DAYS
C
      SSAMT=0.
      DO 400 K=1,NUMWET
  400 SSAMT=SSAMT+(AMT(1,K)-AVGAMT)**2
      VARAMT=SSAMT/NUMWET
C
C   PARAMETERS OF GAMMA DISTRIBUTION
C
      ALPHA=AVGAMT**2/VARAMT
      BETA=AVGAMT/VARAMT
C
C   THE DURATION OF RAINFALL(HOURS) CORRESPONDING TO AVERAGE RAINFALL AMOU
C
      WRITE(6,945)
  945 FORMAT(///,T30,'***** PARAMETERS OF GAMMA DISTRIBUTION AND MARKOV
     2CHAIN MODEL *****')
      WRITE(6,435)AVGAMT,VARAMT,ALPHA,BETA
     2,DRYLAM,WETLAM,TLAMDA,PDRY,PWET
  435 FORMAT(3(/), T40,'AVERAGE RAINFALL PER WET DAY(INCHES) =',F10.3,/,
     2              T40,'VARIANCE OF RAINFALL AMOUNT          =',F10.3,/,
     3           //,T40,'ALPHA OF GAMMA DISTRIBUTION          =',F10.3,/,
     4              T40,'BETA  OF GAMMA DISTRIBUTION          =',F10.3,/,
     5           //,T40,'LAMDA OF DRY DAYS (MARKOV PROCESS)   =',F10.3,/,
     6              T40,'LAMDA OF WET DAYS (MARKOV PROCESS)   =',F10.3,/,
     7              T40,'SUM OF LAMDA OF DRY AND WET DAYS     =',F10.3,/,
     8           //,T40,'PROBABILITY OF DRY DAYS              =',F10.3,/,
     9              T40,'PROBABILITY OF WET DAYS              =',F10.3)
      IF(TIMAX(INDS)/24.LT.1.) GO TO 888
      CALL KATZ(IMAXD,WPROB)
      CALL DRYDAY(IMAXD,YDRAN,WPROB)
  888 CALL FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE,ASOIL,
     2BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPROB,IMAXD)
```

```
77777 CONTINUE
      RETURN
      END
C
C
C**********************************************************************
C*                                                                    *
C*  SIMPSON¢S RULE USED TO INTEGRATE THE GAMMA DISTRIBUTION           *
C*                                                                    *
C**********************************************************************
C
C
      SUBROUTINE SIMP2(AREA2,GAMDIS,XMIN,XMAX,N,ALPHA,BETA)
         H=(XMAX-XMIN)/N
         SUM=0.0
         X=XMIN+H
         DO 4 I=2,N
            IF(MOD(I,2))2,2,3
    2       SUM=SUM+4.*GAMDIS(X,ALPHA,BETA)
            GO TO 4
    3       SUM=SUM+2.*GAMDIS(X,ALPHA,BETA)
    4    X=X+H
        AREA2=H/3.*(GAMDIS(XMIN,ALPHA,BETA)+SUM+GAMDIS(XMAX,ALPHA,BETA))
         RETURN
      END
C
C
C
      FUNCTION GAMDIS(X,ALPHA,BETA)
C   X HAS TO BE GREATER THAN 0. IN GAMMA DISTRIBUTION
         IF(X.LE.0.AND.ALPHA.LE.1) GO TO 3333
         GAMDIS=X**(ALPHA-1.)*EXP(-X*BETA)*(BETA**ALPHA)/(GAMMA(ALPHA))
         RETURN
 3333   GAMDIS=10.
        RETURN
      END
C
C
C**********************************************************************
C*                                                                    *
C*  SIMPSON'S RULE FOR INTEGRATION                                    *
C*                                                                    *
C*  AREA: THE AREA UNDER INTERGRATICN ;                               *
C*  DUMMYF: FUNCTIONS;                                                *
C*  XMIN: MINIMUM VALUE OF X ;                                        *
C*  XMAX: MAXIMUM VALUE OF X ;                                        *
C*  N: NUMBER OF SECTORS;                                             *
C*                                                                    *
C**********************************************************************
C
      SUBROUTINE SIMPSN(AREA,DUMMYF,XMIN,XMAX,N)
      INTEGER N,NA,NB,NC,NJONT,NLANE
      REAL LA,K1,K2,N1,N2
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      H=(XMAX-XMIN)/N
      SUM=0.0
      X=XMIN+H
      DO 4 I=2,N
      IF(MOD(I,2))2,2,3
```

```
   2 SUM=SUM+4.*DUMMYF(X)
     GO TO 4
   3 SUM=SUM+2.*DUMMYF(X)
   4 X=X+H
     AREA=H/3.*(DUMMYF(XMIN)+SUM+DUMMYF(XMAX))
     RETURN
     END
C
C
C*********************************************************************
C*                                                                   *
C*  THE HEIGHT OF WATER LEVEL DUE TO SUBGRADE DRAINAGE ONLY          *
C*                                                                   *
C*  TAREA: TIME;                                                     *
C*  HSUB: HEIGHT OF WATER LEVEL WHICH IS A FUNCTION OF TIME;         *
C*                                                                   *
C*********************************************************************
C
      SUBROUTINE SUBHT(TAREA,HSUB)
      IMPLICIT REAL(J-Z)
      INTEGER N,NA,NB,NC,NJONT,NLANE
      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
      COMMON CASE,HED,HSUBA,HSUBB,NUM,S
      AA=(N1*K2/K1)-(N1**2/N2)
      BB=K2*(1.-N1/N2)*TAREA-HE*(N1*K2/K1-2.*N1**2/N2)
      CC=K2*N1*HE*TAREA/N2-(N1*HE)**2/N2
      SQB=BB**2-4.*AA*CC
      IF(SQB.LE.0.) SQB=0.
