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

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August 1983
ABSTRACT

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

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

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

A gamma distribution is employed for describing the probability density function for the quantity of rain that
falls and a Markov chain model is applied for estimating the probabilities of wet and dry days.

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

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

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

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

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

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

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented within. The contents do not necessarily reflect the official views of policies of the Federal Highway Administration. This report does not constitute a standard, a specification or regulation.
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Pavement engineers and road builders have been aware for a long time that excess water remaining in base courses and subgrades will accelerate the deterioration and destruction of pavements. As the water content of base courses and subgrades increases, there is a significant reduction in load bearing capacity and modulus and an acceleration of unsatisfactory pavement performance, as manifested in premature rutting, cracking, faulting, pumping, increasing roughness, disintegration of stabilized materials, and a relatively rapid decrease in the level of serviceability. In estimating the long-term performance of pavements and in designing pavements to endure the effects of the local climate, it is essential to be able to estimate the effect of rainfall on the modulus of the base course and subgrade. This paper describes a comprehensive means of making such estimates and gives the results of example calculations.

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

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

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

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

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

\[
t_{\text{wet}} = \left(\frac{\gamma_{\text{season}}}{i_{\text{avg}}}\right)[1-\exp(-9c)]t_{\text{drain}}
\]

\[
c = \frac{1}{5280}\left\{\left(\frac{L_{c}+A_{c}}{W_{\text{lane}}}\right)+\left[(SH \times W_{\text{wet}})/2W_{\text{lane}}\right]n_{\text{lane}}\right\}+(J \times W_{\text{wet}})
\]

\[
F_{\text{red}} = \left(\frac{t_{\text{season}}-0.5t_{\text{wet}}}{t_{\text{season}}}\right)
\]

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

\( \gamma_{\text{season}} \) = seasonal rainfall in inches input by the user;

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

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

\( t_{\text{drain}} \) = 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;

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

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

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

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

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

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

where $n = \text{effective porosity of the base course,}$

$L = \text{the width of the base course,}$

$K = \text{the permeability of the base course,}$

$H = \text{the thickness of the base course, assumed to be 1 foot, and}$

$S' = \text{an approximate slope factor, assuming a cross slope of 1/2 inch per foot (0.015 ft/ft).}$
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 \( t_{\text{drain}} \). These three factors are multiplied together in that equation and give the total amount of time \( t_{\text{wet}} \) 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, \( t_{\text{wet}} \), is linearly related to the time required to drain 80% of the water from the sublayer.

3. The drainage analysis is approximately based on Casagrande and Shannon's model (1). (See Chapter 4).
4. Every rainy day has the same effect on a base course.

5. Dry days are subsequent to wet days which are equally spaced in time.

6. The degree of 80% drainage is a critical point for the elastic moduli of the base courses. Before 80% of drainage is completed, the moduli are reduced to 50%. After 80% of the water has drained out of the base course, there is no effect on the elasticity of the base course.

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

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

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

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

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

1. The quantity of rain that falls in a given rainfall. The total quantity in each rainfall varies from one rainfall to the next but historical records show that the quantity follows a probability density function.

2. The intensity and duration of each rainfall.

3. The random occurrence of sequences of wet and dry days.

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

2.1 PROBABILITY MODEL OF QUANTITY OF RAINFALL

Applications of new techniques such as stochastic processes, time series analysis, probabilistic methods, systems engineering, and decision analysis, have been propounded and developed as mathematical and statistical methods in hydrology and water resources engineering through the past few decades.
Many climatologists and statisticians have been engaged in the systematic accumulation of various climatic data and weather records for a long period and analytical distribution models which fit the observed distributions well were proposed.

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

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

2.2 MODELS OF INTENSITY AND DURATION OF RAINFALL

Hydraulic engineers are concerned mainly with the analysis of annual rainfall and runoff records for trends and cycles. Most records of rainfall and runoff can be generalized with fair success as 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

\[ i = \frac{c}{t_R + b} \]  \hspace{1cm} (2-1)

and

\[ i = \frac{kt_p^x}{t_R^n} \]  \hspace{1cm} (2-2)
where  \( t_R \) = the effective rainfall duration in minutes,
\( t_p \) = the recurrence interval in years,
\( i \) = the maximum rainfall intensity in inches per hour during the effective rainfall duration, and
\( c, b, k, x, n \) = functions of the locality, for example, it was found that in the eastern United States, \( n \) averaged about 0.75 and that \( x \) and \( k \) were about 0.25 and 0.30, respectively (9,11).

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

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

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

\[
t_R = \left( \frac{1.65R}{kt_{p}^{x}} \right)^{\frac{1}{1-n}}
\]  

(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)

<table>
<thead>
<tr>
<th>N</th>
<th>k</th>
<th>$W_0(k;5)$</th>
<th>$W_1(k;5)$</th>
<th>$W(k;5)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>0.290</td>
<td>0.199</td>
<td>0.264</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.305</td>
<td>0.290</td>
<td>0.301</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0.228</td>
<td>0.257</td>
<td>0.236</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0.121</td>
<td>0.161</td>
<td>0.133</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>0.045</td>
<td>0.072</td>
<td>0.053</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.010</td>
<td>0.021</td>
<td>0.013</td>
</tr>
</tbody>
</table>

$P_0 = 0.71$, $P_00 = 0.78$, $P_{01} = 0.22$, $P_{10} = 0.54$, $P_{11} = 0.46$

- $N$ = Number of consecutive days
- $k$ = Number of wet days
- $W_0$ = Wet probabilities when zeroth day is dry
- $W_1$ = Wet probabilities when zeroth day is wet
- $W$ = Probability of having $k$ wet days in 5 consecutive days
- $P_{ij}$ = Transitional Probabilities from Markov Chain Model
- $P_0$ = Initial wet probability
which a pavement can drain out all of the excess water. These results are used for further analysis, as described subsequently.
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 $0.1 \text{ ft}^3$ 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 cm³/hr/cm of crack (0.11 ft³/hr/ft or 2.64 ft³/day/ft), and for cracks and joints in portland cement concrete pavements, 28 cm³/hr/cm of crack or joint (0.03 ft³/hr/ft or 0.72 ft³/day/ft).

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

3.2 FIELD OBSERVATIONS

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

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

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

\[ PO = 0.48PV + 0.32 \]  

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 Evaporation (EV) from Cracks/Joints

4. Evaporation from Bases

5. Rain Falls Before Base is dry

6. Repeat Stage 3

FIGURE 2. Rainfall Infiltration and Evaporation through Cracks and Joints in a Low Permeability Base
The wetting front of water in the horizontal direction and the vertical direction are (Appendix D-1):

\[
x_0 = w \frac{2d \lambda}{\pi} \frac{k_h}{k_v}, \text{ and}
\]

\[
y_0 = w \frac{2d \lambda}{\pi} \frac{k_v}{k_h}
\]

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,

\( k_h \) = the horizontal coefficient of permeability,

\( k_v \) = the vertical coefficient of permeability,

\( w \) = the width of cracks or joints, and

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

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

\[
\frac{\partial^2 u}{\partial y^2} = \frac{1}{k} \frac{\partial u}{\partial t} \tag{3-5}
\]

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 AND SHANNON'S METHOD

The subject of base course drainage has received considerable attention over the last three decades. Casagrande and Shannon (1) made field observations on several airfields in the United States to determine the environmental conditions under which base courses may become saturated. They performed a simplified theoretical analysis of the base course drainage. They assumed symmetry along the axis of the pavement and the equations governing drainage for one half of the cross section of the base course layer ABCD (See Figure 4) were developed. In their analysis, the drainage process was divided into two parts. In the first part shown in Figure 4, the free surface gradually changes from position CD to CA due to free drainage through the open edge CD of the pavement. Darcy's Law and the continuity equation were satisfied to establish a relation among time, $t$ and $x(t)$ in terms of $H$, $L$, $k_1$, and $n_1$ as illustrated in Figure 4. In the
FIGURE 3. CROSS SECTION OF A PAVEMENT
FIGURE 4. CASAGRANDE-SHANNON MODEL FOR BASE COURSE DRAINAGE
second part shown in Figure 4, the free surface rotates from position CA to CB due to the loss of water through the face CD. The subgrade is assumed to be impervious through the entire flow calculation. In this part, Casagrande and Shannon (1) established a relation among \( t \) and \( h(t) \) in terms of other parameters mentioned previously. Further details of their development and the drainage equations are presented in the following section of this paper. The theoretical results were compared with field observations by Casagrande and Shannon (1) and the deviations between theory and field results are primarily due to the assumptions that the phreatic surface is a straight line and the subgrade is impervious. Later Barber and Sawyer (22) presented Casagrande and Shannon's (1) equations in the form of a dimensionless chart shown in Figure 5. Most recently Cedergren (2) and Moulton (23) have modified the original definition of the slope factor, \( S \), as the reciprocal of the one shown in Figure 5 and have presented similar drainage charts in their work on highway subdrainage design.

Drainage of a sloping layer of base course involves unsteady flow with a phreatic surface. The assumptions by Casagrande and Shannon (1) lead to the simple model shown in Figure 4. In this model, the centerline of the base course, AB, and the bottom of the base course, BC, are considered as impervious boundaries. Free discharge is
SLOPE FACTOR, $S = \frac{H}{L \tan \alpha}$

TIME FACTOR, $T = \frac{tk_1 H}{n_1 L^2}$

DEGREE OF DRAINAGE, $U$

$= \frac{DRAINED \ AREAL}{TOTAL \ AREA}$

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

<table>
<thead>
<tr>
<th>Stage</th>
<th>$0 \leq U \leq 50%$</th>
<th>$50% \leq U &lt; 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>$T = 2U^2$</td>
<td>$T = \frac{U}{2-2U}$</td>
</tr>
</tbody>
</table>

(B) Sloping Bases

<table>
<thead>
<tr>
<th>Stage</th>
<th>$0 \leq U \leq 50%$</th>
<th>$50% \leq U &lt; 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>$T = 2US - S^2 \ln \left(\frac{S+2U}{S}\right)$</td>
<td>$T = S + S \ln \left(\frac{(2S-2US+1)}{(2-2U)(S+1)}\right) - S^2 \ln\left(\frac{S+1}{S}\right)$</td>
</tr>
</tbody>
</table>

in which

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

Slope Factor, $S = \frac{H}{Ltana}$

Time Factor, $T = \frac{Tk_1H}{n_1L^2}$
where \( H \) = thickness of base course,
\( L \) = half width of the pavement,
\( \alpha \) = 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

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\frac{0}{3} \leq U \leq \frac{1}{3}$</th>
<th>$T = 3U^2$</th>
<th>(4-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{1}{3} \leq U &lt; 1$</td>
<td>$T = \frac{8}{9} \left( \frac{1}{1-U} \right)^{-1}$</td>
<td>(4-6)</td>
</tr>
</tbody>
</table>

(B) Sloping Bases

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\frac{0}{3} \leq U \leq \frac{1}{3}$</th>
<th>$T = \frac{3}{2}SU - \frac{3}{8}S^2 \ln\left[ \frac{S+4U}{S} \right]$</th>
<th>(4-7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{1}{3} \leq U &lt; 1$</td>
<td>$T = \frac{S}{2} \frac{3}{8} S^2 \ln\left[ \frac{3S+4}{3S} \right] + S \ln\left[ \frac{9S-9SU+8}{3(1-U)(3S+4)} \right]$</td>
<td>(4-8)</td>
</tr>
</tbody>
</table>
FIGURE 6. TTI MODEL FOR BASE COURSE DRAINAGE WITH AN IMPERMEABLE SUBGRADE
The results of these drainage equations are presented in the form of a dimensionless drainage chart in Figure 7. Also, the calculated results from the new model are compared with field data reported by Casagrande and Shannon (1) on three of their five pavement test sections in Figures 8 to 10. In the Texas Transportation Institute (TTI) model drainage proceeds slower than in the Casagrande-Shannon model, and has roughly the same shape.

