

ENVIRONMENTAL EFFECTS ON PAVEMENTS

Damage Analysis

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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 EARMAR 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

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

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

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

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 = 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

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

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, $\gamma_{\text{season}}/i_{\text{avg}}$; (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's 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 changing water contents on the moduli of base courses and subgrades. Ground water sources and the side infiltration from the pavement shoulders are not considered in this report.

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 (14) rate of infiltration of water through cracks and joints, which was determined in a field experiment, or the regression equations of Dempsey and Robnett (20) 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 (26), and Thompson and Robnett (30,33), 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.

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 arithmetically 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

$$i = \frac{C}{t_R + b} \quad (2-1)$$

and

$$i = \frac{k t_p^x}{t_R^n} \quad (2-2)$$

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)

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

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

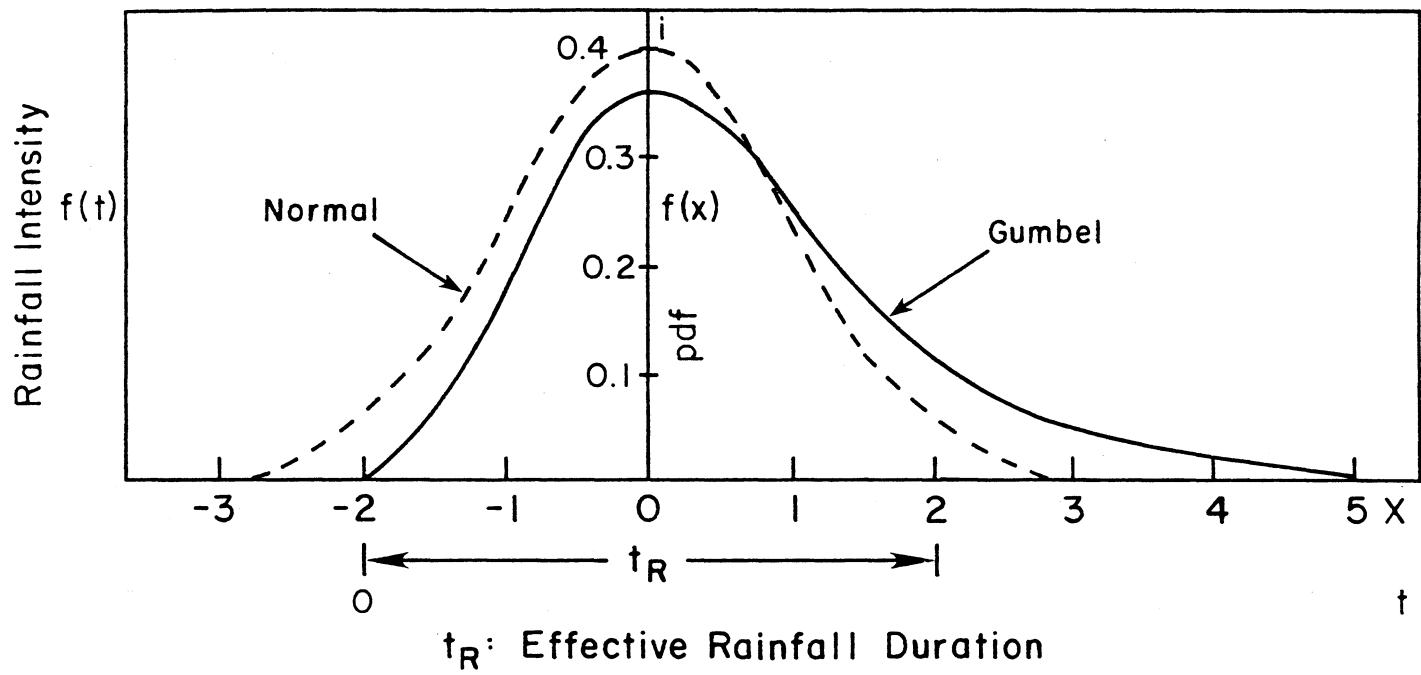


FIGURE 1. Comparison of Normal and Gumbel Distributions (5)

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 0. Therefore, the probability of having a dry day at time t when time 0 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 |

$$P_0 = 0.71 \quad P_{\emptyset\emptyset} = 0.78 \quad P_{\emptyset 1} = 0.22 \quad P_{1\emptyset} = 0.54 \quad P_{11} = 0.46$$

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_{\emptyset} = 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 ($100 \text{ cm}^3/\text{hr/cm}$) can be used for design purposes.

In the analysis, the following average infiltration rates are chosen for cracks in bituminous concrete pavement,

100 $\text{cm}^3/\text{hr}/\text{cm}$ of crack ($0.11 \text{ ft}^3/\text{hr}/\text{ft}$ or $2.64 \text{ ft}^3/\text{day}/\text{ft}$), and for cracks and joints in portland cement concrete pavements, 28 $\text{cm}^3/\text{hr}/\text{cm}$ of crack or joint ($0.03 \text{ ft}^3/\text{hr}/\text{ft}$ or $0.72 \text{ ft}^3/\text{day}/\text{ft}$).

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,

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

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

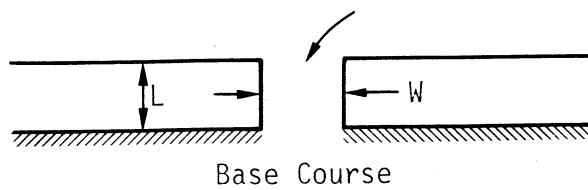
The preceding analyses of base drainage assume that the free water penetrates into the base course instantaneously,

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.

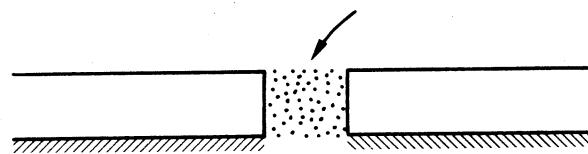
3.3.1 Water Entry into Low Permeability Bases

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.

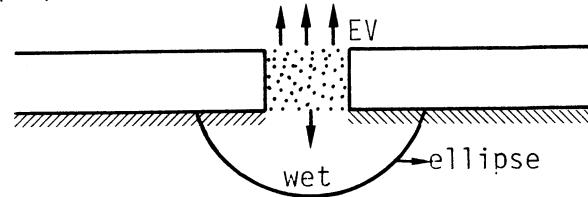
1. Dry Period



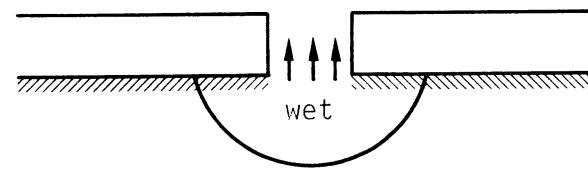
2. Rain Falls



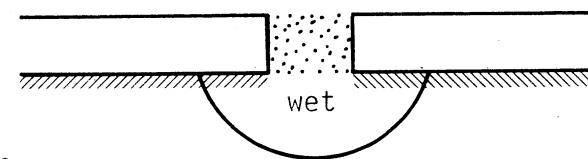
3. Penetration of Rainfall into Base Course and
and Evaporation (EV) from Cracks/Joints
6.



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):

$$x_0 = w \frac{2d\lambda}{\pi} \frac{kh}{kv}, \text{ and} \quad (3-2)$$

$$y_0 = w \frac{2d\lambda}{\pi} \frac{kv}{kh} \quad (3-3)$$

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

λ = 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),

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

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

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

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'S 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 , α , k_1 , and n_1 as illustrated in Figure 4. In the

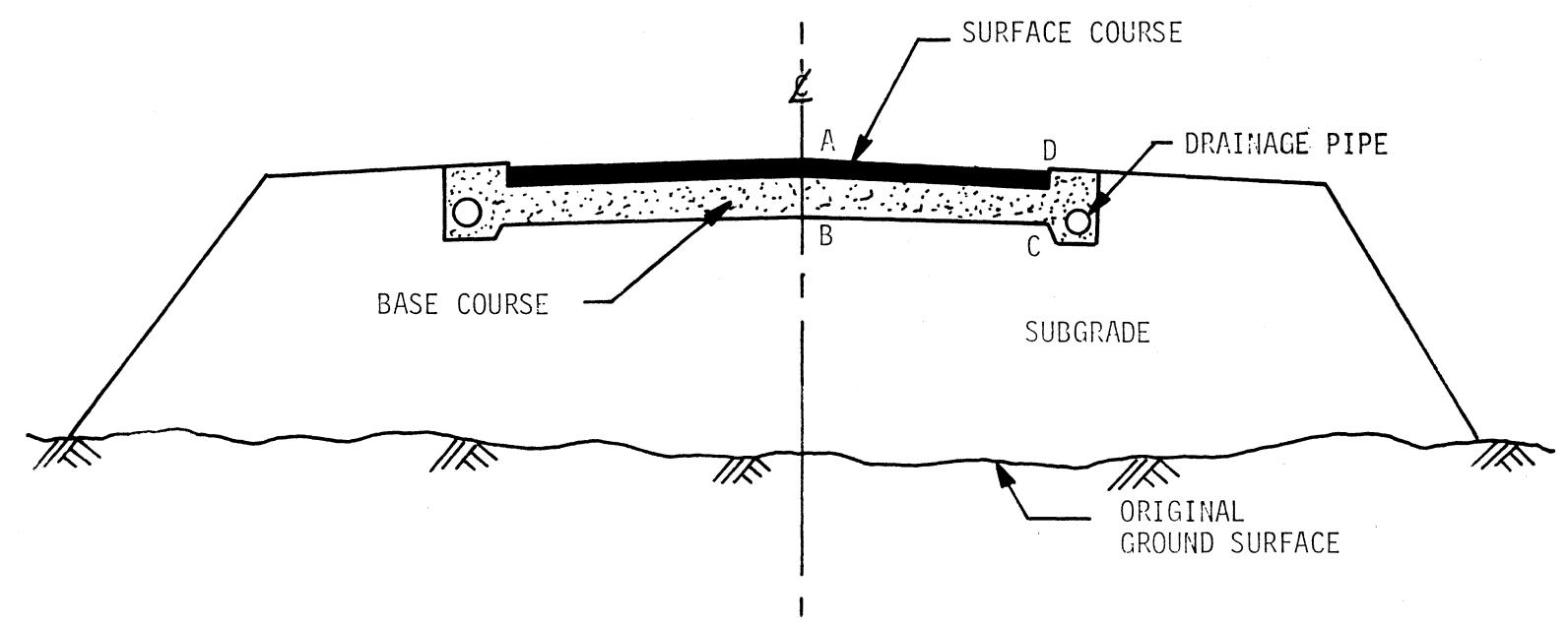
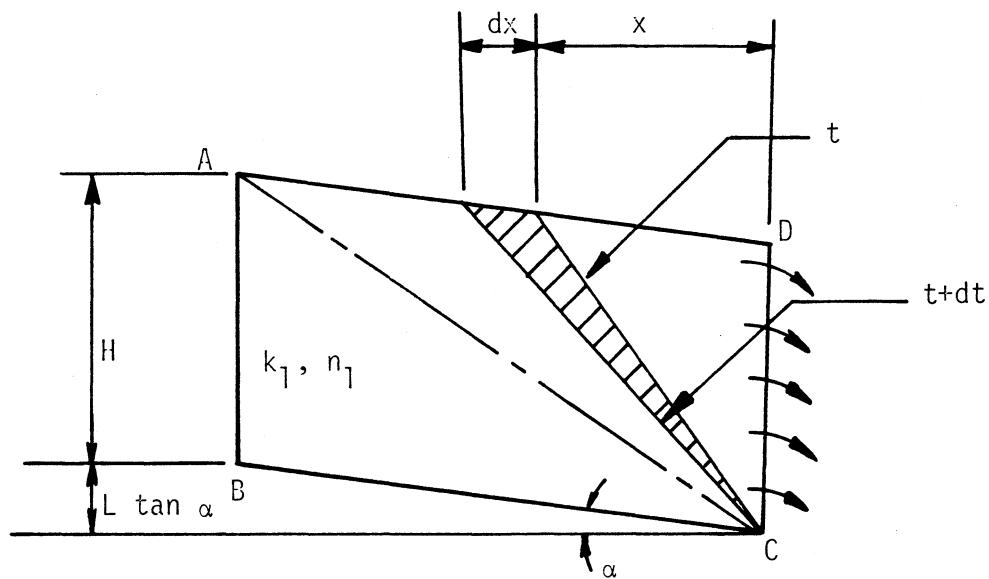
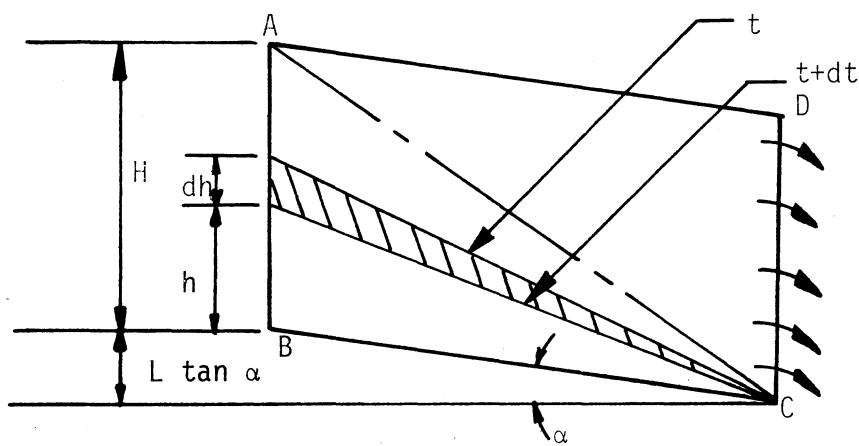


FIGURE 3 . CROSS SECTION OF A PAVEMENT



STAGE 1 $U \leq 50\%$



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's 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

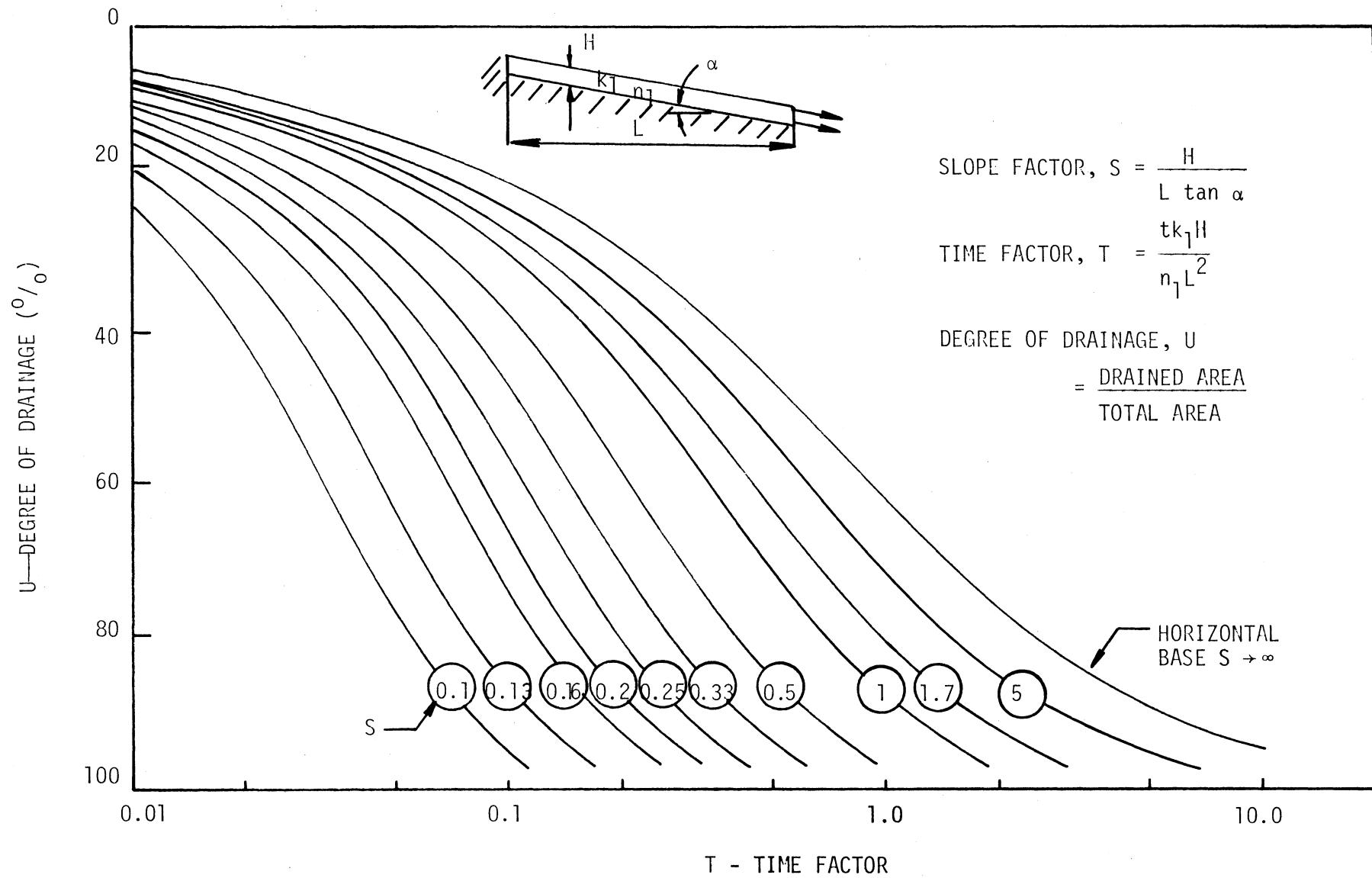


FIGURE 5. VARIATION OF DRAINAGE AREA WITH SLOPE FACTOR AND TIME FACTOR (1).

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

$$\begin{aligned} \text{Stage 1} \quad 0 &\leq U \leq 50\% \\ T &= 2U^2 \end{aligned} \tag{4-1}$$

$$\begin{aligned} \text{Stage 2} \quad 50\% &\leq U < 100\% \\ T &= \frac{U}{2-2U} \end{aligned} \tag{4-2}$$

(B) Sloping Bases

$$\begin{aligned} \text{Stage 1} \quad 0 &\leq U \leq 50\% \\ T &= 2 US - S^2 \ln \left[\frac{S+2U}{S} \right] \end{aligned} \tag{4-3}$$

$$\begin{aligned} \text{Stage 2} \quad 50\% &\leq U < 100\% \\ T &= S + S \ln \left[\frac{(2S-2US+1)}{(2-2U)(S+1)} \right] - S^2 \ln \left[\frac{S+1}{S} \right] \end{aligned} \tag{4-4}$$

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

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

$$\text{Time Factor, } T = \frac{t k_1 H}{n_1 L^2}$$

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

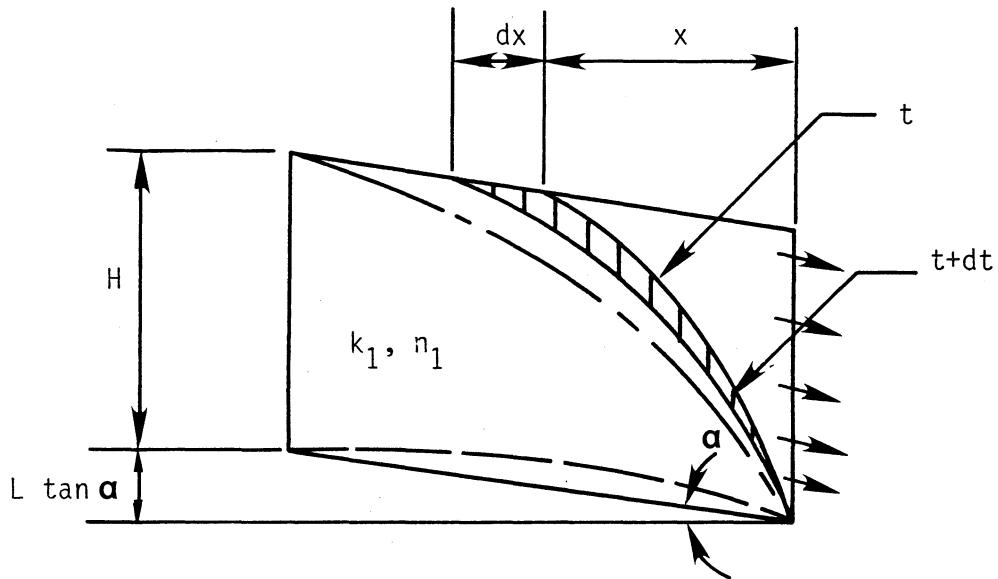
$$\begin{aligned} \text{Stage 1} \quad 0 &\leq U \leq \frac{1}{3} \\ T &= 3U^2 \end{aligned} \tag{4-5}$$

$$\begin{aligned} \text{Stage 2} \quad \frac{1}{3} &\leq U < 1 \\ T &= \frac{8}{9} \left(\frac{1}{1-U} \right) - 1 \end{aligned} \tag{4-6}$$

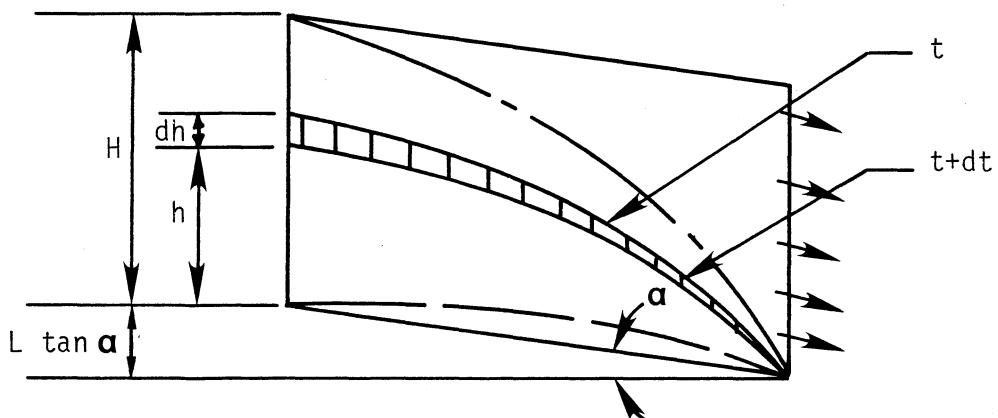
(B) Sloping Bases

$$\begin{aligned} \text{Stage 1} \quad 0 &\leq U \leq \frac{1}{3} \\ T &= \frac{3}{2}SU - \frac{3}{8}S^2 \ln\left[\frac{S+4U}{S}\right] \end{aligned} \tag{4-7}$$

$$\begin{aligned} \text{Stage 2} \quad \frac{1}{3} &\leq U < 1 \\ T &= \frac{S}{2} - \frac{3}{8}S^2 \ln\left[\frac{3S+4}{3S}\right] + S \ln\left[\frac{9S-9SU+8}{3(1-U)(3S+4)}\right] \end{aligned} \tag{4-8}$$