      HSUB=(SQRT(SQB)-BB)/(2.*AA)
      RETURN
      END
```

PROBLEM NUMBER 1 ANALYSIS OF HOUSTON PAVEMENT IN MAY, 1970.

SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINGE

LENGTH	HEIGHT	SLOPE%	PERM.1	PERM.2	PORO.1	PORO.2
75.00	0.50	1.50	10.00000	0.00000	0.1000	0.0100

SLOPE FACTOR= 0.444

NOTE: THE FOLLOWING ANALYSIS IS BASED ON PARABOLIC SHAPE PLUS SUBGRADE DRAINAGE

HEAD ON X COOR.	HT.(SUB.DRAIN ONLY)	AVG. HEIGHT.	TIME(STAGE 1)	DRAINAGE DEG.
0.2500E 01	0.5000E 00	0.4944E 00	0.3788E-01	0.1111E-01
0.5000E 01	0.5000E 00	0.4889E 00	0.1452E 00	0.2222E-01
0.7500E 01	0.5000E 00	0.4833E 00	0.3108E 00	0.3333E-01
0.1000E 02	0.5000E 00	0.4778E 00	0.5260E 00	0.4444E-01
0.1250E 02	0.5000E 00	0.4722E 00	0.7839E 00	0.5556E-01
0.1500E 02	0.5000E 00	0.4667E 00	0.1079E 01	0.6667E-01
0.1750E 02	0.5000E 00	0.4611E 00	0.1407E 01	0.7778E-01
0.2000E 02	0.5000E 00	0.4556E 00	0.1764E 01	0.8889E-01
0.2250E 02	0.5000E 00	0.4500E 00	0.2146E 01	0.1000E 00
0.2500E 02	0.5000E 00	0.4444E 00	0.2552E 01	0.1111E 00
0.2750E 02	0.5000E 00	0.4389E 00	0.2978E 01	0.1222E 00
0.3000E 02	0.5000E 00	0.4333E 00	0.3424E 01	0.1333E 00
0.3250E 02	0.5000E 00	0.4278E 00	0.3887E 01	0.1444E 00
0.3500E 02	0.5000E 00	0.4222E 00	0.4365E 01	0.1556E 00
0.3750E 02	0.5000E 00	0.4167E 00	0.4858E 01	0.1667E 00
0.4000E 02	0.5000E 00	0.4111E 00	0.5365E 01	0.1778E 00
0.4250E 02	0.5000E 00	0.4056E 00	0.5884E 01	0.1889E 00
0.4500E 02	0.5000E 00	0.4000E 00	0.6414E 01	0.2000E 00
0.4750E 02	0.5000E 00	0.3944E 00	0.6955E 01	0.2111E 00
0.5000E 02	0.5000E 00	0.3889E 00	0.7505E 01	0.2222E 00
0.5250E 02	0.5000E 00	0.3833E 00	0.8065E 01	0.2333E 00
0.5500E 02	0.5000E 00	0.3778E 00	0.8634E 01	0.2444E 00
0.5750E 02	0.5000E 00	0.3722E 00	0.9211E 01	0.2556E 00
0.6000E 02	0.5000E 00	0.3667E 00	0.9796E 01	0.2667E 00
0.6250E 02	0.5000E 00	0.3611E 00	0.1039E 02	0.2778E 00
0.6500E 02	0.5000E 00	0.3556E 00	0.1099E 02	0.2889E 00
0.6750E 02	0.5000E 00	0.3500E 00	0.1159E 02	0.3000E 00
0.7000E 02	0.5000E 00	0.3444E 00	0.1220E 02	0.3111E 00
0.7250E 02	0.5000E 00	0.3389E 00	0.1282E 02	0.3222E 00
0.7500E 02	0.5000E 00	0.3333E 00	0.1344E 02	0.3333E 00

HEAD ON Y COOR.	HT.(SUB.DRAIN ONLY)	AVG. HEIGHT	TIME(STAGE 2)	DRAINAGE DEG.
0.4833E 00	0.5000E 00	0.3222E 00	0.1472E 02	0.3556E 00
0.4667E 00	0.5000E 00	0.3111E 00	0.1605E 02	0.3778E 00
0.4500E 00	0.5000E 00	0.3000E 00	0.1744E 02	0.4000E 00
0.4333E 00	0.5000E 00	0.2889E 00	0.1890E 02	0.4222E 00
0.4167E 00	0.5000E 00	0.2778E 00	0.2043E 02	0.4444E 00
0.4000E 00	0.5000E 00	0.2667E 00	0.2203E 02	0.4667E 00
0.3833E 00	0.5000E 00	0.2556E 00	0.2372E 02	0.4889E 00
0.3667E 00	0.5000E 00	0.2444E 00	0.2550E 02	0.5111E 00
0.3500E 00	0.5000E 00	0.2333E 00	0.2738E 02	0.5333E 00
0.3333E 00	0.5000E 00	0.2222E 00	0.2936E 02	0.5556E 00
0.3167E 00	0.5000E 00	0.2111E 00	0.3147E 02	0.5778E 00
0.3000E 00	0.5000E 00	0.2000E 00	0.3371E 02	0.6000E 00
0.2833E 00	0.5000E 00	0.1889E 00	0.3611E 02	0.6222E 00
0.2667E 00	0.5000E 00	0.1778E 00	0.3867E 02	0.6444E 00
0.2500E 00	0.5000E 00	0.1667E 00	0.4142E 02	0.6667E 00
0.2333E 00	0.5000E 00	0.1556E 00	0.4439E 02	0.6889E 00
0.2167E 00	0.5000E 00	0.1444E 00	0.4762E 02	0.7111E 00
0.2000E 00	0.5000E 00	0.1333E 00	0.5113E 02	0.7333E 00
0.1833E 00	0.5000E 00	0.1222E 00	0.5499E 02	0.7556E 00
0.1667E 00	0.5000E 00	0.1111E 00	0.5926E 02	0.7778E 00
0.1500E 00	0.5000E 00	0.1000E 00	0.6402E 02	0.8000E 00
0.1333E 00	0.5000E 00	0.8889E-01	0.6940E 02	0.8222E 00
0.1167E 00	0.5000E 00	0.7778E-01	0.7557E 02	0.8444E 00
0.1000E 00	0.5000E 00	0.6667E-01	0.8276E 02	0.8667E 00
0.8333E-01	0.5000E 00	0.5556E-01	0.9135E 02	0.8889E 00
0.6667E-01	0.5000E 00	0.4444E-01	0.1020E 03	0.9111E 00
0.5000E-01	0.5000E 00	0.3333E-01	0.1158E 03	0.9333E 00
0.3333E-01	0.5000E 00	0.2222E-01	0.1356E 03	0.9556E 00
0.1667E-01	0.5000E 00	0.1111E-01	0.1697E 03	0.9778E 00
0.8333E-02	0.5000E 00	0.5556E-02	0.2041E 03	0.9889E 00

DRAINAGE%	TIME	PROBLEM NO.