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

4.3 ANALYSIS OF SUBGRADE DRAINAGE

In order to study the influence of subgrade drainage on base course drainage, two models were developed. In these models the phreatic surfaces in the base course were assumed to be linear and parabolic. The two distinct stages of drainage in the first permeable subgrade model are shown in Figure 11. In this model, the properties of the subgrade are defined by the coefficient of permeability \( k_2 \), and porosity, \( n_2 \). An advancing wetting front, \( FC \), was assumed at an unknown depth of \( y_0(t) \) as shown in Figure 12. Similar to the Casagrande-Shannon model, the drainage problem begins with a saturated base-subgrade composite system and the faces EC and DC are opened instantaneously,
FIGURE 7. TTI DRAINAGE CHART WITH AN IMPERMEABLE SUBGRADE

SLOPE FACTOR, \( S = \frac{H}{L \tan \alpha} \)

TIME FACTOR, \( T = \frac{tkH}{n_1L^2} \)

DEGREE OF DRAINAGE, \( U = \frac{\text{DRAINED AREA}}{\text{TOTAL AREA}} \)
FIGURE 8. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE
FIGURE 9. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE
FIGURE 10. COMPARISON OF RESULTS FOR AN IMPERMEABLE SUBGRADE
STAGE 1

STAGE 2

FIGURE 11. PERMEABLE SUBGRADE WITH CASAGRANDE-SHANNON DRAINAGE MODEL.
FIGURE 12. Definition Sketch For Subgrade Drainage Model
allowing free drainage. In order to keep the model simple, a one-dimensional flow into the subgrade is assumed in accordance with Polubarinova-Kochina (4). From this formulation the velocity of drainage, \( v \), into the subgrade is given by (see Appendix C-1):

\[
v = \frac{y_0(t) + h(t) - H}{\frac{h(t)}{k_1} - \frac{(y_0(t) - H)}{k_2}}
\]  

(4-9)

\[y_0(t) = H + \frac{n_1}{n_2} (H - h(t))\]  

(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, \( k_1 = 2.4 \) m/day (7.8 ft/day), and the porosity, \( n_1 = 0.04 \). It is required to
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.
\[ k_1 = 0.0024 \text{ m/day (0.0078 ft/day)} \]
\[ K = \frac{k_2}{k_1} = 0.001 \]
\[ t = 5 \text{ days} \]

b) Subgrade material is a glacial till.
\[ k_1 = 0.0048 \text{ m/day (0.0156 ft/day)} \]
\[ K = 0.002 \]
\[ t = 2.5 \text{ days} \]

c) Subgrade material is a silty sand.
\[ k_1 = 0.24 \text{ m/day (0.78 ft/day)} \]
\[ K = 0.1 \]
\[ t = 84 \text{ minutes} \]

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.
L = 23 m \quad k_1 = 2.4 \text{ m/day} \\
H = 0.8 m \quad n_1 = 0.04 \\
\tan \alpha = 0.01 \\
K = \frac{k_2}{k_1} \\

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)

<table>
<thead>
<tr>
<th>AMOUNT OF FINES</th>
<th>&lt;2.5% FINES</th>
<th>5% FINES</th>
<th>10% FINES</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE OF FINES</td>
<td>FILLER SILT CLAY</td>
<td>FILLER SILT CLAY</td>
<td>FILLER SILT CLAY</td>
</tr>
<tr>
<td>GRAVEL</td>
<td>70 60 40</td>
<td>60 40 20</td>
<td>40 30 10</td>
</tr>
<tr>
<td>SAND</td>
<td>57 50 35</td>
<td>50 35 15</td>
<td>25 18 8</td>
</tr>
</tbody>
</table>

* 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

$$S_a = 1 - P.D. \times U$$

(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)
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


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

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

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

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)

\[ E_s = \frac{E_1 d_1^3 + E_2 d_2^3}{d_3^3} \]  

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

1. The Gamma distribution (7) for the rainfall amount distribution.

2. Dempsey and Robnett's (20) regression equations, as well as Ridgeway's (14) laboratory results from which an estimation of the amount of rainfall which, in turn, permits an estimate of the duration of the rainfall, for infiltration analysis.

3. The TTI drainage model (25), the parabolic phreatic surface with subgrade drainage, as developed for base course and subgrade drainage analysis.

4. Markov Chain Model (7,12) and Katz's recurrence equations (13) for the calculation of dry and wet probabilities of the weather and the base course.

5. Evaluation of base course (26) and subgrade moduli (31,33) as they are affected by moisture contents in the materials.

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

6.1 CONCEPTUAL FLOW CHART FOR RAINFALL, INFILTRATION AND DRAINAGE ANALYSIS

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

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

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

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

Rainfall Frequency → Markov Chain Method → Dry & Wet Probabilities

Rainfall Amount → Gamma Distribution

B. Water Infiltration

No

Cracks & Joints Data

Yes

Dempsey's Field Test (Regression Analysis)

Water Amount in Pavement

Ridgeway's Lab Results (Infiltration Data)

C. Drainage Analysis

Parabolic free surface & subgrade drainage

Base Course Properties

Base Drainage Design Evaluation

\[ t_{1.0 > 1} \]

Average drainage time \[ t_{0.5} \]

Base saturation distribution

Base wet probability

Base & Subgrade Load-Carrying Capacity

FIGURE 20. Flow Chart for Conceptual Model of Rainfall Infiltration and Drainage Analysis of Pavements
FIGURE 21. Synthesis of Models Used in Systematic Analysis of Rainfall Infiltration and Drainage Analysis of a Pavement
course and drainage analysis, are applied to estimate the probability of a base course remaining dry or wet. After taking the climatic condition, water penetration and drainage design of a base course into consideration, the distribution of various saturation levels in a base and a subgrade is then used for predicting the load carrying capacity of a pavement.

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

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

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

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

\[ BC_{\text{dry}} = P_i \times W(0; T_i) \text{ for } t_{1.0} > 1 \]  \hspace{1cm} (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 is corresponds to a certain degree of water saturation,
- \( W(0; T_i) \) = 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 \( t_{1.0} \leq 1 \), i.e., all the free water can be drained from a base course within one day, the following equation is applied

\[ BC_{\text{dry}} = 1 - (P_{\text{wet}})^{t_{0.5}} \text{ for } t_{1.0} < 1 \]  \hspace{1cm} (6-2)

where

- \( BC_{\text{dry}} \) and \( t_{1.0} \) defined as in Equation 6-1.
- \( P_{\text{wet}} \) = 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 $0.1 \leq 1$, respectively.

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

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

Based on the weather data and pavement structure, the drainage time, degree of drainage and corresponding probabilities are calculated in Table 7. Table 8 gives the characteristics of gamma distribution and related material properties under local rainfall conditions, and Table 9 shows the rainfall effect on the base and subgrade moduli.
### TABLE 5. TTI DRAINAGE MODEL FOR AN ANALYSIS OF A HOUSTON PAVEMENT

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

**System Analysis of Rainfall Infiltration and Drainage**

<table>
<thead>
<tr>
<th>Length</th>
<th>Height</th>
<th>Slope%</th>
<th>Perm.1</th>
<th>Perm.2</th>
<th>Poro.1</th>
<th>Poro.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.00</td>
<td>0.50</td>
<td>1.50</td>
<td>10.0000</td>
<td>0.00100</td>
<td>0.2000</td>
<td>0.0500</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Drainage %</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.202E 00</td>
</tr>
<tr>
<td>10.0</td>
<td>0.760E 00</td>
</tr>
<tr>
<td>15.0</td>
<td>0.165E 01</td>
</tr>
<tr>
<td>20.0</td>
<td>0.282E 01</td>
</tr>
<tr>
<td>25.0</td>
<td>0.426E 01</td>
</tr>
<tr>
<td>30.0</td>
<td>0.595E 01</td>
</tr>
<tr>
<td>35.0</td>
<td>0.788E 01</td>
</tr>
<tr>
<td>40.0</td>
<td>0.101E 02</td>
</tr>
<tr>
<td>45.0</td>
<td>0.125E 02</td>
</tr>
<tr>
<td>50.0</td>
<td>0.151E 02</td>
</tr>
<tr>
<td>55.0</td>
<td>0.198E 02</td>
</tr>
<tr>
<td>60.0</td>
<td>0.256E 02</td>
</tr>
<tr>
<td>65.0</td>
<td>0.323E 02</td>
</tr>
<tr>
<td>70.0</td>
<td>0.403E 02</td>
</tr>
<tr>
<td>75.0</td>
<td>0.499E 02</td>
</tr>
<tr>
<td>80.0</td>
<td>0.620E 02</td>
</tr>
<tr>
<td>85.0</td>
<td>0.779E 02</td>
</tr>
<tr>
<td>90.0</td>
<td>0.100E 03</td>
</tr>
<tr>
<td>95.0</td>
<td>0.137E 03</td>
</tr>
<tr>
<td>100.0</td>
<td>0.187E 03</td>
</tr>
</tbody>
</table>
### TABLE 6. TTI DRAINAGE MODEL FOR EVALUATION OF A DRAINAGE DESIGN OF A HOUSTON PAVEMENT

<table>
<thead>
<tr>
<th>Evaluation of Drainage Design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Drained Percentage Due to Gravel</td>
<td>80.00</td>
</tr>
<tr>
<td>Percentage of Gravel in the Sample</td>
<td>70.00</td>
</tr>
<tr>
<td>Water Drained Percentage Due to Sand</td>
<td>65.00</td>
</tr>
<tr>
<td>Percentage of Sand in the Sample</td>
<td>30.00</td>
</tr>
<tr>
<td>Percentage of Water Will be Drained</td>
<td>75.50</td>
</tr>
<tr>
<td>Critical Drainage Degree (85% Saturation)</td>
<td>19.87</td>
</tr>
<tr>
<td>Draining Time for 85% Saturation (Hours)</td>
<td>2.79</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Drainage (%)</th>
<th>Prob (Consecutive Dry Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58.72</td>
<td>0.710</td>
</tr>
<tr>
<td>2</td>
<td>74.08</td>
<td>0.554</td>
</tr>
<tr>
<td>3</td>
<td>83.32</td>
<td>0.432</td>
</tr>
<tr>
<td>4</td>
<td>89.17</td>
<td>0.338</td>
</tr>
<tr>
<td>5</td>
<td>98.02</td>
<td>0.264</td>
</tr>
<tr>
<td>6</td>
<td>95.57</td>
<td>0.206</td>
</tr>
<tr>
<td>7</td>
<td>97.30</td>
<td>0.161</td>
</tr>
<tr>
<td>8</td>
<td>100.00</td>
<td>0.125</td>
</tr>
</tbody>
</table>
TABLE 8. Stochastic Models for a System Analysis of Rainfall Infiltration and Drainage Analysis of a Houston Pavement

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

(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)

<table>
<thead>
<tr>
<th>Probability Distribution of Modulus of Base Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation Level (%)</td>
</tr>
<tr>
<td>Water in Base (sq.ft.)</td>
</tr>
<tr>
<td>Rainfall Qt. (inches)</td>
</tr>
<tr>
<td>Rain Duration (hours)</td>
</tr>
<tr>
<td>Base Moduli (ksi)</td>
</tr>
<tr>
<td>Ratio of Dry Modulus</td>
</tr>
<tr>
<td>Subgrade Moduli (ksi)</td>
</tr>
<tr>
<td>Probability Density</td>
</tr>
<tr>
<td>Probability</td>
</tr>
<tr>
<td>Cumulative Probability</td>
</tr>
</tbody>
</table>
TABLE 9. EVALUATION OF RAINFALL EFFECT
ON PAVEMENT PERFORMANCE OF A HOUSTON PAVEMENT

<table>
<thead>
<tr>
<th>Distribution Characteristics of Rainfall Effect</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Free Water in Base (Sq Feet)</td>
<td>1.07</td>
</tr>
<tr>
<td>Duration of Average Rainfall Amount (Hours)</td>
<td>0.08</td>
</tr>
<tr>
<td>Average Rainfall Amount Per Day (Inches)</td>
<td>0.479</td>
</tr>
<tr>
<td>Average Base Course Modulus in Wet State (ksi)</td>
<td>41.45</td>
</tr>
<tr>
<td>Average Base Course Modulus (ksi)</td>
<td>53.41</td>
</tr>
<tr>
<td>Average Subgrade Modulus (ksi)</td>
<td>27.30</td>
</tr>
</tbody>
</table>
6.3 DATA REQUIRED FOR ANALYSIS AND SAMPLE RESULTS

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

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

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

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

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

(4) Climatic data, which include: intended evaluation period, rainfall amount of every rainy day (precipitation $\geq 0.01$ 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.
REFERENCES


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


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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:

\[
f(R; \alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} R^{\alpha-1} e^{-\beta R}, \quad R > 0
\]

\[
= 0, \quad R < 0
\]

where

\[R = \text{precipitation amount and}
\]

\[\Gamma(\alpha) = \text{Gamma function where } (n+1)! = n! \quad n=0, 1, 2, \ldots
\]

The parameters \(\alpha\) and \(\beta\) may be estimated by the moments method:

\[
\alpha = \frac{\bar{R}^2}{S^2} \quad \bar{R} = \text{mean} = \frac{\sum R_i}{n} \tag{A-2}
\]

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

\[
i = \frac{k t_p^x}{t_R^n}
\]

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,
- \( k, x, \) 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

\[
\frac{(t_R)i}{R} = \frac{t_R x_i}{0.95} = \frac{3.92 \times 0.3989}{0.95} = 1.65
\]

which is called the shape factor (SF).

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

\[
R = \frac{t_R}{SF}
\]

\[
= (t_R)(kt_x^p)/(t_R^n)(SF)
\]

\[
= kt_R \frac{(1-n)t_x^p}{(SF)}
\]

Thus, \(t_R = \left[\frac{R(SF)}{kt_x^p}\right]^{\frac{1}{1-n}}\) (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.