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,

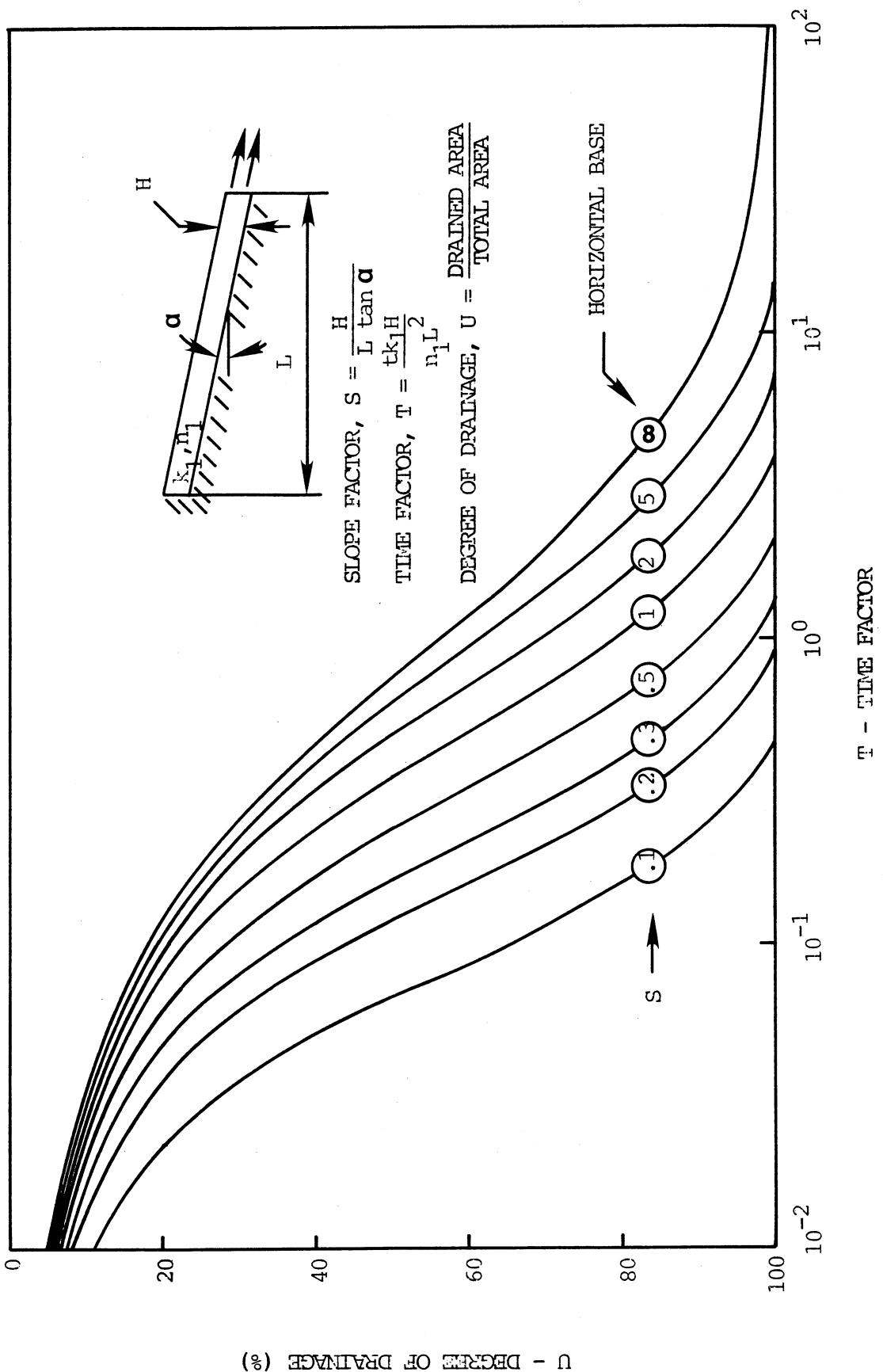


FIGURE 7. TFI DRAINAGE CHART WITH AN IMPERMEABLE SUBGRADE

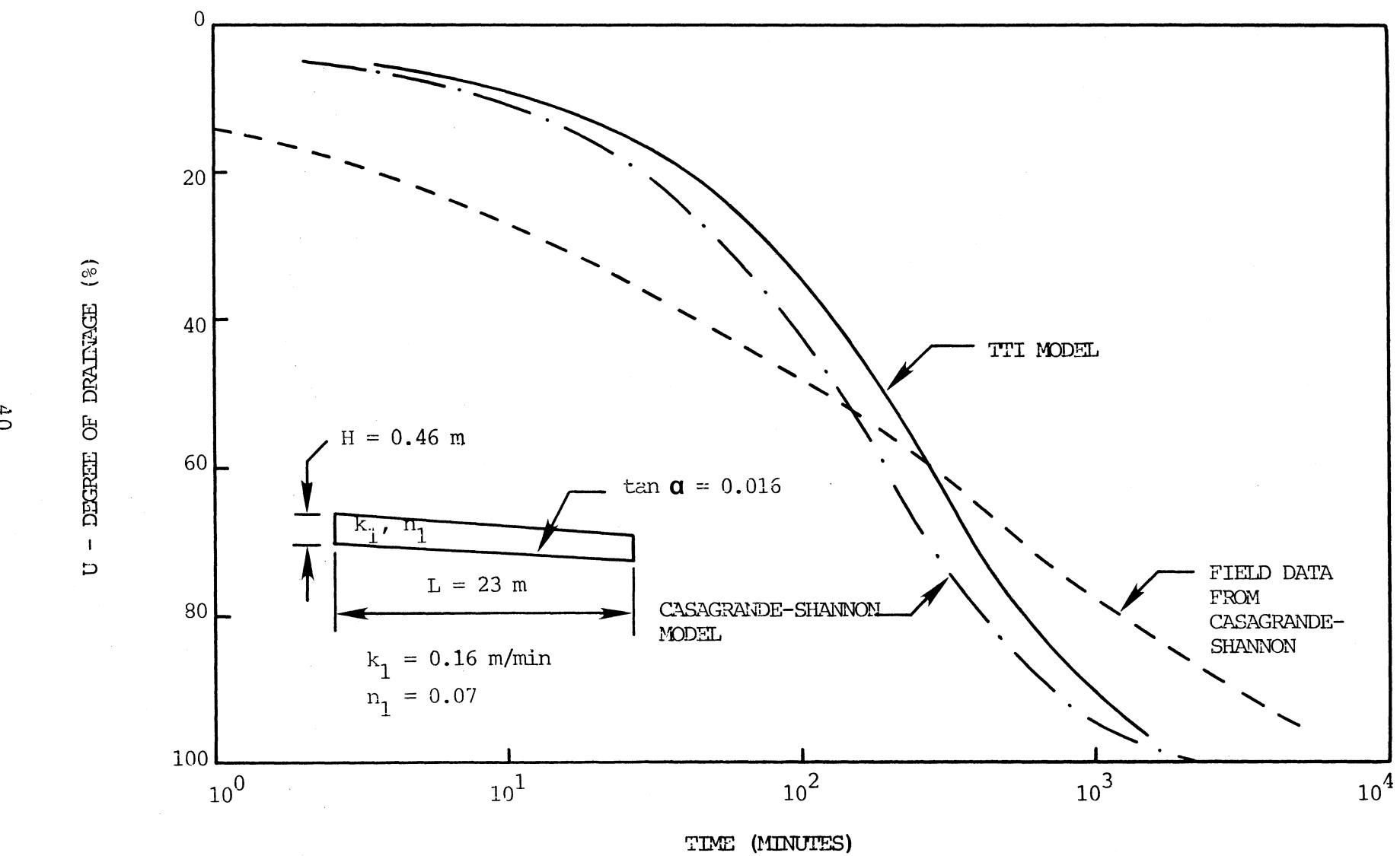


FIGURE 8. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE

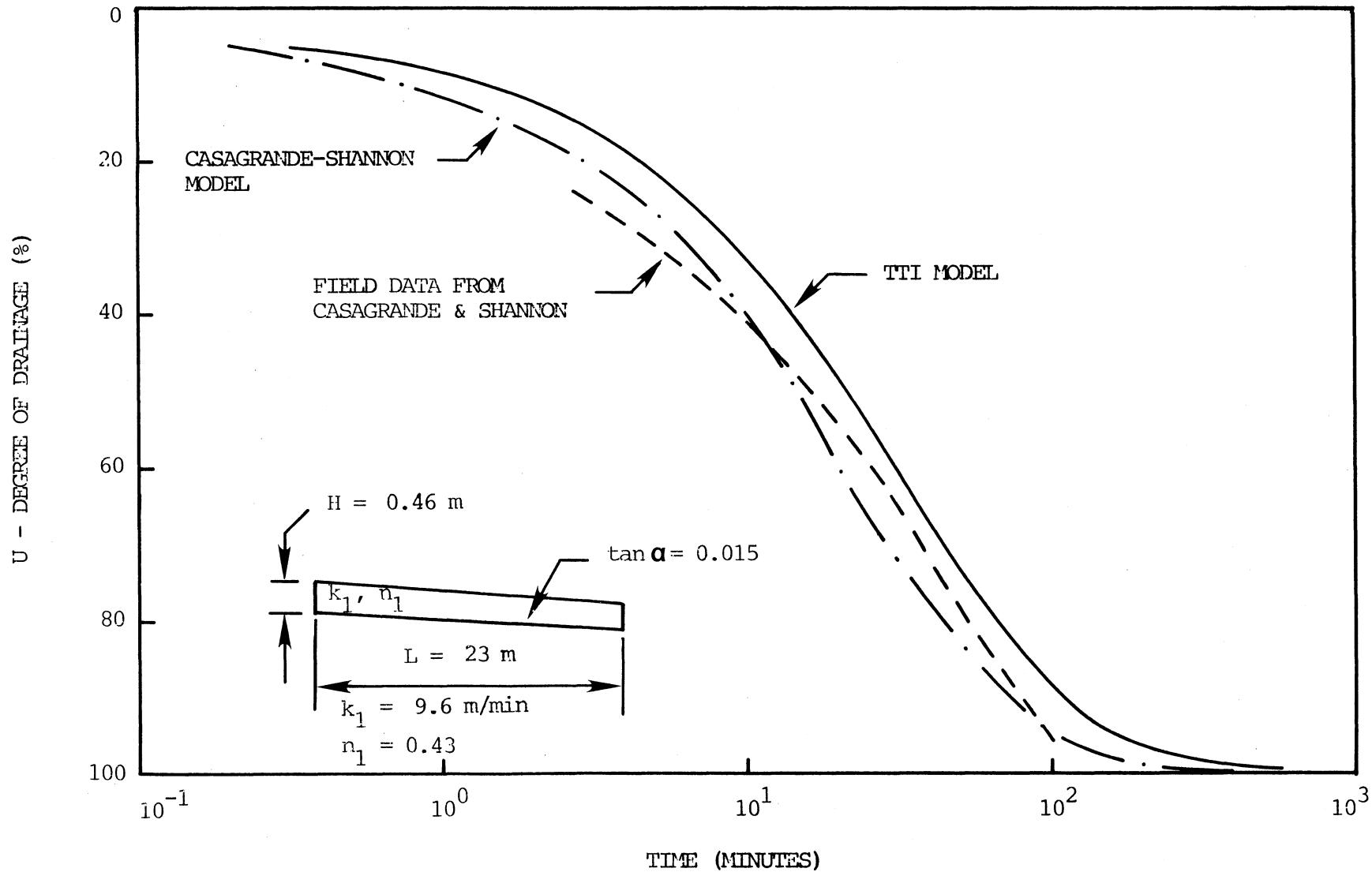


FIGURE 9. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE

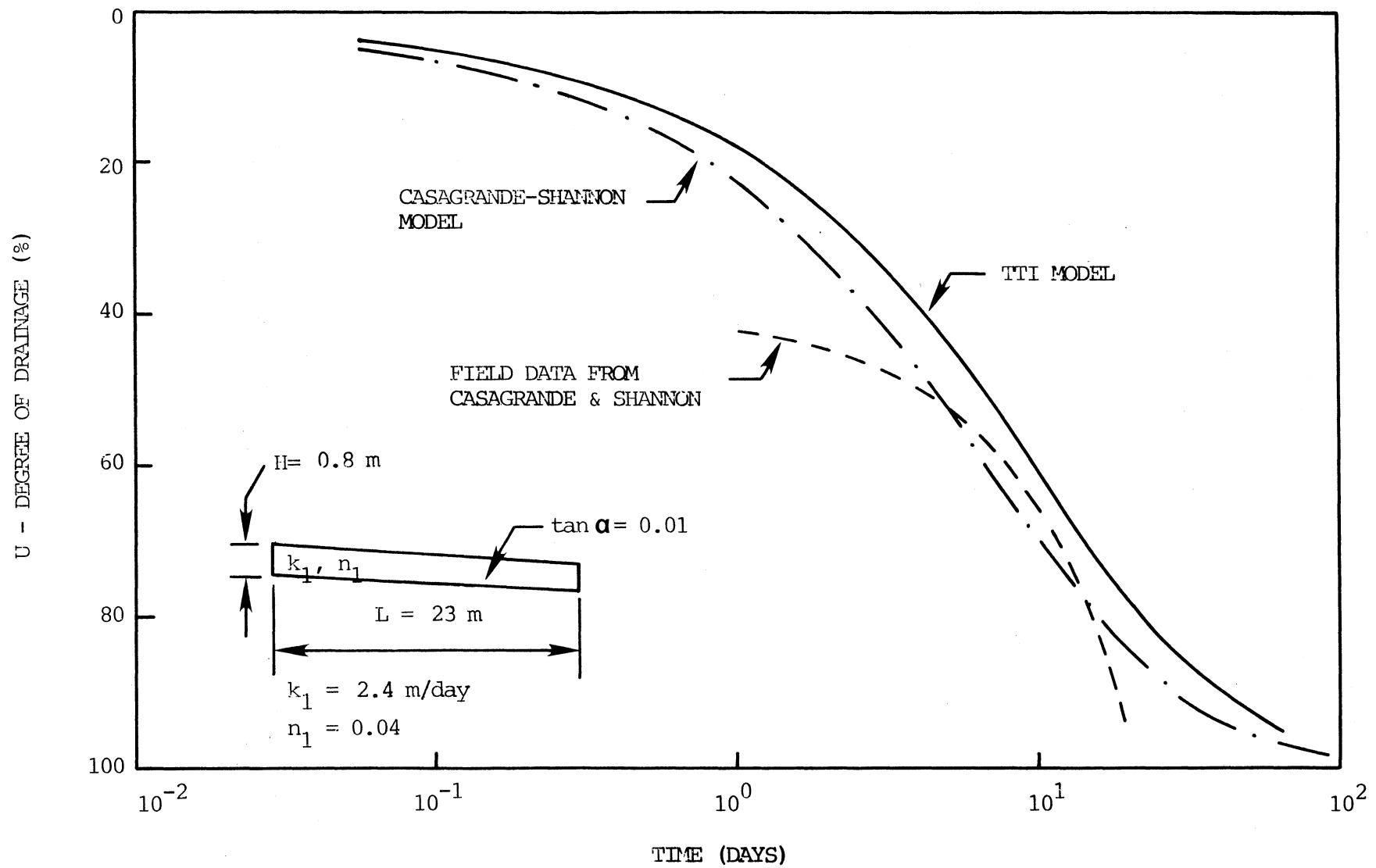


FIGURE 10. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE

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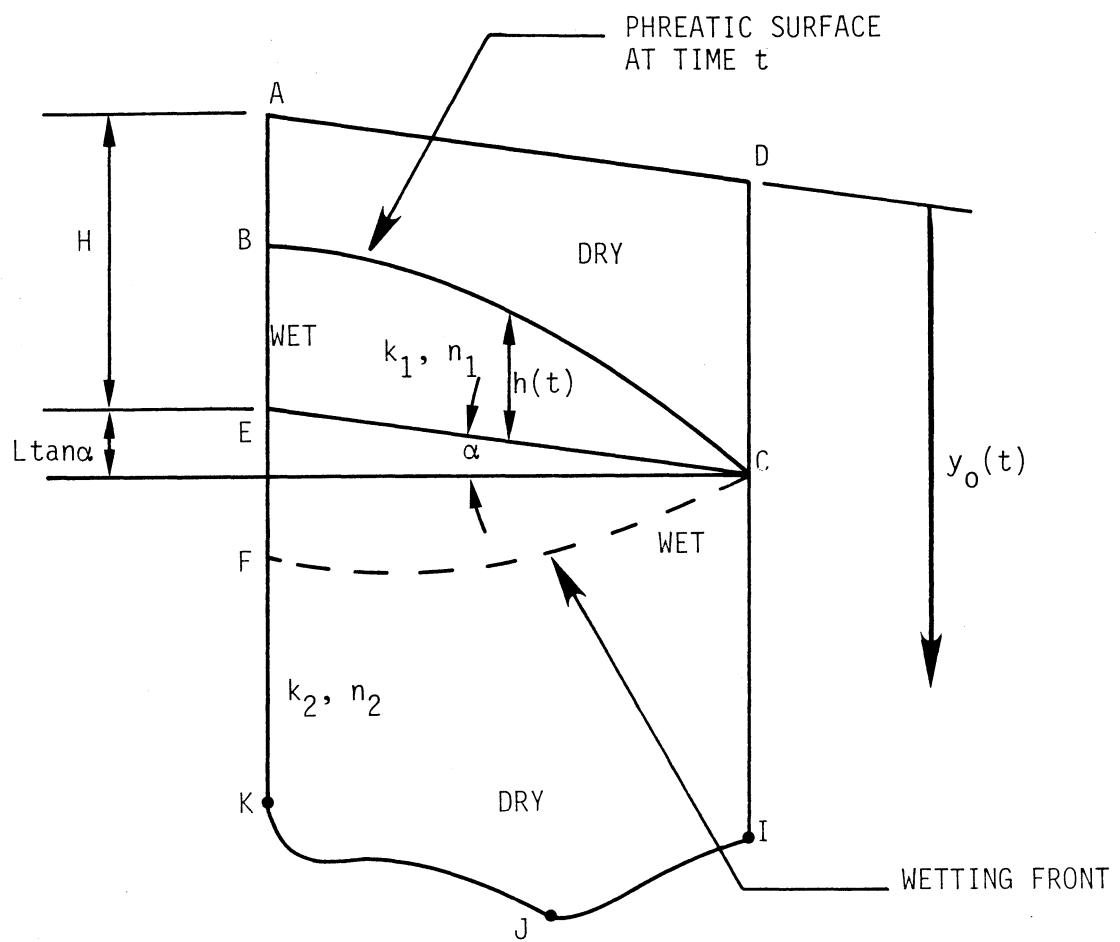


FIGURE 12. Definition Sketch For Subgrade Drainage Model

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):

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

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

$h(t)$ = 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.

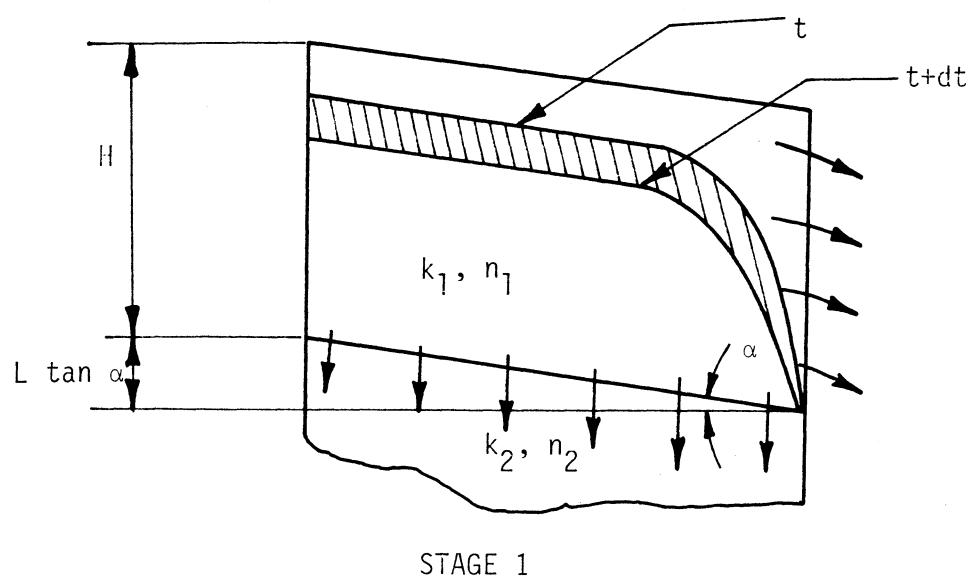
Five field cases were studied using this model and the results for two of these are shown in Figures 14 and 15. It is interesting to note in Figure 14 that the field curve follows a trend very similar to that of the two drainage curves ($k_2/k_1 = K=0$ and 0.0002) given by the present model and lies 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 ($K = 0.0001$) is in closer agreement with the field data than the Casagrande-Shannon model.

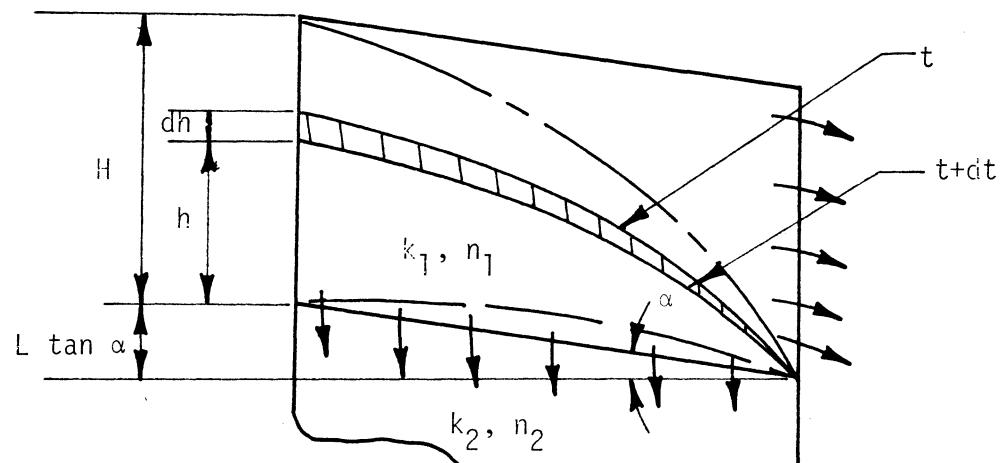
As a result of the studies reported here, the parabolic phreatic surface model with permeable subgrades was chosen for all future drainage analyses.

4.5 APPLICATION TO PAVEMENT DRAINAGE DESIGN

As an illustration of the importance of subgrade drainage, a base course 0.8 m (2.5 ft) thick and 46 m (150 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, $k_1 = 2.4\text{ m/day}$ (7.8 ft/day), and the porosity, $n_1 = 0.04$. It is required to



STAGE 1



STAGE 2

FIGURE 13. SUBGRADE DRAINAGE MODEL WITH PARABOLIC PHREATIC SURFACES

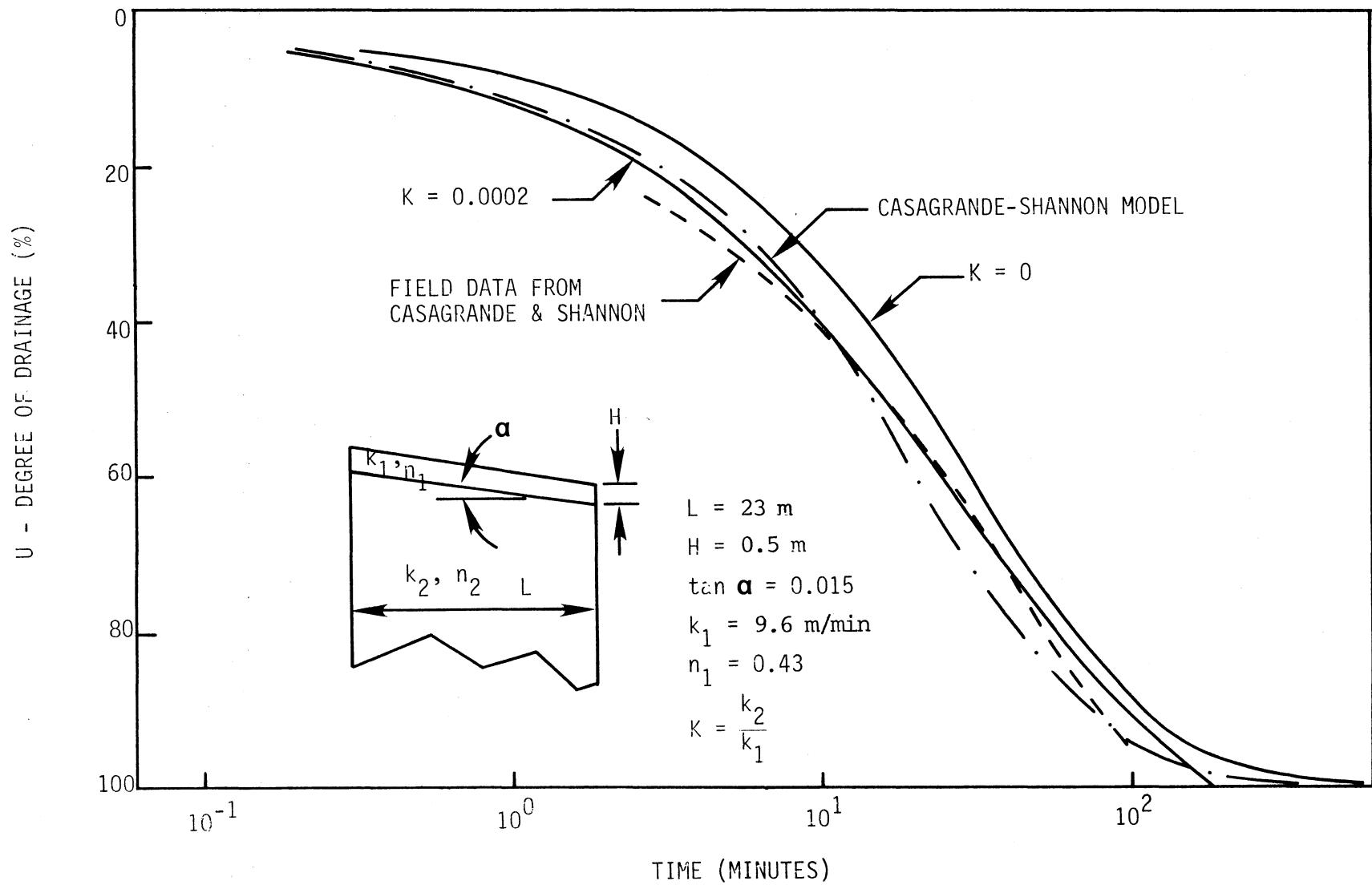


FIGURE 14. RESULTS OF TTI MODEL WITH PERMEABLE SUBGRADES

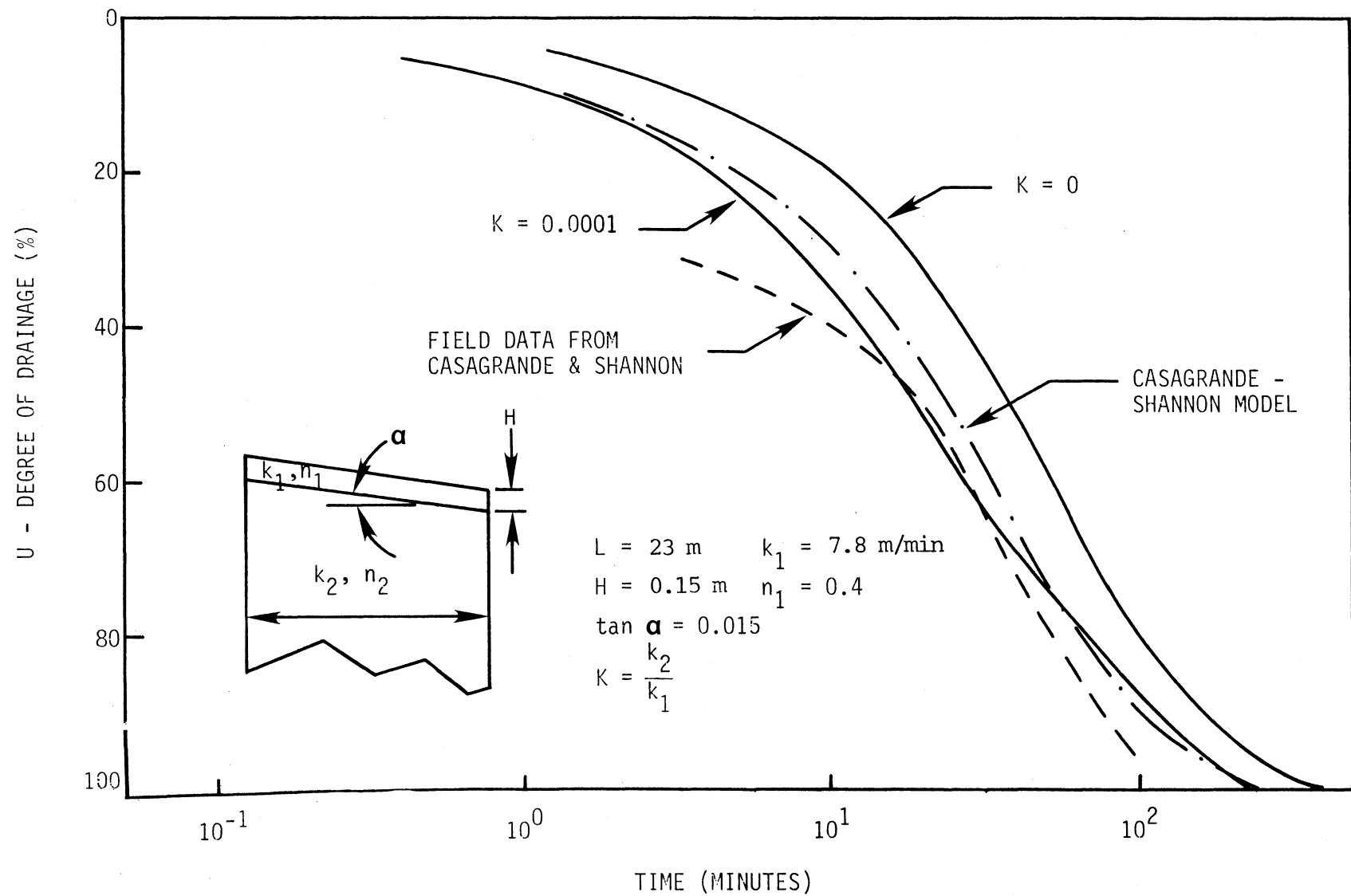


FIGURE 15. RESULTS OF TTI MODEL WITH PERMEABLE SUBGRADES

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.

$$k_1 = 0.0024 \text{ m/day} (0.0078 \text{ ft/day})$$

$$K = k_2/k_1$$

$$= 0.001$$

$$t = 5 \text{ days}$$

- b) Subgrade material is a glacial till.

$$k_1 = 0.0048 \text{ m/day} (0.0156 \text{ ft/day})$$

$$K = 0.002$$

$$t = 2.5 \text{ days}$$

- c) Subgrade material is a silty sand.

$$k_1 = 0.24 \text{ m/day} (0.78 \text{ ft/day})$$

$$K = 0.1$$

$$t = 84 \text{ minutes}$$

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.