5.0	0.655E 00	1
10.0	0.215E 01	1
15.0	0.413E 01	1
20.0	0.641E 01	1
25.0	0.892E 01	1
30.0	0.116E 02	1
35.0	0.144E 02	1
40.0	0.174E 02	1
45.0	0.208E 02	1
50.0	0.246E 02	1
55.0	0.289E 02	1
60.0	0.337E 02	1
65.0	0.394E 02	1
70.0	0.460E 02	1
75.0	0.540E 02	1
80.0	0.640E 02	1
85.0	0.774E 02	1
90.0	0.967E 02	1
95.0	0.131E 03	1
98.9	0.204E 03	1

******** EVALUATION OF DRAIANGE DESIGN ********

WATER DRAINED PERCENTAGE DUE TO GRAVEL	=	80.00
PERCENTAGE OF GRAVEL IN THE SAMPLE	=	70.00
WATER DRAINED PERCENTAGE DUE TO SAND	=	65.00
PERCENTAGE OF SAND IN THE SAMPLE	=	30.00
PERCENTAGE OF WATER WILL BE DRAINED	=	75.50

CRITICAL DRAINAGE DEGREE (85% SATURATION)	=	19.87
DRAINING TIME FOR 85% SATURATION (HOURS)	=	6.35

$$$$ THIS DRAINAGE DESIGN IS IN THE MARGINALLY ACCEPTABLE REGION $$$$

***** PAVEMENT TYPES DATA AND PERIOD *****

PVMT TYPE	SOIL CLASS	HORIZON	CRK.JT. FT.	SURVEYED FT	PERIOD(YEAR)
BCP	A-7-6	ABC	0.0	100.0	10.

*****CHARACTERISTICS OF RAINFALL INTENSITY-DURATION-RECURRENCE EQUATION*****

K(I-D-R EQ)	REC. POWER	DUR. POWER	CURVE SHAPE
0.30	0.25	0.75	1.65

RAINFALL DATA AND ANALYSIS OF HOUSTON FAA AIRPORT; MAY, 1970.

***** RAINFALL AMOUNT DATA*****

NO. OF COUNTS = 9

1.65 0.01 4.20 0.45 4.22 0.01 1.04 2.25 1.01

***** SEQUENCE OF DRY DAYS *****

NO. OF COUNTS = 4

8 4 4 6

***** SEQUENCE OF WET DAYS *****

NO. OF COUNTS = 5

1 1 2 3 2

***** PARAMETERS OF GAMMA DISTRIBUTION AND MARKOV CHAIN MODEL *****

AVERAGE RAINFALL PER WET DAY(INCHES)	=	1.649
VARIANCE OF RAINFALL AMOUNT	=	2.341
ALPHA OF GAMMA DISTRIBUTION	=	1.161
BETA OF GAMMA DISTRIBUTION	=	0.704
LAMDA OF DRY DAYS (MARKOV PROCESS)	=	0.409
LAMDA OF WET DAYS (MARKOV PROCESS)	=	1.000
SUM OF LAMDA OF DRY AND WET DAYS	=	1.409
PROBABILITY OF DRY DAYS	=	0.710
PROBABILITY OF WET DAYS	=	0.290

********** TRANSITION PROBABILITY MATRIX **********

P00=0.781 P01=0.219

P10=0.536 P11=0.464

PROBLEM NO.	TIME(DAYS)	DRAINAGE(%)	PROB(CONSECUTIVE DRY DAYS)
1	1	49.24	0.710
1	2	71.35	0.554
1	3	83.16	0.432
1	4	89.86	0.338
1	5	93.80	0.264
1	6	96.11	0.206
1	7	97.67	0.161
1	8	100.00	0.125

WATER CARRYING CAPACITY OF BASE(SQ.FT)= 3.750
AVERAGE DEGREE OF DRAINAGE PER HOUR = 2.032
OVERALL PROBABILITYT OF SATURATED BASE= 0.498

DRY PROBABILITY OF BASE COURSE = 0.354
WET PROBABILITY OF BASE COURSE = 0.646

(THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED ON DEMPSEY¢S FIELD EQUATION)

**********PROBABILITY DISTRIBUTION OF MODULUS OF BASE COURSE**********

SATURATION LEVEL (%)	10	20	30	40	50	60	70	80	90	100
WATER IN BASE(SQ.FT)	0.38	0.75	1.13	1.50	1.88	2.25	2.63	3.00	3.38	3.75
RAINFALL QT.(INCHES)	0.09	0.21	0.34	0.46	0.59	0.71	0.84	0.96	1.09	1.21
RAIN DURATION(HOURS)	0.00	0.00	0.02	0.07	0.18	0.39	0.75	1.31	2.13	3.29
BASE MODULI (KSI)	64.60	64.60	64.60	64.60	64.60	64.60	29.36	19.00	5.07	2.14
RATIO OF DRY MODULUS	1.00	1.00	1.00	1.00	1.00	1.00	0.45	0.29	0.08	0.03
SUBGRADE MODULI(KSI)	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22
PROBABILITY DENSITY	0.45	0.48	0.47	0.46	0.43	0.41	0.39	0.36	0.34	0.31
PROBABILITY	0.04	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04
CUMULATIVE PROB.	0.04	0.09	0.15	0.21	0.27	0.32	0.37	0.42	0.46	0.50

***** DISTRIBUTION CHARACTERISTICS OF RAINFALL EFFECT *****

AVERAGE FREE WATER IN BASE (SQ.FEET)= 1.55

DURATION OF AVERAGE RAINFALL AMOUNT (HOURS)= 0.080

AVERAGE RAINFALL AMOUNT PER DAY (INCHES)= 0.479

AVERAGE BASE COURSE MODULUS IN WET STATE(KSI)= 25.84

AVERAGE BASE COURSE MODULUS (KSI)= 39.55

AVERAGE SUBGRADE MODULUS (KSI)= 31.22

(b) Water Penetration Into and Evaporation from a Low Permeability Base Course