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

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

The transition probability matrix of the Markov chain model is derived from the assumption that the sequence of events, i.e., wet and dry days, is a negative exponential distribution.
\[ x > 0, \quad \lambda > 0, \quad \text{and} \]
\[ f(x) = \lambda e^{-\lambda x} \]
\[ x = \text{wet or dry days} \quad \text{(A-9)} \]

The variable \( \lambda \) 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
\[ \bar{x}_{\text{dry}} = \text{the average number of dry days in a given period} \]
\[ \bar{x}_{\text{wet}} = \text{the average number of wet days in that same period.} \]

So that the transition matrix is derived as \( (34) \)
\[ p(t) = \frac{1}{\lambda_w + \lambda_d} \begin{bmatrix} \lambda_w + \lambda_d e^{-t} & \lambda_d \left[ 1 - e^{-t} \right] \\ \lambda_w \left[ 1 - e^{-t} \right] & \lambda_d + \lambda_w e^{-t} \end{bmatrix} \quad \text{(A-11)} \]

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 \( (13) \).

\[ \begin{bmatrix} W_0(k;N) \\ W_1(k;N) \end{bmatrix} = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} x \begin{bmatrix} W_0(k;N-1) \\ W_1(k-1;N-1) \end{bmatrix} \quad \text{(A-12)} \]

Transition Matrix

where
\[ W_0(k;N) = \text{the probability of } k \text{ wet days during } N \text{ consecutive days when the zero-th day is} \]
dry (the subscript 0 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

\[ W(k;N) = (1-p_0)W_0(k;N) + p_0W_1(k;N) \]  

(A-13)

where

\[ W(k;N) = \text{the probability of having } k \text{ wet days during } N \text{ consecutive days} \]

\[ p_0 = \text{initial probability of having a wet day.} \]

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) $W_0(k; N)$

\begin{align*}
&\text{First day} \\
&\text{Zeroth day} \\
&\text{N-1 days}
\end{align*}

(2) $W_1(k; N)$

\begin{align*}
&\text{First day} \\
&\text{Zeroth day} \\
&\text{N-1 days}
\end{align*}

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
\[ W_0(k;N) = P_{00}W_0(k;N-1) + P_{01}W_1(k-1;N-1) \]  
(A-14)

Similarly, if the zero-th day is wet, the probability of k 
wet days out of a sequence of N days is
\[ W_1(k;N) = P_{10}W_0(k;N-1) + P_{11}W_1(k-1;N-1) \]  
(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.

\[ y = \sqrt{ax} \quad \text{(B-1)} \]

\[ a = \frac{H^2}{x_1} \]

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

The rate of water amount (q) change is

\[ dq = n_1 \cdot \frac{dA}{dx_1} \cdot dx_1 = \frac{n_1H}{3} \cdot dx_1 \quad \text{(B-3)} \]

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 \( y \);

\[ \frac{dq(x)}{dt} = k_1iy = k_1 \cdot \frac{dy}{dx} \cdot y = \frac{k_1}{2x_1} H^2 \quad \text{(B-4)} \]
Stage I. $0 \leq U \leq \frac{1}{3}$

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

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

FIGURE 24. Stages of Parabolic Phreatic Surface in a Horizontal Base
Combining Equations B-3 and B-4, a differential equation can be derived, the solution of which leads to

\[ t = \frac{1}{3} \frac{n_1 x_1^2}{k_1 H} \]  

(B-5)

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

\[ U = \frac{\text{Drained Area}}{\text{Total Area}} \]  

(B-6)

\[ T = \frac{tk_1 H}{n_1 L^2} \]  

(B-7)

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

\[ T = 3U^2 \quad T = 3U^2 \]  

(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.

\[ A' = HL - \frac{2}{3} hL \]  

(B-9)

\[ dq = - \frac{2}{3} n_1 Ldh \]  

(B-10)

\[ \frac{dq}{dt} = \frac{k_1}{2L} h^2 \]  

(B-11)
Combining Equations B-10 and B-11,

\[ \int_{t_H}^{t_h} \text{dt} = -\frac{4}{3} \int_{H}^{h} \frac{n_1}{k_1 h^2} \text{dh} \]  \hspace{1cm} \text{(B-12)}

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

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

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

\[ t_H = \frac{1}{3} \frac{n_1 L^2}{k_1 H} \]  \hspace{1cm} \text{and}

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

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

\[ U = 1 - \frac{2h}{3H} \]  \hspace{1cm} \text{and}

\[ T = \frac{8}{9(1-U)} - 1 \]  \hspace{1cm} \text{(B-15)}

which are valid for \( \frac{1}{3} < U < 1 \) 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.
FIGURE 25. Stages of Parabolic Phreatic Surface in a sloping Base
\[ y = \sqrt{ax} + x \tan \alpha \]
\[ a = \frac{H^2}{x_1} \]
\[ y = \frac{H}{\sqrt{x_1}} \sqrt{x} + x \tan \alpha \]

Drained Area
\[ A' = (H + x_1 \tan \alpha) x_1 - \frac{x_1^2}{2} \tan \alpha \]
\[ - \int_0^{x_1} \left( \sqrt{\frac{H^2}{x_1}} \sqrt{x} + x \tan \alpha \right) dx \]
\[ = \frac{H}{3} x_1 \]

Darcy's law \( \frac{dq}{dt} = k_1 i_y \)
Therefore, \( dq(x) = k_1 \cdot (y - x \tan \alpha) \cdot \frac{dy}{dx} \cdot dt \)
\[ = k_1 \left( \frac{H^2}{2x_1} + \frac{H \sqrt{x} \tan \alpha}{\sqrt{x_1}} \right) \]

The average rate of flow can be expressed by
\[ \frac{dq}{dt} = \frac{k_1}{x_1} \int_0^{x_1} dq(x) dx \]
\[ = k_1 \left( \frac{H^2}{2x_1} + \frac{2}{3} H \tan \alpha \right) \]

From Equations B-17 and B-18
\[ \int_0^t \frac{dq}{dt} dt = \int_0^{x_1} \frac{2n_1 x_1}{k_1 (3H + 4x_1 \tan \alpha)} dx_1 \]
\[ t = \frac{2n_1}{k_1} \left[ \frac{x_1}{4 \tan \alpha} - \frac{H}{16 \tan^2 \alpha} \ln \left( \frac{3H + 4x_1 \tan \alpha}{3H} \right) \right] \]

Let \( T = \frac{k_1 H}{n_1 L^2} \)
Since \( U = \frac{x}{3L} \) and \( S = \frac{H}{L \tan \alpha} \)

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

which is valid for \( 0 < U < \frac{1}{3} \) 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

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

\[
= HL - \frac{2}{3} hL \tag{B-22}
\]

\[
dq = n_1 \frac{dA'}{dh} dh = -\frac{2}{3} n_1 L dh \tag{B-23}
\]

Using Darcy's law,

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

\[
= k_1 \left( \frac{h^2}{2L} + \frac{h \tan \alpha}{\sqrt{L}} \right) \sqrt{x} \tag{B-24}
\]

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

\[
= k_1 \left( \frac{h^2}{2L} + \frac{2}{3} h \tan \alpha \right) \tag{B-25}
\]
From Equations B-23 and B-24

\[
\frac{d}{dt} \int_{t_H}^{t_h} dt = \int_{H}^{h} \frac{-4 L^2 n_1 dh}{k_1 (3h^2 + 4hLtana)}
\]

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

(B-26)

Let \( U = \frac{HL - \frac{2}{3} hL}{HL} = 1 - \frac{2}{3} \frac{h}{H} \)

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

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

(B-27)

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

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

\( T_{II} = T_{I \text{maximum}} + \Delta T \)

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

(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.
o

Subgrade

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 $\varnothing$ in Figure 26.

The velocity of water is generally defined as

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

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

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

where $v$ is the velocity,

$\phi$ is the velocity potential,

$h$ is the total head of water,

$k$ is the coefficient of permeability,

$\gamma_w$ 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 $\phi_1$, and $\phi_2$, respectively. Applying Equations C-1 to C-3 we achieve

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

$$\phi_2 = -k_2 \left( \frac{P_2}{\gamma_w} - y \right), \quad v_2 = \frac{d\phi_2}{dy} \quad \phi_2 = v_2 y + c_2 \quad \text{(C-5)}$$
The subscript 1 stands for the parameters of the base course and 2 for those of the subgrade. At the interface of the base course and the subgrade (line BC), $y=H$,

$$v_1 = v_2 = v,$$ and thus

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

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

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 $y=H-h$, $p=0$

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

$$c_1 = (H-h)(k_1 - v_1) . \quad (C-7)$$

at $y=y_0$, $p=0$

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

$$c_2 = (k_2 - v_2) y_0 . \quad (C-8)$$

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:
\[
\frac{vH+(H-h)(k_1-v)}{k_1} = \frac{vH+(k_2-v)Y_0}{k_2} \quad \text{and}
\]

\[
v = \frac{Y_0 - H+h}{h} + \frac{Y_0-H}{k_1 + \frac{Y_0-H}{k_2}} \quad \text{(C-9)}
\]

Furthermore, the wetting front \( Y_0 \) must be determined.

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

\[
\int_{y_0}^{h} n_2 dy_0 = -n_1 \int_{h}^{H} dh, \quad \text{we have}
\]

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

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

\[
v = \frac{n_1}{n_2} (H-h) + h \quad \text{(C-11)}
\]

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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

\[
\begin{align*}
\text{Stage 1} \quad dq_x &= k_1 \left( \frac{h_o^2}{2x_1} + \frac{2}{3} h_o \tan \alpha \right) dt \\
\text{Stage 2} \quad dq_x &= k_1 \left( \frac{h^2}{2L} + \frac{2}{3} h \tan \alpha \right) dt
\end{align*}
\]

(C-12)  
(C-13)
FIGURE 28. Stages of Parabolic Phreatic Surface with both Lateral and Subgrade Drainage for a Sloping Base
The water quantity flowing through subgrade is

\[ \frac{dq_y}{dx} = n_2 dy_0 \ dx \]

\[ = v \ dx \ dt \]

In Stage 1,

(a) from origin to \( x_1 \),

\[ y = \sqrt{ax} + xtan\alpha \] for parabolic free surface on Figure 28

\[ \dot{y} = y - xtan\alpha = \frac{h_0}{\sqrt{x_1}} \] (C -14)

\[ dq_y (0-x_1) = v \ dx \ dt \]

\[ \dot{y} (1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2} \]

\[ = k_2 \left( \frac{k_2}{k_1} - \frac{n_1}{n_2} \right) \ dx \ dt \] (C -15a)

(b) from \( x_1 \) to \( L \)

\[ dq_y (x_1-L) = \frac{h_0 (1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}}{h_0 (k_2 \frac{n_1}{k_1} - \frac{n_1}{n_2} + \frac{n_1}{n_2})} \ dx \ dt \] (C-15b)

Therefore, total \( \frac{dq_y}{dt} \)

\[ = \frac{1}{L} \left[ k_2 \int_0^{x_1} \frac{\dot{y} (1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}}{\dot{y} (\frac{k_2}{k_1} - \frac{n_1}{n_2} + \frac{n_1}{n_2})} \ dx \right. \]

\[ \left. + \frac{h_0 (1 - \frac{n_1}{n_2}) + \frac{n_1}{n_2}}{h_0 (k_2 \frac{n_1}{k_1} - \frac{n_1}{n_2} + \frac{n_1}{n_2})} (L-x_1) \right] \] (C -16)
In Stage 2,

\[ \dot{y} = \frac{h}{\sqrt{L}} \sqrt{x} \]

\[ \text{Total } \frac{dq_Y}{dt} = k_2 \int_0^L \frac{h}{\sqrt{L}} \sqrt{x} \left( \frac{n_1}{n_2} \right) + \frac{n_1H}{n_2} \, dx \quad \text{(C-17)} \]

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

\[ dq = dq_x + dq_y \]

Stage 1

\[ dq_x = \text{Equation C-12} \]

\[ dq_y = \text{Equation C-15} \]

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 \( O \) 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 \( O \).

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

\[
dq = wdl = dA
\]

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

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,
\[ \frac{dg}{dt} = w \frac{\partial g}{\partial t} = \frac{dA}{dt} = \frac{\pi}{2} b \left( \frac{dx}{dt} \right) + \frac{\pi}{2} a \left( \frac{dy}{dt} \right) \]  
\tag{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.

\[ v_y = \frac{dy}{dt} = \frac{-k_v}{n} \frac{\partial h}{\partial y} = \frac{-k_v}{n} \frac{\partial}{\partial y} \left( \frac{p}{\gamma} - y \right) \]  
\tag{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
\[ \gamma \] is the unit weight of water.

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

\[ h = a_1 y + c_1 \]

at \( y=0, h = \ell = c_1 \)

and \( y=y_0, h=a_1 y_0 + \ell \)

where \( y_0 \) is the wetting front in the vertical direction.

Since \( h = -y_0 - h_k \),

\[ a_1 = \frac{-y_0 - h_k - \ell}{y_0} \]  
\tag{D-6}
where \( h_k \) is the capillary head.

Thus

\[
  h = \frac{-(y_0 + h_k + \ell)}{y_0} \quad y + \ell
\]  

\[
  \frac{dh}{dy} = \frac{-(y_0 + h_k + \ell)}{y_0}
\]

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,

\[
  \frac{y_0}{y_0 + h_k + \ell} \, dy_0 = \frac{k_v}{n} \, dt
\]

\[
  v_x = \frac{dx}{dt} = \frac{-k_h}{n} \frac{dh}{dx}
\]

Assume \( h = a_2 x + c_2 \)

\[
  x = 0 \quad h = \ell = c_2
\]

and \( x = x_0 \)

\[
  h = ax_0 + \ell = -h_k
\]

where \( x_0 \) is the wetting front in horizontal direction.
Therefore,

\[ a_2 = \frac{-\lambda - h_k}{x_0} \quad (D-11) \]

\[ \frac{dx}{dt} = \frac{k_h}{n} \frac{(\lambda + h_k)}{x_0} \quad (D-12) \]

therefore,

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

From Eq. D-5 and since \( x_0 = a \), \( y_0 = b \),

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

This differential equation is accompanied by the initial conditions

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

\[ w d \ell = \frac{\pi}{2} x_0 y_0 \]

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

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 \( \Delta l \) from the Equation D-14.