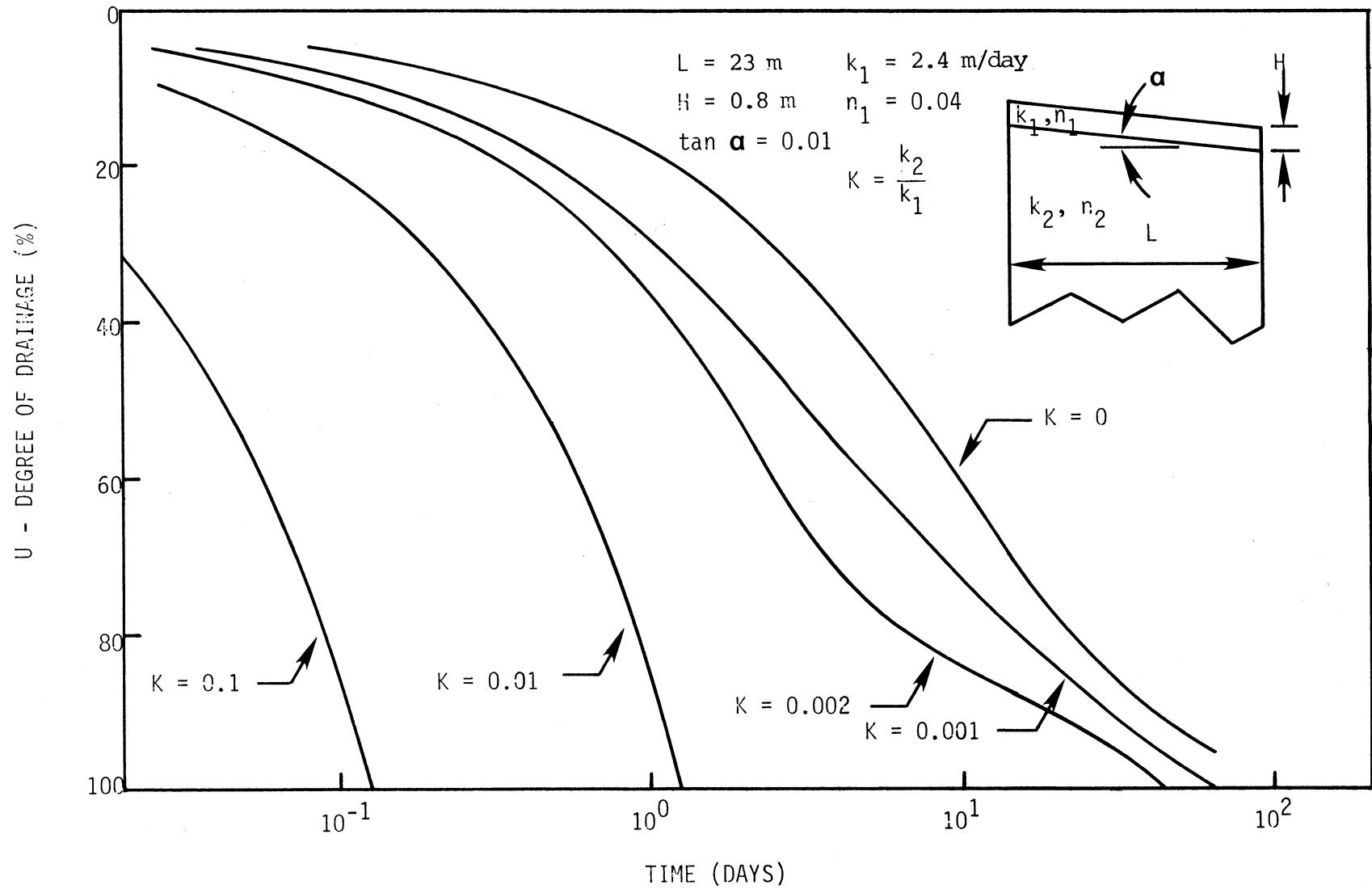


FIGURE 16. DRAINAGE CURVES FOR TTI MODEL WITH PERMEABLE SUBGRADES

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

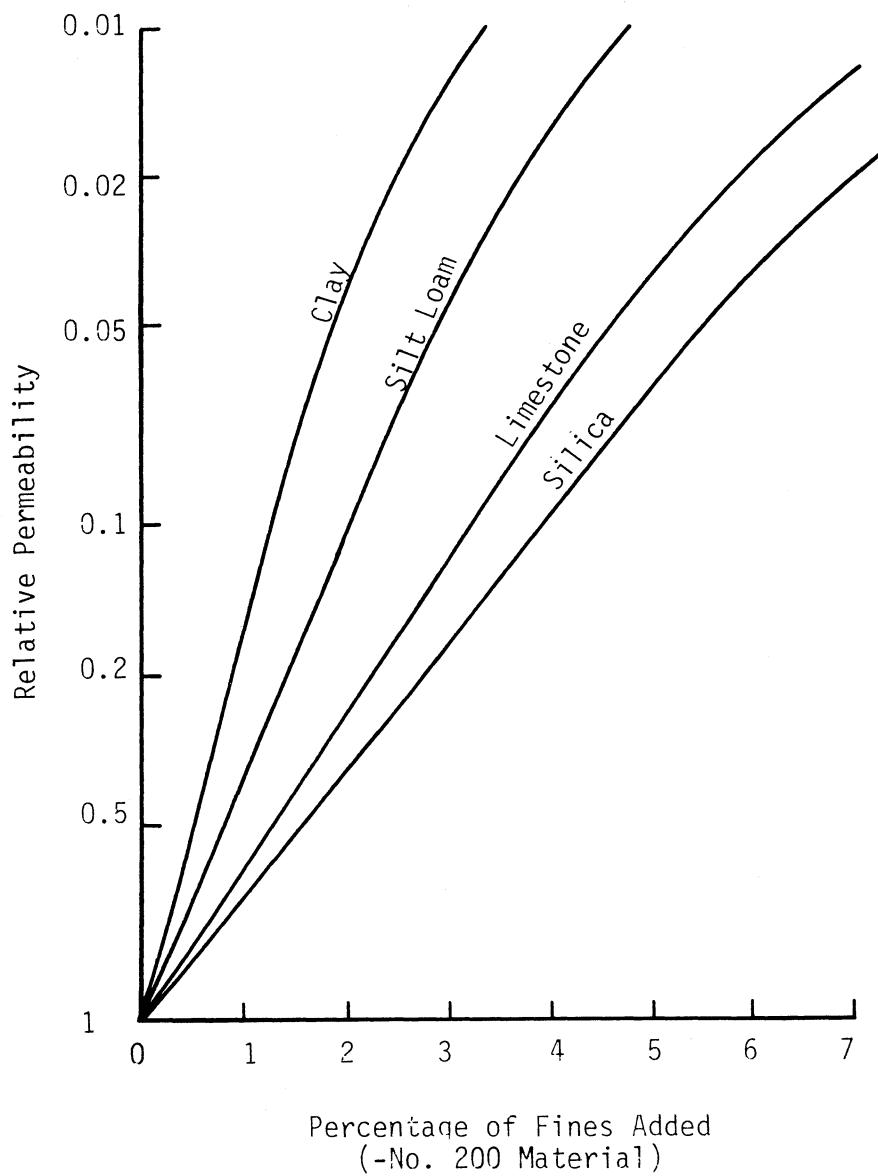


FIGURE 17. Effect of Amount and Type of Fines
on the Permeability (26)

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

$$S_a = 1 - P.D. \times U \quad (4-11)$$

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.

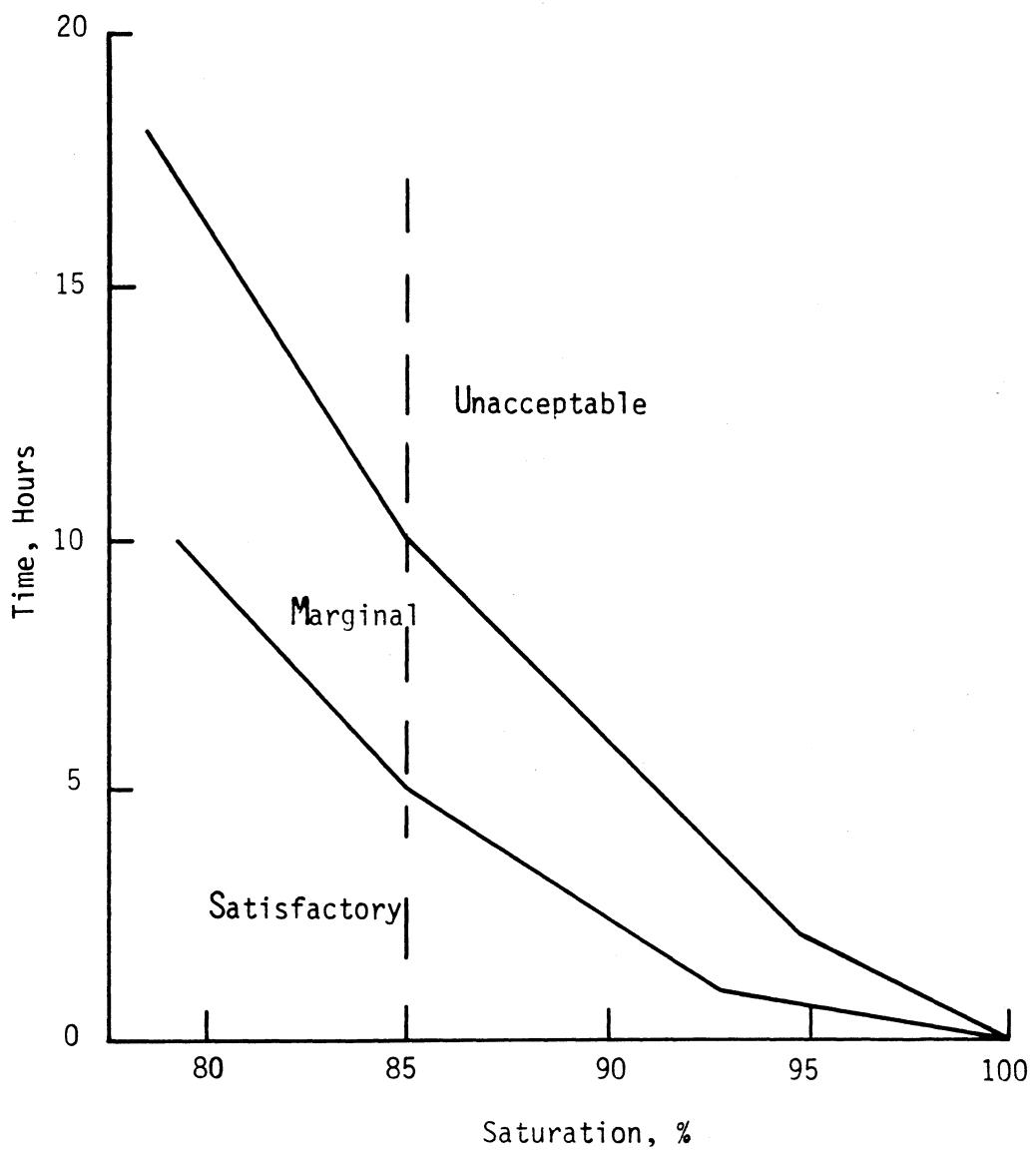


FIGURE 18. Drainage Criteria for Granular Layers (26)

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

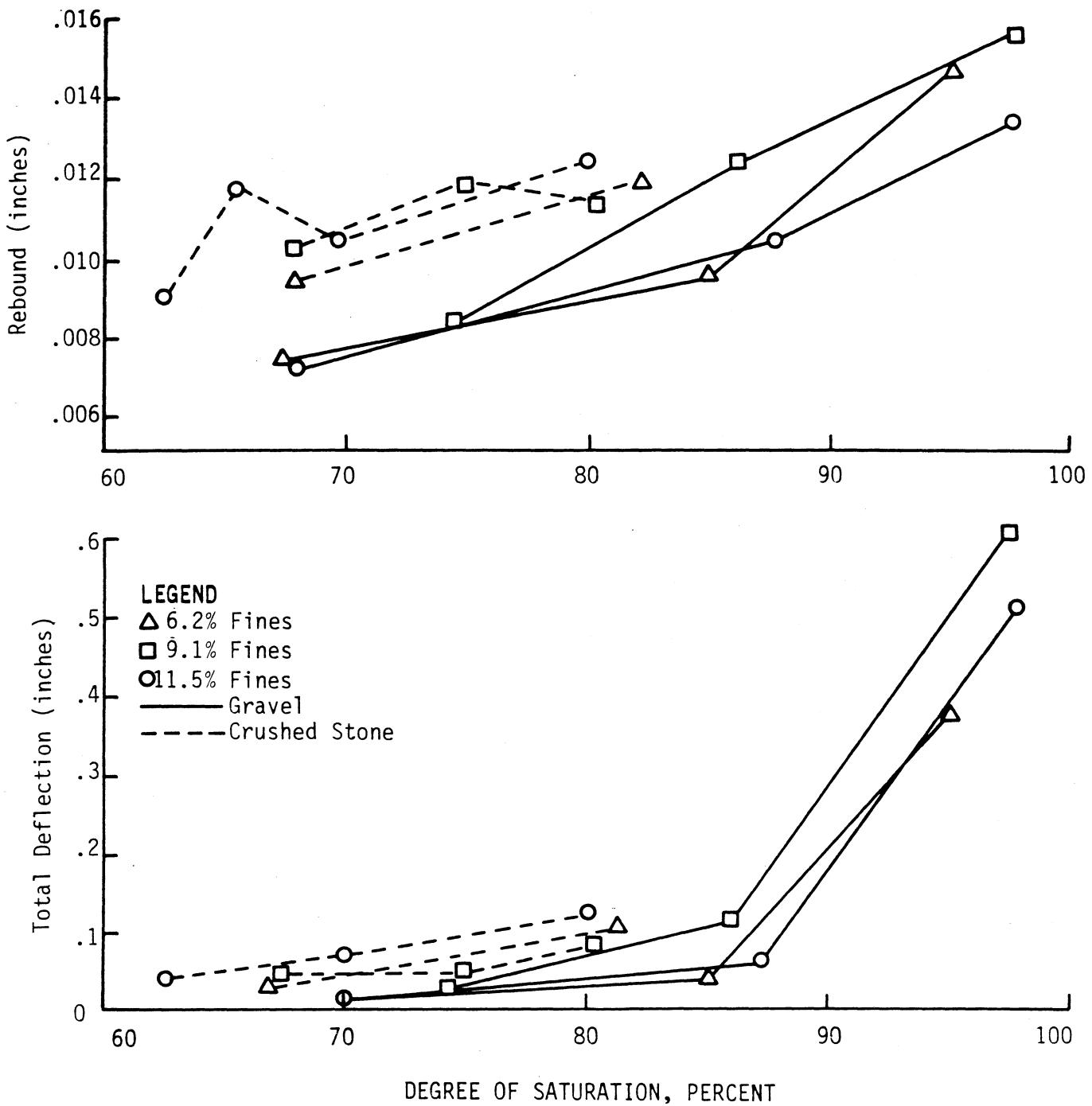


FIGURE 19. Effect of the Degrees of Saturation on the Repeated-Load Deformation Properties of the AASHO Granular Materials (27)

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

| Materials | Unit Weight, 1b/ft ³ | Poisson's Ratio | Calculated Elastic Modulus 1b/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 | 39.83 | 0.453 |
| | BC | 27.54 | 0.266 |
| A-4 | ABC | 17.33 | 0.158 |
| | BC | 16.76 | 0.146 |
| A-7-6 | ABC | 31.22 | 0.294 |
| | BC | 24.65 | 0.196 |
| A-6 | ABC | 36.15 | 0.362 |
| | BC | 35.67 | 0.354 |
| (b) Unified | | | |
| CL, ML-CL | ABC | 31.89 | 0.312 |
| | BC | 32.13 | 0.311 |
| CH | ABC | 21.93 | 0.151 |
| | BC | 23.02 | 0.161 |
| ML, MH | ABC | 31.39 | 0.331 |
| | BC | 29.01 | 0.284 |

$$\text{Equation: } E_s = a - bS_a$$

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)

$$E_s = \frac{E_1 d_1^3 + E_2 d_2^3}{d^3} \quad (5-1)$$

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) field test 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), which uses a parabolic phreatic surface and permits subgrade drainage, was 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 in Figure 20 to give a clear profile of the entire model, and a synthesis of the various models mentioned above into a systematic analysis of the rainfall, infiltration and drainage analysis of a pavement is sketched in Figure 21.

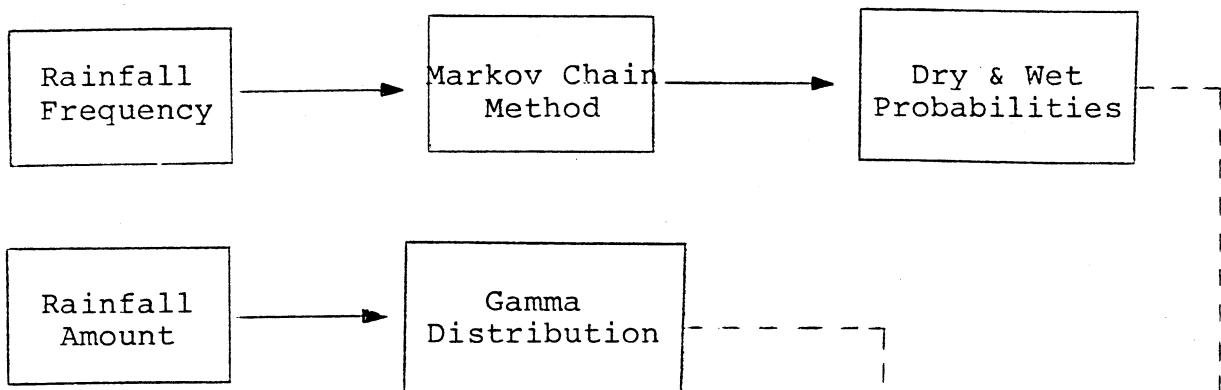
6.1 CONCEPTUAL FLOW CHART FOR RAINFALL, INFILTRATION AND DRAINAGE ANALYSIS

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

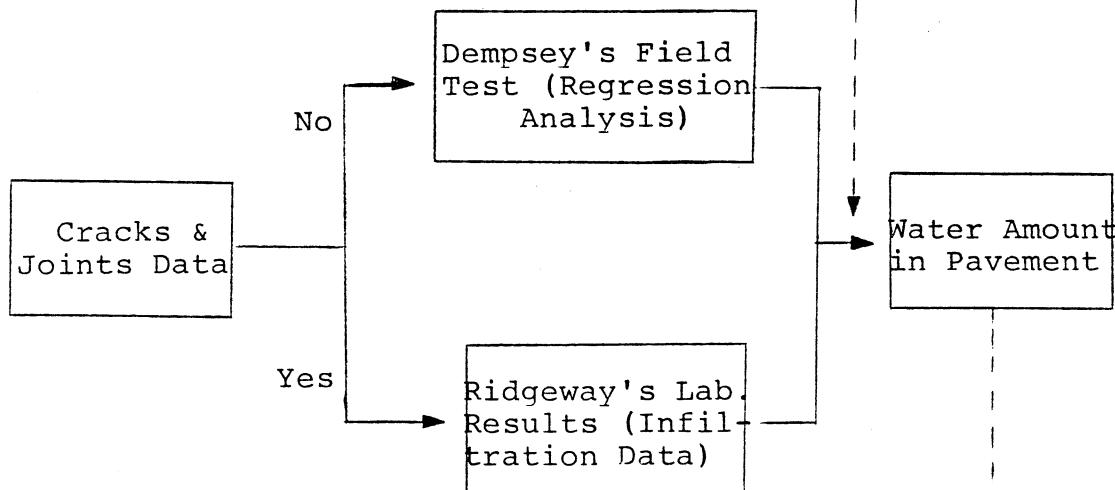
The amount of water penetration into the base through cracks and joints is estimated either by Ridgeway's laboratory results or by Dempsey-Robnett's regression equation, which depend on whether the data of cracks and joints are provided.

Drainage analysis is based on the TTI model, which determines the time required for water to flow both laterally out of a base course and simultaneously into the subgrade. Also, the design of the base course drainage is evaluated by classifying it as satisfactory, marginal, and unacceptable using criteria established by Carpenter, Darter, and Dempsey (26).

A. Rainfall



B. Water Infiltration



C. Drainage Analysis

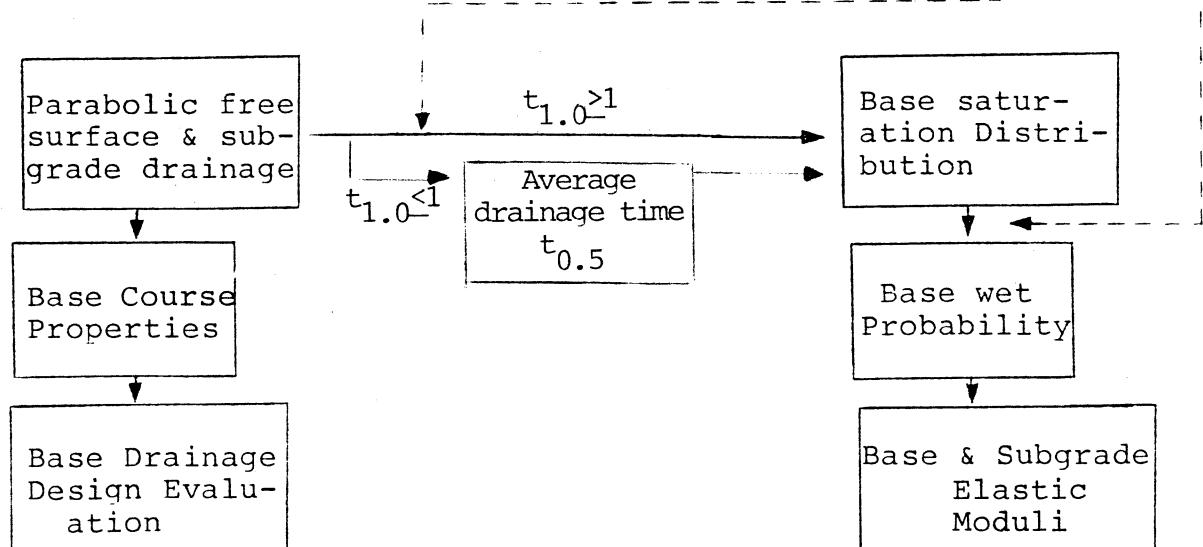


FIGURE 20. Flow Chart for Conceptual Model of Rainfall Infiltration and Drainage Analysis of Pavements

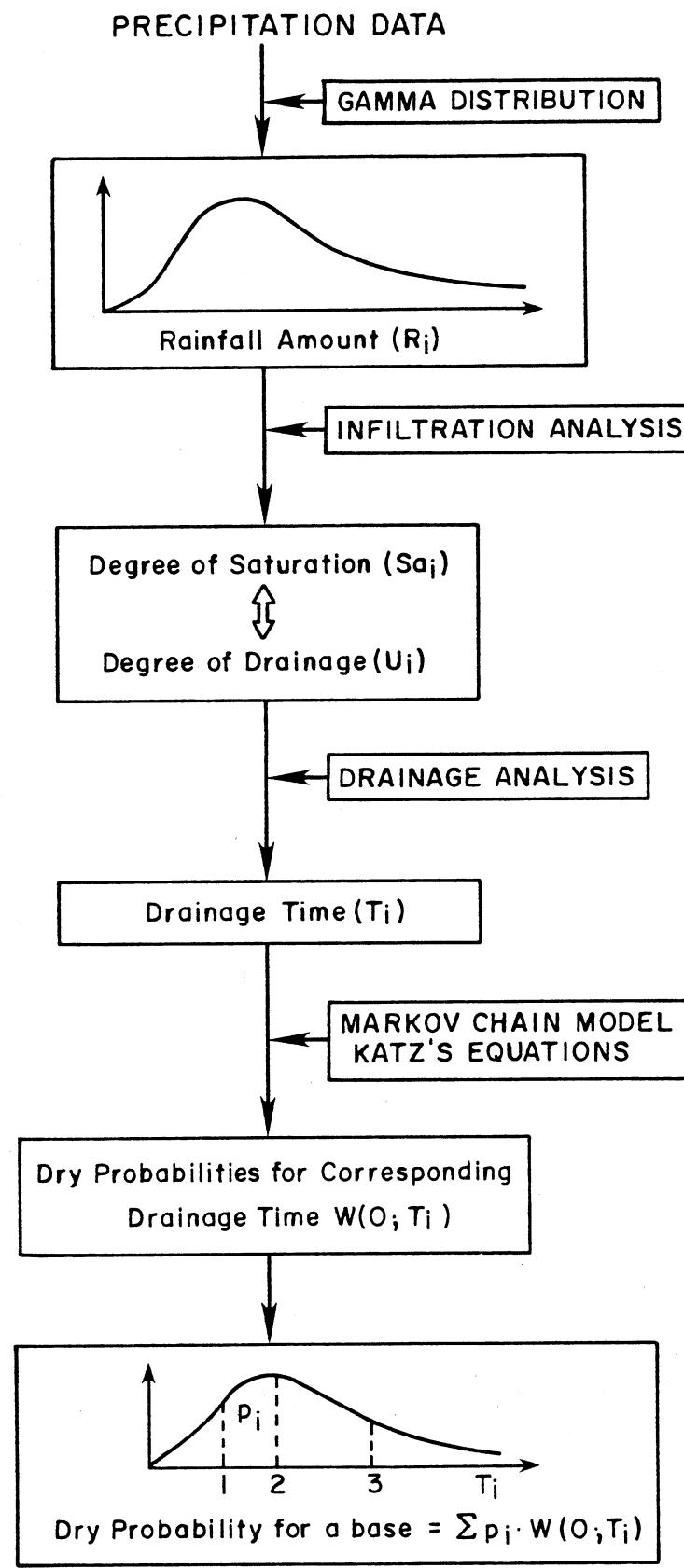


FIGURE 21. Synthesis of Models Used in Systematic Analysis of Rainfall Infiltration and Drainage Analysis of a Pavement

Katz's recurrence equations (13), which are associated with the Markov chain model, together with the gamma distribution for the quantity of rainfall, the infiltration of water into the base course and the 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 elastic moduli of these pavement layers.

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) field test data. 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 of rainfall 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 0 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.

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

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 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 $t_{1.0} < 1$, i.e., all the free water can be drained from a base course within one day, the following equation is applied

$$BC_{dry} = 1 - (P_{wet})^{t_{0.5}} \quad \text{for } t_{1.0} \leq 1 \quad (6-2)$$

where

BC_{dry} and $t_{1.0}$ 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 $t_{1.0} \leq 1$, 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 are 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

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

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.

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 E 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.

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 |

- (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 0.3, 0.25, 0.75 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.

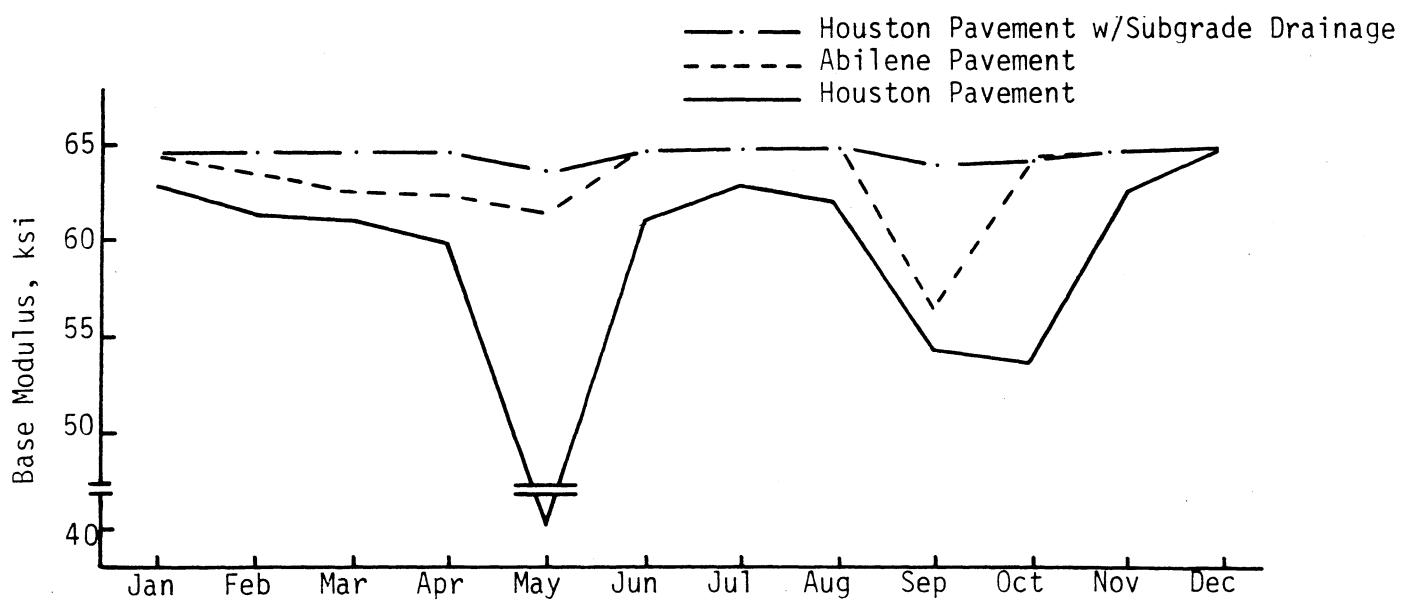
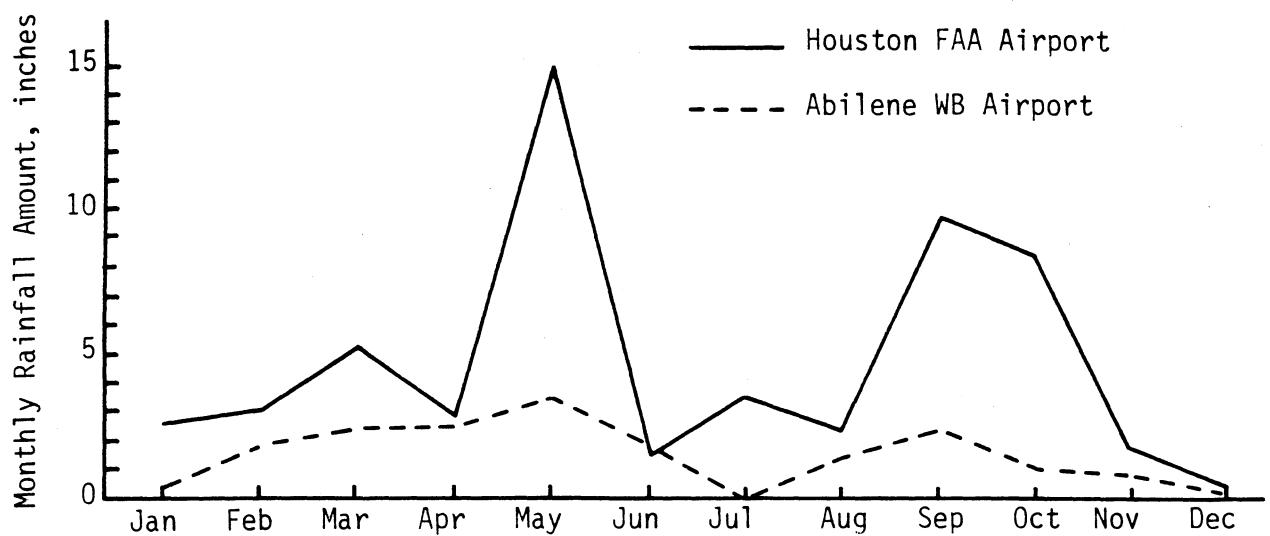


FIGURE 22. Effects of Rainfall Amount and Subgrade Drainage on Load-Carrying Capacity of Pavements

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.