```
C
C***********************************************************************
C                                                                     *
C  WATER INFILTRATION AND EVAPORATION OF A LOW PERMEABLE BASE COURSE  *
C                                                                     *
C                        TEXAS TRANSPORTATION INSTITUTE               *
C                                                                     *
C                                  AUGUST 1983                        *
C                                                                     *
C***********************************************************************
      DIMENSION ASUBN(20),USOIL(50,50),SIGMA(20),ZROOT(20)
      DIMENSION EVWT(1000),SERIES(20)
      CALL LOWPER(DEPTH,INFILT)
      CALL EVAPOR(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
      CALL EVWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
      WRITE(6,115)
  115 FORMAT(1H1)
      STOP
      END
C
C
C***********************************************************************
C                                                                     *
C  EVAPORATION OF WATER FROM SOIL WITH P. MITCHELL'S SOLUTION         *
C                                                                     *
C***********************************************************************
C
C  THIS SUBPROGRAM IS TO COMPARE THE SUCTION LEVELS OF DIFFERENT DEPTH
C  AT CERTAIN TIME IN ORDER TO CHECK WITH MITCHELL'S SOLUTION
      SUBROUTINE EVAPOR(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
      DIMENSION ASUBN(20),USOIL(50,50),SIGMA(20),ZROOT(20)
C
C  UATM  : SUCTION OF ATMOSPHERE IN PF (LOG H)
C  UNOT  : INITIAL SUCTION STATE OF SOIL IN PF
C  DIFC  : DIFFUSION COEFFICIENT OF A SOIL (CM**2/SEC)
C  DEPTH : WATER DEPTH IN SOIL (CM)
C  YVERT : VERTICAL DISTANCE FROM SOIL BOTTOM (CM)
C  EVTIME: ELAPSED TIME FOR EVAPORATION (SEC)
C  HRTIME: ELAPSED TIME FOR EVAPORATION (HOUR)
C  DYTIME: ELAPSED TIME FOR EVAPORATION (DAYS)
C  ASUBN : COEFFICIENT OF FOURIER SERIES
C  SIGMA : EVERY SINGLE TERM OF THE FOURIER SERIES
C  TSIGMA: TOTAL SUM FOR TEN TERMS OF FOURIER SERIES
C  USOIL : SOIL SUCTION IN DIFFERENT DEPTH AND TIME (I2:DEPTH,I1:TIME)
C  ZROOT : ROOTS OF COTAN(Z)=Z/(DEPTH*EVAPC)
C  EVAPC : EVAPORATION COEFFICIENT IN CM/SEC
C  DQDU  : THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF)
C
      READ(5,305) UATM,UNOT,DIFC,DQDU,EVAPC
  305 FORMAT(5E10.3)
      WRITE(6,405)UATM,UNOT,DIFC,DQDU,EVAPC,DEPTH
  405 FORMAT(1H1,///,T30,'********** EVAPORATION OF WATER FROM SOIL ****
     2******',
     3            //,T15,'SUCTION OF ATMOSPHERE (PF)         =',E10.3,
     4            //,T15,'INITIAL SUCTION OF SOIL (PF)       =',E10.3,
     5            //,T15,'DIFFUSION COEFFICIENT (CM**2/SEC) =',E10.3,
     6            //,T15,'SLOPE OF WATER CONTENT/ SUCTION    =',E10.3,
     7            //,T15,'EVAPORATION COEFFICIENT (CM/SEC)   =',E10.3,
     8            //,T15,'DEPTH OF WATER PENETRATION (CM)    =',E10.3)
```

```
      CALL EVROOT(ZROOT,DEPTH,EVAPC)
           DO 3000 I=1,10
           ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
     2                  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
 3000      CONTINUE
      WRITE(6,105)
  105 FORMAT(///,T30,'********* SUCTION DISTRIBUTION IN SOIL DUE TO EVAP
     2ORATION **********',3(/),T40,' TIME    (DAYS)',
     3T60,'SOIL DEPTH (CM)', T80,'SUCTION (PF)',3(/))
      DO 3300 I1=1,5
      DYTIME=I1*1.