(4) Compute the water quantity, in terms of length, left in the cracks or joints.
D-2. Water Evaporation from a base of low permeability.

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

Initial Condition: \[ u(y,0) = u_0 \] (D-20)

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

\[ \frac{\partial u(y_0,t)}{\partial x} = -\beta \{u(y_0,t) - h_0\} \] (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):

\[ u = u_a + \sum_{n=1}^{\infty} A_n \exp \left( -\frac{y_n^2 t \kappa}{Y_0^2} \right) \cos \left( y_n \frac{x}{Y_0} \right) \] (D-23)

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

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

\[ u_a = \text{suction of atmosphere,} \]

\[ u_0 = \text{original suction throughout soil,} \]

\[ Y_0 = \text{wetting front of water penetration,} \]

\[ \beta = \text{evaporation constant, and} \]

\[ \kappa = \text{diffusion coefficient.} \]

The amount of water evaporated from the base, \( \Delta w \), is determined by integration of suction loss times the rate of moisture change with respect to suction;

\[ \Delta w = \int_{0}^{Y_0} \Delta u(y,t_f) \left[ \frac{\partial}{\partial u} \right] dy, \] (D-25)
where

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

$\quad t_f$ 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

START

Input
Length, Height,
Slope, Permeability,
Porosity

Base Course
Drainage
Computation

TTI
Drainage
Model

Output

Drainage
Design
Evaluation

A

123
Water Carrying Capacity of Base Course (CC)

PCC
0.03 ft³/hr/ft

BCP
0.11 ft³/hr/ft

Maximum Water that Could Enter Base Course (MAX.FLOW)

Degree of Saturation and Drainage

Distribution of Drainage Time

MAX FLOW Greater Than 1 Day

No

Yes

$ t_{0.5}$

Katz's Model

D

Period to be Evaluated
E-2. COMPUTER PROGRAMS AND SAMPLE RESULTS

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

SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND PAVEMENT DRAINAGE

AUGUST, 1983

BASE AND SUBGRADE DRAINAGE MODELS

PARABOLIC FREE SURFACE PLUS SUBGRADE DRAINAGE

DO 300 IND$=1,10
C INPUT THE DATA
READ(5,55555,END=99999) IPROB,INEED,ITITLE
55555 FORMAT(I5,I3,18A4)
WRITE(6,55556) IPROB,ITITLE
55556 FORMAT(3(//,5X,'PROBLEM NUMBER',I5,2X,18A4)
IF(INEED.EQ.0) WRITE(6,55557)
IF(INEED.EQ.1) WRITE(6,55558)
IF(INEED.EQ.2) WRITE(6,55559)
55557 FORMAT(3(//) ,5X,'DRAINAGE ANALYSIS USING TTI DRAINAGE MODEL')
55558 FORMAT(3(//) ,5X,'DRAINAGE ANALYSIS AND DESIGN EVALUATION')
55559 FORMAT(3(//) ,5X,'SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINAGE')
C
c c
55 FORMAT(7(F10.0)
TA=TAPER/100.
HORIZONTAL BASE COURSE
IF(TA.LE.0.) TA=0.1E-06
IF(N2.LE.0.) CALL POR02
C
IF(N1.EQ.N2.AND.K2.EQ.K1)
K2=K2*1.0001
WRITE(6,25)
25 FORMAT(3(//,5X,'LENGTH' ,4X,'HEIGHT' ,4X,'SLOPE%',
1.8X,'PERM.1' ,4X,'PERM.2' ,4X,'PORO.1' ,4X,'PORO.2')
WRITE(6,55)LA,HE,TAPER,K1,K2,N1,N2
55 FORMAT(1X,3(FlO.2) ,2(FlO.5) ,2tF10.4)
TWETA=LA*HE
S=HE/(LA*TAP)
WRITE(6,35)S
35 FORMAT(2/5X,'SLOPE FACTOR=',F6.3//)
WRITE(6,255)
255 FORMAT(5X,'NOTE: THE FOLLOWING ANALYSIS IS BASED ON PARABOLIC SHAP +E PLUS SUBGRADE DRAINAGE')
C
RUNGE-KUTTA METHOD FOR PARABOLIC(DQX) AND HORIZONTAL(DQY) EQUATION OF CA
WRITE(6,115)
115 FORMAT(6,115)
WRITE(6,115)
115 FORMAT(6,115)
WRITE(6,115)
115 FORMAT(6,115)
WRITE(6,115)
TIME=TIME+(AK1+AK2)/2.
NUM=1.
CALL SUBHT(TIME,HSUB1)
HSUBA=HSUB1
CALL CONSFC(XM,A)
DTDX=DUMMYF(XM)
AK1=DTDX*DELT
WET1=(HE-HSUBA)*LA+HSUBA*Xm/3.
UE1=WET1/TWETA
HAVG1=(TWETA-WET1)/LA
IF(HSUBA.LE.0.OR.HSUBA.LE.HAVG1) HSUBA=HAVG1
WRITE(6,135)XM,HSUBA,HAVG1,TIME,UE1
135 FORMAT(5(E20.4))
XTIME(I2,IA)=TIME
YAREA(I2,IA)=UE1
700 CONTINUE
C
USE SIMPSON'S RULE IN CALCULATING TIME FOR CASE 2
C HSUBA(MAXIMUM HEIGHT IN CASE 2),XM(TOTAL LENGTH IN CASE 1)
C AND TIME(MAXIMUM TIME IN CASE 1) WERE ALL RESERVED FROM UPPER DO LOOP
WRITE(6,45)
45 FORMAT(1H1,6(/),5X,'HEAD ON Y COOR.',7X,'HT.(SUB.DRAIN ONLY)',
     +8X,'AVG. HEIGHT',7X,'TIME(STAGE 2)',7X,'DRAINAGE DEG.'//)
CASE=2.
HMAX=HSUBA
HMAX2=HMAX
DELT=HMAX/13
DC 800 I3=1,NB
HMIN=HMAX2-DELT*I3
I5=I3+NA
IF(I3.EQ.NB.OR.HMIN.LE.0.) HMIN=HMAX*0.5
CALL CONSFC(XM,HMIN)
CALL SIMPSN(AREA,DUMMYF,HMIN,HMAX,K)
TIME=TIME+AREA
CALL SUBHT(TIME,HTSU)
WET2=TWETA-2.*HMIN*LA/3.
UE2=WET2/TWETA
HAVG2=(TWETA-TWETA-2.*HMIN*LA/3.)/LA
IF(HTSU.LE.0.OR.HTSU.LE.HAVG2) HTSU=HAVG2
WRITE(6,135)HMIN,HTSU,HAVG2,TIME,UE2
XTIME(I5,IA)=TIME
YAREA(I5,IA)=UE2
UAREA(I5,IA)=YAREA(I5,IA)*100.
HMAX=HMIN
IF(I3.EQ.NB) TIMAX(IA)=TIME
IF(I3.EQ.NB) UEMAX(IA)=UE2
800 CONTINUE
IMAXD=TIMAX(IA)/24.+0.5
CALL INPOLA(TDRAN,UDRAN,IA,LOGTIM)
IF(Ineed.NE.0)
1CALL JUDGE(IA,INT,ITYPFI,IQFINE,GRAVPC,SANJPC)
IF(Ineed.EQ.2) CALL RAIN(TDRAN,IMAXD)
300 CONTINUE
99999 WRITE(6,125)
125 FORMAT(1H1)
STOP
END
C
C
VARIOUS CONSTANTS EMPLOYED IN EQUATIONS

XM: MAXIMUM HORIZONTAL DISTANCE IN CASE 1;

HMIN: MINIMUM VALUE OF HEIGHT

SUBROUTINE CONSFC(XM,HMIN)

IMPLICIT REAL(J-Z)
INTEGER N, NA, NB, NC, NJONT, NLANE
COMMON LA, HE, TA, K1, K2, N1, N2, A1, B1, B2, C1, G1, G2, G3, R1
COMMON CASE, HED, HSUBA, HSUBB, NUM, S

IF(NUM.EQ.1.) HSUB=HSUBA
IF(NUM.EQ.2.) HSUB=HSUBB
 IF(CASE.EQ.1.) XM=LA
 Al=HSUB/SQR(XM)
 Bl=Al*(1.-N1/N2)
 B2=A1*(K2/K1-N1/N2)
 C1=N1*HE/N2
 Gl=Bl/B2
 G2=C1*(1.-Gl)/E2
 G3=C1*G2
 R1=G3/B2

RETURN
END

SUBROUTINE DRYDAY(IMAXD,YDRAN,WFROB)

COMMON /RAW/ XTIME(120,10), YAREA(120,10), INDS, TIMAX(10), UMAX(10)
COMMON /NUM/ INABT
DIMENSION YDRAN(100), WFROB(50,50)

IA=INDS
DO 6000 I=1,100
IDRY=I
   DO 6100 I2=1,100
      IF(I2.EQ.INABT) GO TO 6222
      IF(XTIME(I2,IA).LT.IDRY*24.) GO TO 6111
6100 CONTINUE
6111 I1=I2-1
 IF(I1.LE.0) GO TO 6001
   REGCOE=(YAREA(I2,IA)-YAREA(I1,IA))/XTIME(I2,IA)-XTIME(I1,IA))
   CONCOE=YAREA(I2,IA)-REGCOE*XTIME(I2,IA)
   YDRAN(IDRY)=(CONCOE+REGCOE*IDRY*24.)*100.
   GO TO 6000
6001 YDRAN(IDRY)=100.*YAREA(I2,IA)*IDRY*24./XTIME(I2,IA)
6000 CONTINUE
6222 IF(IMAXD.LE.0) RETURN
IMAXD=IDRY
IMAXD=39
YDRAN(IMAXD)=100.
WRITE(6,5005)
6005 FORMAT(1H1,5(/),T34,'PROBLEM NO.',5X,'TIME(DAYS)',4X,'DRAINAGE(%)'
2,2X,'PROB(CONSECUTIVE DRY DAYS)',5(/))
IN=1
DO 6600 I=1,IMAXD
IN=IN+1
WRITE(6,5010)IA,I,YDRAN(I),WPROB(1,IN)
6600 CONTINUE
RETURN
END
C***********************************************************************
C*
C* ROUTINE FOR COMPUTING ALL THE FUNCTIONS
C*
C*
C**************************************~************** ******************
CFUNCTION CUMMYF(X)
IMPLICIT REAL(J-Z)
INTEGER N,NA,NB,NC,NJONT,NLANE
COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
COMMON CASE,HED,HSUBA,HSUBB,NUH,S
IF(NUM.EQ.1.) HSUB=HSUBA
IF(NUM.EQ.2.) HSUB=HSUBB
IF(CASE.EQ.2.) A5=X
IF(CASE.EQ.2.) X=LA
IF(CASE.EQ.2.) HSUB=HED
IF(N2.GT.0.1E-05.AND.K2.NE.O.) GO TO 5555
DUM3=0.
GO TO 6666
5555 FAC1=G1*X+2.*G2*SQRT(X)
FAC2=2*R1*ALOG(ABS(B2*SQRT(X)+C1)/Cl)
FACR=FAC1-FAC2
IF(N2.LE.0.1E-05) DQY=0.
IF(N2.GT.0.1E-05) DQY=(HSUB* (1.-N1/N2)+C1)/(HSUB* (K2/K1-N1/N2)+C1)
DUM3=6.*K2*X*((LA-X)*DQY+FACR)/LA
6666 CONTINUE
IF(CASE.EQ.1.) DUM1=2.*N1*HSUB*X
IF(CASE.EQ.2.) DUM1=4.*N1*LA**2
DUM2=K1*(3.*HSUB**2+4.*HSUB*X*TA)
DUMMYF=DUM1/(DUM2+DUM3)
IF(CASE.EQ.2.) X=AE
IF(CASE.EQ.2.) HSUB=HED
RETURN
END
C***********************************************************************
C*
C* EVALUATE THE MODULI OF BASE AND SUBGRADE BY DISTRIBUTION
C*
C* OF MATERIAL SATURATION FROM THE RAINFALL
* 03000

C* ALPH, BETA: PARAMETERS OF GAMMA DISTRIBUTION
* 03010

C* FWT, FDRY: PROBABILITY OF WET AND DRY DAYS IN STEADY STATE
* 03020

C* HALFT: TIME OF 50% DRAINAGE (HOUR);
* 03030

C*
* 03040

C*
* 03050

C*
* 03060

C***************************
03070

C
03080

C
03090

C SUBROUTINE FLOWIN(ALPHA, BETA, PDRY, FWT, HALFT, CRKJN, IBC, ITYPE,
2ASOIL, BHORIZ, FLTONG, YEAR, AVGRAZ, YDRAN, WPROB, IMAXD)
03100