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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:

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

where

R = precipitation amount and

$\Gamma(\alpha)$ = Gamma function where $(n+1)=n!$ $n=0, 1, 2, \dots$.

The parameters and may be estimated by the moments method:

$$\alpha = \bar{R}^2 / S^2 \quad \bar{R} = \text{mean} = \sum R_i / n \quad (A-2)$$

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

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)

$$i = \frac{kt_p^x}{t_R^n} \quad (A-4)$$

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 0.3989 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

$$\frac{(t_R)_i}{R} = \frac{t_R x_i}{0.95} = \frac{3.92 \times 0.3989}{0.95} = 1.65 \quad (A-5)$$

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:

$$\begin{aligned} R &= \frac{t_R i}{SF} \\ &= (t_R) (k t_p^x) / (t_R^n) (SF) \\ &= k t_R^{(1-n)} t_p^x / (SF) \end{aligned} \quad (A-6)$$

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

The constant for shape factor (SF) could be determined and entered by the user (for example, 1.0 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 0.75, 0.25, 0.30,

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.

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

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 θ ; the subscript θ 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 θ 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.

$x > \emptyset, \emptyset > \emptyset$, and

$$f(x) = \lambda e^{-\lambda x}$$

$$x = \text{wet or dry days} \quad (\text{A-9})$$

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

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

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)

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

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).

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

Transition Matrix

where

$W_0(k; N)$ = the probability of k wet days during N consecutive days when the zero-th day is

dry (the subscript \emptyset 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)

$$W(k;N) = (1-p_0)W_0(k;N) + p_0 W_1(k;N) \quad (A-13)$$

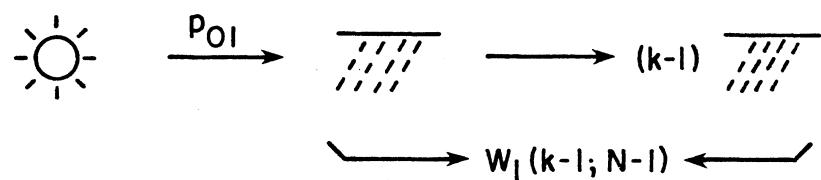
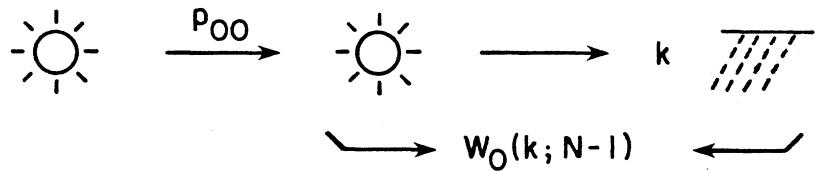
where

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

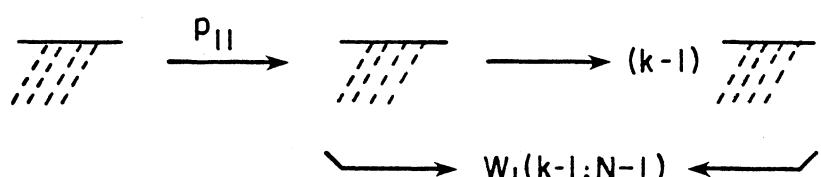
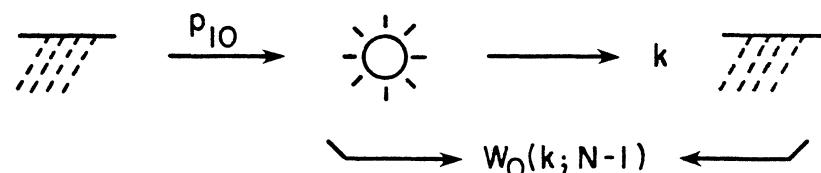
p_0 = initial probability of having a wet day.

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., $W_0(k;N-1)$, 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_{00} and the probability for the first day being wet if p_{01} . Therefore, when the zero-th day is dry, the probability of exactly k wet days out of N consecutive days is the

(1) $W_0(k; N)$



(2) $W_1(k; N)$



For N days: Zeroth day

First day

$N-1$ days

For $N-1$ days

Zeroth day

$N-1$ days

FIGURE 23. Definition Sketch of Katz Model

probability of the first day remaining dry from zero-th day (p_{00}) multiplied by the probability of having k wet days of the remaining $N-1$ days, $w_0(k;N-1)$, plus the probability of changing from a dry zero-th day to a wet first day (p_{01}) multiplied by the probability of having $k-1$ wet days in the remaining $N-1$ days, $w_1(k-1;N-1)$; so that

$$w_0(k;N) = p_{00} w_0(k;N-1) + p_{01} w_1(k-1;N-1) \quad (A-14)$$

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

$$w_1(k;N) = p_{10} w_0(k;N-1) + p_{11} w_1(k-1;N-1) \quad (A-15)$$

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_0 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 remain 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.

$$y = \sqrt{ax} \quad (B-1)$$

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

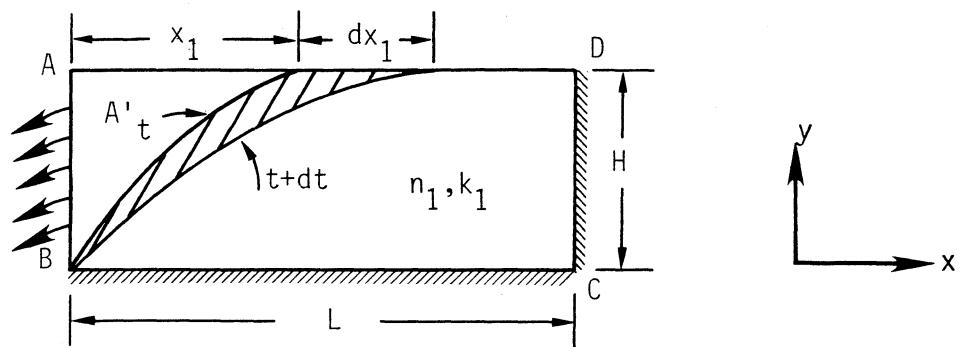
$$\text{Drained Area} = A' = \frac{Hx_1}{3} \quad (B-2)$$

The rate of water amount (q) change is

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

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 ;

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



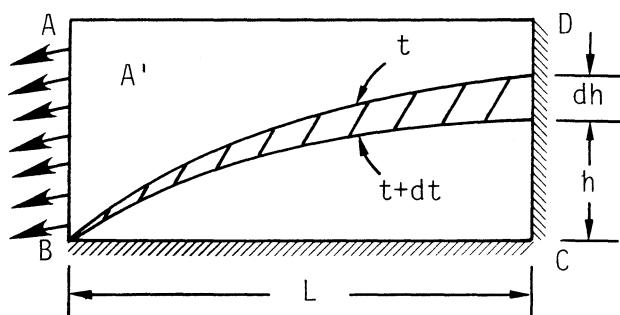
$$\text{Stage I. } 0 \leq U \leq \frac{1}{3}$$

U = Degree of Drainage.

n_1 = Effective porosity of the base course.

k_1 = Coefficient of permeability of the base course.

t^1 = Time.



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

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

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

Two dimensionless quantities, introduced by Casagrande and Shannon (1), are called the degree of drainage (U) and the time factor (T), respectively:

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

$$T = \frac{tk_1 H}{n_1 L^2} \quad (B-7)$$

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

$$T = 3U^2 \quad T = 3U^2 \quad (B-8)$$

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.

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

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

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

Combining Equations B-10 and B-11,

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

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

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

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

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

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

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

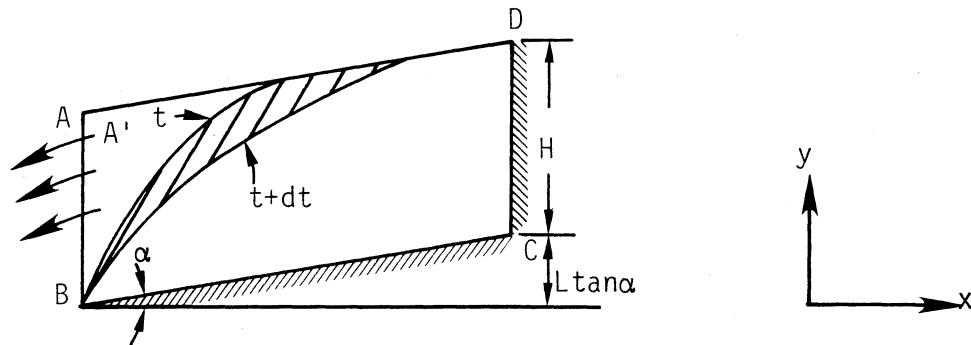
$$U = 1 - \frac{2h}{3H} , \text{ and}$$

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

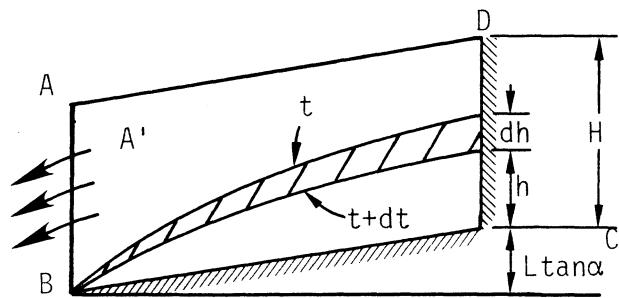
which are valid for $\frac{1}{3} \leq U < 1$ of horizontal bases.

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 ($\tan \alpha$) 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

$$\begin{aligned} A' &= (H + x_1 \tan \alpha) x_1 - \frac{x_1^2}{2} \tan \alpha \\ &- \int_0^{x_1} \left(\sqrt{\frac{H^2}{x_1}} \sqrt{x} + x \tan \alpha \right) dx \\ &= \frac{H}{3} x_1 \end{aligned} \quad (B-16)$$

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

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

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

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

The average rate of flow can be expressed by

$$\begin{aligned} \frac{dq}{dt} &= \frac{k_1}{x_1} \int_0^{x_1} dq(x) dx \\ &= k_1 \left(\frac{H^2}{2x_1} + \frac{2}{3} H \tan \alpha \right) \end{aligned} \quad (B-19)$$

From Equations B-17 and B-18

$$\begin{aligned} \int_0^t dt &= \int_0^{x_1} \frac{2n_1 x_1}{k_1 (3H+4x_1 \tan \alpha)} dx_1 \\ t &= \frac{2n_1}{k_1} \left[\frac{x_1}{4 \tan \alpha} - \frac{H}{16 \tan^2 \alpha} \ln \left(\frac{3H+4x_1 \tan \alpha}{3H} \right) \right] \end{aligned} \quad (B-20)$$

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

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

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

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

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

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

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

Using Darcy's law,

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

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

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

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

From Equations B-23 and B-24

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

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

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

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

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

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

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

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

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

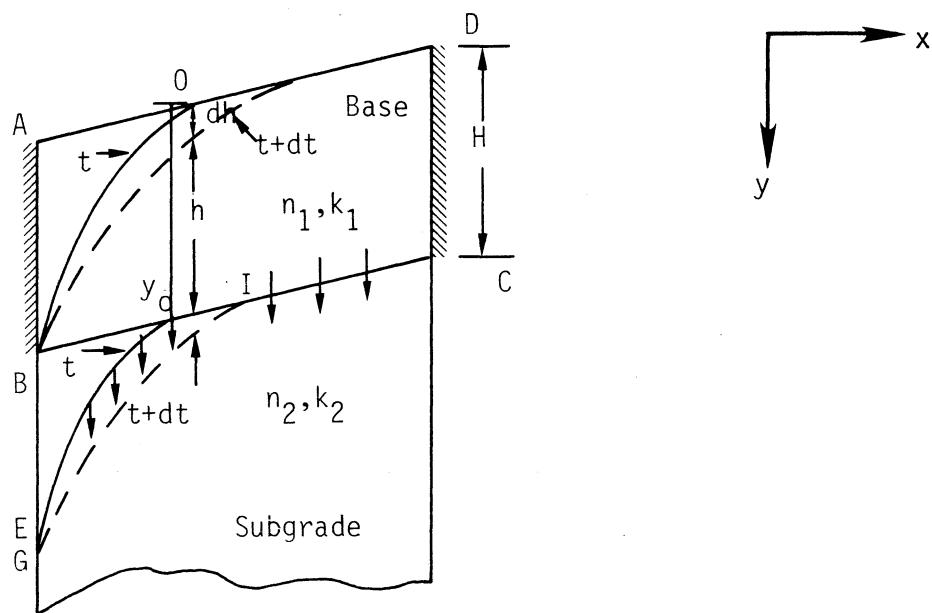
APPENDIX C

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

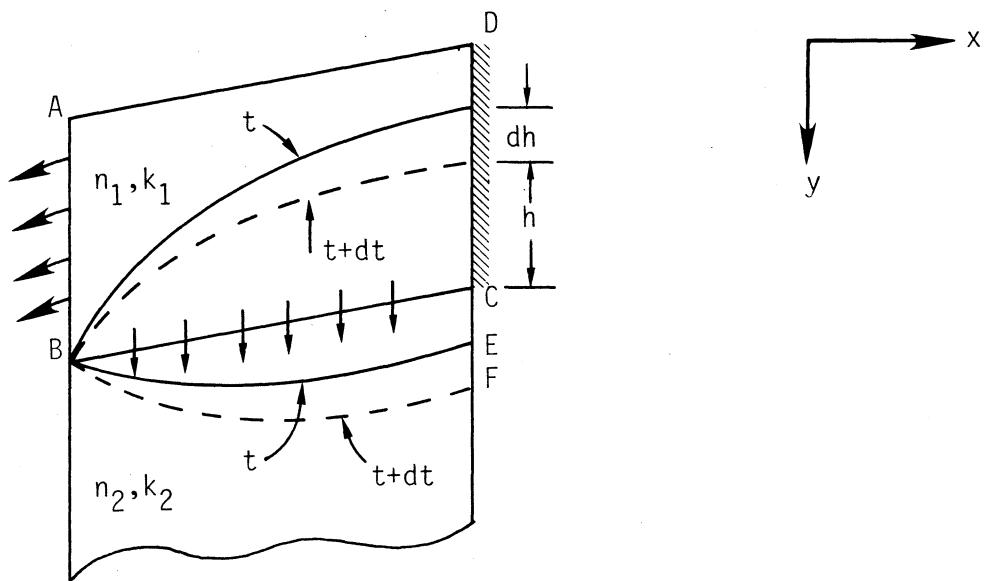


FIGURE 27. Water Penetration into a Subgrade with Lateral Drainage

The parabola drawn here is only to be consistent with the previous derivations. The datum is located at point 0 in Figure 26.

The velocity of water is generally defined as

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

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

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

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

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

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

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), $y=H$,

$$v_1 = v_2 = v, \text{ and thus}$$

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

$$\frac{vH + c_1}{k_1} = \frac{vH + c_2}{k_2} \quad (C-6)$$

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 $y=y_0$ (the wetting front) are chosen.

at $y=H-h$, $P=0$

$$\begin{aligned} \phi_1 &= -k_1(-y) = k_1y = k_1(H-h) = v_1(H-h) + c_1, \text{ so that} \\ c_1 &= (H-h)(k_1 - v_1). \end{aligned} \quad (C-7)$$

at $y=y_0$, $P=0$

$$\begin{aligned} \phi_2 &= v_2 y_0 + c_2 = k_2 y_0, \text{ so that} \\ c_2 &= (k_2 - v_2) y_0. \end{aligned} \quad (C-8)$$

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:

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

$$v = \frac{\frac{y_0 - H+h}{h}}{\frac{1}{k_1} + \frac{y_0 - H}{k_2}} \quad (C-9)$$

Furthermore, the wetting front y_0 must be determined.

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

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

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

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

$$v = \frac{\frac{n_1}{n_2} (H-h) + h}{\frac{1}{k_1} + \frac{\frac{n_1}{n_2} (H-h)}{k_2}} \quad (C-11)$$

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 .

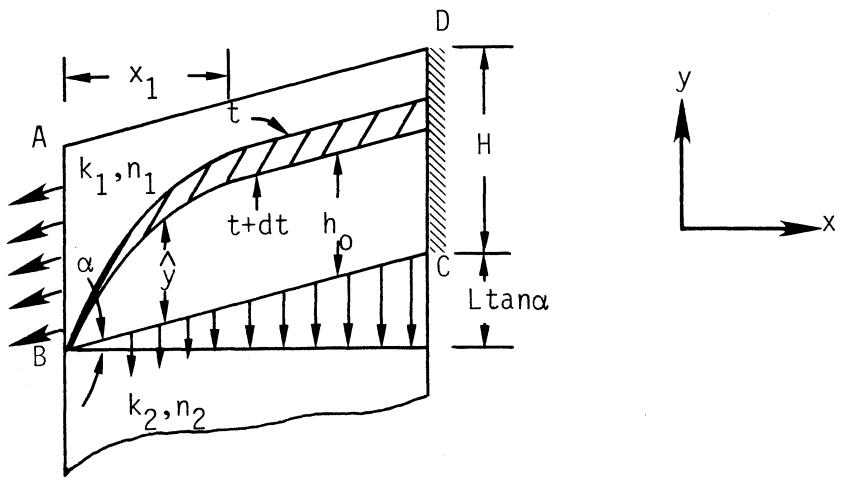
Incorporating the lateral and subgrade drainage, the model is sketched as Figure 28. Point B is the datum.

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.

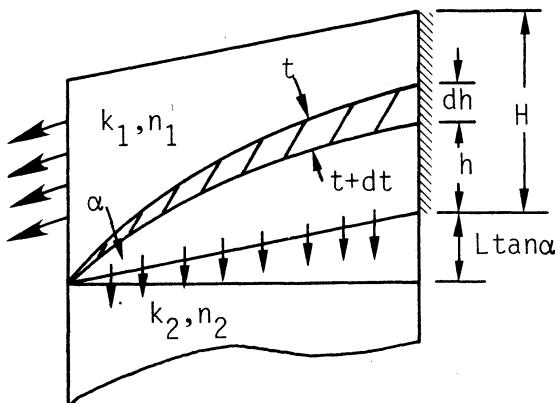
Again, by employing the same techniques used in deriving the previous equations, the geometry and the rate of the water quantity draining out are

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

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



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

$$\begin{aligned} dq_y &= n_2 dy_0 dx \\ &= v dx dt \end{aligned}$$

In Stage 1,

(a) from origin to x_1 ,

$$v = \sqrt{ax} + xt \tan \alpha \text{ for parabolic free surface}$$

on Figure 28

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

$$\begin{aligned} dq_y(0-x_1) &= v dx dt \\ &= k_2 \frac{\hat{y} (1 - \frac{n_1}{n_2}) + \frac{n_1 H}{n_2}}{\hat{y} (\frac{k_2}{k_1} - \frac{n_1}{n_2}) + \frac{n_1 H}{n_2}} dx dt \end{aligned} \quad (C-15a)$$

(b) from x_1 to L

$$dq_y(x_1-L) = \frac{h_0 (1 - \frac{n_1}{n_2}) + \frac{n_1 H}{n_2}}{h_0 (\frac{k_2}{k_1} - \frac{n_1}{n_2}) + \frac{n_1 H}{n_2}} dx dt . \quad (C-15b)$$

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

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

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

In Stage 2,

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

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

$$dq_x = \text{Equation C-12}$$

$$dq_y = \text{Equation C-15}$$

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

Stage 2

$$dq_x = \text{Equation C-13}$$

$$dq_y = \text{Equation C-17}$$

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 θ 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 θ .

The rate of change of water amount in Area ABCD

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

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

The rate of change of water amount in Area ABCD

$$dq = wdl = dA$$

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

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

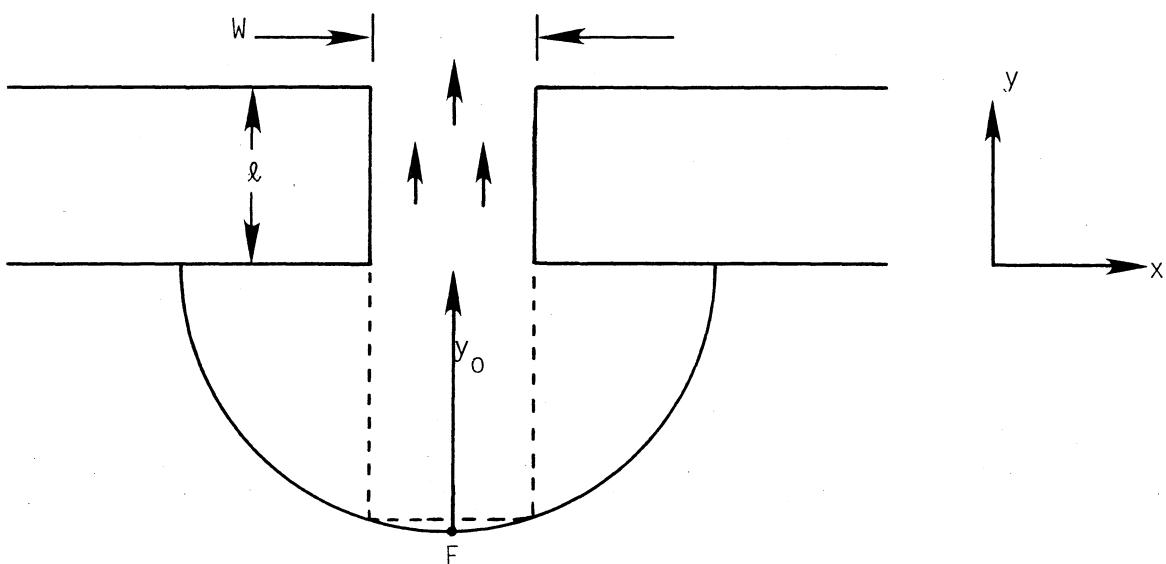
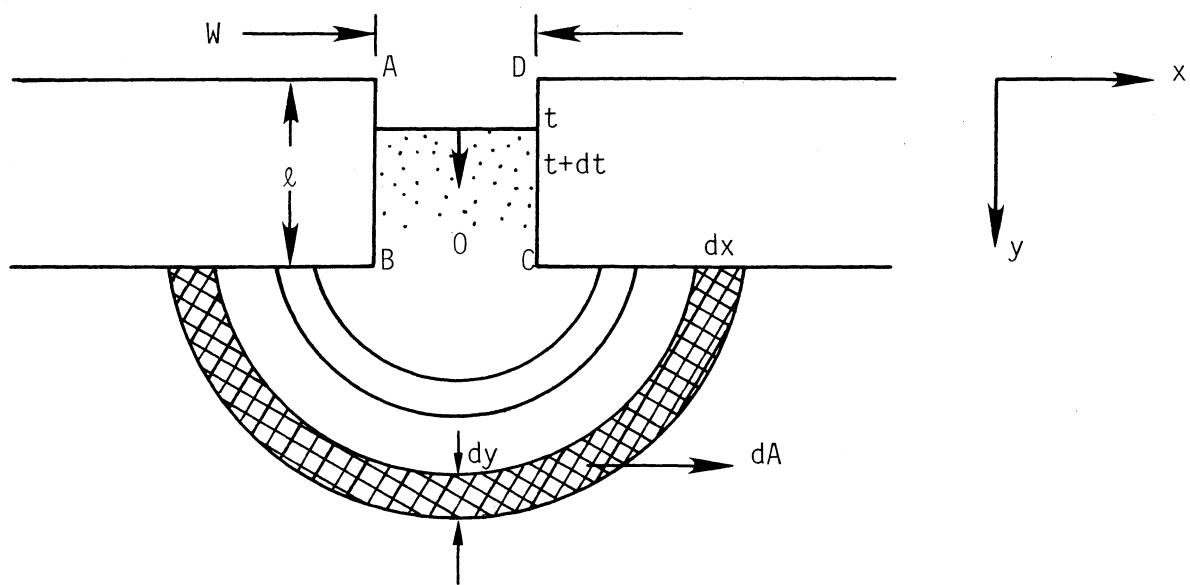


FIGURE 29. The Elliptical Shape of Water Penetration and the Evaporation in a Low Permeability Base Course

of the ellipse. By the continuity equation,

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

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

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

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

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

$$h = a_1 y + c_1$$

$$\text{at } y=0, h=\ell=c_1$$

$$\text{and } y=y_0, h=a_1 y_0 + \ell$$

where y_0 is the wetting front in the vertical direction.

$$\text{Since } h = -y_0 - h_k,$$

$$a_1 = \frac{-y_0 - h_k - \ell}{y_0}, \quad (D-6)$$

where h_k is the capillary head.

Thus

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

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

From Eq. D-1

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

therefore,

$$\frac{y_0}{y_0 + h_k + \ell} dy_0 = \frac{k_v}{n} dt \quad (D-9)$$

$$v_x = \frac{dx}{dt} = \frac{-k_h}{n} \frac{dh}{dx} \quad (D-10)$$

Assume $h = a_2 x + c_2$

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

$$\text{and } x = x_0 \quad h = ax_0 + \ell = -h_k$$

where x_0 is the wetting front in horizontal direction.

Therefore,

$$a_2 = \frac{-\ell - h_k}{x_0} \quad (D-11)$$

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

therefore,

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

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

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

This differential equation is accompanied by the initial conditions

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

$$wd\ell = \frac{\pi}{2} x_0 y_0$$

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

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

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

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) Evaluate Δl 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.

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

$$\text{Initial Condition: } u(y, 0) = u_0 \quad (\text{D-20})$$

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

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

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):

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

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

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

$$u_a = \text{suction of atmosphere,}$$

$$u_0 = \text{original suction throughout soil,}$$

$$y_0 = \text{wetting front of water penetration,}$$

$$\beta = \text{evaporation constant, and}$$

$$\kappa = \text{diffusion coefficient.}$$

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

$$\begin{aligned}\Delta u(y, t_f) &= u(y, 0) - u(y, t_f) \\ &= u_0 - u(y, t_f), \text{ and}\end{aligned}\quad (D-26)$$

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.