      EVTIME=DYTIME*3600.*24.
           DO 3200 I2=1,10
           TSIGMA=0.
           YVERT=DEPTH/10.*I2
                DO 3100 I=1,10
           POWER=ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2)
           IF(ABS(POWER).GE.100.) GO TO 3333
                SIGMA(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTIME*DIFC/
     2                   (DEPTH**2))*COS(ZROOT(I)*YVERT/DEPTH)
                TSIGMA=TSIGMA+SIGMA(I)
 3100           CONTINUE
 3333      USOIL(I2,I1)=UATM+TSIGMA
           WRITE(6,205) DYTIME,YVERT,USOIL(I2,I1)
  205      FORMAT(2(/),T40,F15.3,T60,F15.3,T80,E12.5)
 3200      CONTINUE
 3300 CONTINUE
      RETURN
      END
C
C
C*********************************************************************
C                                                                    *
C       PERIODIC ROOTS FOR FOURIER SERIES OF WATER EVAPORATION       *
C       FROM SOIL MODEL WITH P. MITCHELL'S SOLUTION                  *
C                                                                    *
C*********************************************************************
C
C
      SUBROUTINE EVROOT(ZROOT,DEPTH,EVAPC)
C
C  BISECTION METHOD TO SOLVE FOR ROOTS OF 'DEPTH*EVAPC*COT(Z)-Z=0'
C  DEPTH: LENGTH OF SOIL COLUMN IN CENTIMETER
C  EVAPC: EVAPORATION COEFFICIENT IN CM/SEC
C
      DIMENSION ZROOT(20)
      DATA EPSI/0.1E-05/
      DO 1000 I=1,10
        AMPLIT=EVAPC*DEPTH
C
C  INPUT THE INITIAL VALUES ON BOTH SIDES (XL & XR)
C
        XL=3.1416*(I-1)+0.1
        XR=3.14*I
        DO 100 IK=1,100
        XM=(XL+XR)/2.
        FOFXL=AMPLIT*COTAN(XL)-XL
        FOFXM=AMPLIT*COTAN(XM)-XM
        IF(FOFXM*FOFXL) 20,30,40
   20   XR=XM
```

```
          GO TO 50
   30     IF(FOFXM.EQ.0.) ZROOT(I)=XM
          IF(FOFXL.EQ.0.) ZROOT(I)=XL
          GO TO 2222
   40     XL=XM
   50     IF(ABS(XL-XR)-EPSI) 210,210,100
  100     CONTINUE
  210     ZROOT(I)=XM
 2222     FZROOT=AMPLIT*COTAN(ZROOT(I))-ZROOT(I)
 1000     CONTINUE
        RETURN
        END
C
C
C**********************************************************************
C                                                                    *
C  WATER AMOUNT EVAPORATED FROM BARE SOIL                            *
C                                                                    *
C**********************************************************************
C
C
        SUBROUTINE EVWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
         DIMENSION ASUBN(20),EVWT(1000),SERIES(20),ZROOT(20)
C  COMPUTATION OF AMOUNT OF WATER EVAPORATED FROM SOIL
C  EVWT  : WATER AMOUNT EVAPORATED FROM SOIL IN CM
C  SERIES: SINGLE TERM FOR THE FOURIES SERIES
C  TSERIE: SUM OF THE SERIES WHICH IS INTEGRATED FROM SUCTION AT
C          SPECIFIC TIME
C  DQDU  : THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF)
C
        WRITE(6,405)
  405 FORMAT(1H1,2(/),T30,'*********** WATER AMOUNT EVAPORATED FROM SOIL
     2 **********',3(/),T33,'EVAPORATION TIME(HOUR)',T60,'EVAPORATION AM
     3OUNT (CM)',3(/))
        DO 4100 IK=1,720
        TSERIE=0.
        HRTIME=IK*1.
        EVTIME=HRTIME*3600.
             DO 4000 I=1,10
             POWER=ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2)
             IF(ABS(POWER).GE.100.) GO TO 4411
             SERIES(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2))
     2                 *SIN(ZROOT(I))/ZROOT(I)
             TSERIE=TSERIE+SERIES(I)
 4000        CONTINUE
 4411 EVWT(IK)=(UATM-UNOT+TSERIE)*DEPTH*DQDU
C
C  OUTPUT THE RESULTS EVERY 2 HOURS
C
        I2=IK/2*2
        IF(I2.NE.IK.AND.EVWT(IK).LT.DEPTH) GO TO 4100
        WRITE(6,415) HRTIME,EVWT(IK)
  415 FORMAT(2(/),T45,F10.2,T60,F23.4)
        IF(EVWT(IK).GE.DEPTH) GO TO 4444
 4100 CONTINUE
 4444 RETURN
        END
C
C
C**********************************************************************
```

```
C*                                                                    *  01800
C*   WATER PENETRATION INTO A BASE COURSE OF LOW PERMEABILITY         *  01810
C*                                                                    *  01820
C*********************************************************************** 01830
C                                                                        01840
      SUBROUTINE LOWPER(DEPTH,INFILT)                                    01850
C                                                                        01860
C THIS SUBPROGRAM IS USED TO COMPUTE THE WATER DISTRIBUTION IN A LOW     01870
C PERMEABILITY BASE COURSE FROM THE CRACKS/JOINTS IN A PAVEMENT          01880
C EULER'S METHOD IS APPLIED AS A NUMERICAL ANALYSIS                      01890