C GANDIS: GAMMA DISTRIBUTION AS A FUNCTION
03110

C AINTER, BSLOPE: INTERCEPT AND SLOPE OF THE LINEAR FUNCTION OF BASE COUR03120

C MODULUS VS. WATER SATURATION DEGREE
03130

C EMPDF: PROBABILITY DENSITY FUNCTION OF BASE COURSE MODULUS IN WET STAO3140

C PAVE: INFILTRATION RATE OF PCC(1) OR BCP(2), UNIT=FT**3/(HOUR*FT)
03150

C FLOAVG: INFILTRATION RATE SELECTED ACCORDING TO PAVEMENT TYPE
03160

C PVA, PVB: THE INTERCEPT AND SLOPE OF REGRESSION EQUATION IN DEMPSEY'S TE03170

C PX: SPECIFIC RAINFALL AMOUNT
03180

C CFHALF: THE AVERAGE DEGREE OF FREE WATER DRAINAGE PER HOUR
03190

C DEFL: DEFLECTION OF BASE MATERIALS (INCHES)
03200

C DERATE: RATIO OF BASE MODULUS OF ELASTICITY
03210

C BCMAT: BASE MODULUS OF ELASTICITY (KSI)
03220

C BCRATE: SLOPE OF DEFLECTION CHANGE WITH RESPECT TO DEGREE OF SATURATION03230

C TURNPT: 1. DEFLECTION OF DRY BASE MATERIAL
03240

C 2. DEFLECTION OF 95% SATURATION LEVEL
03250

C REAL LA, KL, K2, N1, N2
03260

C EXTERNAL GAMDIS
03270

C COMMON LA, HE, TA, K1, K2, N1, N2, A1, B1, B2, CL, G1, G2, G3, RL
03280

C COMMON CASE, HED, HSUBA, HSUBB, NUM, S
03290

C COMMON /EDR/CONST, RECPOW, DURPOW, SHAPE
03300

C COMMON /RAW/ XTIME(120, 10), YAREA(120, 10), INDS, TMAX(10), UMAX(10)
03310

C COMMON /NUM/ INAPT
03320

C COMMON /SGWET/ SGWET(100), SGDRY(100), SGW(100), SGD(100)
03330

C COMMON /KOGAMA/ NUMWET, AVGAMT, TOHTSUM
03340

C DIMENSION EMPDF(100), SEG(100), AINTER(2, 9), BSLOPE(2, 9)
03350

C DIMENSION PAVE(2), SOIL(9), HORIZ(2), PTYPE(2), FREE(100)
03360

C DIMENSION PX(100), DURAT(100), SECT(20), CDF(20), IIA(100)
03370

C DIMENSION DEFL(100), DERATE(100), BCRATE(2), BCMAT(6), TURNPT(2),
03380

C 2BCEM(100)
03390

C DIMENSION FREE2(100), DURATB(100), PXB(100), SECTB(50)
03400

C DIMENSION YDRAN(100), WPROB(50, 50)
03410

C INTEGER PTYPF/ 'PCC', 'BCP'/
03420

C DATA PAVE/0.03, 0.11/
03430

C DATA PVA, PVB/0.32, 0.48/
03440

C DATA BCMAT/425.3, 236.3, 209.3, 64.6, 29.8, 17.1/
03450

C DATA BCRATE/0.24, 3.5, 0.02, 0.08/
03460

C REAL 8 SOIL/'A-7-5', 'A-4', 'A-7-6', 'A-6', 'CL', 'ML-CL',
03470

C 'ML', 'MH', 'ASOIL/
03480

C INTEGER HORIZ/ 'ABC', 'BC', 'BHORIZ/
03490

C DATA AINTER/39.83, 27.54, 17.33, 16.76, 31.22, 24.65, 36.15, 35.67,
03500

C 2 31.89, 32.13, 31.89, 32.13, 21.93, 23.02, 31.39, 29.01,
03510

C 3 31.39, 29.01/
03520

C DATA BSLOPE/0.453, 0.266, 0.159, 0.146, 0.294, 0.196, 0.362, 0.354,
03530

C 2 0.312, 0.311, 0.312, 0.311, 0.151, 0.161, 0.331, 0.284,
03540

C 3 0.331, 0.284/
03550

C IF(IMAXD.GE.39) IMAXD=39
03560

133
IF (ITYPE.EQ.PTYPE(1)) FLOAVG=PAVE(1)
IF (ITYPE.EQ.PTYPE(2)) FLOAVG=PAVE(2)

DO 7100 I=1,9
   IF (ASOIL.NE.SOIL(I)) GO TO 7100
   INDEXB=I
   GO TO 7555
7100 CONTINUE

7555 IF (BHORIZ.EQ.HORIZ(1)) INDEXA=1
   IF (BHORIZ.EQ.HORIZ(2)) INDEXA=2
   C
   FREE = AMOUNT OF FREE WATER IN PAVEMENT (FEET**2)
   DURAT = DURATION OF SPECIFIC RAINFALL AMOUNT (HOURS)
   ITEST = 1 USING RIDGEWAY'S EQUATION; 2 USING DEMPSEY'S FOR NO CRACKS
   DATA AND WHEN RIDGEWAY'S METHOD TURNS OUT TO BE UNREASONABLE
   IF (NUKWET-I) 33333,22222,11111
   DO 7000 I=5,100,5
      FREE(I)=CC*I*0.01
   7000 CONTINUE

   SGWET : WET DEPTH OF SUBGRADE
   SGRY : DRY DEPTH OF SUBGRADE
   SGW : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (E1**3)
   SGD : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE
   SGEX : SUBGRADE MODULUS

   SGW(I)=(AINTER(INDEXA, INDEXB)-BSLPE(INDEXA,INDEXB)*10.)
      *(SGWET(I)**3)
   IF (SGW(I).LE.0.) SGW(I)=0.
   SGD(I)=AINTER(INDEXA, INDEXB)*(SGDRY(I)**3)
   SGEM(I)=(SGW(I)+SGD(I))*(5.83333-HE)**3
   IF (SGEM(I).LE.0.) SGEM(I)=0.
   IF (CRKJON.EQ.0.) GO TO 7777
   ITEST=1
   DURAT(I)=(FREE(I)*FTLONG)/(CRKJON*FLOAVG)
   PX(I)=(60.*DURAT(I)**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE
   RIDGE=BETA*PX(I)
   IF (RIDGE.GE.174.) GO TO 7777
   GO TO 7788
   7777 ITEST=2
   DURAT(I)=((PX(I)*SHAPE)/(CONST*(YEAR**RECPOW)))**(1./1.-DURPOW)
   2/60.
   7788 PX2=PX(I)

   EMPDF(I)=GAMDIS(PX2,ALPHA,BETA)
   IF (I.GT.85) GO TO 7755
   IF (I.LE.60) GO TO 7744
   DEFL(I)=TURNPT(1)+BCRATE(1)*0.01*(I-60)
   DERATE(I)=TURNPT(1)/DEFL(I)
420. \( \text{BCEM}(I) = \text{BCMAT}(IBC) \times \text{DERATE}(I) \) 04200
421. \( \text{GO TO 7766} \) 04210
422. \( 7744 \text{ BCEM}(I) = \text{BCMAT}(IBC) \) 04220
423. \( \text{DERATE}(I) = 1.0 \) 04230
424. \( \text{GO TO 7766} \) 04240
425. \( 7755 \text{ DEFL}(I) = \text{TURNPT}(2) + \text{BCRATE}(2) \times 0.01 \times (I-85) \) 04250
426. \( \text{DERATE}(I) = \text{TURNPT}(1) / \text{DEFL}(I) \) 04260
427. \( \text{BCEM}(I) = \text{BCMAT}(IBC) \times \text{DERATE}(I) \) 04270
428. \( 7766 \text{ IIB}=I/10 \times 10 \) 04280
429. \( \text{IF(IIB.NE.I) GO TO 7000} \) 04290
430. \( \text{CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA)} \) 04300
431. \( K=K+1 \) 04310
432. \( \text{IF(SECTOR.LE.0.0) SECTOR=0.} \) 04320
433. \( \text{IF(SECTOR.GT.1.0) SECTOR=1.0} \) 04330
434. \( \text{SECT}(K) = \text{SECTOR} \) 04340
435. \( \text{CDFSUM}=\text{CDFSUM}+\text{SECT}(K) \) 04350
436. \( \text{IF(CDFSUM.GE.1.0) CDFSUM=1.0} \) 04360
437. \( \text{CDF}(K) = \text{CDFSUM} \) 04370
438. \( \text{PX1}=\text{PX2} \) 04380
439. \( 7000 \text{ CONTINUE} \) 04390
440. \( \text{C} \) 04400
441. \( \text{C} \) \text{CALCULATE THE PART WHICH IS BEYOND THE FIELD CAPACITY IN GAMMA DISTRIBUTION} \) 04410
442. \( \text{C} \) \text{PX2 IS THE MAXIMUM INFILTRATION AMOUNT AFTER THE ABOVE LOOP} \) 04420
443. \( \text{C} \) \text{TAILPT}=1.0-CDFSUM \) 04430
444. \( \text{C} \) \text{THE DRY AND WET PROBABILITIES OF THE PAVEMENT} \) 04440
445. \( \text{C} \) \text{PADVDRY: THE DRY PROBABILITY OF PAVEMENT} \) 04450
446. \( \text{C} \) \text{PAVWET: THE WET PROBABILITY OF PAVEMENT} \) 04460
447. \( \text{C} \) \text{IF(TIMAX(INDS)/24.LT.1.) GO TO 8833} \) 04470
448. \( \text{C} \) \text{PX1}=0. \) 04480
449. \( \text{K}=0 \) 04490
450. \( \text{DO 8000 I=1,IMAXD} \) 04500
451. \( \text{FREE2(I)=CC*0.01*YDRAN(I)} \) 04510
452. \( \text{IF(CRKJON.EQ.0.) GO TO 8777} \) 04520
453. \( \text{ITEST}=1 \) 04530
454. \( \text{DURATB(I)=(FREE2(I)*FTLONG)/(CRKJON*FLOAVG)} \) 04540
455. \( \text{PXBI}=((60.*DURATB(I)**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE} \) 04550
456. \( \text{RIDGE=BE*A*PXBI} \) 04560
457. \( \text{IF(RIDGE.GE.174.) GO TO 8777} \) 04570
458. \( \text{GO TO 8788} \) 04580
459. \( 8777 \text{ ITTEST}=2 \) 04590
460. \( \text{PXBI}=(((FREE2(I)*FTLONG*0.02832-PVA)/(PVB*0.02832*FTLONG*LA))**12.} \) 04600
461. \( \text{IF(PXB(I).LE.0.) PXB(I)=0.} \) 04610
462. \( \text{DURATB(I)=((PXBI*SHAPE)/(CONST*(YEAR**RECPOW))))} \) 04620
463. \( 2**((1./(-DURPOW))/60.} \) 04630
464. \( 8788 \text{ PX2}=\text{PXBI} \) 04640
465. \( \text{CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA)} \) 04650
466. \( \text{K}=K+1 \) 04660
467. \( \text{IF(SECTOR.LE.0.0) SECTOR=0.} \) 04670
468. \( \text{IF(SECTOR.GT.1.0) SECTOR=1.0} \) 04680
469. \( \text{SECTB(K) = SECTOR} \) 04690
470. \( \text{PX1}=\text{PX2} \) 04700
471. \( 8000 \text{ CONTINUE} \) 04710
472. \( \text{PADVDRY}=0. \) 04720
473. \( \text{IN}=1 \) 04730
474. \( \text{DO 8100 K=1,IMAXD} \) 04740
475. \( \text{IN}=IN+1 \) 04750
476. \( \text{8100} \) 04760
477. \( \text{8100} \) 04770
478. \( \text{8100} \) 04780
479. \( \text{IN}=IN+1 \) 04790
PAVDRY = PAVDRY + SECTB(K) * WPROB(1, IN)

8100 CONTINUE

PAVDRY = PAVDRY + WPROB(1, IN) * TAILPT

GO TO 8844

8833 DHALF = HALFT / 24.

PAVDRY = 1. - PWET * DHALF

8844 PAVWET = 1. - PAVDRY

C

C CALCULATE THE PROBABILITIES OF SATURATION LEVELS:

C

SECT1: 0-60%; SECT2: 60-85%; SECT3: 85-100%

C

C

CALL SIMP2(SECT1, GAMDIS, 0., PX(60), 60, ALPHA, BETA)

IF(SECT1.GE.1.0) SECT1 = 1.0

CALL SIMP2(SECT2, GAMDIS, PX(60), PX(85), 60, ALPHA, BETA)

CALL SIMP2(SECT3, GAMDIS, PX(85), PX(100), 60, ALPHA, BETA)

SECT3 = SECT3 + TAILPT

GO TO 44444

C

NUMBER OF RAINFALL QUANTITY EQUALS TO 0 OR 1 (NO GAMMA DISTRIBUTION)

C

YRAIN1: DRAINAGE LEVEL OF ONE RAINY DAY (IN DECIMAL POINT)

C TRAIN1: TIME FOR THE CORRESPONDING DRAINAGE LEVEL OF ONE RAINY DAY

22222 ITEST = 1

IF(CRKJON.EQ.0.) GO TO 9191

AVGDUR = (AVGRAS * 0.08333 * LA * FTLONG) / (CRKJON * FLOAVG)

AVGFLO = (60. * AVGDUR) ** (1. - DURPOW) * CONST * (YEAR ** RECPOW) / SHAPE

GO TO 9292

9191 ITEST = 2

AVGDUR = (SHAPE * AVGRAS / (CONST * (YEAR ** RECPOW))) ** (1. / (1. - DURPOW)) / 60.