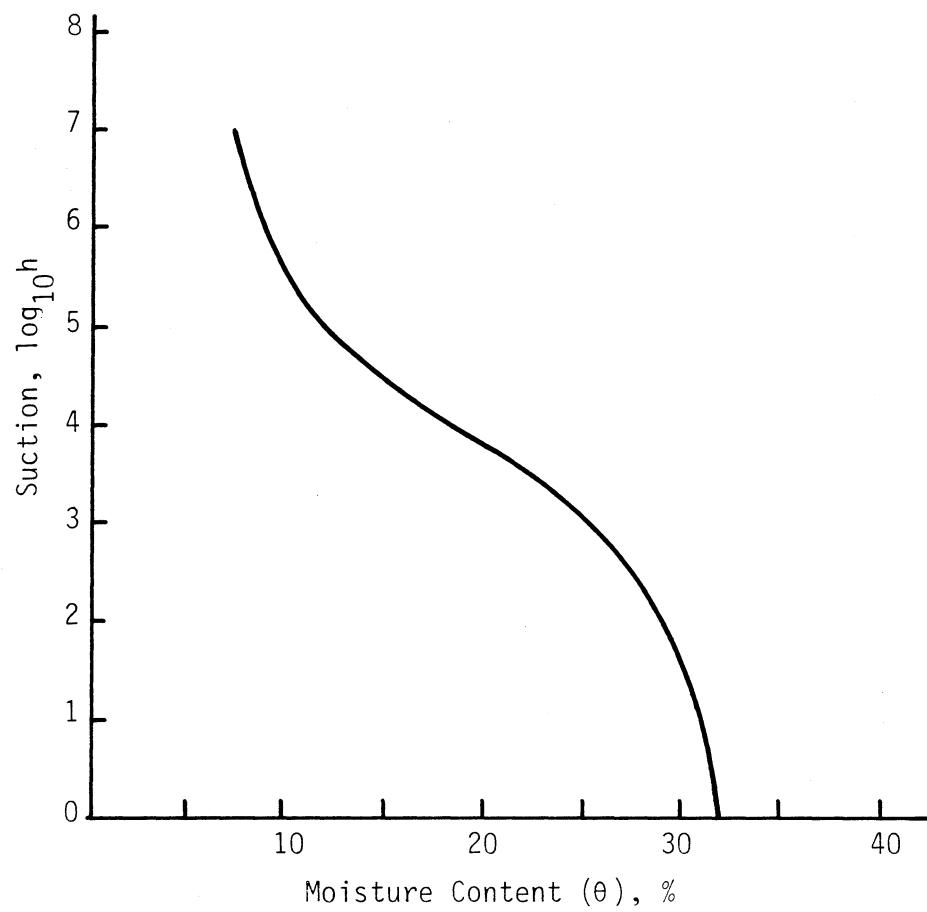


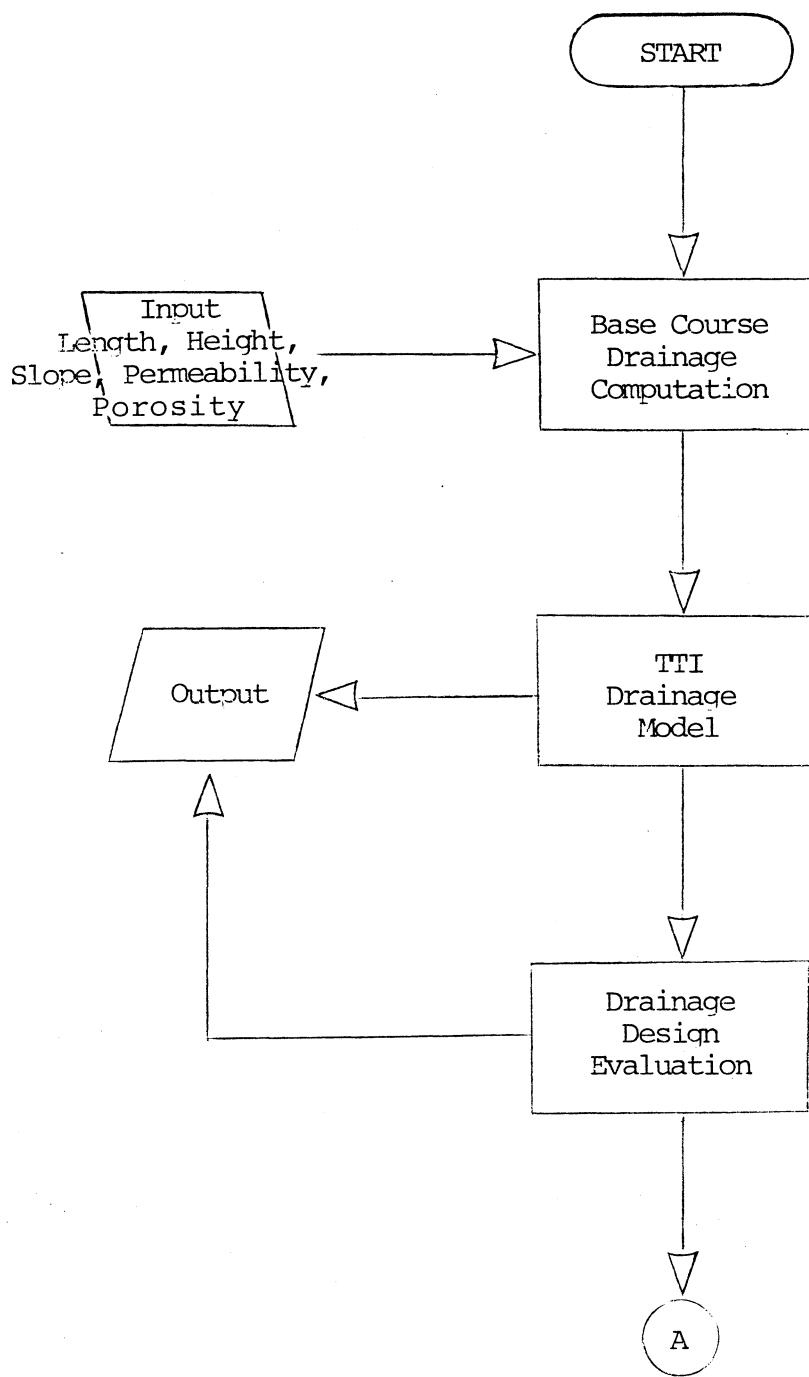
FIGURE 30. Relationship between Suction (Water Potential) and Moisture Content in Soil.

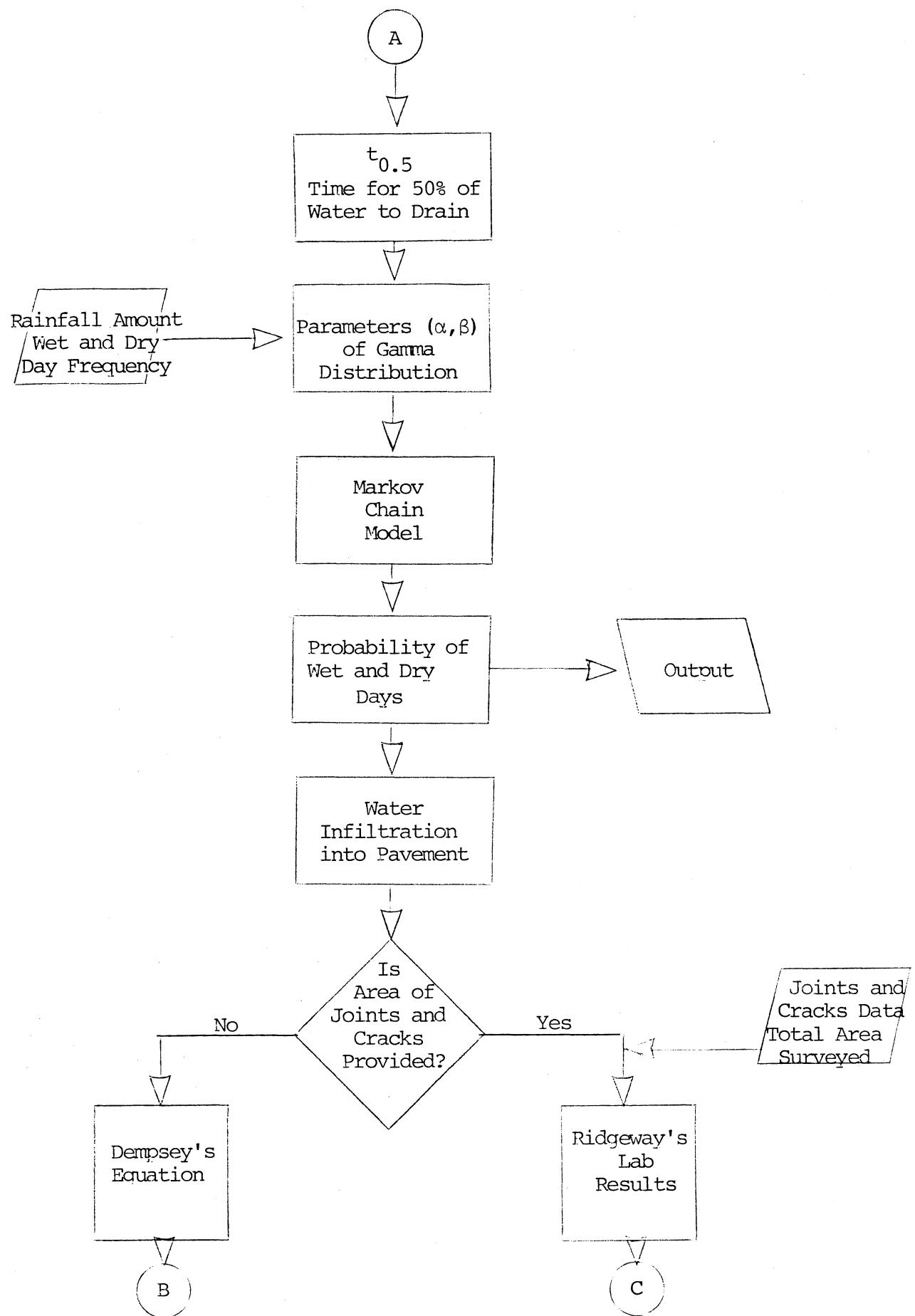
APPENDIX E
FLOW CHART, COMPUTER PROGRAMMING, AND USER'S GUIDE

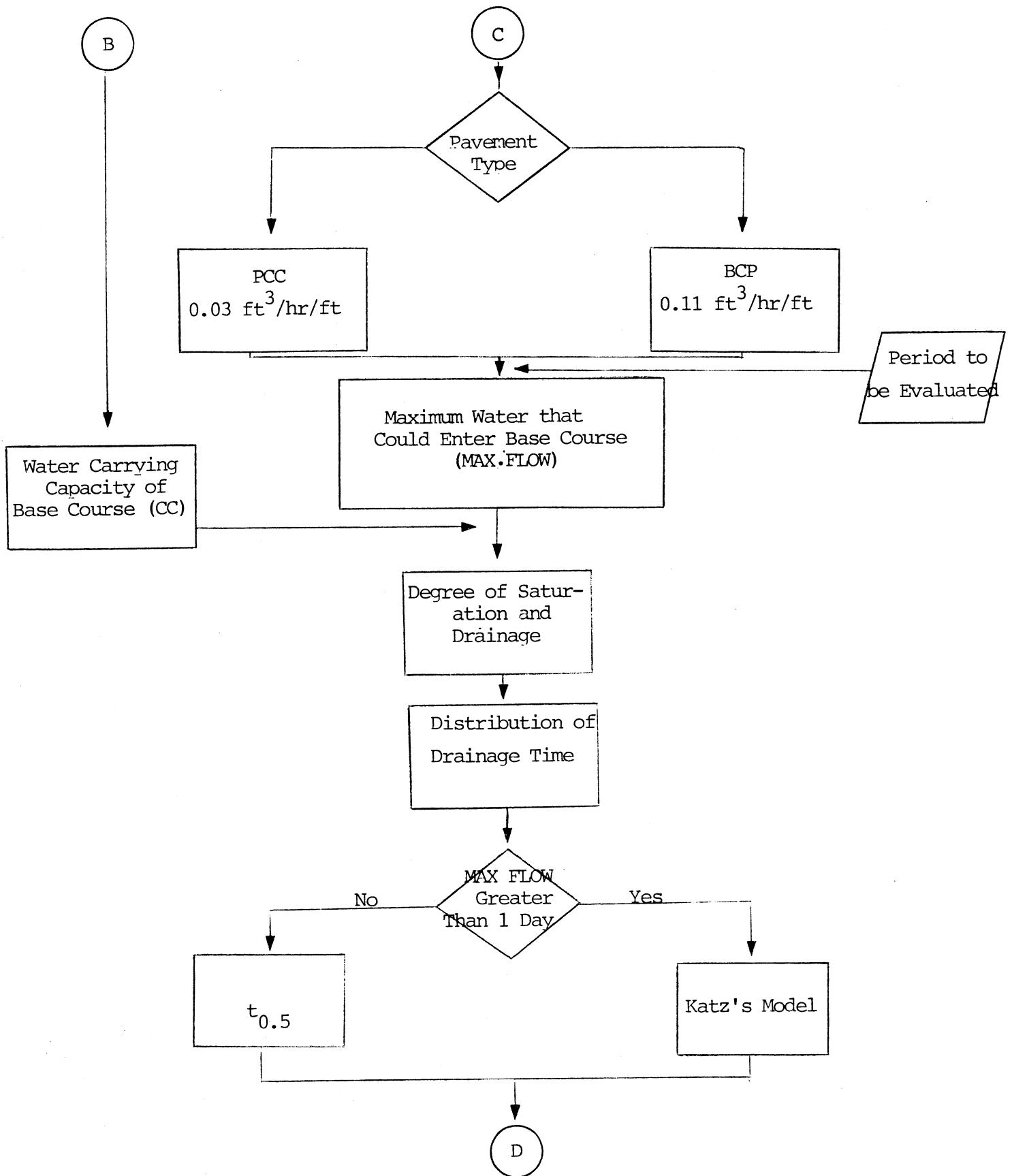
This computer program for the simulation model of rainfall infiltration and drainage analysis is constructed mainly in five parts:

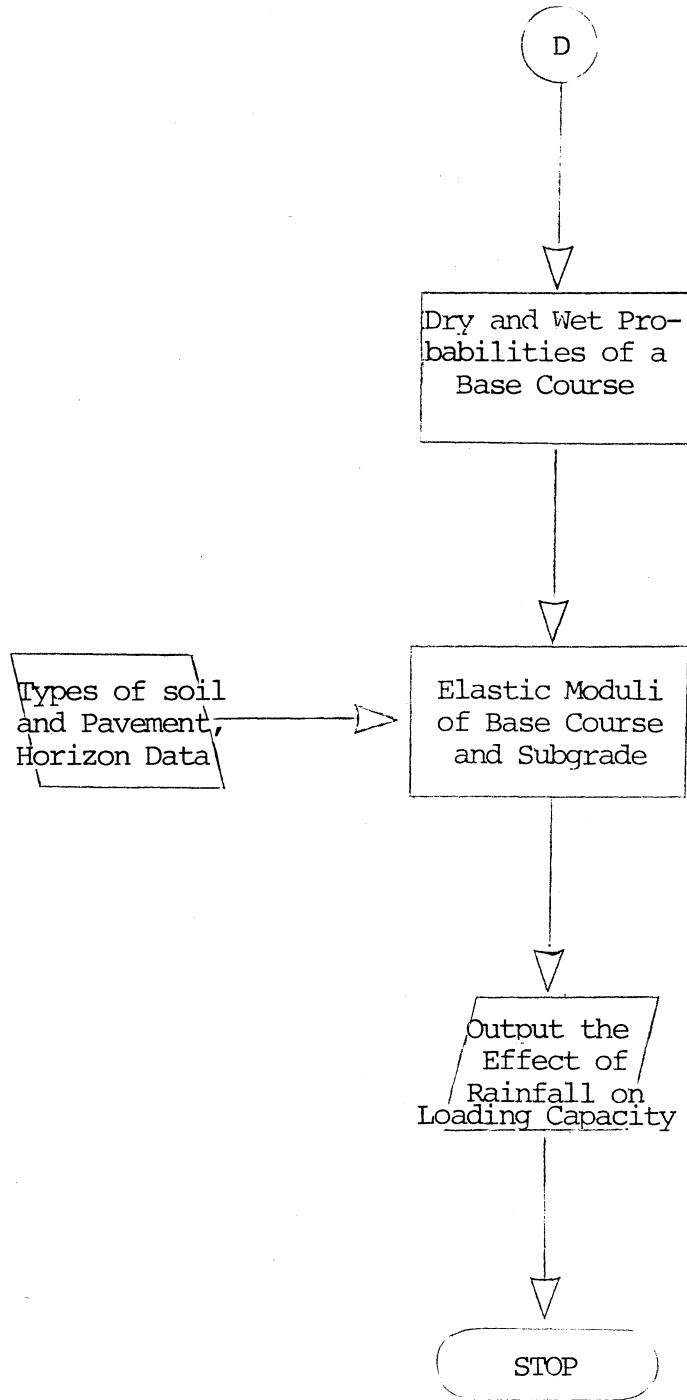
- (1) Drainage calculation by using the TTI model.
- (2) Drainage design evaluation.
- (3) Estimation of parameters of Gamma distribution for rainfall amount, calculation of rainfall duration.
- (4) Dry and wet probabilities of the weather and the base course from the Markov chain model and Katz's recurrence equations.
- (5) Estimation of elastic moduli of base course and subgrade.

E-1. FLOW CHART FOR COMPUTER PROGRAMMING









E-2. COMPUTER PROGRAMS AND SAMPLE RESULTS

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

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1.      C          00010
2.      C*****          00020
3.      C*          *
4.      C*          TEXAS TRANSPORTATION INSTITUTE      * 00030
5.      C*          *
6.      C*          *
7.      C*          SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND PAVEMENT DRAINAGE * 00040
8.      C*          *
9.      C*          AUGUST,1983          * 00050
10.     C*          *
11.     C*****          00060
12.     C          00070
13.     C*****          00080
14.     C*          00090
15.     C*          *
16.     C*          BASE AND SUBGRADE DRAINAGE MODELS      * 00100
17.     C*          *
18.     C*          PARABOLIC FREE SURFACE PLUS SUBGRADE DRAINAGE      * 00120
19.     C*          *
20.     C*          *
21.     C*****          00130
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24.     C          00160
25.     C          00170
26.     C          00180
27.     C          00190
28.     C          00200
29.     C*****          00210
30.     C          00220
31.     C          IMPLICIT REAL(J-Z)          00230
32.     C          INTEGER N,NA,NB,NC          00240
33.     C          EXTERNAL DUMMYF,GAMDIS          00250
34.     C          COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1          00260
35.     C          COMMON CASE,HED,HSUBA,HSUBB,NUM,S          00270
36.     C          COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)          00280
37.     C          COMMON /TNUM/ INABT          00290
38.     C          DIMENSION UAREA(120,10)          00300
39.     C          DIMENSION LOGTIM(120,10)          00310
40.     C          DIMENSION ITITLE(18)          00320
41.     C          DATA UDRAN/0.5/          00330
42.     C          *
43.     C          C UDRAN : 50 PERCENT DRAINAGE          00340
44.     C          C INDS : NUMBER OF DATA SET          00350
45.     C          C NA : NO. OF SECTORS IN RUNGE-KUTTA METHOD FOR CASE 1          00360
46.     C          C NE : NO. OF SECTORS IN DIVIDING HEIGHT FOR CASE 2          00370
47.     C          C N : NO. OF SECTORS IN SIMPSON'S RULE          00380
48.     C          C INABT : SUM OF NA AND NB          00390
49.     C          C LA : LENGTH OF BASE (FEET)          00400
50.     C          C HE : HEIGHT OF BASE (FEET)          00410
51.     C          C TAPER : SLOPE RATIO OR THE VALUE OF TANGENT ALPHA (IN PERCENT)          00420
52.     C          C K1 : PERMEABILITY OF BASE COURSE (FEET PER HOUR)          00430
53.     C          C K2 : PERMEABILITY OF SUBGRADE (FEET PER HOUR)          00440
54.     C          C N1 : POROSITY OF BASE COURSE          00450
55.     C          C N2 : POROSITY OF SUBGRADE          00460
56.     C          C TA : SLOPE RATIO (IN DECIMAL POINTS),TAPER/100.          00470
57.     C          C
58.     C          C INEED : 0      DRAINAGE ANALYSIS ONLY          00480
59.     C          C           1      DRAINAGE ANALYSIS AND EVALUATION OF DRAINAGE DESIGN          00490
60.     C          C           2      SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINAGE          00500
61.     C          C
62.     C          NA=30          00510
63.     C          NB=30          00520
64.     C          INT=NA+NB          00530
65.     C          INABT=INT          00540
66.     C          N=10          00550
67.     C          DO 300 INDS=1,10          00560
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60.      C          00600
61.      C      INPUT THE DATA 00610
62.      C          00620
63.      READ(5,55555,END=99999) IPROB,INeed,ITITLE 00630
64.      55555 FORMAT(I5,I3,18A4) 00640
65.      WRITE(6,55556) IPROB,ITITLE 00650
66.      55556 FORMAT(1H1,2(/),5X,'PROBLEM NUMBER',I5,2X,18A4) 00660
67.      IF(INeed.EQ.0) WRITE(6,55557) 00670
68.      IF(INeed.EQ.1) WRITE(6,55558) 00680
69.      IF(INeed.EQ.2) WRITE(6,55559) 00690
70.      55557 FORMAT(3(/),5X,'DRAINE ANALYSIS USING TTI DRAINAGE MODEL') 00700
71.      55558 FORMAT(3(/),5X,'DRAINAGE ANALYSIS AND DESIGN EVALUATION') 00710
72.      55559 FORMAT(3(/),5X,'SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAIN 00720
73.          AGE') 00730
74.          IA=INDS 00740
75.          READ(5,15)LA,HE,TAPER,K1,K2,N1,N2 00750
76.          15 FORMAT(7(F10.0)) 00760
77.          TA=TAPER/100. 00770
78.      C          00780
79.      C      HORIZONTAL BASE COURSE 00790
80.      C          00800
81.      IF(TA.LE.0.) TA=0.1E-06 00810
82.      IF(N2.LE.0.) CALL PORO2 00820
83.      C          00830
84.      C      IF N1 EQUALS TO N2 AND K1 EQUALS K2 WHICH IMPLIES BASE COURSE IS 00840
85.      C      INFINITIVELY DEEP AND THE PROGRAM WILL NOT WORK 00850
86.      C          00860
87.      IF(N1.EQ.N2.AND.K2.EQ.K1) K2=K2*1.0001 00870
88.      WRITE(6,25) 00880
89.      25 FORMAT(3(/),5X,'LENGTH',4X,'HEIGHT',4X,'SLOPE%', 00890
90.          +4X,'PERM.1',4X,'PERM.2',4X,'PORO.1',4X,'PORO.2') 00900
91.      WRITE(6,55)LA,HE,TAPER,K1,K2,N1,N2 00910
92.      55 FORMAT(1X,3(F10.2),2(F10.5),2(F10.4)) 00920
93.          TWETA=LA*HE 00930
94.          S=HE/(LA*TA) 00940
95.          WRITE(6,35)S 00950
96.          35 FORMAT(//,5X,'SLOPE FACTOR=',F6.3//) 00960
97.          WRITE(6,255) 00970
98.          255 FORMAT(5X,'NOTE: THE FOLLOWING ANALYSIS IS BASED ON PARABOLIC SHAP 00980
99.              +E PLUS SUBGRADE DRAINAGE') 00990
100.     C          01000
101.     C      RUNGE-KUTTA METHOD FOR PARABOLIC(DQX) AND HORIZONTAL(DQY) EQUATION OF CA01010
102.     C          01020
103.     WRITE(6,115) 01030
104.     115 FORMAT(6(/), 5X,'HEAD ON X COOR.',' HT.(SUB.DRAIN ONLY)' 01040
105.         1,8X,'AVG. HEIGHT.',7X,'TIME(STAGE 1)',7X,'DRAINAGE DEG.'//) 01050
106.         TIME=0. 01060
107.         XM=0. 01070
108.         AK1=0. 01080
109.         DELT=LA/NA 01090
110.         CASE=1. 01100
111.         DO 700 I2=1,NA 01110
112.         TIME2=TIME+AK1 01120
113.         XM=XM+DELT 01130
114.         NUM=2. 01140
115.         CALL SUBHT(TIME2,HSUB2) 01150
116.         HSUBB=HSUB2 01160
117.         CALL CONSFC(XM,A) 01170
118.         DTDX=DUMMYF(XM) 01180
119.         AK2=DTDX*DELT 01190

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120.      TIME=TIME+(AK1+AK2)/2.          01200
121.      NUM=1.                      01210
122.      CALL SUBHT(TIME,HSUB1)        01220
123.      HSUBA=HSUB1                01230
124.      CALL CONSFC(XM,A)          01240
125.      DTDX=DUMMYF(XM)          01250
126.      AK1=DTDX*DELT            01260
127.      WET1=(HE-HSUBA)*LA+HSUBA*XM/3. 01270
128.      UE1=WET1/TWETA           01280
129.      HAVG1=(TWETA-WET1)/LA       01290
130.      IF(HSUBA.LE.0.OR.HSUBA.LE.HAVG1) HSUBA=HAVG1 01300
131.      WRITE(6,135)XM,HSUBA,HAVG1,TIME,UE1        01310
132.      135 FORMAT(5(E20.4))        01320
133.      XTIME(I2,IA)=TIME         01330
134.      YAREA(I2,IA)=UE1          01340
135.      700 CONTINUE              01350
136.      C                         01360
137.      C USE SIMPSON'S RULE IN CALCULATING TIME FOR CASE 2 01370
138.      C HSUBA(MAXIMUM HEIGHT IN CASE 2),XM(TOTAL LENGTH IN CASE 1) 01380
139.      C AND TIME(MAXIMUM TIME IN CASE 1) WERE ALL RESERVED FROM UPPER DO LOOP 01390
140.      C                         01400
141.      WRITE(6,45)                01410
142.      45 FORMAT(1H1,6(/), 5X,'HEAD ON Y COOR.',' HT.(SUB.DRAIN ONLY)', 01420
143.          +8X,'AVG. HEIGHT',7X,'TIME(STAGE 2)',7X,'DRAINAGE DEG.'//) 01430
144.          CASE=2.                01440
145.          HMAX=HSUBA             01450
146.          HMAX2=HMAX             01460
147.          DELTH=HMAX/NB          01470
148.          DO 800 I3=1,NB          01480
149.              HMIN=HMAX2-DELTH*I3 01490
150.              I5=I3+NA            01500
151.              IF(I3.EQ.NB.OR.HMIN.LE.0.) HMIN=HMAX*0.5 01510
152.              CALL CONSFC(XM,HMIN)        01520
153.              CALL SIMPSN(AREA,DUMMYF,HMIN,HMAX,N) 01530
154.              TIME=TIME+AREA          01540
155.              CALL SUBHT(TIME,HTSU)        01550
156.              WET2=TWETA-2.*HMIN*LA/3. 01560
157.              UE2=WET2/TWETA          01570
158.              HAVG2=(TWETA-WET2)/LA       01580
159.              IF(HTSU.LE.0.OR.HTSU.LE.HAVG2) HTSU=HAVG2 01590
160.              WRITE(6,135)HMIN,HTSU,HAVG2,TIME,UE2        01600
161.              XTIME(I5,IA)=TIME         01610
162.              YAREA(I5,IA)=UE2          01620
163.              UAREA(I5,IA)=YAREA(I5,IA)*100. 01630
164.              HMAX=HMIN             01640
165.              IF(I3.EQ.NB) TIMAX(IA)=TIME 01650
166.              IF(I3.EQ.NB) UEMAX(IA)=UE2 01660
167.              800 CONTINUE              01670
168.              IMAXD=TIMAX(IA)/24.+0.5 01680
169.              CALL INPOLA(TDRAN,UDRAN,IA,LOGTIM) 01690
170.              IF(INEED.NE.0)          01700
171.                  1CALL JUDGE(IA,INT,ITYPF1,IQFINE,GRAVPC,SANDFC) 01710
172.                  IF(INEED.EQ.2) CALL RAIN(TDRAN,IMAXD) 01720
173.                  300 CONTINUE              01730
174.                  99999 WRITE(6,125)        01740
175.                  125 FORMAT(1H1)          01750
176.                  STOP                 01760
177.                  END                 01770
178.                  C                         01780
179.                  C                         01790