C UNITS:  TIME - HOUR;   LENGTH - CENTIMETER;                            01900
C         PERMEABILITY - CENTIMETER/HOUR                                 01910
C         UNITS ARE FREE AS LONG AS THEY ARE CONSISTENT. ABOVE IS IN GENER01920
C  WC    : WIDTH OF CCRACKS/JOINTS                                       01930
C  TL    : DEPTH OF CRACKS/JOINTS                                        01940
C  HPERM : HORIZONTAL PERMEABILITY OF BASE                               01950
C  VPERM : VERTICAL   PERMEABILITY OF BASE                               01960
C  DPWA  : DEPTH OF WATER LEFT IN CRACKS/JOINTS                          01970
C  TIME  : TIME PASSED FOR WATER PENETRATION                             01980
C  YOFT  : VERTICAL DISTANCE INTO WHICH WATER INFILTRATES                01990
C  XOFT  : HORIZONTAL DISTANCE INTO WHICH WATER FLOWS                    02000
C  PORO1 : POROSITY OF BASE SOIL                                         02010
C  INFILT: TIME FOR ALL WATER FROM CRACKS/JOINTS INFILTRATES INTO BASE   02020
C                                                                        02030
      DIMENSION DPWA(1000),TIME(1000),XOFT(1000),YOFT(1000),DL(1000)     02040
      READ(5,25)WC,TL,HPERM,VPERM,PORO1,HTCP                             02050
   25 FORMAT(6(E10.3))                                                   02060
      WRITE(6,45)                                                        02070
   45 FORMAT(1H1,//,T30,'********** WATER DISTRIBUTION OF LOW PERMEABILI 02080
     2Y BASE COURSE **********',//)                                      02090
      WRITE(6,55)WC,TL,HPERM,VPERM,PORO1,HTCP                            02100
   55 FORMAT( //,T20,'WIDTH OF CRACK/JOINT (CM)               =',E10.3,  02110
     2        //,T20,'DEPTH OF CRACK/JOINT (CM)               =',E10.3,  02120
     3        //,T20,'VERTICAL   PERMEABILITY OF BASE (CM/HR)=',E10.3,   02130
     4        //,T20,'HORIZONTAL PERMEABILITY OF BASE (CM/HR)=',E10.3,   02140
     5        //,T20,'POROSITY OF BASE COURSE                 =',E10.3,  02150
     6        //,T20,'CAPILLARY HEAD OF BASE (CM)             =',E10.3)  02160
      WRITE(6,65)                                                        02170
   65 FORMAT(///,13X,'TIME  (HOUR)',5X,'HORIZONTAL DIST.(CM)',           02180
     27X,'VERTICAL DIST.(CM)',4X,'CRACK WATER DEPTH(CM)',//)             02190
      DPWA(1)=TL                                                         02200
      YOFT(1)=0.                                                         02210
      TIME(1)=0.                                                         02220
      DELY=0.01                                                          02230
      DO 100 I=2,1000                                                    02240
      IM1=I-1                                                            02250
      YOFT(I)=YOFT(IM1)+DELY                                             02260
      DT=PORO1*YOFT(I)*DELY/(VPERM*(YOFT(I)+HTCP+TL))                    02270
      TIME(I)=TIME(IM1)+DT                                               02280
        XOFT(I)=SQRT(2.*HPERM*TIME(I)*(TL+HTCP)/PORO1)                   02290
        DENT=(HPERM*YOFT(I)*(TL+HTCP)/XOFT(I)+                           02300
     2        VPERM*XOFT(I)*(YOFT(I)+TL+HTCP)/YOFT(I))*1.5708/PORO1      02310
        DL(I)=(DENT*DT)/WC                                               02320
        DPWA(I)=DPWA(IM1)-DL(I)                                          02330
C                                                                        02340
C  OUTPUT ONE SET OF RESULTS OUT OF EVERY TEN CALCULATIONS               02350
C                                                                        02360
        IF(DPWA(I).LE.0.) GO TO 222                                      02370
        ID=IM1/10*10                                                     02380
        IF(ID-IM1)100,111,100                                            02390
```

```
  111 WRITE(6,75) TIME(I),XOFT(I),YOFT(I),DPWA(I)
   75 FORMAT(4(10X,E15.3))
  100 CONTINUE
C
C USE INTRAPOLATION TO ENUMERATE THE FINAL DEPTH WHERE WATER WILL REACH
C
  222 DEPTH=YOFT(I)-(YOFT(I)-YOFT(IM1))/(DPWA(I)-DPWA(IM1))*DPWA(I)
      YOFT(I)=DEPTH
      DELY2=DEPTH-YOFT(IM1)
      DT=PORO1*DEPTH*DELY2/(VPERM*(DEPTH+HTCP+TL))
      TIME(I)=TIME(IM1)+DT
      INFILT=TIME(I)
      XOFT(I)=SQRT(2.*HPERM*TIME(I)*(TL+HTCP)/PORO1)
      DENT=(HPERM*DEPTH*(TL+HTCP)/XOFT(I)+
     2       VPERM*XOFT(I)*(DEPTH+TL+HTCP)/DEPTH)*1.5708/PORO1
      DL(I)=(DENT*DT)/WC
      DPWA(I)=DPWA(IM1)-DL(I)