AVGFLO = (PVB * AVGRAS * 0.08333 * FTLONG * LA * 0.02832 + PVA) / (0.02832 * FTLONG)

9292 YRAIN1 = AVGFLO / CC

C FIND THE CORRESPONDING TIME FOR DEGREE OF DRAINAGE

C

DO 9900 I2 = 2, 100

IF(I2.EQ.INABT) GO TO 9922

IF(YAREA(I2, IND$).GE.YRAIN1) GO TO 9911

9900 CONTINUE

9911 I1 = I2 - 1

REGCOE = (XTIME(I2, IND$) - XTIME(I1, IND$)) / 2

(YAREA(I2, IND$) - YAREA(I1, IND$))

CONCOE = XTIME(I2, IND$) - REGCOE * YAREA(I1, IND$)

TRAIN1 = CONCOE + REGCOE * YRAIN1

GO TO 9933

9922 TRAIN1 = TIMAX(IND$)

9933 PAVWET = TRAIN1 / (TOTSUM * 24.)

PAVDRY = 1. - PAVWET

IF(YRAIN1 - 0.85) 9944, 9944, 9955

9944 SECT3 = 0.

GO TO 9966

9955 SECT3 = XTIME(103, IND$) / TOTSUM

9966 IF(YRAIN1 .LT. 60.) 9998, 9988, 9977

9977 SECT2 = (XTIME(108, IND$) - XTIME(103, IND$)) / TOTSUM

GO TO 9999

9988 SECT2 = 0.

9999 SECT1 = 1. - SECT2 - SECT3

44444 DEFL(73) = TURNPT(1) + BCRATE(1) * 0.125

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DERATE(73)=TURNPT(1)/DEFL(73)  
DEFL(93)=TURNPT(2)+BCRATE(2)*0.075  
DERATE(93)=TURNPT(1)/DEFL(93)  
AVBCEM=BCMAT(IBC)*(1.*SECT1+DERATE(73)*SECT2+DERATE(93)*SECT3)  
GESBEM=AVBCEM*PAVWET+BCMAT(IBC)*PAVDRY  

C AVERAGE RAINFALL DURATION AND BASE COURSE MODULUS  
C AVGDUR: DURATION CORRESPONDING TO THE AVERAGE RAINFALL AMOUNT  
C AVGFLO: FREE WATER IN PAVEMENT DUE TO AVERAGE RAINFALL AMOUNT  
C GesGEM: TOTAL AVERAGE OF SUBGRADE MODULI  
C AVBCEM: AVERAGE BASE MODULI IN WET STATE  
C GEBCEM: TOTAL AVERAGE OF BASE MODULI  

AVGDUR=(SHAPE*AVGRAS/(CONST*(YEAR**RECPOW))**(1./(1.-DURPOW))*60.  
IF(ITEST.EQ.2) GO TO 8888  
AVGFLO=FLAVG*AVGDUR*CRKJON/FTLONG  
GO TO 8899  
8886 AVGFLO=(PVB*AVGRAS*0.08333*FTLONG*LA*0.02832+PVA)/(0.02832*FTLONG)  
8899 IF(AVGFLO.GE.CC) AVGFLO=CC  
CALCULATE SUBGRADE MODULI  
9100 EXACT2=AVGFLO/CC  
DO 9100 I2=1,100  
IF(EXACT2.GE.1.) GO TO 9222  
IF(YAREA(I2,INDS) .GT.EXACT2) GO TO 9111  
CONTINUE  
9111 11=I2-1  
IF(I1.LE.O) GO TO 9001  
PEGCOE=(XTIME(I2,INDS)-XTIME(I1,INDS))/2  
INSI2=XTIME(I2,INDS)-REGCOE*YAREA(I2,INDS)  
TSGAVW=INCI2+REGCOE*EXACT2  
GO TO 9333  
9001 TSGAVW=XTIME(I1,INDS)*EXACT2/YAREA(I1,INDS)  
GO TO 9333  
9222 TSGAVW=TIMAX(INDS)  
9333 CALL SUBHT(TSGAVW,HSUBEM)  

SGWETD: AVERAGE WET DEPTH OF SUBGRADE DURING THE SEASON  
SGDRYD: AVERAGE DRY DEPTH OF SUBGRADE  
SG1 : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (E1**3)  
SG2 : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE  

SGWETD=(HE-HSUBEM)*N1/N2  
IF(SGWETD.LE.0 OR.K2.EQ.0.) SGWETD=0.  
SGDRYD=5.83333-HE-SGWETD  
SG1=(AINTER(INDEXA,INDEXB)-BSLOPE(INDEXA,INDEXB)*100.)*(SGWETD**3)  
IF(SG1.LE.0.) SG1=0.  
SG2=AINTER(INDEXA,INDEXB)*(SGDRYD**3)  
GESGEM=(SG1+SG2)/((5.83333-HE)**3)  

IF(NUMWET.LE.l) GO TO 55555  
WRITE(6,735)CC,CFHALF,TAILPT,PAVDRY,PAVWET  
735 FORMAT(3(/),T40,'WATER CARRYING CAPACITY OF BASE(SQ.FT)=' ,FIO.3,/,  
T40,'AVERAGE DEGREE OF DRAINAGE PER HOUR =',F10.3,/,  
T40,'OVERALL PROBABILITY OF SATURATED BASE=' ,F10.3,/,  
T40,'DRIY PROBABILITY OF BASE COURSE =',F10.3)  
5599 5
DO 7200 I=1,10
WRITE(6,715) (IIA(I),I=1,10), (FREE(I),I=10,100,10), (PX(I),I=10,100,10), (DURAT(I),I=10,100,10), (BCEM(I),I=10,100,10), (DERATE(I),I=10,100,10), (SGEM(I),I=10,100,10), (EMPDF(I),I=10,100,10), (SECT(K),K=1,10), (CDF(K),K=1,10)

WRITE(6,775)AVGFLO,AVGDUR,AVGRAS,AVBCEM,GEBCEM,GESGEM

WRITE(6,785)AVGFLO,AVGDUR,AVGRAS,AVBCEM,GEBCEM,GESGEM

RETURN
| 660. | DRY PROBABILITY OF BASE COURSE =',F10.3, 6600 |
| 661. | WET PROBABILITY OF BASE COURSE =',F10.3, 6610 |
| 662. | AVERAGE FREE WATER IN BASE (SQ.FEET)=',F10.2, 6620 |
| 663. | DURATION OF AVERAGE RAINFALL AMOUNT (HOURS)=',F10.3, 6630 |
| 664. | AVERAGE RAINFALL AMOUNT PER DAY (INCHES)=',F10.3, 6640 |
| 665. | AVERAGE BASE COURSE MODULUS IN WET STATE (KSI)=',F10.2, 6650 |
| 666. | AVERAGE BASE COURSE MODULUS (KSI)=',F10.2, 6660 |
| 667. | AVERAGE SUBGRADE MODULUS (KS1)=',F10.2, 6670 |
| 668. | RETURN END |

```
SUBROUTINE KATZ(IMAXD,W)
DIMENSION WZERO(50,50),WONE(50,50),W(50,50)

COMON /DRYWET/ TLAMDA,DRYLAM,WETLAM,PWET

* KATZ'S METHOD TO COMPUTE THE DISTRIBUTION OF WET AND DRY DAYS

* IN CERTAIN PERIOD, WHICH IS ASSOCIATED WITH MARKOV CHAIN MODEL

* WZERO(I,J): THE PROBABILITY OF 1-10 WET DAYS IN J CONSECUTIVE DAYS
* WHEN THE ZEROTH DAY IS DRY

* WONE(I,J): THE PROBABILITY OF 1-10 WET DAYS IN J CONSECUTIVE DAYS
* WHEN THE ZEROTH DAY IS WET

* MAXWT: TIME REQUIRED TO DRAIN OUT 99% WATER IN THE PAVEMENT

IF(TLAMDA.GE.174.) EXPCON=0.
IF(TLAMDA.LT.174.) EXPCON=EXP(-TLAMDA)

POO=(WETLAM-DRYLAM*EXPCON)/TLAMDA
P01=DRYLAM*(1.-EXPCON)/TLAMDA
P10=WETLAM*EXPCON)/TLAMDA
P11=(DRYLAM+WETLAM*EXPCON)/TLAMDA

WRITE(6,45) POO,P01,PIO,P11

45 FORMAT(5(/),T30,'*********** TRANSITION PROBABILITY MATRIX ***********
2**,3(/),T40,'POO=',F5.3,10X,'P01=',F5.3,//,
3 T40,'P10=',F5.3,10X,'P11=',F5.3)

DO 200 NJ=2,MXWT1
DO 100 K=1,NJ

WZERO(10,11)=POO
WZERO(11,11)=PO1
WONE(10,11)=P10
WONE(11,11)=P11

WZERO(10,10)=1.
WONE(10,10)=1.

IF(IMAXD.GE.39) IMAXD=39
MXWT1=IMAXD+1
DO 200 NJ=2,MXWT1
DO 100 K=1,NJ

WZERO(-1,N-1)=0.
WONE(9,NJ)=0.
WZERO(N,J-1)=0.
WZERO(NJ9,NJS)=0.

```

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720. \[ WZERO(K9,NJ9) = P00 \cdot WZERO(K9,NJ8) + P01 \cdot ONE(K8,NJ8) \]
721. \[ WONE(K9,NJ9) = P10 \cdot WZERO(K9,NJ8) + P11 \cdot ONE(K8,NJ8) \]
722. \[ W(K9,NJ9) = (1. - PWET) \cdot WZERO(K9,NJ9) + PWET \cdot WONE(K9,NJ9) \]

723. 100 CONTINUE
724. 200 CONTINUE
725. C
726. C CONVERT THE I+10 SEQUENCE TO LOWER SERIES STARTING FROM 1
727. C WHICH STANDS FOR DRY DAY, 2 FOR 1 WET DAY......
728. C
729. C
730. C
731. DO 500 I=1,MXWTPl
732. DO 500 J=1,I
733. I10=I+9
734. J10=J+9
735. WONE(J10,I10)=WONE(J,I)
736. WZERO(J10,I10)=WZERO(J,I)
737. IF(I.GT.1)W(J,I)=W(J10,I10)
738. 500 CONTINUE

739. C
740. C
741. C WRITE(6,35)
742. C 35 FORMAT(1H1,5X,'************** PROBABILITIES OF K WET DAYS IN COSEQUITIV
743. C 2E N DAYS ***********',5(/),T40,45('(''),//,T40,4X,'N',4X,'K',
744. C +3X,'WO(K;N)',3X,'Wi(K;N)',4X,'W(K;N)'
745. C DC 400 J2=1,IMAXD
746. C J3=J2+1
747. C WRITE(6,25)
748. C 25 FORMAT(//,T40,45('(''),//}}
749. C DO 300 I2=1,J3
750. C J210=J2+1
751. C I29=I2
752. C I1=I2-1
753. C WRITE(6,15)J:11,WZERO(I29,J210),WONE(I29,J210),
754. C 2 W(I29,J210)
755. C 15 FORMAT(T40,15,15,3F10,3)
756. C 300 CONTINUE
757. C 400 CONTINUE
758. RETURN
759. END

760. C
761. C
762. C******************************************************************************
763. C* CALCULATE THE DESIRED DRAINING AREA BY INTRAPOLATION
764. C*
765. C* XTIME: TIME ( X COORDINATE ) ;
766. C* YAREA: DRAINING AREA ( Y COORDINATE ) ;
767. C* TDRAIN: TIME OF 50 PERCENT DRAINAGE;
768. C* UDRAN: 50 PERCENT DRAINAGE;
769. C* TIMAX: MAXIMUM VALUE FOR TIME;
770. C* UEMAX: MAXIMUM VALUE FOR DRAINAGE;
771. C*
772. C******************************************************************************
773. C
774. C
775. SUBROUTINE INPOLA(TDRAN,UDRAN,IA,LOGTIM)
776. IMPLICIT REAL(J-Z)
777. COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
778. COMMON /TNUM/ INABT
779. COMMON LA,HE,TA,Kl,K2,N1,N2,Al,Bl,B2,Cl,Gl,G2,G3,R1

140
COMMON CASE,HED,HSUBA,HSUBB,NUM,S
COMMON /SGWET1/ SGWET(100),SGDRY(100),SGW(100),SGD(100)
DIMENSION LOGTIM(120,10),YAPER(120,10)
DATA IPT/20/
REAL INCEPT

SGEMT : TOTAL SUBGRADE MODULUS
SGWET : WET DEPTH OF SUBGRADE
SGDRY : DRY DEPTH OF SUBGRADE
SGDEP : DEPTH OF SUBGRADE (TOTAL DEPTH OF BASE AND SUBGRADE IS 70IN)