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180.      C*****  

181.      C*  

182.      C* VARIOUS CONSTANTS EMPLOYED IN EQUATIONS  

183.      C*  

184.      C* XM: MAXIMUM HORIZONTAL DISTANCE IN CASE 1;  

185.      C* HMIN: MINIMUM VALUE OF HEIGHT  

186.      C*  

187.      C*****  

188.      C  

189.      SUBROUTINE CONSFC(XM,HMIN)          01800  

190.      IMPLICIT REAL(J-Z)                 01810  

191.      INTEGER N,NA,NB,NC,NJONT,NLANE       01820  

192.      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1 01830  

193.      COMMON CASE,HED,HSUBA,HSUBB,NUM,S        01840  

194.      IF(NUM.EQ.1.) HSUB=HSUBA            01850  

195.      IF(NUM.EQ.2.) HSUB=HSUBB            01860  

196.          IF(CASE.EQ.2.) HSUB=HMIN         01870  

197.          IF(CASE.EQ.2.) XM=LA             01880  

198.          A1=HSUB/SQRT(XM)                01890  

199.          B1=A1*(1.-N1/N2)                01900  

200.          B2=A1*(K2/K1-N1/N2)              01910  

201.          C1=N1*HE/N2                  01920  

202.          G1=B1/B2                    01930  

203.          G2=C1*(1.-G1)/B2              01940  

204.          G3=C1*G2                    01950  

205.          R1=G3/B2                  01960  

206.          RETURN                     01970  

207.          END                         01980  

208.          C  

209.          C  

210.          C*****  

211.          C*  

212.          C* CALCULATE DRAINAGE AREA CORRESPONDING TO DESIRED NUMBER OF DRY DAYS* 02100  

213.          C* YAREA,XTIME,TIMAX,UEMAX ARE THE SAME AS PREVIOUSLY DEFINED      * 02110  

214.          C* IDRY : NUMBER OF DRY DAYS ;                                * 02120  

215.          C* YDRAN: DRAINING AREA (IN %) COMPUTED BY INTRAPOLATION ;      * 02130  

216.          C*  

217.          C*****  

218.          C*  

219.          C*  

220.          SUBROUTINE DRYDAY(IMAXD,YDRAN,WPROB)           02140  

221.          COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10) 02150  

222.          COMMON /TNUM/ INABT                   02160  

223.          DIMENSION YDRAN(100),WPROB(50,50)           02170  

224.          IA=INDS                      02180  

225.          DO 6000 I=1,100                  02190  

226.          IDRY=I  

227.              DO 6100 I2=1,100  

228.                  IF(I2.EQ.INABT) GO TO 6222          02200  

229.                  IF(XTIME(I2,IA).GT.IDRY*24.) GO TO 6111 02210  

230.          6100 CONTINUE                   02220  

231.          6111 I1=I2-1  

232.              IF(I1.LE.0) GO TO 6001          02230  

233.              REGCOE=(YAREA(I2,IA)-YAREA(I1,IA))/(XTIME(I2,IA)-XTIME(I1,IA)) 02240  

234.              CONCOE=YAREA(I2,IA)-REGCOE*XTIME(I2,IA)          02250  

235.              YDRAN(IDRY)=(CONCOE+REGCOE*IDRY*24.)*100. 02260  

236.              GO TO 6000                   02270  

237.          6001 YDRAN(IDRY)=100.*YAREA(I2,IA)*IDRY*24./XTIME(I2,IA) 02280  

238.          6000 CONTINUE                   02290  

239.          6222 IF(IMAXD.LE.0) RETURN          02300

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240.      IMAXD=IDRY          02400
241.      IF(IMAXD.GE.39) IMAXD=39 02410
242.      YDRAN(IMAXD)=100.    02420
243.      WRITE(6,6005)        02430
244. 6005 FORMAT(1H1,5(/),T34,'PROBLEM NO.',5X,'TIME(DAYS)',4X,'DRAINAGE(%)' 02440
245.           2,2X,'PROB(CONSECUTIVE DRY DAYS)',5(/)) 02450
246.           IN=1            02460
247.           DO 6600 I=1,IMAXD 02470
248.           IN=IN+1          02480
249.           WRITE(6,6010)IA,I,YDRAN(I),WPROB(1,IN) 02490
250. 6010 FORMAT(T30,I15,I15,F15.2,20X,F8.3,5(/)) 02500
251. 6600 CONTINUE          02510
252.      RETURN             02520
253.      END                02530
254. C                     02540
255. C                     02550
256. C*****               02560
257. C*                   * 02570
258. C* ROUTINE FOR COMPUTING ALL THE FUNCTIONS      * 02580
259. C*                   * 02590
260. C* X: MAXIMUM X VALUE FOR CASE 1; X=LA FOR CASE 2;      * 02600
261. C* MINIMUM X VALUE FOR CASE 3;                      * 02610
262. C*                   * 02620
263. C*****               02630
264. C                     02640
265. C                     02650
266. FUNCTION DUMMYF(X)          02660
267. IMPLICIT REAL(J-Z)        02670
268. INTEGER N,NA,NB,NC,NJONT,NLANE 02680
269. COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1 02690
270. COMMON CASE,HED,HSUBA,HSUBB,NUM,S 02700
271. IF(NUM.EQ.1.) HSUB=HSUBA 02710
272. IF(NUM.EQ.2.) HSUB=HSUBB 02720
273.     IF(CASE.EQ.2.) AE=X 02730
274.     IF(CASE.EQ.2.) X=LA 02740
275.     IF(CASE.EQ.2.) HSUB=AE 02750
276.     HED=HSUB 02760
277. IF(N2.GT.0.1E-05.AND.K2.NE.0.) GO TO 5555 02770
278. DUM3=0. 02780
279. GO TO 6666 02790
280. 5555 FAC1=G1*X+2.*G2*SQRT(X) 02800
281.     FAC2=2*R1* ALOG(ABS((B2*SQRT(X)+C1)/C1)) 02810
282.     FACR=FAC1-FAC2 02820
283.     IF(N2.LE.0.1E-05) DQY=0. 02830
284.     IF(N2.GT.0.1E-05) DQY=(HSUB*(1.-N1/N2)+C1)/(HSUB*(K2/K1-N1/N2)+C1) 02840
285.     DUM3=6.*K2*X*((LA-X)*DQY+FACR)/LA 02850
286. 6666 CONTINUE          02860
287.     IF(CASE.EQ.1.) DUM1=2.*N1*HSUB*X 02870
288.     IF(CASE.EQ.2.) DUM1=4.*N1*LA**2 02880
289.     DUM2=K1*(3.*HSUB**2+4.*HSUB*X*TA) 02890
290.     DUMMYF=DUM1/(DUM2+DUM3) 02900
291.     IF(CASE.EQ.2.) X=AE 02910
292.     IF(CASE.EQ.2.) HSUB=HED 02920
293.     RETURN             02930
294.     END                02940
295. C                     02950
296. C                     02960
297. C*****               02970
298. C*                   * 02980
299. C* EVALUATE THE MODULI OF BASE AND SUBGRADE BY DISTRIBUTION * 02990

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300. C* OF MATERIAL SATURATION FROM THE RAINFALL * 03000
301. C* * 03010
302. C* ALPHA,BETA: PARAMETERS OF GAMMA DISTRIBUTION * 03020
303. C* PWET,PDRY : PROBABILITY OF WET AND DRY DAYS IN STEADY STATE * 03030
304. C* HALFT : TIME OF 50% DRAINAGE(HOUR); * 03040
305. C* * 03050
306. C* * 03060
307. C***** * 03070
308. C * 03080
309. C * 03090
310. C SUBROUTINE FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE, 03100
311. 2ASOIL,BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPROB,IMAXD) 03110
312. C * 03120
313. C GAMDIS: GAMMA DISTRIBUTION AS A FUNCTION 03130
314. C AINTER,BSLOPE: INTERCEPT AND SLOPE OF THE LINEAR FUNCTION OF BASE COUR03140
315. C MODULUS VS. WATER SATURATION DEGREE 03150
316. C EMPDF : PROBABILITY DENSITY FUNCTION OF BASE COURSE MODULUS IN WET STA03160
317. C PAVE : INFILTRATION RATE OF PCC(1) OR BCP(2),UNIT=FT**3/(HOUR*FT) 03170
318. C FLOAVG: INFILTRATION RATE SELECTED ACCORDING TO PAVEMENT TYPE 03180
319. C PVA,PVB:THE INTERCEPT AND SLOPE OF REGRESSION EQUATION IN DEMPSEY'S TE03190
320. C PX : SPECIFIC RAINFALL AMOUNT 03200
321. C CFHALF: THE AVERAGE DEGREE OF FREE WATER DRAINAGE PER HOUR 03210
322. C DEFL : DEFLECTION OF BASE MATERIALS (INCHES) 03220
323. C DERATE: RATIO OF BASE MODULUS OF ELASTICITY 03230
324. C BCMAT : BASE MODULI OF ELASTICITY (KSI) 03240
325. C BCRATE: SLOPE OF DEFLECTION CHANGE WITH RESPECT TO DEGREE OF SATURATIO03250
326. C TURNPT: 1. DEFLECTION OF DRY BASE MATERIAL 03260
327. C 2. DEFLECTION OF 85% SATURATION LEVEL 03270
328. C * 03280
329. REAL LA,K1,K2,N1,N2 * 03290
330. EXTERNAL GAMDIS * 03300
331. COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1 * 03310
332. COMMON CASE,HED,HSUBA,HSUBB,NUM,S * 03320
333. COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE * 03330
334. COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10) 03340
335. COMMON /TNUM/ INAPT * 03350
336. COMMON /SGWET1/ SGWET(100),SGDRY(100),SGW(100),SGD(100) * 03360
337. COMMON /NOGAMA/ NUMWET,AVGAMT,TOTSUM * 03370
338. DIMENSION EMPDF(100),SGEM(100),AIINTER(2,9),BSLOPE(2,9) * 03380
339. DIMENSION PAVE(2),SOIL(9),HORIZ(2),PTYPE(2),FREE(100) * 03390
340. DIMENSION PK(100),DURAT(100),SECT(20),CDF(20),IIA(100) * 03400
341. DIMENSION DEFL(100),DERATE(100),BCRATE(2),BCMAT(6),TURNPT(2), * 03410
342. 2BCEM(100) * 03420
343. DIMENSION FREE2(100),DURATB(100),PXB(100),SECTB(50) * 03430
344. DIMENSION YDRAN(100),WPROB(50,50) * 03440
345. INTEGER PTYPE/'PCC','BCP'/ * 03450
346. DATA PAVE/0.03,0.11/ * 03460
347. DATA PVA,PVB/0.32,0.48/ * 03470
348. DATA BCMAT/425.3,236.3,209.3,64.6,29.8,17.1/ * 03480
349. DATA BCRATE/0.24,3.5/,TURNPT/0.02,0.08/ * 03490
350. REAL*8 SOIL/'A-7-5','A-4','A-7-6','A-6','CL','ML-CL', * 03500
351. 2'CH','ML','MH'/,ASOIL * 03510
352. INTEGER HORIZ/'ABC','BC'/,BHORIZ * 03520
353. DATA AINTER/39.83,27.54,17.33,16.76,31.22,24.65,36.15,35.67, * 03530
354. 2 31.89,32.13,31.89,32.13,21.93,23.02,31.39,29.01, * 03540
355. 3 31.39,29.01/ * 03550
356. DATA BSLOPE/0.453,0.266,0.158,0.146,0.294,0.196,0.362,0.354, * 03560
357. 2 0.312,0.311,0.312,0.311,0.151,0.161,0.331,0.284, * 03570
358. 3 0.331,0.284/ * 03580
359. IF(IMAXD.GE.39) IMAXD=39 * 03590

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360.      IF(ITYPE.EQ.PTYPE(1)) FLOAVG=PAVE(1)          03600
361.      IF(ITYPE.EQ.PTYPE(2)) FLOAVG=PAVE(2)          03610
362.      DO 7100 I=1,9                                03620
363.          IF(ASOIL.NE.SOIL(I)) GO TO 7100           03630
364.          INDEXB=I                                03640
365.          GO TO 7555                               03650
366. 7100 CONTINUE                                 03660
367. 7555 IF(BHORIZ.EQ.HORIZ(1)) INDEXA=1            03670
368.      IF(BHORIZ.EQ.HORIZ(2)) INDEXA=2            03680
369. C
370. C     FLOWMX: THE MAXIMUM AMOUNT WHICH WATER WOULD ENTER THE PAVEMENT 03700
371. C     CC : CARRYING CAPACITY OF WATER IN BASE COURSE (N1*L*H)        03710
372. C
373.     CC=N1*LA*HE                                03730
374.     CFHALF=(0.5/HALFT)*100.                      03740
375. C
376. C     DISTRIBUTION OF PAVEMENT MODULI AND DRY, WET PROBABILITIES       03760
377. C
378. C     FREE : AMOUNT OF FREE WATER IN PAVEMENT(FEET**2)                  03780
379. C     DURAT : DURATION OF SPECIFIC RAINFALL AMOUNT(HOURS)              03790
380. C     ITEST : 1 USING RIDGEWAY'S EQUATION; 2 USING DEMPSEY'S FOR NO CRACKS 03800
381. C             DATA AND WHEN RIDGEWAY'S METHOD TURNS OUT TO BE UNREASONABLE 03810
382. C
383.     IF(NUMWET-1)33333,22222,11111                03830
384. 11111 PX1=0.
385.     K=0                                         03850
386.     CDFSUM=0.                                  03860
387.     DO 7000 I=5,100,5                           03870
388.     FREE(I)=CC*I*0.01                         03880
389. C
390. C     SGWET : WET DEPTH OF SUBGRADE               03900
391. C     SGDRY : DRY DEPTH OF SUBGRADE              03910
392. C     SGW : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (E1**3)            03920
393. C     SGD : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE                   03930
394. C     SGEM : SUBGRADE MODULUS                   03940
395. C
396.     SGW(I)=(AINTER(INDEXA,INDEXB)-BSLCPE(INDEXA,INDEXB)*100.)          03960
397.     2           *(SGWET(I)**3)                  03970
398.     IF(SGW(I).LE.0.) SGW(I)=0.                  03980
399.     SGD(I)=AINTER(INDEXA,INDEXB)*(SGDRY(I)**3)                         03990
400.     SGEM(I)=(SGW(I)+SGD(I))/((5.83333-HE)**3)                         04000
401.     IF(SGEM(I).LE.0.) SGEM(I)=0.                  04010
402.     IF(CRKJON.EQ.0.) GO TO 7777                04020
403.     ITEST=1                                    04030
404.     DURAT(I)=(FREE(I)*FTLONG)/(CRKJON*FLOAVG)                         04040
405.     PX(I)=(60.*DURAT(I))** (1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE    04050
406.     RIDGE=BETA*PX(I)                            04060
407.     IF(RIDGE.GE.174.) GO TO 7777                04070
408.     GO TO 7788                                04080
409. 7777 ITEST=2
410.     PX(I)=((FREE(I)*FTLONG*0.02832-PVA)/(PVB*0.02832*FTLONG*LA))*12. 04100
411.     IF(PX(I).LE.0.) PX(I)=0.                  04110
412.     DURAT(I)=((PX(I)*SHAPE)/(CONST*(YEAR**RECPOW)))** (1./(1.-DURPOW)) 04120
413.     2 /60.                                     04130
414. 7788 PX2=PX(I)                                04140
415.     EMPDF(I)=GAMDIS(PX2,ALPHA,BETA)           04150
416.     IF(I.GT.85) GO TO 7755                   04160
417.     IF(I.LE.60) GO TO 7744                   04170
418.     DEFL(I)=TURNPT(1)+BCRATE(1)*0.01*(I-60) 04180
419.     DERATE(I)=TURNPT(1)/DEFL(I)               04190

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420.          BCEM(I)=BCMAT(IBC)*DERATE(I)          04200
421.          GO TO 7766                         04210
422. 7744 BCEM(I)=BCMAT(IBC)                   04220
423.          DERATE(I)=1.0                      04230
424.          GO TO 7766                         04240
425. 7755 DEFL(I)=TURNPT(2)+BCRATE(2)*0.01*(I-85) 04250
426.          DERATE(I)=TURNPT(1)/DEFL(I)        04260
427.          BCEM(I)=BCMAT(IBC)*DERATE(I)       04270
428. 7766 IIB=I/10*10                         04280
429.          IF(IIB.NE.I) GO TO 7000           04290
430.          CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA) 04300
431.          K=K+1                           04310
432.          IF(SECTOR.LE.0.) SECTOR=0.         04320
433.          IF(SECTOR.GT.1.0) SECTOR=1.0       04330
434.          SECT(K)=SECTOR                  04340
435.          CDFSUM=CDFSUM+SECT(K)            04350
436.          IF(CDFSUM.GE.1.0) CDFSUM=1.0      04360
437.          CDF(K)=CDFSUM                  04370
438.          PX1=PX2                        04380
439. 7000 CONTINUE                         04390
440.          C                           04400
441.          C   CALCULATE THE PART WHICH IS BEYOND THE FIELD CAPACITY IN GAMMA DISTRIBO 04410
442.          C   PX2 IS THE MAXIMUM INFILTRATION AMOUNT AFTER THE ABOVE LOOP      04420
443.          C                           04430
444.          TAILPT=1.0-CDFSUM             04440
445.          C                           04450
446.          C   THE DRY AND WET PAOBABILITIES OF THE PAVEMENT                 04460
447.          C                           04470
448.          C   PAVDRY: THE DRY PROBABILITY OF PAVEMENT                     04480
449.          C   PAVWET: THE WET PROBABILITY OF PAVEMENT                   04490
450.          C                           04500
451.          IF(TIMAX(INDS)/24.LT.1.) GO TO 8833          04510
452.          PX1=0.                         04520
453.          K=0                           04530
454.          DO 8000 I=1,IMAXD             04540
455.          FREE2(I)=CC*0.01*YDRAN(I)        04550
456.          IF(CRKJON.EQ.0.) GO TO 8777      04560
457.          ITEST=1                       04570
458.          DURATB(I)=(FREE2(I)*FTLONG)/(CRKJON*FLOAVG) 04580
459.          PXB(I)=(60.*DURATB(I))**(.1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE 04590
460.          RIDGE=BETA*PXB(I)              04600
461.          IF(RIDGE.GE.174.) GO TO 8777      04610
462.          GO TO 8788                      04620
463. 8777 ITEST=2                         04630
464.          PXB(I)=((FREE2(I)*FTLONG*0.02832-PVA)/(PVB*0.02832*FTLONG*LA))*12. 04640
465.          IF(PXB(I).LE.0.) PXB(I)=0.        04650
466.          DURATB(I)=((PXB(I)*SHAPE)/(CONST*(YEAR**RECPOW))) 04660
467.          2**(.1./(.1.-DURPOW))/60.        04670
468. 8788 PX2=PXB(I)                      04680
469.          CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA) 04690
470.          K=K+1                         04700
471.          IF(SECTOR.LE.0.) SECTOR=0.       04710
472.          IF(SECTOR.GT.1.0) SECTOR=1.0     04720
473.          SECTB(K)=SECTOR                04730
474.          PX1=PX2                        04740
475. 8000 CONTINUE                         04750
476.          PAVDRY=0.                      04750
477.          IN=1                          04770
478.          DO 8100 K=1,IMAXD             04780
479.          IN=IN+1                      04790

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480.      PAVDRY=PAVDRY+SECTB(K)*WPROB(1,IN)          04800
481.      8100 CONTINUE                                04810
482.      PAVDRY=PAVDRY+WPROB(1,IN)*TAILPT           04820
483.      GO TO 8844                                  04830
484.      8833 DHALF=HALFT/24.                         04840
485.      PAVDRY=1.-PWET*DHALF                         04850
486.      8844 PAVWET=1.-PAVDRY                        04860
487.      C                                         04870
488.      C                                         04880
489.      C      CALCULATE THE PROBABILITIES OF SATURATION LEVELS: 04890
490.      C          SECT1: 0-60%;   SECT2: 60-85%;   SECT3: 85-100% 04900
491.      C                                         04910
492.      C                                         04920
493.      CALL SIMP2(SECT1,GAMDIS,0.,PX(60),60,ALPHA,BETA) 04930
494.      IF(SECT1.GE.1.0) SECT1=1.0                  04940
495.      .. CALL SIMP2(SECT2,GAMDIS,PX(60),PX(85),60,ALPHA,BETA) 04950
496.      CALL SIMP2(SECT3,GAMDIS,PX(85),PX(100),60,ALPHA,BETA) 04960
497.      SECT3=SECT3+TAILPT                         04970
498.      C                                         04980
499.      GO TO 44444                               04990
500.      C      NUMBER OF RAINFALL QUANTITY EQUALS TO 0 OR 1 (NO GAMMA DISTRIBUTION) 05000
501.      C                                         05010
502.      C      YRAIN1: DRAINAGE LEVEL OF ONE RAINY DAY (IN DECIMAL POINT) 05020
503.      C      TRAIN1: TIME FOR THE CORRESPONDING DRAINAGE LEVEL OF ONE RAINY DAY 05030
504.      C                                         05040
505.      22222 ITEST=1                            05050
506.      IF(CRKJON.EQ.0.) GO TO 9191              05060
507.      AVGDUR=(AVGRAS*0.08333*LA*FTLONG)/(CRKJON*FLOAVG) 05070
508.      AVGFLO=(60.*AVGDUR)**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE 05080
509.      GO TO 9292                                05090
510.      9191 ITEST=2                            05100
511.      AVGDUR=(SHAPE*AVGRAS/(CONST*(YEAR**RECPOW)))**((1.-(1.-DURPOW))/60. 05110
512.      AVGFLO=(PVB*AVGRAS*0.08333*FTLONG*LA*0.02832+PVA)/(0.02832*FTLONG) 05120
513.      9292 YRAIN1=AVGFLO/CC                   05130
514.      C                                         05140
515.      C      FIND THE CORRESPONDING TIME FOR DEGREE OF DRAINAGE 05150
516.      C                                         05160
517.      DO 9900 I2=2,100                          05170
518.      IF(I2.EQ.INABT) GO TO 9922              05180
519.      IF(YAREA(I2,INDS).GE.YRAIN1) GO TO 9911 05190
520.      9900 CONTINUE                            05200
521.      9911 I1=I2-1                            05210
522.      REGCOE=(XTIME(I2,INDS)-XTIME(I1,INDS))/ 05220
523.      2          (YAREA(I2,INDS)-YAREA(I1,INDS)) 05230
524.      CONCOE=XTIME(I2,INDS)-REGCOE*YAREA(I2,INDS) 05240
525.      TRAIN1=CONCOE+REGCOE*YRAIN1             05250
526.      GO TO 9933                                05260
527.      9922 TRAIN1=TIMAX(INDS)                 05270
528.      9933 PAVWET=TRAIN1/(TOTSUM*24.)        05280
529.      PAVDRY=1.-PAVWET                         05290
530.      IF(YRAIN1-0.85) 9944,9944,9955       05300
531.      9944 SECT3=0.                           05310
532.      GO TO 9966                                05320
533.      9955 SECT3=XTIME(103,INDS)/TOTSUM      05330
534.      9966 IF(YRAIN1-60.)9988,9988,9977     05340
535.      9977 SECT2=(XTIME(108,INDS)-XTIME(103,INDS))/TOTSUM 05350
536.      GO TO 9999                                05360
537.      9988 SECT2=0.                           05370
538.      9999 SECT1=1.-SECT2-SECT3             05380
539.      44444 DEFL(73)=TURNPT(1)+BCRATE(1)*0.125 05390

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540.      DERATE(73)=TURNPT(1)/DEFL(73)                                05400
541.      DEFL(93)=TURNPT(2)+BCRATE(2)*0.075                         05410
542.      DERATE(93)=TURNPT(1)/DEFL(93)                                05420
543.      AVBCEM=BCMAT(IBC)*(1.*SECT1+DERATE(73)*SECT2+DERATE(93)*SECT3) 05430
544.      GEBCEM=AVBCEM*PAVWET+BCMAT(IBC)*PAVDRY                      05440
545.      C
546.      C AVERAGE RAINFALL DURATION AND BASE COURSE MODULUS          05450
547.      C
548.      C AVGDUR: DURATION CORRESPONDING TO THE AVERAGE RAINFALL AMOUNT 05480
549.      C AVGFL0: FREE WATER IN PAVEMENT DUE TO AVERAGE RAINFALL AMOUNT 05490
550.      C GESGEM: TOTAL AVERAGE OF SUBGRADE MODULI                     05500
551.      C AVBCEM: AVERAGE BASE MODULI IN WET STATE                   05510
552.      C GEBCEM: TOTAL AVERAGE OF BASE MODULI                      05520
553.      C
554.      AVGDUR=(SHAPE*AVGRAS/(CONST*(YEAR**RECP0W)))** (1. / (1.-DURPOW))/60. 05540
555.      IF(I TEST.EQ.2) GO TO 8888                                 05550
556.      AVGFL0=FLOAVG*AVGDUR*CRKJON/FTLONG                         05560
557.      GO TO 8899                                              05570
558.      8888 AVGFL0=(PVB*AVGRAS*0.08333*FTLONG*LA*0.02832+PVA)/(0.02832*FTLONG) 05580
559.      8899 IF(AVGFL0.GE.CC) AVGFL0=CC                           05590
560.      C
561.      C CALCULATE SUBGRADE MODULI                            05610
562.      C
563.      EXACT2=AVGFL0/CC                                         05620
564.      DO 9100 I2=1,100                                         05640
565.      IF(EXACT2.GE.1.) GO TO 9222                           05650
566.      IF(YAREA(I2,INDS).GT.EXACT2) GO TO 9111               05660
567.      9100 CONTINUE                                         05670
568.      9111 I1=I2-1                                         05680
569.      IF(I1.LE.0) GO TO 9001                               05690
570.      PEGCOE=(XTIME(I2,INDS)-XTIME(I1,INDS))/              05700
571.      2 (YAREA(I2,INDS)-YAREA(I1,INDS))                  05710
572.      INCEPT=XTIME(I2,INDS)-REGCOE*YAREA(I2,INDS)        05720
573.      TSGAVW=INCEPT+REGCOE*EXACT2                         05730
574.      GO TO 9333                                         05740
575.      9001 TSGAVW=XTIME(1,INDS)*EXACT2/YAREA(1,INDS)       05750
576.      GO TO 9333                                         05760
577.      9222 TSGAVW=TIMAX(INDS)                             05770
578.      9333 CALL SUBHT(TSGAVW,HSUBEM)                      05780
579.      C
580.      C SGWETD: AVERAGE WET DEPTH OF SUBGRADE DURING THE SEASON 05800
581.      C SGDRYD: AVERAGE DRY DEPTH OF SUBGRADE                 05810
582.      C SG1 : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (E1**3) 05820
583.      C SG2 : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE       05830
584.      C
585.      SGWETD=(HE-HSUBEM)*N1/N2                           05840
586.      IF(SGWETD.LE.0.OR.K2.EQ.0.) SGWETD=0.                05850
587.      SGDRYD=5.83333-HE-SGWETD                         05860
588.      SG1=(AINTER(INDEXA,INDEXB)-BSLOPE(INDEXA,INDEXB)*100.)*(SGWETD**3) 05870
589.      IF(SG1.LE.0.) SG1=0.                                05880
590.      SG2=AINTER(INDEXA,INDEXB)*(SGDRYD**3)             05890
591.      GESGEM=(SG1+SG2)/((5.83333-HE)**3)                05900
592.      C
593.      IF(NUMWET.LE.1) GO TO 55555                         05910
594.      WRITE(6,735)CC,CFHALF,TAILPT,PAVDRY,PAVWET           05920
595.      735 FORMAT(3(/),T40,'WATER CARRYING CAPACITY OF BASE(SQ.FT)=',F10.3//, 05930
596.      2 T40,'AVERAGE DEGREE OF DRAINAGE PER HOUR =',F10.3//, 05940
597.      3 T40,'OVERALL PROBABILITY OF SATURATED BASE=',F10.3//, 05950
598.      4 //,T40,'DRY PROBABILITY OF BASE COURSE            =',F10.3//, 05960
599.      5 T40,'WET PROBABILITY OF BASE COURSE              =',F10.3) 05970

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600.      IF(ITEST.EQ.2)    WRITE(6,745)          06000
601.      745 FORMAT(//,T30,'(THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED 06010
602.           ZON DEMPSEY&S FIELD EQUATION)')
603.           IF(ITEST.EQ.1)    WRITE(6,755)          06020
604.           755 FORMAT(//,T30,'(THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED 06030
605.           ZON RIDGEWAY&S LAB EQUATION)')
606.           WRITE(6,705)          06040
607.           705 FORMAT(//,T35,'*****PROBABILITY DISTRIBUTION OF MODULUS OF BA 06050
608.           2SE COURSE*****',//)          06060
609.           DO 7200 I=1,10          06070
610.           7200 IIA(I)=I*10          06080
611.           WRITE(6,715)(IIA(I),I=1,10),(FREE(I),I=10,100,10),          06090
612.             2                  (PX(I),I=10,100,10),(DURAT(I),I=10,100,10), 06100
613.             3                  (BCEM(I),I=10,100,10),(DERATE(I),I=10,100,10), 06110
614.             4                  (SGEM(I),I=10,100,10),(EMPDF(I),I=10,100,10), 06120
615.             5                  (SECT(K),K=1,10),(CDF(K),K=1,10)          06130
616.           715 FORMAT(T25,'SATURATION LEVEL (%)',10I7,//,          06140
617.             1                  T25,'WATER IN BASE(SQ.FT)',10F7.2,//, 06150
618.             2                  T25,'RAINFALL QT.(INCHES)',10F7.2,//, 06160
619.             3                  T25,'RAIN DURATION(HOURS)',10F7.2,//, 06170
620.             4                  T25,'BASE MODULI (KSI)',10F7.2,//, 06180
621.             5                  T25,'RATIO OF DRY MODULUS',10F7.2,//, 06190
622.             6                  T25,'SUBGRADE MODULI(KSI)',10F7.2,//, 06200
623.             7                  T25,'PROBABILITY DENSITY',10F7.2,//, 06210
624.             8                  T25,'      PROBABILITY',10F7.2,//, 06220
625.             9                  T25,'CUMULATIVE PROB.',10F7.2)          06230
626.           WRITE(6,775)AVGFLO,AVGDUR,AVGRAS,AVBCEM,GEBCEM,GESGEM          06240
627.           775 FORMAT(//,T40,'***** DISTRIBUTION CHARACTERISTICS OF RAINFALL EFFE 06250
628.           2CT *****',          06260
629.             3//,T30,'AVERAGE FREE WATER IN BASE          (SQ.FEET)=',F10.2, 06270
630.             4//,T30,'DURATION OF AVERAGE RAINFALL AMOUNT (HOURS)=',F10.3, 06280
631.             5//,T30,'AVERAGE RAINFALL AMOUNT PER DAY (INCHES)=',F10.3, 06290
632.             6//,T30,'AVERAGE BASE COURSE MODULUS IN WET STATE(KSI)=',F10.2, 06300
633.             7//,T30,'AVERAGE BASE COURSE MODULUS          (KSI)=',F10.2, 06310
634.             8//,T30,'AVERAGE SUBGRADE MODULUS          (KSI)=',F10.2)          06320
635.           RETURN          06330
636.           C          06340
637.           C A SEASON IS COMPLETE DRY          06350
638.           C          06360
639.           33333 PAVDRY=1.          06370
640.           PAVWET=0.          06380
641.           AVGRAS=0.          06390
642.           AVGDUR=0.          06400
643.           AVGFLO=0.          06410
644.           AVBCEM=BCMAT(IBC)          06420
645.           GEBCEM=AVBCEM          06430
646.           AVSGEM=AINTER(INDEXA,INDEXB)          06440
647.           GESGEM=AINTER(INDEXA,INDEXB)          06450
648.           C          06460
649.           C PRINTOUT FOR ONLY ONE RAINY DAY OR A COMPLETE DRY SEASON 06470
650.           C          06480
651.           55555 WRITE(6,785)          06490
652.           785 FORMAT(3(/),T40,'*****',/,          06500
653.             2                  //,T10,'NO GAMMA DISTRIBUTION IS APPLIED TO THIS ANALYSI 06510
654.             3S DUE TO ONLY ONE OR NO RAINFALL QUANTITY IS FOUND',//)          06520
655.           IF(ITEST.EQ.2)    WRITE(6,745)          06530
656.           IF(ITEST.EQ.1)    WRITE(6,755)          06540
657.           WRITE(6,765)PAVDRY,PAVWET,          06550
658.             2                  AVGFLO,AVGDUR,AVGRAS,AVBCEM,GEBCEM,GESGEM 06560
659.           765 FORMAT(          06570