      WRITE(6,75) TIME(I),XOFT(I),DEPTH,DPWA(I)
     RETURN
     END
```

********** WATER DISTRIBUTION OF LOW PERMEABILIY BASE COURSE **********

WIDTH OF CRACK/JOINT (CM) = 0.200E 01

DEPTH OF CRACK/JOINT (CM) = 0.250E 02

VERTICAL PERMEABILITY OF BASE (CM/HR)= 0.200E 00

HORIZONTAL PERMEABILITY OF BASE (CM/HR)= 0.200E-01

POROSITY OF BASE COURSE = 0.100E 00

CAPILLARY HEAD OF BASE (CM) = 0.300E 03

TIME (HOUR)	HORIZONTAL DIST.(CM)	VERTICAL DIST.(CM)	CRACK WATER DEPTH(CM)
0.846E-04	0.332E 00	0.100E 00	0.250E 02
0.323E-03	0.648E 00	0.200E 00	0.249E 02
0.715E-03	0.964E 00	0.300E 00	0.248E 02
0.126E-02	0.128E 01	0.400E 00	0.246E 02
0.196E-02	0.160E 01	0.500E 00	0.244E 02
0.281E-02	0.191E 01	0.600E 00	0.241E 02
0.382E-02	0.223E 01	0.700E 00	0.238E 02
0.498E-02	0.254E 01	0.800E 00	0.234E 02
0.629E-02	0.286E 01	0.900E 00	0.230E 02
0.775E-02	0.317E 01	0.100E 01	0.225E 02
0.937E-02	0.349E 01	0.110E 01	0.220E 02
0.111E-01	0.381E 01	0.120E 01	0.214E 02
0.131E-01	0.412E 01	0.130E 01	0.208E 02
0.151E-01	0.444E 01	0.140E 01	0.201E 02
0.174E-01	0.475E 01	0.150E 01	0.194E 02
0.198E-01	0.507E 01	0.160E 01	0.186E 02
0.223E-01	0.538E 01	0.170E 01	0.178E 02
0.250E-01	0.570E 01	0.180E 01	0.169E 02
0.278E-01	0.601E 01	0.190E 01	0.160E 02
0.308E-01	0.633E 01	0.200E 01	0.150E 02
0.339E-01	0.664E 01	0.210E 01	0.140E 02
0.372E-01	0.696E 01	0.220E 01	0.130E 02
0.407E-01	0.727E 01	0.230E 01	0.118E 02
0.443E-01	0.759E 01	0.240E 01	0.107E 02
0.480E-01	0.790E 01	0.250E 01	0.945E 01
0.519E-01	0.822E 01	0.260E 01	0.819E 01
0.560E-01	0.853E 01	0.270E 01	0.688E 01
0.602E-01	0.884E 01	0.280E 01	0.551E 01
0.645E-01	0.916E 01	0.290E 01	0.410E 01
0.690E-01	0.947E 01	0.300E 01	0.264E 01
0.737E-01	0.979E 01	0.310E 01	0.113E 01
0.772E-01	0.100E 02	0.317E 01	0.112E-03

********** EVAPORATION OF WATER FROM SOIL **********

SUCTION OF ATMOSPHERE (PF)	=	0.634E 01
INITIAL SUCTION OF SOIL (PF)	=	0.397E 01
DIFFUSION COEFFICIENT (CM**2/SEC)	=	0.350E-04
SLOPE OF WATER CONTENT/ SUCTION	=	0.200E 01
EVAPORATION COEFFICIENT (CM/SEC)	=	0.540E 00
DEPTH OF WATER PENETRATION (CM)	=	0.317E 01

********* SUCTION DISTRIBUTION IN SOIL DUE TO EVAPORATION **********

TIME (DAYS)	SOIL DEPTH (CM)	SUCTION (PF)
1.000	0.317	0.43524E 01
1.000	0.635	0.43822E 01
1.000	0.952	0.44319E 01
1.000	1.269	0.45011E 01
1.000	1.586	0.45896E 01
1.000	1.904	0.46970E 01
1.000	2.221	0.48224E 01
1.000	2.538	0.49650E 01
1.000	2.855	0.51233E 01
1.000	3.173	0.52958E 01
2.000	0.317	0.48874E 01

2.000	0.635	0.49105E 01
2.000	0.952	0.49487E 01
2.000	1.269	0.50017E 01
2.000	1.586	0.50688E 01
2.000	1.904	0.51493E 01
2.000	2.221	0.52425E 01
2.000	2.538	0.53474E 01
2.000	2.855	0.54627E 01
2.000	3.173	0.55874E 01
3.000	0.317	0.52835E 01
3.000	0.635	0.53003E 01
3.000	0.952	0.53281E 01
3.000	1.269	0.53667E 01
3.000	1.586	0.54155E 01
3.000	1.904	0.54742E 01
3.000	2.221	0.55420E 01
3.000	2.538	0.56183E 01
3.000	2.855	0.57022E 01
3.000	3.173	0.57929E 01
4.000	0.317	0.55717E 01

4.000	0.635	0.55839E 01
4.000	0.952	0.56041E 01
4.000	1.269	0.56322E 01
4.000	1.586	0.56677E 01
4.000	1.904	0.57104E 01
4.000	2.221	0.57597E 01
4.000	2.538	0.58151E 01
4.000	2.855	0.58762E 01
4.000	3.173	0.59421E 01
5.000	0.317	0.57812E 01
5.000	0.635	0.57901E 01
5.000	0.952	0.58049E 01
5.000	1.269	0.58252E 01
5.000	1.586	0.58511E 01
5.000	1.904	0.58821E 01
5.000	2.221	0.59180E 01
5.000	2.538	0.59583E 01
5.000	2.855	0.60027E 01
5.000	3.173	0.60506E 01

*********** WATER AMOUNT EVAPORATED FROM SOIL **********

EVAPORATION TIME(HOUR)	EVAPORATION AMOUNT (CM)
2.00	0.5339
4.00	0.9948
6.00	1.4172
8.00	1.8123
10.00	2.1860
12.00	2.5422
14.00	2.8837
16.00	3.2123

E-3. GUIDE FOR DATA INPUT TO COMPUTER PROGRAM

(a) Simulation Model of Rainfall Infiltration and Drainage Analysis

1. Identification Card (I5, I3, 18A4)

cc 1-5	IPROB	Problem Number (≤ 1Ø)
cc 6-8	INEED	Analytical procedures required Ø: Drainage analysis only 1: Drainage analysis and drainage design evaluation 2: System analysis of rainfall infiltration and drainage
cc 11-8Ø	ITITLE	Problem title

2. Characteristics of base and subgrade (7F1Ø.Ø)

cc 1-1Ø	LA	One side width of base (feet)
cc 11-2Ø	HE	Depth of base (feet)
cc 21-3Ø	TAPER	Slope ratio or value of tan of base (%) e.g., tan α = Ø.Ø16, input 1.6
cc 31-4Ø	K1	Permeability of Base (Feet/Hour)
cc 41-5Ø	K2	Permeability of Subgrade (Feet/Hour)
cc 51-6Ø	N1	Porosity of Base
cc 61-7Ø	N2	Porosity of Subgrade*

*If N2 is not available, put 0.0 in columns 68-70, N2 will be calculated by the equation

$$\frac{K1(1-N1)^2}{(N1)^3} = \frac{K2(1-N2)^2}{(N2)^3} ,$$

which is assumed that the base and subgrade are of the same material.