IA=INDS
DO 1000 I=1,IPT
   EXACT=1.0*I/IPT
   IX=100*I/IPT
   SGDEP=5.83333-HE
   DO 1100 12=1,100
      IF(I2.EQ.INABT) GO TO 2222
      IF(YAREA(I2,IA) .GT.EXACT) GO TO 1111
      1100 CONTINUE
      IL00=I2=1,100
      INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA)
      IL00=Hl00
      XTIME(IL00,IA)=INCEPT+REGCOE*EXACT
      YAREA(IL00,IA)=EXACT
      CALL SUBHT(XTIME(IL00,IA) ,HSUBX)
      SGWET(IX)=(HE-HSUEX)*N1/N2
      IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
      IF(SGWET(IX) .LE.0.OR.K2.EQ.O.) SGWET(IX)=0.
      SGDRY(IX)=5.83333-HE-SGWET(IX)
      IF(IFIX(100*EXACT) .EQ.IFIX(100*UDRAN) TDRAN=XTIME(I100,IA)
      GO TO 1000
      1001 IL00=I+100
      XTIME(IL00,IA)=TIMAX(IA)
      YAREA(IL00,IA)=UEMAX(IA)
      CALL SUBHT(XTIME(IL00,IA) ,HSUBX)
      SGWET(IX)=(HE-HSUEX)*N1/N2
      IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
      IF(SGWET(IX) .LE.0.OR.K2.EQ.O.) SGWET(IX)=0.
      SGDRY(IX)=5.83333-HE-SGWET(IX)
      WRITE(6,2)
      2 FORMAT(1H1,5(/),T30,'DRAINAGE%',11X,'TIME',5X,'PROBLEM NO.'
      DO 1200 I7=101,IMAX
         YAPER(I7,IA)=YAREA(I7,IA)*100.
      1200 CONTINUE
      DO 1600 IB=1,20
         IB100=13+100
         WRITE(6,305)YAPER(IB100,IA) ,XTIME(IB100,IA),IA
      305 FORMAT(T30,F9.1,5X,E10.3,I15)
SU3ROUTINE JUDGE(IA,INT,ITYPFI,IQFINE,GRAVPC,SANDPC)
COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
DIMENSION GRAVEL(3,4),SAND(3,4)
REAL INCEPT
DATA GRAVEL/3*80.,70.,60.,40.,60.,40.,20.,40.,30.,10./
DATA SAND/3*65.,57.,50.,35.,50.,35.,15.,25.,18.,8./
READ(5,345)ITYPFI,IQFINE,GRAVPC,SANDPC
345 FORMAT(215,2F10.0)
PERIND=(GRAVPC*GRAVEL(ITYPFI,IQFINE)+SANDPC*SAND(ITYPFI,IQFINE)*0.01
UCRIT=15./PERIND
UCRPER=100.-UCRIT
DO 400 I2=1,INT
IF(YAREA(I2,IA).LT.UCRIT) GO TO 400
11=12-1
REGCOE=(XTIME(I2,IA)-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA)
INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA)
TCRIT=INCEPT+REGCOE*UCRIT
IF(YAREA(I2,IA).GE.UCRIT) GO TO 4411
400 CONTINUE
4411 WRITE(6,415)GRAVEL(ITYPFI,IQFINE),GRAVPC,SAND(ITYPFI,IQFINE),
415 FORMAT(5(/),T30,******** EVALUATION OF DRAINAGE DESIGN ********',
1,T30,'WATER DRAINED PERCENTAGE DUE TO GRAVEL =',F11.2,
2,T30,'PERCENTAGE OF GRAVEL IN THE SAMPLE =',F11.2,
3,T30,'WATER DRAINED PERCENTAGE DUE TO SAND =',F11.2,
4,T30,'PERCENTAGE OF SAND IN THE SAMPLE =',F11.2,
5,T30,'PERCENTAGE OF WATER WILL BE DRAINED =',F11.2,3(/)
IF(UCRIT.GE.1.) WRITE(6,1115)
1115 FORMAT(1/,T30,'CRITICAL DRAINAGE DEGREE (85% SATURATION)='
2,T30,'DRAINING TIME FOR 85% SATURATION (HOURS) =',F11.2,3(/)
IF(TCRIT.GT.10.) WRITE(6,1115)
1115
SUBROUTINE POR02

IMPLICIT REAL(J-Z)
INTEGER N,NA,NB,NC,NJONT,NLANE
COMMON LA,HE,TA,K1,K2,N1,N2,AL,B1,B2,CL,G1,G2,G3,R1
COMMON CASE,HED,HSUBA,HSUBB,NUM,S
DATA EPSI/0.1E-03/
DELK=0.10
IF(K2.LE.K1) GO TO 455
-N1=N1
GO TO 999
455 AFCTR=((1.-N1)**2)*K1/(K2*(K1**3))
K=K2*0.1/K1
FOFK1=AFCTR*K**3-K**2+2.*K-1.
204 KN=K+DELK
FOFKN=AFCTR*KN**3-KN**2+2.*KN-1.
IF(FOFK1*FOFKN)206,205,207
205 CONTINUE
IF(FOFK1.EQ.0.) N2=K
IF(FOFKN.EQ.0.) N2=KN
RETURN
207 K=KN
FOFK1=FOFKN
GO TO 204
206 N21=KN
208 FOFN=AFCTR*N21**3-N21**2+2.*N21-1.
DFDN=3.*AFCTR*N21**2-2.*N21+2.
N2=N21-FOFN/DFDN
IF(ABS(N2-N21)-EPSI)210,210,209
209 N21=N2
GO TO 208
210 FOFN2=AFCTR*N2**3-N2**2+2.*N2-1.
999 RETURN
END
SUBROUTINE RAIN(HALFT,IMAXD)
IMPLICIT INTEGER (I-N)
DIMENSION ITITL2(20)
DIMENSION AMT(5,300),SUM(10),NUM(10),YDRAN(100),WPROB(50,50)
COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE
COMMON /DRYWET/ TLAMDA,DRYLAM,WETLAM,PWET
COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10)
COMMON /NOGAMA/ NUMWET,AVGAMT,TOTSUM
READ THE RAINFALL AMOUNT DATA IN AND COUNT THE NUMBER OF WET DAYS
AMT(1): THE RAINFALL AMOUNT DURING THE PERIOD IS CONCERNED (IN INCHES)
AMT(2): THE SEQUENCE OF DRY DAYS
AMT(3): THE SEQUENCE OF WET DAYS
ITYPE: TYPE OF PAVEMENT, EITHER PCC OR BCP
ASOIL: SOIL TYPES CLASSIFIED BY 'AASHTO' OR 'UNIFIED'.
BHORIZ: HORIZON (ABC OR BC). P.86, ASCE TRAN. ENGR. J., JAN, 1979
IBC: INDEX OF BASE MATERIALS
CRKJON: THE LENGTH OF CRACKS AND JOINTS (IN FEET) FROM FIELD SURVEY
FTLONG: THE TOTAL LENGTH SURVEYED FOR CRACKS AND JOINTS
YEAR: THE EVALUATED PERIOD IN YEARS
CONST: CONSTANT 'K' FOR INTENSITY-DURATION-RECURRENT EQUATION
DEFAULT = 0.3
RECPOW: POWER OF RECURRENT INTERNAL (PERIOD EVALUATED)
DEFAULT = 0.25
DURPOW: POWER OF RAINFALL DURATION
DEFAULT = 0.75
SHAPE: THE CONSTANT DUE TO CURVE SHAPE OF RAINFALL INTENSITY VS. PERIOD
DEFAULT = 1.65 (GAUSSIAN CURVE)
REAL*8 ASOIL
INTEGER BHORIZ
C INPUT MATERIAL PROPERTIES OF BASE AND SUBGRADE
READ(5,445)IBC,ITYPE,ASOIL,BHORIZ
445 FORMAT(I4,A4,A8,A4)
READ (5, 485) CRKJON,FTLONG
485 FORMAT(2F10.0)
READ(5,475)YEAR,CONST,RECPOW,DURPOW,SHAPE
475 FORMAT(5F10.2)
IF(CONST.EQ.0.) CONST=0.3
IF(RECPOW.EQ.0.) RECPOW=0.25
IF(DURPOW.EQ.0.) DURPOW=0.75
1020.
IF(SHAPE.EQ.0.) SHAPE=1.65
1021.
WRITE(6,955)
1022.
955 FORMAT(1H1,T30,'***** PAVEMENT TYPES DATA AND PERIOD *****',/IX,
1023. 2T20,'PVMT TYPE ',5X,'SOIL CLASS',5X,' HORIZON',6X,' CRK.JT. FT.',
1024. 35X,' SURVEYED FT',5X,' PERIOD(YEAR)',/)
1025.
WRITE(6,965)ITYPE,ASOIL,BHORIZ,CRKJON,FTLONG,YEAR
1026.
965 FORMAT(T20,A10,7X,A8,11X,A4,2(5X,F13.1),5X,F13.0,//)
1027.
WRITE(6,455)
1028.
455 FORMAT(T30,'*****CHARACTERISTICS OF RAINFALL INTENSITY-DURATION-RE
1029. 2CURRENCE EQUATION*****',//,T3G,
1030. 3'K(I-D-R EQ)', 'REC. POWER', ' DUR. POWER',
1031. 4' CURVE SHAPE',//)
1032.
WRITE (6, 465)CONST,RECPOW, DURPOW, SHAPE
1033.
465 FORMAT(T3C,4F13.2)
1034.
READ ~N RAINFALL DATA. ISEQ:
1035. 1,RAINFALL AMOUNT EACH RAINY DAY;
1036. C 2,SEQUENCE OF DRY DAYS FREQUENCY
1037. C 3,SEQUENCE OF WET DAYS FREQUENCY
1038.
READ(5,985)
1039.
985 FORMAT(I3)
1040.
DO 77777 ITIME=1,IRAIN
1041.
DO 415 INT=(L-1)*16+l,IRAIN
1042.
READ(5,405) ITITL2
1043.
WRITE(6,495) ITITL2
1044.
DO 500 ISEQ=1,3
1045.
200 NUM(ISEQ)=0
1046.
DO 100 L=1,20
1047.
INT=(L-1)*16+1,20
1048.
IEN=(L-1)*16+16
1049.
READ(5,415) (AMT(ISEQ,I),I=INT,IEN)
1050.
FC1mAT
1051.
DO 200 I=INT,ITIML2
1052.
IF(AMT(ISEQ,I) .EQ.O.) GO TC 5QJ
1053.
NUH(ISEQ)=I
1054.
CONTINUE
1055.
500 CONTINUE
1056.
DO 800 IJ=1,3
1057.
K=NUM(IJ)
1058.
IF(K.EQ.0) K=1
1059.
IF(IJ.EQ.1) WRITE(6,915) NUM(1)
1060.
IF(IJ.EQ.2) WRITE(6,925) NUM(2)
1061.
995 FORMAT(T40,1615)
1062.
IF(IJ.EQ.3) WRITE(6,935) NUM(3)
1063.
905 FORMAT(T40,16FS.2)
1064.
915 FORMAT('I,J,EQ.1 WRITE(6,995)(IFIX(AMT(IJ,I)),I=1,K)
1065.
1073.
1074.
TOTSUM: TOTAL NUMBER OF DAYS IN A PERIOD
1075.
TOTNUM: TOTAL NUMBER OF COUNTS FROM DRY AND WET DAYS' SEQUENCE
1076.
IF(IJ.EQ.1) WRITE(6,905)(AMT(IJ,I),I=1,K)
1077.
800 CONTINUE
1078.
C THE AVERAGE AND VARIANCE
1079.
C
DO 600 IB=1,3
  SUM(IB)=0.
  IVALUE=NUM(IB)
  IF(IVALUE.EQ.0) IVALUE=1
  DO 300 J=1,IVALUE
    SUM(IB)=SUM(IB)+AMT(IB,J)
  300 CONTINUE
  600 CONTINUE
C
NUMWET=NUM(1)
IF(NUMWET.EQ.0) GO TO 333
AVGAMT=SUM(1)/NUM(1)
IF(IVALUE.EQ.0) IVALUE=1
DO 300 J=1,IVALUE
  SUM(IB)=SUM(IB)+AMT(IB,J)
300 CONTINUE
NUMWET=NUM(1)
IF(NUMWET.EQ.0) GO TO 333
AVGAMT=SUM(1)/NUM(1)
GO TO 444
333 AVGAMT=0.
444 TOTNUM=NUM(2)+NUM(3)
TOTSUM=SUM(2)+SUM(3)
AVGRAS=SUM(1)/TOTSUM
IF(NUMWET.LE.1) GO TO 888
DRYLAM=TOTNUM/SUM(2)
WETLAM=TOTNUM/SUM(3)
TLAMDA=DRYLAM+WETLAM
PDRY=DRYLAM/TLAMDA
PWET=WETLAM/TLAMDA
AVGAMT: AVERAGE RAINFALL AMOUNT PER RAINY DAY
AVGRAS: AVERAGE RAINFALL AMOUNT PER DAY
WETLAM: RECIPROCAL OF THE AVERAGE OF WET DAYS
DRYLAM: RECIPROCAL OF THE AVERAGE OF DRY DAYS
SSAMT=0.
DO 400 K=1,NUMWET
  AMT(1,K)=AMT(1,K)-AVGAMT
400 SSAMT=SSAMT+(AMT(1,K)-AVGAMT)**2
VARAMT=SSAMT/NUMWET
PARAMETERS OF GAMMA DISTRIBUTION
ALPHA=AVGAMT**2/VARAMT
BETA=AVGAMT/VARAMT
THE DURATION OF RAINFALL(HOURS) CORRESPONDING TO AVERAGE RAINFALL
WRITE(6,945)
FORMAT(///,T30,'***** PARAMETERS OF GAMMA DISTRIBUTION AND MARKOV
2CHAIN MODEL *****')
WRITE(6,435)AVGAMT,VARAMT,ALPHA,BETA
2,DRYLAM,WETLAM,TLAMDA,PDRY,PWET
435 FORMAT(///,T40,'AVERAGE RAINFALL AMOUNT PER WET DAY(INCHES) =',F10.3,/,1260)
2
T40,'VARIANCE OF RAINFALL AMOUNT =',F10.3,/,1270
3
T40,'ALPHA OF GAMMA DISTRIBUTION =',F10.3,/,1280
4
T40,'BETA OF GAMMA DISTRIBUTION =',F10.3,/,1290
5
T40,'LAMDA OF DRY DAYS (MARKOV PROCESS) =',F10.3,/,1300
6
T40,'LAMDA OF WET DAYS (MARKOV PROCESS) =',F10.3,/,1310
7
T40,'SUM OF LAMDA OF DRY AND WET DAYS =',F10.3,/,1320
8
T40,'PROBABILITY OF DRY DAYS =',F10.3,/,1330
9
T40,'PROBABILITY OF WET DAYS =',F10.3,/,1340
IF(TIMAX(INDS)/24.LT.1.) GO TO 888
CALL KATZ(IMAXD,WPROB)
CALL DRYDAY(IMAXD,YDRAN,WPRGB)
CALL FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE,ASOIL,
2BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPROB,IMAXD)
SUBROUTINE SH1P2 (AREA2, GAMDIS, XMIN, XMAX, N, ALPHA, BETA)