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660.      2//,T30,'DRY PROBABILITY OF BASE COURSE          =',F10.3,    06600
661.      3//,T30,'WET PROBABILITY OF BASE COURSE          =',F10.3,    06610
662.      4//,T30,'AVERAGE FREE WATER IN BASE           (SQ.FEET)=',F10.2,    06620
663.      5//,T30,'DURATION OF AVERAGE RAINFALL AMOUNT   (HOURS)=',F10.3,    06630
664.      6//,T30,'AVERAGE RAINFALL AMOUNT PER DAY       (INCHES)=',F10.3,    06640
665.      7//,T30,'AVERAGE BASE COURSE MODULUS IN WET STATE(KSI)=' ,F10.2,    06650
666.      8//,T30,'AVERAGE BASE COURSE MODULUS          (KSI)=',F10.2,    06660
667.      9//,T30,'AVERAGE SUBGRADE MODULUS            (KSI)=',F10.2)    06670
668.      RETURN                                     06680
669.      END                                         06690
670.      C                                           06700
671.      C                                           06710
672.      *****                                         06720
673.      C*                                         * 06730
674.      C* COMPUTING PROBABILITIES OF CONSECUTIVE DRY DAYS BY KATZ'S METHOD * 06740
675.      C*                                         * 06750
676.      *****                                         06760
677.      C                                           06770
678.      C                                           06780
679.      SUBROUTINE KATZ(IMAXD,W)                   06790
680.      DIMENSION WZERO(50,50),WONE(50,50),W(50,50) 06800
681.      COMMON /DRYWET/ TLAMDA,DRYLAM,WETLAM,PWET 06810
682.      C KATZ'S METHOD TO COMPUTE THE DISTRIBUTION OF WET AND DRY DAYS 06820
683.      C IN CERTAIN PERIOD, WHICH IS ASSOCIATED WITH MARKOV CHAIN MODEL 06830
684.      C WZERO(I,J): THE PROBABILITY OF I-10 WET DAYS IN J CONSECUTIVE DAYS 06840
685.      C WHEN THE ZEROTH DAY IS DRY                  06850
686.      C WONE (I,J): THE PROBABILITY OF I-10 WET DAYS IN J CONSECUTIVE DAYS 06860
687.      C WHEN THE ZEROTH DAY IS WET                  06870
688.      C MAXWET: TIME REQUIRED TO DRAIN OUT 99% WATER IN THE PAVEMENT 06880
689.      C                                         06890
690.      IF(TLAMDA.GE.174.)      EXPCON=0.          06900
691.      IF(TLAMDA.LT.174.)      EXPCON=EXP(-TLAMDA) 06910
692.      P00=(WETLAM+DRYLAM*EXPON)/TLAMDA        06920
693.      P01=DRYLAM*(1.-EXPON)/TLAMDA        06930
694.      P10=WETLAM*(1.-EXPON)/TLAMDA        06940
695.      P11=(DRYLAM+WETLAM*EXPON)/TLAMDA 06950
696.      WRITE(6,45) P00,P01,P10,P11        06960
697.      45 FORMAT(5(/),T30,'***** TRANSITION PROBABILITY MATRIX *****' 06970
698.      2**',3(/),T40,'P00=',F5.3,10X,'P01=',F5.3,/, 06980
699.      3          T40,'P10=',F5.3,10X,'P11=',F5.3) 06990
700.      C WZERO(10,11)=P00                      07000
701.      C WZERO(11,11)=P01                      07010
702.      C WONE(10,11)=P10                      07020
703.      C WONE(11,11)=P11                      07030
704.      WZERO(10,10)=1.                      07040
705.      WONE(10,10)=1.                      07050
706.      IF(IMAXD.GE.39) IMAXD=39          07060
707.      MXWTP1=IMAXD+1                      07070
708.      DO 200 NJ=2,MXWTP1                 07080
709.      DO 100 K=1,NJ                      07090
710.          NJ10=NJ+10                     07100
711.          K10=K+10                      07110
712.          NJ9=NJ10-1                    07120
713.          NJ8=NJ9-1                    07130
714.          K9=K10-1                     07140
715.          K8=K9-1                      07150
716.      C WONE(-1;N-1)=0.                  07160
717.          WONE(9,NJS)=0.                07170
718.      C WZERO(N;N-1)=0.                  07180
719.          WZERO(NJ9,NJS)=0.              07190

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720.          WZERO(K9,NJ9)=P00*WZERO(K9,NJ8)+P01*WONE(K8,NJ8)          07200
721.          WONE(K9,NJ9)=P10*WZERO(K9,NJ8)+P11*WONE(K8,NJ8)          07210
722.          W(K9,NJ9)=(1.-PWET)*WZERO(K9,NJ9)+PWET*WONE(K9,NJ9)        07220
723.          100 CONTINUE                                              07230
724.          200 CONTINUE                                              07240
725.          C                                                       07250
726.          C                                                       07260
727.          C          CONVERT THE I+10 SEQUENCE TO LOWER SERIES STARTING FROM 1 07270
728.          C          WHICH STANDS FOR DRY DAY, 2 FOR 1 WET DAY.....      07280
729.          C                                                       07290
730.          C                                                       07300
731.          DO 500 I=1,MXWTP1                                         07310
732.          DO 500 J=1,I                                           07320
733.          I10=I+9                                              07330
734.          J10=J+9                                              07340
735.          WONE(J,I)=WONE(J10,I10)                                07350
736.          WZERO(J,I)=WZERO(J10,I10)                                07360
737.          IF(I.GT.1)W(J,I)=W(J10,I10)                            07370
738.          500 CONTINUE                                              07380
739.          C                                                       07390
740.          C                                                       07400
741.          C          WRITE(6,35)                                         07410
742.          C          35 FORMAT(1H1,5X,'***** PROBABILITIES OF K WET DAYS IN COSECUITIV 07420
743.          C          2E N DAYS *****',5(/),T40,45(''),//,T40,4X,'N',4X,'K', 07430
744.          C          +3X,'WO(K;N)',3X,'WI(K;N)',4X,'W(K;N)')                07440
745.          C          DC 400 J2=1,IMAXD                               07450
746.          C          J3=J2+1                                              07460
747.          C          WRITE(6,25)                                         07470
748.          C          25 FORMAT(//,T40,45(''),//)                         07480
749.          C          DO 300 I2=1,J3                                         07490
750.          C          J210=J2+1                                         07500
751.          C          I29=I2                                              07510
752.          C          I1=I2-1                                             07520
753.          C          WRITE(6,15)J2,I1,WZERO(I29,J210),WONE(I29,J210), 07530
754.          C          2          W(I29,J210)                           07540
755.          C          15         FORMAT(T40,I5,I5,3F10.3)                 07550
756.          C          300 CONTINUE                                         07560
757.          C          400 CONTINUE                                         07570
758.          RETURN                                              07580
759.          END                                                 07590
760.          C                                                       07600
761.          C                                                       07610
762.          *****                                                 07620
763.          C*                                                 * 07630
764.          C*          CALCULATE THE DESIRED DRAINING AREA BY INTRAPOLATION * 07640
765.          C*                                                 * 07650
766.          C*          XTIME: TIME ( X COORDINATE ) ;                      * 07660
767.          C*          YAREA: DRAINING AREA ( Y COORDINATE ) ;           * 07670
768.          C*          TDRAN: TIME OF 50 PERCENT DRAINAGE;            * 07680
769.          C*          UDRAN: 50 PERCENT DRAINAGE;                         * 07690
770.          C*          TIMAX: MAXIMUM VALUE FOR TIME;                   * 07700
771.          C*          UEMAX: MAXIMUM VALUE FOR DRAINAGE;             * 07710
772.          C*                                                 * 07720
773.          *****                                                 07730
774.          C                                                       07740
775.          SUBROUTINE INPOLA(TDRAN,UDRAN,IA,LOGTIM)                  07750
776.          IMPLICIT REAL(J-Z)                                     07760
777.          COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10) 07770
778.          COMMON /TNUM/ INABT                                     07780
779.          COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1       07790

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780. COMMON CASE,HED,HSUBA,HSUBB,NUM,S 07800
781. COMMON /SGWET1/ SGWET(100),SGDRY(100),SGW(100),SGD(100) 07810
782. DIMENSION LOGTIM(120,10),YAPER(120,10) 07820
783. DATA IPT/20/ 07830
784. REAL INCEPT 07840
785. C 07850
786. C SGEMT : TOTAL SUBGRADE MODULUS 07860
787. C SGWET : WET DEPTH OF SUBGRADE 07870
788. C SGDRY : DRY DEPTH OF SUBGRADE 07880
789. C SGDEP : DEPTH OF SUBGRADE (TOTAL DEPTH OF BASE AND SUBGRADE IS 70IN) 07890
790. C 07900
791. IA=INDS 07910
792. DO 1000 I=1,IPT 07920
793. EXACT=1.0*I/IPT 07930
794. IX=100*I/IPT 07940
795. SGDEP=5.83333-HE 07950
796. DO 1100 I2=1,100 07960
797. IF(I2.EQ.INABT) GO TO 2222 07970
798. IF(YAREA(I2,IA).GT.EXACT) GO TO 1111 07980
799. 1100 CONTINUE 07990
800. 1111 II=I2-1 08000
801. IF(II.LE.0) GO TO 1001 08010
802. REGCOE=(XTIME(I2,IA)-XTIME(II,IA))/(YAREA(I2,IA)-YAREA(II,IA)) 08020
803. INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA) 08030
804. I100=I+100 08040
805. XTIME(I100,IA)=INCEPT+REGCOE*EXACT 08050
806. YAREA(I100,IA)=EXACT 08060
807. CALL SUBHT(XTIME(I100,IA),HSUBX) 08070
808. SGWET(IX)=(HE-HSUBX)*N1/N2 08080
809. IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP 08090
810. IF(SGWET(IX).LE.0.OR.K2.EQ.0.) SGWET(IX)=0. 08100
811. SGDRY(IX)=5.83333-HE-SGWET(IX) 08110
812. IF(IFIX(100*EXACT).EQ.IFIX(100*UDRAN)) TDRAN=XTIME(I100,IA) 08120
813. GO TO 1000 08130
814. 1001 I100=I+100 08140
815. XTIME(I100,IA)=XTIME(I2,IA)*EXACT/YAREA(I2,IA) 08150
816. YAREA(I100,IA)=EXACT 08160
817. CALL SUBHT(XTIME(I100,IA),HSUBX) 08170
818. SGWET(IX)=(HE-HSUBX)*N1/N2 08180
819. IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP 08190
820. IF(SGWET(IX).LE.0.OR.K2.EQ.0.) SGWET(IX)=0. 08200
821. SGDRY(IX)=5.83333-HE-SGWET(IX) 08210
822. 1000 CONTINUE 08220
823. 2222 IMAX=I100+1 08230
824. XTIME(IMAX,IA)=TIMAX(IA) 08240
825. YAREA(IMAX,IA)=UEMAX(IA) 08250
826. CALL SUBHT(XTIME(IMAX,IA),HSUBX) 08260
827. SGWET(IX)=(HE-HSUBX)*N1/N2 08270
828. IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP 08280
829. IF(SGWET(IX).LE.0.OR.K2.EQ.0.) SGWET(IX)=0. 08290
830. SGDRY(IX)=5.83333-HE-SGWET(IX) 08300
831. WRITE(6,2) 08310
832. 2 FORMAT(1H1,5(/),T30,'DRAINAGE%',11X,'TIME',5X,'PROBLEM NO.') 08320
833. DO 1200 I7=101,IMAX 08330
834. YAPER(I7,IA)=YAREA(I7,IA)*100. 08340
835. 1200 CONTINUE 08350
836. DO 1600 IB=1,20 08360
837. IB100=IB+100 08370
838. WRITE(6,305)YAPER(IB100,IA),XTIME(IB100,IA),IA 08380
839. 305 FORMAT(T30,F9.1,5X,E10.3,I15) 08390

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840.      1600 CONTINUE          08400
841.      RETURN               08410
842.      END                  08420
843.      C                     08430
844.      C                     08440
845.      *****                  08450
846.      C*                   * 08460
847.      C* EVALUATION OF THE DRAINAGE DESIGN FOR GRANULAR LAYERS * 08470
848.      C*                   * 08480
849.      C* 85% SATURATION ;   * 08490
850.      C*           SATISFACTORY: LESS THAN 5 HOURS             * 08500
851.      C*           MARGINAL : 5 TO 10 HOURS                      * 08510
852.      C*           UNACCEPTABLE: GREATER THAN 10 HOURS        * 08520
853.      C*                   * 08530
854.      C* PERIND: PERCENTAGE INDEX, THE PERCENTAGES OF WATER       * 08540
855.      C*           CAN BE DRAINED IN A SATURATED SAMPLE .. * 08550
856.      C* IQFINE: CATEGORY OF FINES AMOUNT (1. 0%, 2. 2.5%, 3. 5%, 4. 10%) * 08560
857.      C* ITYPFI: TYPE OF FINES (1. INERT FILLER, 2. SILT, 3. CLAY)    * 08570
858.      C* UCRIT : DEGREE OF DRAINAGE CORRESPONDING TO 85% SATURATION * 08580
859.      C* TCRIT : TIME (HOUR) CORRESPONDING TO 85% SATURATION        * 08590
860.      C* GRAVPC: PERCENTAGE OF GRAVEL IN THE SAMPLE                 * 08600
861.      C* SANDPC: PERCENTAGE OF SAND IN THE SAMPLE                   * 08610
862.      C*                   * 08620
863.      C* *****                  08630
864.      C                     08640
865.      C                     08650
866.      SUBROUTINE JUDGE(IA,INT,ITYPFI,IQFINE,GRAVPC,SANDPC)          08660
867.      COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10) 08670
868.      DIMENSION GRAVEL(3,4),SAND(3,4)                                08680
869.      REAL INCEPT          08690
870.      DATA GRAVEL/3*80.,70.,60.,40.,60.,40.,20.,40.,30.,10./        08700
871.      DATA SAND /3*65.,57.,50.,35.,50.,35.,15.,25.,18.,8./        08710
872.      READ(5,345)ITYPFI,IQFINE,GRAVPC,SANDPC                      08720
873.      345 FORMAT(2I5,2F10.0)          08730
874.      PERIND=(GRAVPC*GRAVEL(ITYPFI,IQFINE)+SANDPC*SAND(ITYPFI,IQFINE)) 08740
875.      1*0.01                08750
876.      UCRIT=15./PERIND          08760
877.      UCRPER=100.*UCRIT          08770
878.      DO 400 I2=1,INT          08780
879.      IF(YAREA(I2,IA).LT.UCRIT) GO TO 400          08790
880.      I1=I2-1                08800
881.      REGCOE=(XTIME(I2,IA)-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA)) 08810
882.      INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA)          08820
883.      TCRIT=INCEPT+REGCOE*UCRIT          08830
884.      IF(YAREA(I2,IA).GE.UCRIT) GO TO 4411          08840
885.      400 CONTINUE          08850
886.      4411 WRITE(6,415)GRAVEL(ITYPFI,IQFINE),GRAVPC,SAND(ITYPFI,IQFINE), 08860
887.      1 SANDPC,PERIND          08870
888.      415 FORMAT(5(/),T30,'***** EVALUATION OF DRAINAGE DESIGN *****', 08880
889.      1//,T30,'WATER DRAINED PERCENTAGE DUE TO GRAVEL =',F11.2, 08890
890.      2/, T30,'PERCENTAGE OF GRAVEL IN THE SAMPLE =',F11.2, 08900
891.      3/, T30,'WATER DRAINED PERCENTAGE DUE TO SAND =',F11.2, 08910
892.      4/, T30,'PERCENTAGE OF SAND IN THE SAMPLE =',F11.2, 08920
893.      5/, T30,'PERCENTAGE OF WATER WILL BE DRAINED =',F11.2,3(/)) 08930
894.      IF(UCRIT.GE.1.) GO TO 4444          08940
895.      WRITE(6,425)UCRPER,TCRIT          08950
896.      425 FORMAT( 08960
897.      1/,T30,'CRITICAL DRAINAGE DEGREE (85% SATURATION)=',F11.2, 08970
898.      2/,T30,'DRAINING TIME FOR 85% SATURATION (HOURS) =',F11.2,3(/)) 08980
899.      IF(TCRIT.GT.10.) WRITE(6,1115)          08990

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900.    1115 FORMAT(//,T30,'$$$$ THIS DRAINAGE DESIGN IS NOT ACCEPTABLE $$$$')      09000
901.          IF(TCRIT.GE.5.AND.TCRIT.LE.10.) WRITE(6,1125)                           09010
902.    1125 FORMAT(//,T30,'$$$$ THIS DRAINAGE DESIGN IS IN THE MARGINALLY ACCE     09020
903.          2PTABLE REGION $$$$')                                                 09030
904.          IF(TCRIT.LT.5.) WRITE(6,1135)                                         09040
905.    1135 FORMAT(//,T30,'$$$$ THIS DRAINAGE DESIGN IS SATISFACTORY $$$$')        09050
906.          GO TO 4455                                                       09060
907.    4444 WRITE(6,1145)                                         09070
908.    1145 FORMAT(//,T40,'!!!! THIS DRAINAGE DESIGN WILL NOT ALLOW THE SATURA     09080
909.          2TION LEVEL REACH OR LOWER THAN 85% !!!!!')                         09090
910.    4455 RETURN                                         09100
911.          END                                                       09110
912.    C                                                       09120
913.    C                                                       09130
914.    C*****                                                 09140
915.    C*                                                       * 09150
916.    C* COMPUTE THE N2 VIA KNOWN K1,K2,N1 WITH NEWTON-RAPHSON'S METHOD       * 09160
917.    C*                                                       * 09170
918.    C* EQUATION:   K*(1-N)**2/(N**3) = CONSTANT                         * 09180
919.    C*           K: PERMEABILITY;   N: POROSITY                          * 09190
920.    C*                                                       * 09200
921.    C*****                                                 09210
922.    C                                                       09220
923.          SUBROUTINE PORO2                                         09230
924.          IMPLICIT REAL(J-Z)                                     09240
925.          INTEGER N,NA,NB,NC,NJONT,NLANE                            09250
926.          COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1      09260
927.          COMMON CASE,HED,HSUBA,HSUBB,NUM,S                      09270
928.          DATA EPSI/0.1E-03/                                    09280
929.          DELK=0.10                                         09290
930.          IF(K2.LE.K1) GO TO 455                                09300
931.          N2=N1                                         09310
932.          GO TO 999                                         09320
933.    455  IF(K2.GT.0.) GO TO 555                                09330
934.          N2=0.1E-05                                         09340
935.          GO TO 999                                         09350
936.    555  AFCTR=((1.-N1)**2)*K1/(K2*(N1**3))                09360
937.          K=K2*0.1/K1                                         09370
938.          FOFK1=AFCTR*K**3-K**2+2.*K-1.                     09380
939.    204  KN=K+DELK                                         09390
940.          FOFKN=AFCTR*KN**3-KN**2+2.*KN-1.                  09400
941.          IF(FOFK1*FOFKN) 206,205,207                      09410
942.    205  CONTINUE                                         09420
943.          IF(FOFK1.EQ.0.) N2=K                               09430
944.          IF(FOFKN.EQ.0.) N2=KN                            09440
945.          RETURN                                         09450
946.    207  K=KN                                         09460
947.          FOFK1=FOFKN                                         09470
948.          GO TO 204                                         09480
949.    206  N21=KN                                         09490
950.    208  FOFN=AFCTR*N21**3-N21**2+2.*N21-1.            09500
951.          DFDN=3.*AFCTR*N21**2-2.*N21+2.                 09510
952.          N2=N21-FOFN/DFDN                                09520
953.          IF(ABS(N2-N21)-EPSI) 210,210,209              09530
954.    209  N21=N2                                         09540
955.          GO TO 208                                         09550
956.    210  FOFN2=AFCTR*N2**3-N2**2+2.*N2-1.            09560
957.          999 RETURN                                         09570
958.          END                                                       09580
959.    C                                                       09590

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960. C 09600
961. C***** 09610
962. C* * 09620
963. C* PRECIPITATION AS WELL AS DRY AND WET SEQUENCE * 09630
964. C* * 09640
965. C* GAMMA DISTRIBUTION FOR RAINFALL AMOUNT * 09650
966. C* MARKOV CHAIN MODEL FOR DRY AND WET SEQUENCE * 09660
967. C* * 09670
968. C* READ THE RAINFALL AMOUNT AS WELL AS DRY AND WET SEQUENCE DATA IN * 09680
969. C* INPUT MATERIAL PROPERTIES AND CHARACTERISTICS OF BASE AND SUBGRADE * 09690
970. C* COMPUTE THE ALPHA AND BETA OF GAMMA DISTRIBUTION * 09700
971. C* * 09710
972. C* HALFT: TIME FOR 50% DRAINAGE(HOUR) * 09720
973. C* * 09730
974. C***** 09740
975. C 09750
976. C 09760
977. SUBROUTINE RAIN(HALFT,IMAXD) 09770
978. IMPLICIT INTEGER (I-N) 09780
979. DIMENSION ITITL2(20) 09790
980. DIMENSION AMT(5,300),SUM(10),NUM(10),YDRAN(100),WPROB(50,50) 09800
981. COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE 09810
982. COMMON /DRYWET/ TLAMDA,DRYLAM,WETLAM,PWET 09820
983. COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10) 09830
984. COMMON /NOGAMA/ NUMWET,AVGAMT,TOTSUM 09840
985. C 09850
986. C READ THE RAINFALL AMOUNT DATA IN AND COUNT THE NUMBER OF WET DAYS 09860
987. C 09870
988. C AMT(1): THE RAINFALL AMOUNT DURING THE PERIOD IS CONCERNED (IN INCHES) 09880
989. C AMT(2): THE SEQUENCE OF DRY DAYS 09890
990. C AMT(3): THE SEQUENCE OF WET DAYS 09900
991. C ITYPE : TYPE OF PAVEMENT, EITHER PCC OR BCP 09910
992. C ASOIL : SOIL TYPES CLASSIFIED BY 'AASHTO' OR 'UNIFIED'. 09920
993. C BHORIZ: HORIZON (ABC OR BC). P.86,ASCE TRANS.ENGR.J.,JAN,1979 09930
994. C IBC : INDEX OF BASE MATERIALS 09940
995. C CRKJON: THE LENGTH OF CRACKS AND JOINTS(IN FEET) FROM FIELD SURVEY 09950
996. C FTLONG: THE TOTAL LENGTH SURVEYED FOR CRACKS AND JOINTS 09960
997. C YEAR : THE EVALUED PERIOD IN YEARS 09970
998. C CONST : CONSTANT 'K' FOR INTENSITY-DURATION-RECURRENCE EQUATION 09980
999. C DEFAULT = 0.3 09990
1000. C RECPOW: POWER OF RECURRENCE INTERNAL( PERIOD EVALUATED ) 10000
1001. C DEFAULT = 0.25 10010
1002. C DURPOW: POWER OF RAINFALL DURATION 10020
1003. C DEFAULT = 0.75 10030
1004. C SHAPE : THE CONSTANT DUE TO CURVE SHAPE OF RAINFALL INTENSITY VS. PERI10040
1005. C DEFAULT = 1.65 (GAUSSIAN CURVE) 10050
1006. C 10060
1007. REAL*8 ASOIL 10070
1008. INTEGER BHORIZ 10080
1009. C 10090
1010. C INPUT MATERIAL PROPERTIES OF BAE AND SUBGRADE 10100
1011. C 10110
1012. READ(5,445)IBC,IATYPE,ASOIL,BHORIZ 10120
1013. 445 FORMAT(I4,A4,A8,A4) 10130
1014. READ(5,435)CRKJON,FTLONG 10140
1015. 465 FORMAT(2F10.0) 10150
1016. READ(5,475)YEAR,CONST,RECPOW,DURPOW,SHAPE 10160
1017. 475 FORMAT(5F10.2) 10170
1018. IF(CONST.EQ.0.) CONST=0.3 10180
1019. IF(RECPOW.EQ.0.) RECPOW=0.25 10190

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1020.      IF(DURPOW.EQ.0.) DURPOW=0.75          10200
1021.      IF(SHAPE.EQ.0.) SHAPE=1.65           10210
1022.      WRITE(6,955)                         10220
1023.      955 FORMAT(1H1,T30,'***** PAVEMENT TYPES DATA AND PERIOD *****'//,1X, 10230
1024.          2T20,'PVMT TYPE ',5X,'SOIL CLASS',5X,' HORIZON',6X,' CRK.JT. FT.', 10240
1025.          35X,' SURVEYED FT',5X,' PERIOD(YEAR)',//)                      10250
1026.          WRITE(6,965) ITYPE,ASOIL,BHORIZ,CRKJON,FTLONG,YEAR                10260
1027.      965 FORMAT(T20,A10,7X,A8,11X,A4,2(5X,F13.1),5X,F13.0,//)            10270
1028.          WRITE(6,455)                         10280
1029.      455 FORMAT(T30,'*****CHARACTERISTICS OF RAINFALL INTENSITY-DURATION-RE 10290
1030.          2CURRENCE EQUATION*****',//,T30,                                10300
1031.          3'K(I-D-R EQ)','    REC. POWER','    DUR. POWER',               10310
1032.          4'  CURVE SHAPE',//)                                         10320
1033.          WRITE(6,465) CONST,RECPOW,DURPOW,SHAPE                      10330
1034.      465 FORMAT(T30,4F13.2)                         10340
1035. C
1036. C   READ IN RAINFALL DATA. ISEQ: 1,RAINFALL AMOUNT EACH RAINY DAY; 10360
1037. C                                     2,SEQUENCE OF DRY DAYS FREQUENCY 10370
1038. C                                     3,SEQUENCE OF WET DAYS FREQUENCY 10380
1039. C
1040.     READ(5,985) IRAIN                         10400
1041.     985 FORMAT(I3)                           10410
1042.     DO 77777 ITIME=1,IRAIN                  10420
1043.     READ(5,405) ITITL2                     10430
1044.     405 FORMAT(20A4)                         10440
1045.     WRITE(6,495) ITITL2                   10450
1046.     495 FORMAT(1H1,T30,20A4)                 10460
1047.     DO 500 ISEQ=1,3                         10470
1048.     NUM(ISEQ)=0                           10480
1049.     DO 100 L=1,20                          10490
1050.     INT=(L-1)*16+1                        10500
1051.     IEN=(L-1)*16+16                       10510
1052.     READ(5,415) (AMT(ISEQ,I),I=INT,IEN)  10520
1053.     415 FORMAT(16F5.0)                      10530
1054.     DO 200 I=INT,IEN                      10540
1055.     IF(AMT(ISEQ,I).EQ.0.) GO TO 500       10550
1056.     200 NUM(ISEQ)=I                         10560
1057.     100 CONTINUE                         10570
1058.     500 CONTINUE                         10580
1059.     DO 800 IJ=1,3                          10590
1060.     K=NUM(IJ)                           10600
1061.     IF(K.EQ.0) K=1                         10610
1062.     IF(IJ.EQ.1) WRITE(6,915) NUM(1)        10620
1063.     IF(IJ.EQ.2) WRITE(6,925) NUM(2)        10630
1064.     995 FORMAT(T40,16I5)                    10640
1065.     IF(IJ.EQ.3) WRITE(6,935) NUM(3)        10650
1066.     905 FORMAT(T40,16F5.2)                  10660
1067.     915 FORMAT(//,T40,'***** RAINFALL AMOUNT DATA*****',//, 10670
1068.         2 T40,'NO. OF COUNTS =',I5,//)      10680
1069.     925 FORMAT(//,T40,'***** SEQUENCE OF DRY DAYS *****',//, 10690
1070.         2 T40,'NO. OF COUNTS =',I5,//)      10700
1071.     935 FORMAT(//,T40,'***** SEQUENCE OF WET DAYS *****',//, 10710
1072.         2 T40,'NO. OF COUNTS =',I5,//)      10720
1073.         IF(IJ.NE.1) WRITE(6,995)(IFIX(AMT(IJ,I)),I=1,K) 10730
1074. C   TOTSUM: TOTAL NUMBER OF DAYS IN A PERIOD 10740
1075. C   TOTNUM: TOTAL NUMBER OF COUNTS FROM DRY AND WET DAYS' SEQUENCE 10750
1076.         IF(IJ.EQ.1) WRITE(6,905)(AMT(IJ,I),I=1,K) 10760
1077.     800 CONTINUE                         10770
1078. C
1079. C   THE AVERAGE AND VARIANCE             10790