NOTE: The following cards are needed only when INEED=1 and 2.

3. Material types of base course (2I5, 2F10.0)

cc	5	ITYPE	Types of fines added*
			1. Inert filler
			2. Silt
			3. Clay
cc	6-10	IQFINE	Amount of fines added*
			1. 0%
			2. 2.5%
			3. 5%
			4. 10%

*see Table 2

cc	11-20	GRAVPC	Percentage of Gravel in sample e.g. 80%, Input 80.0
cc	21-30	SANDPC	Percentage of Sand in sample

NOTE: If INEED=0 or 1, skip the following cards.

4. Material properties of base and subgrade (I4, A4, A8, A4)

cc 4	IBC	Index of base course material which corresponds to the elastic modulus (see Table 5-1) 1. Crushed limestone+4% cement 2. Crushed limestone+2% lime 3. Crushed limestone 4. Gravel 5. Sand clay 6. Embankment-compacted plastic clay
cc 5-8	ITYPE	Pavement type (PCC or BCP)
cc 9-16	ASOIL	Types of subgrade soils classified by "AASHO" or Unified (see Table 3)
cc 17-2Ø	BHORIZ	Horizon of subgrade (ABC or BC)

5. Area of cracks and joints and surveyed field length (2F1Ø.Ø)

cc 1-1Ø	CRKJON*	linear length of cracks and joints of one-side pavement (feet)
cc 11-2Ø	FTLONG	Surveyed field length (feet)

*If cracks and joints are not available input Ø.Ø for CRKJON, the model will use Dempsey and Robnett's regression equation to calculate the amount of water flowing into base course.

6. Parameters of intensity-duration-recurrence equation (5F1Ø.Ø) (see Appendix A-2)

cc 1-1Ø	YEAR	Evaluated period (years)
cc 11-2Ø	CONST	Constant K (default=Ø.3)
cc 21-3Ø	RECPOW	Power of recurrence interval (default=Ø.25)
cc 31-4Ø	DURPOW	Power of rainfall duration (default=Ø.15)
cc 41-5Ø	SHAPE	Value corresponding to curve shape of rainfall intensity vs. rainfall period.

7. Number of rainfall amount and frequency data sets (I3)

cc 1 - 3	IRAIN	Number of data set

The number of IRAIN means the number of different periods will be evaluated for their climatic effects on the same pavement and Cards 8-11 will be used repeatedly.

8. Identification card for each season (2ØA4)

cc 1 -8Ø ITITL2 — Title for the source of rainfall data.

9. Rainfall amount data (16/5.Ø)*

AMT (ISEQ,1) — Rainfall amount of each rainy day ($\geq$Ø.Ø1 inches)

1Ø. Sequence of the number of dry days (16 F5.Ø)*

AMT (ISEQ,2) — Number of consecutive dry days in sequence**

11. Sequence of the number of wet days (16 F5.Ø)*

AMT (ISEQ,3) — Number of consecutive wet days in sequence**

*Every set of sequential data has to end with a blank or zero. Three sets of data are in separate cards.

**e.g., in a particular season, the sequence weather is 5 dry days, 1 wet day, 4 dry days, 2 wet days, 2 dry days, ...etc., then in

AMT (ISEQ, 2) input 5.Ø, 4.Ø, 2.Ø, ...and in

AMT (ISEQ, 3) input 1.Ø, 2.Ø, ...

(b) Water Penetration into a Base of Low Permeability

1. Characteristics of cracks/joints and the base course (6E 10.3)

cc 1-10	WC	Width of Crack/Joint (cm)
cc 11-20	TL	Depth of Crack/Joint (cm)
cc 21-30	HPERM	Permeability of Horizontal direction in Base Course (cm/hr)
cc 31-40	VPERM	Permeability of Vertical direction in Base Course (cm/hr)
cc 41-50	PORO1	Porosity of Base Course (dimensionless)
cc 51-60	HTCP	Capillary head in Base Course (cm)

2. Characteristics of water evaporation from the base course and boundary conditions (5E 10.3)

cc 1-10	UATM	Suction of atmosphere (pF)
cc 11-20	UNOT	Initial suction of base soil (pF)
cc 21-30	DIFC	Diffusion Coefficient (cm^2/sec)
cc 31-40	DQDU	Slope ratio between water content and suction
cc 41-50	EVAPC	Evaporation Coefficient (cm/sec)