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1080.      C          10800
1081.      DO 600 IB=1,3          10810
1082.          SUM(IB)=0.          10820
1083.          IVALUE=NUM(IB)          10830
1084.          IF(IVALEUE.EQ.0) IVALUE=1          10840
1085.              DO 300 J=1,IVALEUE          10850
1086.                  SUM(IB)=SUM(IB)+AMT(IB,J)          10860
1087.          300    CONTINUE          10870
1088.          600    CONTINUE          10880
1089.          NUMWET=NUM(1)          10890
1090.          IF(NUMWET.EQ.0) GO TO 333          10900
1091.          AVGAMT=SUM(1)/NUM(1)          10910
1092.          GO TO 444          10920
1093.          333    AVGAMT=0.          10930
1094.          444    TOTNUM=NUM(2)+NUM(3)          10940
1095.          TOTSUM=SUM(2)+SUM(3)          10950
1096.          AVGRAS=SUM(1)/TOTSUM          10960
1097.          IF(NUMWET.LE.1) GO TO 888          10970
1098.          DRYLAM=TOTNUM/SUM(2)          10980
1099.          WETLAM=TOTNUM/SUM(3)          10990
1100.          TLAMDA=DRYLAM+WETLAM          11000
1101.          PWET=DRYLAM/TLAMDA          11010
1102.          PDRY=WETLAM/TLAMDA          11020
1103.      C          11030
1104.      C    AVGAMT: AVERAGE OF RAINFALL AMOUNT PER RAINY DAY          11040
1105.      C    AVGRAS: AVERAGE OF RAINFALL AMOUNT PER DAY          11050
1106.      C    WETLAM: RECIPROCAL OF THE AVERAGE OF WET DAYS          11060
1107.      C    DRYLAM: RECIPROCAL OF THE AVERAGE OF DRY DAYS          11070
1108.      C          11080
1109.          SSAMT=0.          11090
1110.          DO 400 K=1,NUMWET          11100
1111.          400    SSAMT=SSAMT+(AMT(1,K)-AVGAMT)**2          11110
1112.          VARAMT=SSAMT/NUMWET          11120
1113.      C          11130
1114.      C    PARAMETERS OF GAMMA DISTRIBUTION          11140
1115.      C          11150
1116.          ALPHA=AVGAMT**2/VARAMT          11160
1117.          BETA=AVGAMT/VARAMT          11170
1118.      C          11180
1119.      C    THE DURATION OF RAINFALL(HOURS) CORRESPONDING TO AVERAGE RAINFALL AMOUNT          11190
1120.      C          11200
1121.          WRITE(6,945)          11210
1122.          945    FORMAT(///,T30,'***** PARAMETERS OF GAMMA DISTRIBUTION AND MARKOV          11220
1123.              2CHAIN MODEL *****')          11230
1124.          WRITE(6,435)AVGAMT,VARAMT,ALPHA,BETA          11240
1125.          2,DRYLAM,WETLAM,TLAMDA,PDRY,PWET          11250
1126.          435    FORMAT(3(/), T40,'AVERAGE RAINFALL PER WET DAY(INCHES) =',F10.3,,          11260
1127.              2           T40,'VARIANCE OF RAINFALL AMOUNT =',F10.3,,          11270
1128.              3           //,T40,'ALPHA OF GAMMA DISTRIBUTION =',F10.3,,          11280
1129.              4           T40,'BETA OF GAMMA DISTRIBUTION =',F10.3,,          11290
1130.              5           //,T40,'LAMDA OF DRY DAYS (MARKOV PROCESS) =',F10.3,,          11300
1131.              6           T40,'LAMDA OF WET DAYS (MARKOV PROCESS) =',F10.3,,          11310
1132.              7           T40,'SUM OF LAMDA OF DRY AND WET DAYS =',F10.3,,          11320
1133.              8           //,T40,'PROBABILITY OF DRY DAYS =',F10.3,,          11330
1134.              9           T40,'PROBABILITY OF WET DAYS =',F10.3)          11340
1135.          IF(TIMAX(INDS)/24.LT.1.) GO TO 888          11350
1136.          CALL KATZ(IMAXD,WPROB)          11360
1137.          CALL DRYDAY(IMAXD,YDRAN,WPROB)          11370
1138.          888    CALL FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE,ASOIL,          11380
1139.              2BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPROB,IMAXD)          11390

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1140.    77777 CONTINUE                                11400
1141.        RETURN                                 11410
1142.        END                                    11420
1143.        C                                     11430
1144.        C                                     11440
1145.        C*****                                         ***** 11450
1146.        C*                                         * 11460
1147.        C*   SIMPSON$ RULE USED TO INTEGRATE THE GAMMA DISTRIBUTION * 11470
1148.        C*                                         * 11480
1149.        C*****                                         ***** 11490
1150.        C                                     11500
1151.        C                                     11510
1152.        SUBROUTINE SIMP2(AREA2,GAMDIS,XMIN,XMAX,N,ALPHA,BETA) 11520
1153.            H=(XMAX-XMIN)/N                      11530
1154.            SUM=0.0                            11540
1155.            X=XMIN+H                         11550
1156.            DO 4 I=2,N                         11560
1157.                IF(MOD(I,2))2,2,3          11570
1158.            2        SUM=SUM+4.*GAMDIS(X,ALPHA,BETA) 11580
1159.                GO TO 4                     11590
1160.            3        SUM=SUM+2.*GAMDIS(X,ALPHA,BETA) 11600
1161.            4        X=X+H                   11610
1162.            AREA2=H/3.* (GAMDIS(XMIN,ALPHA,BETA)+SUM+GAMDIS(XMAX,ALPHA,BETA)) 11620
1163.            RETURN                           11630
1164.        END                               11640
1165.        C                                     11650
1166.        C                                     11660
1167.        C                                     11670
1168.        FUNCTION GAMDIS(X,ALPHA,BETA)      11680
1169.        C   X HAS TO BE GREATER THAN 0. IN GAMMA DISTRIBUTION 11690
1170.            IF(X.LE.0.AND.ALPHA.LE.1) GO TO 3333 11700
1171.            GAMDIS=X***(ALPHA-1.)*EXP(-X*BETA)*(BETA**ALPHA)/(GAMMA(ALPHA)) 11710
1172.            RETURN                           11720
1173.        3333    GAMDIS=10.                  11730
1174.            RETURN                           11740
1175.        END                               11750
1176.        C                                     11760
1177.        C                                     11770
1178.        C*****                                         ***** 11780
1179.        C*                                         * 11790
1180.        C*   SIMPSON'S RULE FOR INTEGRATION      * 11800
1181.        C*                                         * 11810
1182.        C*   AREA: THE AREA UNDER INTERGRATION ; * 11820
1183.        C*   DUMMYF: FUNCTIONS;                 * 11830
1184.        C*   XMIN: MINIMUM VALUE OF X ;         * 11840
1185.        C*   XMAX: MAXIMUM VALUE OF X ;         * 11850
1186.        C*   N: NUMBER OF SECTORS;             * 11860
1187.        C*                                         * 11870
1188.        C*****                                         ***** 11880
1189.        C                                     11890
1190.        SUBROUTINE SIMPSN(AREA,DUMMYF,XMIN,XMAX,N) 11900
1191.            INTEGER N,NA,NB,NC,NJONT,NLANE 11910
1192.            REAL LA,K1,K2,N1,N2 11920
1193.            COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1 11930
1194.            COMMON CASE,HED,HSUBA,HSUBB,NUM,S 11940
1195.            H=(XMAX-XMIN)/N 11950
1196.            SUM=0.0 11960
1197.            X=XMIN+H 11970
1198.            DO 4 I=2,N 11980
1199.                IF(MOD(I,2))2,2,3 11990

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1200.      2 SUM=SUM+4.*DUMMYF(X)          12000
1201.      GO TO 4                      12010
1202.      3 SUM=SUM+2.*DUMMYF(X)          12020
1203.      4 X=X+H                      12030
1204.      AREA=H/3.* (DUMMYF(XMIN)+SUM+DUMMYF(XMAX)) 12040
1205.      RETURN                         12050
1206.      END                           12060
1207.      C                            12070
1208.      C                            12080
1209.      *****                         12090
1210.      C*
1211.      C*   THE HEIGHT OF WATER LEVEL DUE TO SUBGRADE DRAINAGE ONLY    *
1212.      C*                                         * 12110
1213.      C*   TAREA: TIME;             * 12120
1214.      C*   HSUB: HEIGHT OF WATER LEVEL WHICH IS A FUNCTION OF TIME;    * 12130
1215.      C*                                         * 12140
1216.      C*****                         12150
1217.      C                            12160
1218.      SUBROUTINE SUBHT(TAREA,HSUB)        12170
1219.      IMPLICIT REAL(J-Z)           12180
1220.      INTEGER N,NA,NB,NC,NJONT,NLANE 12190
1221.      COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1 12200
1222.      COMMON CASE,HED,HSUBA,HSUBB,NUM,S 12210
1223.      AA=(N1*K2/K1)-(N1**2/N2)        12220
1224.      BB=K2*(1.-N1/N2)*TAREA-HE*(N1*K2/K1-2.*N1**2/N2) 12230
1225.      CC=K2*N1*HE*TAREA/N2-(N1*HE)**2/N2 12240
1226.      SQB=BB**2-4.*AA*CC            12250
1227.      IF(SQB.LE.0.) SQB=0.          12260
1228.      HSUB=(SQRT(SQB)-BE)/(2.*AA) 12270
1229.      RETURN                         12280
1230.      END                           12290
                                12300

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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 |
|--------|--------|--------|----------|---------|---------|---------|
| 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 |
| 0.5000E 01 | 0.5000E 00 | 0.4889E 00 | 0.1452E 00 |
| 0.7500E 01 | 0.5000E 00 | 0.4833E 00 | 0.3108E 00 |
| 0.1000E 02 | 0.5000E 00 | 0.4778E 00 | 0.5260E 00 |
| 0.1250E 02 | 0.5000E 00 | 0.4722E 00 | 0.7839E 00 |
| 0.1500E 02 | 0.5000E 00 | 0.4667E 00 | 0.1079E 01 |
| 0.1750E 02 | 0.5000E 00 | 0.4611E 00 | 0.1407E 01 |
| 0.2000E 02 | 0.5000E 00 | 0.4556E 00 | 0.1764E 01 |
| 0.2250E 02 | 0.5000E 00 | 0.4500E 00 | 0.2146E 01 |
| 0.2500E 02 | 0.5000E 00 | 0.4444E 00 | 0.2552E 01 |
| 0.2750E 02 | 0.5000E 00 | 0.4389E 00 | 0.2978E 01 |
| 0.3000E 02 | 0.5000E 00 | 0.4333E 00 | 0.3424E 01 |
| 0.3250E 02 | 0.5000E 00 | 0.4278E 00 | 0.3887E 01 |
| 0.3500E 02 | 0.5000E 00 | 0.4222E 00 | 0.4365E 01 |
| 0.3750E 02 | 0.5000E 00 | 0.4167E 00 | 0.4858E 01 |
| 0.4000E 02 | 0.5000E 00 | 0.4111E 00 | 0.5365E 01 |
| 0.4250E 02 | 0.5000E 00 | 0.4056E 00 | 0.5884E 01 |
| 0.4500E 02 | 0.5000E 00 | 0.4000E 00 | 0.6414E 01 |
| 0.4750E 02 | 0.5000E 00 | 0.3944E 00 | 0.6955E 01 |
| 0.5000E 02 | 0.5000E 00 | 0.3889E 00 | 0.7505E 01 |
| 0.5250E 02 | 0.5000E 00 | 0.3833E 00 | 0.8065E 01 |
| 0.5500E 02 | 0.5000E 00 | 0.3778E 00 | 0.8634E 01 |
| 0.5750E 02 | 0.5000E 00 | 0.3722E 00 | 0.9211E 01 |
| 0.6000E 02 | 0.5000E 00 | 0.3667E 00 | 0.9796E 01 |
| 0.6250E 02 | 0.5000E 00 | 0.3611E 00 | 0.1039E 02 |
| 0.6500E 02 | 0.5000E 00 | 0.3556E 00 | 0.1099E 02 |
| 0.6750E 02 | 0.5000E 00 | 0.3500E 00 | 0.1159E 02 |
| 0.7000E 02 | 0.5000E 00 | 0.3444E 00 | 0.1220E 02 |
| 0.7250E 02 | 0.5000E 00 | 0.3389E 00 | 0.1282E 02 |
| 0.7500E 02 | 0.5000E 00 | 0.3333E 00 | 0.1344E 02 |

| 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 *****

155

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 PROBABILITY 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

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1.      C          00010
2.      C***** 00020
3.      C          * 00030
4.      C  WATER INFILTRATION AND EVAPORATION OF A LOW PERMEABLE BASE COURSE * 00040
5.      C          * 00050
6.      C          TEXAS TRANSPORTATION INSTITUTE * 00060
7.      C          * 00070
8.      C          AUGUST 1983 * 00080
9.      C          * 00090
10.     C***** 00100
11.     DIMENSION ASUBN(20),USOIL(50,50),SIGMA(20),ZROOT(20) 00110
12.     DIMENSION EVWT(1000),SERIES(20) 00120
13.     CALL LOWPER(DEPTH,INFILT) 00130
14.     CALL EVAPOR(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU) 00140
15.     CALL EVWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU) 00150
16.     WRITE(6,115) 00160
17.     115 FORMAT(1H1) 00170
18.     STOP 00180
19.     END 00190
20.     C 00200
21.     C 00210
22.     C***** 00220
23.     C          * 00230
24.     C  EVAPORATION OF WATER FROM SOIL WITH P. MITCHELL'S SOLUTION * 00240
25.     C          * 00250
26.     C***** 00260
27.     C 00270
28.     C  THIS SUBPROGRAM IS TO COMPARE THE SUCTION LEVELS OF DIFFERENT DEPTH 00280
29.     C  AT CERTAIN TIME IN ORDER TO CHECK WITH MITCHELL'S SOLUTION 00290
30.     SUBROUTINE EVAPOR(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU) 00300
31.     DIMENSION ASUBN(20),USOIL(50,50),SIGMA(20),ZROOT(20) 00310
32.     C 00320
33.     C  UATM : SUCTION OF ATMOSPHERE IN PF (LOG H) 00330
34.     C  UNOT : INITIAL SUCTION STATE OF SOIL IN PF 00340
35.     C  DIFC : DIFFUSION COEFFICIENT OF A SOIL (CM**2/SEC) 00350
36.     C  DEPTH : WATER DEPTH IN SOIL (CM) 00360
37.     C  YVERT : VERTICAL DISTANCE FROM SOIL BOTTOM (CM) 00370
38.     C  EVTIME: ELAPSED TIME FOR EVAPORATION (SEC) 00380
39.     C  HRTIME: ELAPSED TIME FOR EVAPORATION (HOUR) 00390
40.     C  DYTIME: ELAPSED TIME FOR EVAPORATION (DAYS) 00400
41.     C  ASUBN : COEFFICIENT OF FOURIER SERIES 00410
42.     C  SIGMA : EVERY SINGLE TERM OF THE FOURIER SERIES 00420
43.     C  TSIGMA: TOTAL SUM FOR TEN TERMS OF FOURIER SERIES 00430
44.     C  USOIL : SOIL SUCTION IN DIFFERENT DEPTH AND TIME (I2:DEPTH,I1:TIME) 00440
45.     C  ZROOT : ROOTS OF COTAN(Z)=Z/(DEPTH*EVAPC) 00450
46.     C  EVAPC : EVAPORATION COEFFICIENT IN CM/SEC 00460
47.     C  DQDU : THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF) 00470
48.     C 00480
49.     READ(5,305) UATM,UNOT,DIFC,DQDU,EVAPC 00490
50.     305 FORMAT(5E10.3) 00500
51.     WRITE(6,405)UATM,UNOT,DIFC,DQDU,EVAPC,DEPTH 00510
52.     405 FORMAT(1H1,///,T30,'***** EVAPORATION OF WATER FROM SOIL ****') 00520
53.     2*****', 00530
54.     3           //,T15,'SUCTION OF ATMOSPHERE (PF)      =',E10.3, 00540
55.     4           //,T15,'INITIAL SUCTION OF SOIL (PF)      =',E10.3, 00550
56.     5           //,T15,'DIFFUSION COEFFICIENT (CM**2/SEC) =',E10.3, 00560
57.     6           //,T15,'SLOPE OF WATER CONTENT/ SUCTION =',E10.3, 00570
58.     7           //,T15,'EVAPORATION COEFFICIENT (CM/SEC) =',E10.3, 00580
59.     8           //,T15,'DEPTH OF WATER PENETRATION (CM)   =',E10.3, 00590

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60.      CALL EVROOT(ZROOT,DEPTH,EVAPC)          00600
61.      DO 3000 I=1,10                         00610
62.      ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/ 00620
63.          (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I))) 00630
64. 3000      CONTINUE                           00640
65.      WRITE(6,105)                           00650
66. 105  FORMAT(///,T30,'***** SUCTION DISTRIBUTION IN SOIL DUE TO EVAP' 00660
67.      2ORATION *****',3(/),T40,' TIME (DAYS)', 00670
68.      3T60,'SOIL DEPTH (CM)', T80,'SUCTION (PF)',3(/)) 00680
69.      DO 3300 II=1,5                         00690
70.      DYTME=II*1.                           00700
71.      EVTME=DYTME*3600.*24.                  00710
72.      DO 3200 I2=1,10                         00720
73.      TSIGMA=0.                            00730
74.      YVERT=DEPTH/10.*I2                     00740
75.      DO 3100 I=1,10                         00750
76.      POWER=ZROOT(I)**2*EVTME*DIFC/(DEPTH**2) 00760
77.      IF(ABS(POWER).GE.100.) GO TO 3333       00770
78.      SIGMA(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTME*DIFC/ 00780
79.          (DEPTH**2))*COS(ZROOT(I)*YVERT/DEPTH) 00790
80.      TSIGMA=TSIGMA+SIGMA(I)                 00800
81. 3100      CONTINUE                           00810
82. 3333      USOIL(I2,II)=UATM+TSIGMA        00820
83.      WRITE(6,205) DYTME,YVERT,USOIL(I2,II)    00830
84. 205  FORMAT(2(/),T40,F15.3,T60,F15.3,T80,E12.5) 00840
85. 3200      CONTINUE                           00850
86. 3300      CONTINUE                           00860
87.      RETURN                                00870
88.      END                                    00880
89. C                                         00890
90. C                                         00900
91. C*****                                         00910
92. C                                         * 00920
93. C      PERIODIC ROOTS FOR FOURIER SERIES OF WATER EVAPORATION      * 00930
94. C      FROM SOIL MODEL WITH P. MITCHELL'S SOLUTION                   * 00940
95. C                                         * 00950
96. C*****                                         00960
97. C                                         00970
98. C                                         00980
99.      SUBROUTINE EVROOT(ZROOT,DEPTH,EVAPC)          00990
100. C
101. C      BISECTION METHOD TO SOLVE FOR ROOTS OF 'DEPTH*EVAPC*COT(Z)-Z=0' 01010
102. C      DEPTH: LENGTH OF SOIL COLUMN IN CENTIMETER                      01020
103. C      EVAPC: EVAPORATION COEFFICIENT IN CM/SEC                        01030
104. C
105.      DIMENSION ZROOT(20)                                     01050
106.      DATA EPSI/0.1E-05/                                 01060
107.      DO 1000 I=1,10                                01070
108.      AMPLIT=EVAPC*DEPTH                           01080
109. C
110. C      INPUT THE INITIAL VALUES ON BOTH SIDES (XL & XR)           01100
111. C
112.      XL=3.1416*(I-1)+0.1                         01120
113.      XR=3.14*I                                     01130
114.      DO 100 IK=1,100                             01140
115.      XM=(XL+XR)/2.                               01150
116.      FOFXL=AMPLIT*COTAN(XL)-XL                01160
117.      FOFXM=AMPLIT*COTAN(XM)-XM                01170
118.      IF(FOFXM*FOFXL) 20,30,40                  01180
119.      20  XR=XM                                  01190

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120.      GO TO 50                                         01200
121.      30  IF(FOFXM.EQ.0.) ZROOT(I)=XM                01210
122.          IF(FOFXL.EQ.0.) ZROOT(I)=XL                01220
123.          GO TO 2222                                 01230
124.          40  XL=XM                                01240
125.          50  IF(ABS(XL-XR)-EPSI) 210,210,100        01250
126.          100 CONTINUE                            01260
127.          210 ZROOT(I)=XM                           01270
128.          2222 FZROOT=AMPLIT*COTAN(ZROOT(I))-ZROOT(I) 01280
129.          1000 CONTINUE                            01290
130.          RETURN                                 01300
131.          END                                    01310
132.          C                                     01320
133.          C                                     01330
134.          C*****                                         01340
135.          C                                     * 01350
136.          C  WATER AMOUNT EVAPORATED FROM BARE SOIL   * 01360
137.          C                                     * 01370
138.          C*****                                         01380
139.          C                                     01390
140.          C                                     01400
141.          SUBROUTINE EVWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU) 01410
142.          DIMENSION ASUBN(20),EVWT(1000),SERIES(20),ZROOT(20) 01420
143.          C  COMPUTATION OF AMOUNT OF WATER EVAPORATED FROM SOIL 01430
144.          C  EVWT : WATER AMOUNT EVAPORATED FROM SOIL IN CM       01440
145.          C  SERIES: SINGLE TERM FOR THE FOURIES SERIES           01450
146.          C  TSERIE: SUM OF THE SERIES WHICH IS INTEGRATED FROM SUCTION AT 01460
147.          C  SPECIFIC TIME                               01470
148.          C  DQDU : THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF) 01480
149.          C                                     01490
150.          WRITE(6,405)                                01500
151.          405 FORMAT(1H1,2(/),T30,'***** WATER AMOUNT EVAPORATED FROM SOIL 01510
152.          2 *****',3(/),T33,'EVAPORATION TIME(HOUR)',T60,'EVAPORATION AM 01520
153.          3OUNT (CM)',3(/))                         01530
154.          DO 4100 IK=1,720                          01540
155.          TSERIE=0.                                01550
156.          HRTIME=IK*1.                            01560
157.          EVTIME=HRTIME*3600.                      01570
158.          DO 4000 I=1,10                          01580
159.          POWER=ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2) 01590
160.          IF(ABS(POWER).GE.100.) GO TO 4411        01600
161.          SERIES(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2)) 01610
162.          2          *SIN(ZROOT(I))/ZROOT(I)        01620
163.          TSERIE=TSERIE+SERIES(I)                  01630
164.          4000 CONTINUE                            01640
165.          4411 EVWT(IK)=(UATM-UNOT+TSERIE)*DEPTH*DQDU 01650
166.          C                                     01660
167.          C  OUTPUT THE RESULTS EVERY 2 HOURS        01670
168.          C                                     01680
169.          I2=IK/2*2                                01690
170.          IF(I2.NE.IK.AND.EVWT(IK).LT.DEPTH) GO TO 4100 01700
171.          WRITE(6,415) HRTIME,EVWT(IK)             01710
172.          415 FORMAT(2(/),T45,F10.2,T60,F23.4)    01720
173.          IF(EVWT(IK).GE.DEPTH) GO TO 4444        01730
174.          4100 CONTINUE                            01740
175.          4444 RETURN                                01750
176.          END                                    01760
177.          C                                     01770
178.          C                                     01780
179.          C*****                                         01790

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240.    111  WRITE(6,75) TIME(I),XOFT(I),YOFT(I),DPWA(I)          02400
241.      75  FORMAT(4(10X,E15.3))                           02410
242.      100 CONTINUE                                         02420
243. C
244. C   USE INTRAPOLATION TO ENUMERATE THE FINAL DEPTH WHERE WATER WILL REACH 02440
245. C
246.    222  DEPTH=YOFT(I)-(YOFT(I)-YOFT(IM1))/(DPWA(I)-DPWA(IM1))*DPWA(I) 02460
247.          YOFT(I)=DEPTH                                02470
248.          DELY2=DEPTH-YOFT(IM1)                         02480
249.          DT=PORO1*DEPTH*DELY2/(VPERM*(DEPTH+HTCP+TL)) 02490
250.          TIME(I)=TIME(IM1)+DT                          02500
251.          INFILT=TIME(I)                            02510
252.          XOFT(I)=SQRT(2.*HPERM*TIME(I)*(TL+HTCP)/PORO1) 02520
253.          DENT=(HPERM*DEPTH*(TL+HTCP)/XOFT(I)+        02530
254.          2     VPERM*XOFT(I)*(DEPTH+TL+HTCP)/DEPTH)*1.5708/PORO1 02540
255.          DL(I)=(DENT*DT)/WC                         02550
256.          DPWA(I)=DPWA(IM1)-DL(I)                   02560
257.          WRITE(6,75) TIME(I),XOFT(I),DEPTH,DPWA(I) 02570
258.          RETURN                                     02580
259.          END                                       02590

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***** WATER DISTRIBUTION OF LOW PERMEABILITY 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 (< 10)

cc 6-8 INEED Analytical procedures required

0: Drainage analysis only

1: Drainage analysis and drainage design evaluation

2: System analysis of rainfall infiltration and drainage

cc 11-80 ITITLE Problem title

2. Characteristics of base and subgrade (7F10.0)

cc 1-10 LA One side width of base (feet)

cc 11-20 HE Depth of base (feet)

cc 21-30 TAPER Slope ratio or value of tan of base (%) e.g., $\tan \alpha = 0.016$, input 1.6

cc 31-40 K1 Permeability of Base (Feet/Hour)

cc 41-50 K2 Permeability of Subgrade (Feet/Hour)

cc 51-60 N1 Porosity of Base

cc 61-70 N2 Porosity of Subgrade*

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

$$\frac{K_1(1-N_1)^2}{(N_1)^3} = \frac{K_2(1-N_2)^2}{(N_2)^3},$$

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 3)

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 17-20 BHORIZ Horizon of subgrade (ABC or BC)

5. Area of cracks and joints and surveyed field length (2F10.0)

cc 1-10 CRKJON* linear length of cracks and joints of one-side pavement (feet)

cc 11-20 FTLONG Surveyed field length (feet)

*If cracks and joints are not available input 0.0 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 (5Fl0.0) (see Appendix A-2)

| | |
|-----------------|---|
| cc 1-10 YEAR | Evaluated period (years) |
| cc 11-20 CONST | Constant K (default=0.3) |
| cc 21-30 RECPOW | Power of recurrence interval (default=0.25) |
| cc 31-40 DURPOW | Power of rainfall duration (default=0.15) |
| cc 41-50 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 (20A4)

CC 1 -80 ITITL2 Title for the source of rainfall data.

9. Rainfall amount data (16/5.0)*

AMT (ISEQ,1) Rainfall amount of each rainy day (>0.01 inches)

10. Sequence of the number of dry days (16 F5.0)*

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

11. Sequence of the number of wet days (16 F5.0)*

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 5.0, 4.0, 2.0, ...and in

AMT (ISEQ, 3) input 1.0, 2.0, ...

(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 POROL | 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) |