H = (XMAX - XMIN) / N
SUM = 0.0
X = XMIN + H
DO 4 I = 2, N
   IF (MOD(I, 2)) 2, 2, 3
   SUM = SUM + 4. * GAMDIS (X, ALPHA, BETA)
   GO TO 4
   SUM = SUM + 2. * GAMDIS (X, ALPHA, BETA)
   X = X + H
4   CONTINUE

AREA2 = H / 3. * (GAMDIS (XMIN, ALPHA, BETA) + SUM + GAMDIS (XMAX, ALPHA, BETA))
RETURN

FUNCTION GAMDIS (X, ALPHA, BETA)

X HAS TO BE GREATER THAN 0. IN GAMMA DISTRIBUTION
IF (X .LE. 0. AND. ALPHA .LE. 1) GO TO 3333
GAMDIS = X ** (ALPHA - 1.) * EXP (-X * BETA) * (BETA ** ALPHA) / (GAMMA (ALPHA))
RETURN
3333  GAMDIS = 10.
RETURN
END

SUBROUTINE SIMPSN (AREA, DUMMYF, XMIN, XMAX, N)

INTEGER N, NA, NB, NC, NJONT, NLANE
REAL LA, K1, K2, N1, N2
COMMON LA, HE, TA, K1, K2, N1, N2, A1, B1, B2, CL, CL1, G1, G2, G3, R1
COMMON CASE, HED, HSUBA, HSUBB, NUM, S
H = (XMAX - XMIN) / N
SUM = 0.0
X = XMIN + H
DO 4 I = 2, N
   IF (MOD(I, 2)) 2, 2, 3
SUM=SUM+4.*DUMMYF(X)
GO TO 4
SUM=SUM+2.*DUMMYF(X)
X=X+H
AREA=H/3.*(DUMMYF(XMIN)+SUM+DUMMYF(XMAX))
RETURN
END

C*****************************~*********************** ******************

THE HEIGHT OF WATER LEVEL DUE TO SUBGRADE DRAINAGE ONLY

TAREA: TIME;

HUB: HEIGHT OF WATER LEVEL WHICH IS A FUNCTION OF TIME;

SUBROUTINE SUEHT(TAREA,HSUB)
IMPLICIT REAL(J-Z)
INTEGER N,NA,NB,NC,NJONT,NLANE
COMMON LA,HE,TA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
COMMON CASE,HED,HSUBA,HSUEB,NUM,S
AA=(N1*K2/K1)-(N1**2/N2)
BB=K2*(1.-N1/N2)*TAREA-HE*(N1*K2/K1-2.*N1**2/N2)
CC=K2*N1*HE*TAREA/N2-(N1*HE)**2/N2
SQB=BB**2-4.*AA*CC
IF(SQB.LE.0.) SQB=0.
HSUB=(SQRT(SQB)-BE)/(2.*AA)
RETURN
END
**PROBLEM NUMBER 1**  
ANALYSIS OF HOUSTON PAVEMENT IN MAY, 1970.

**SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINAGE**

<table>
<thead>
<tr>
<th>LENGTH</th>
<th>HEIGHT</th>
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<th>PERM.1</th>
<th>PERM.2</th>
<th>PORD.1</th>
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**SLOPE FACTOR = 0.444**

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

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<th>HEAD ON X COOR.</th>
<th>HT.(SUB.DRAIN ONLY)</th>
<th>AVG. HEIGHT.</th>
<th>TIME(STAGE 1)</th>
<th>DRAINAGE DEG.</th>
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<td>0.3371E 02</td>
<td>0.6000E 00</td>
</tr>
<tr>
<td>0.2833E 00</td>
<td>0.5000E 00</td>
<td>0.2889E 00</td>
<td>0.3611E 02</td>
<td>0.6222E 00</td>
</tr>
<tr>
<td>0.2667E 00</td>
<td>0.5000E 00</td>
<td>0.1778E 00</td>
<td>0.3667E 02</td>
<td>0.6444E 00</td>
</tr>
<tr>
<td>0.2500E 00</td>
<td>0.5000E 00</td>
<td>0.1667E 00</td>
<td>0.4142E 02</td>
<td>0.6667E 00</td>
</tr>
<tr>
<td>0.2333E 00</td>
<td>0.5000E 00</td>
<td>0.1556E 00</td>
<td>0.4439E 02</td>
<td>0.6889E 00</td>
</tr>
<tr>
<td>0.2167E 00</td>
<td>0.5000E 00</td>
<td>0.1444E 00</td>
<td>0.4762E 02</td>
<td>0.7111E 00</td>
</tr>
<tr>
<td>0.2000E 00</td>
<td>0.5000E 00</td>
<td>0.1333E 00</td>
<td>0.5113E 02</td>
<td>0.7333E 00</td>
</tr>
<tr>
<td>0.1833E 00</td>
<td>0.5000E 00</td>
<td>0.1222E 00</td>
<td>0.5499E 02</td>
<td>0.7556E 00</td>
</tr>
<tr>
<td>0.1667E 00</td>
<td>0.5000E 00</td>
<td>0.1111E 00</td>
<td>0.5926E 02</td>
<td>0.7778E 00</td>
</tr>
<tr>
<td>0.1500E 00</td>
<td>0.5000E 00</td>
<td>0.1000E 00</td>
<td>0.6402E 02</td>
<td>0.8000E 00</td>
</tr>
<tr>
<td>0.1333E 00</td>
<td>0.5000E 00</td>
<td>0.8889E-01</td>
<td>0.6940E 02</td>
<td>0.8222E 00</td>
</tr>
<tr>
<td>0.1167E 00</td>
<td>0.5000E 00</td>
<td>0.7778E-01</td>
<td>0.7557E 02</td>
<td>0.8444E 00</td>
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<tr>
<td>0.1000E 00</td>
<td>0.5000E 00</td>
<td>0.6667E-01</td>
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<td>0.8667E 00</td>
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<tr>
<td>0.8333E-01</td>
<td>0.5000E 00</td>
<td>0.5556E-01</td>
<td>0.9135E 02</td>
<td>0.8889E 00</td>
</tr>
<tr>
<td>0.6667E-01</td>
<td>0.5000E 00</td>
<td>0.4444E-01</td>
<td>1.020E 03</td>
<td>0.9111E 00</td>
</tr>
<tr>
<td>0.5000E-01</td>
<td>0.5000E 00</td>
<td>0.3333E-01</td>
<td>1.1158E 03</td>
<td>0.9333E 00</td>
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<tr>
<td>0.3333E-01</td>
<td>0.5000E 00</td>
<td>0.2222E-01</td>
<td>1.356E 03</td>
<td>0.9556E 00</td>
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<tr>
<td>0.1667E-01</td>
<td>0.5000E 00</td>
<td>0.1111E-01</td>
<td>1.697E 03</td>
<td>0.9778E 00</td>
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<td>0.5000E 00</td>
<td>0.5556E-02</td>
<td>2.041E 03</td>
<td>0.9889E 00</td>
</tr>
</tbody>
</table>
## Evaluation of Drainage Design

<table>
<thead>
<tr>
<th>DRAINAGE%</th>
<th>TIME</th>
<th>PROBLEM NO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.655E 00</td>
<td>1</td>
</tr>
<tr>
<td>10.0</td>
<td>0.215E 01</td>
<td>1</td>
</tr>
<tr>
<td>15.0</td>
<td>0.413E 01</td>
<td>1</td>
</tr>
<tr>
<td>20.0</td>
<td>0.641E 01</td>
<td>1</td>
</tr>
<tr>
<td>25.0</td>
<td>0.892E 01</td>
<td>1</td>
</tr>
<tr>
<td>30.0</td>
<td>0.114E 02</td>
<td>1</td>
</tr>
<tr>
<td>35.0</td>
<td>0.144E 02</td>
<td>1</td>
</tr>
<tr>
<td>40.0</td>
<td>0.174E 02</td>
<td>1</td>
</tr>
<tr>
<td>45.0</td>
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<tr>
<td>50.0</td>
<td>0.246E 02</td>
<td>1</td>
</tr>
<tr>
<td>55.0</td>
<td>0.289E 02</td>
<td>1</td>
</tr>
<tr>
<td>60.0</td>
<td>0.337E 02</td>
<td>1</td>
</tr>
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<td>65.0</td>
<td>0.394E 02</td>
<td>1</td>
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<tr>
<td>70.0</td>
<td>0.460E 02</td>
<td>1</td>
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<tr>
<td>75.0</td>
<td>0.540E 02</td>
<td>1</td>
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<tr>
<td>80.0</td>
<td>0.640E 02</td>
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</tr>
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<td>85.0</td>
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<td>90.0</td>
<td>0.967E 02</td>
<td>1</td>
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<tr>
<td>95.0</td>
<td>0.131E 03</td>
<td>1</td>
</tr>
<tr>
<td>98.9</td>
<td>0.204E 03</td>
<td>1</td>
</tr>
</tbody>
</table>

---

**** This drainage design is in the marginally acceptable region ****
***** PAVEMENT TYPES DATA AND PERIOD *****

<table>
<thead>
<tr>
<th>PVMT TYPE</th>
<th>SOIL CLASS</th>
<th>HORIZON</th>
<th>CRK.JT. FT.</th>
<th>SURVEYED FT</th>
<th>PERIOD(YEAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCP</td>
<td>A-7-6</td>
<td>ABC</td>
<td>0.0</td>
<td>100.0</td>
<td>10</td>
</tr>
</tbody>
</table>

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

K(I-D-R EQ)  REC. POWER  DUR. POWER  CURVE SHAPE

0.30  0.25  0.75  1.65
RAINFALL DATA AND ANALYSIS OF HOUSTON FAA AIRPORT; MAY, 1970.

***** RAINFALL AMOUNT DATA*****
NO. OF COUNTS = 9

1.65 0.01 4.20 0.45 4.22 0.01 1.04 2.25 1.01

***** SEQUENCE OF DRY DAYS *****
NO. OF COUNTS = 4

8 4 4 6

***** SEQUENCE OF WET DAYS *****
NO. OF COUNTS = 5

1 1 2 3 2

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

AVERAGE RAINFALL PER WET DAY (INCHES) = 1.649
VARIANCE OF RAINFALL AMOUNT = 2.341

ALPHA OF GAMMA DISTRIBUTION = 1.161
BETA OF GAMMA DISTRIBUTION = 0.704

LAMDA OF DRY DAYS (MARKOV PROCESS) = 0.409
LAMDA OF WET DAYS (MARKOV PROCESS) = 1.000
SUM OF LAMDA OF DRY AND WET DAYS = 1.409

PROBABILITY OF DRY DAYS = 0.710
PROBABILITY OF WET DAYS = 0.290

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

POO = 0.781   P01 = 0.219
P10 = 0.536   P11 = 0.464
<table>
<thead>
<tr>
<th>PROBLEM NO.</th>
<th>TIME(DAYS)</th>
<th>DRAINAGE(%)</th>
<th>PROB(CONSECUTIVE DRY DAYS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>49.24</td>
<td>0.710</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>71.35</td>
<td>0.554</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>83.16</td>
<td>0.432</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>89.86</td>
<td>0.338</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>93.80</td>
<td>0.264</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>96.11</td>
<td>0.206</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>97.67</td>
<td>0.161</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>100.00</td>
<td>0.125</td>
</tr>
</tbody>
</table>
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

(TH E ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED ON DEMPSEY'S FIELD EQUATION)

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

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

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

| AVERAGE FREE WATER IN BASE (SQ.FEET) | 1.55 |
| DURATION OF AVERAGE RAINFALL AMOUNT (HOURS) | 0.080 |
| AVERAGE RAINFALL AMOUNT PER DAY (INCHES) | 0.479 |
| AVERAGE BASE COURSE MODULUS IN WET STATE (KSI) | 25.84 |
| AVERAGE BASE COURSE MODULUS (KSI) | 39.55 |
| AVERAGE SUBGRADE MODULUS (KSI) | 31.22 |
(b) Water Penetration Into and Evaporation from a Low Permeability Base Course
C WATER INFILTRATION AND EVAPORATION OF A LOW PERMEABLE BASE COURSE

TEXAS TRANSPORTATION INSTITUTE
AUGUST 1983

DIMENSION ASUBN(20),USOIL(50,50),SIGMA(20),ZROOT(20)
DIMENSION EVWT(1000),SERIES(20)
CALL LOWPER(DEPTH,INFILT)
CALL EVAPOR(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
CALL EWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
WRITE(6,115)
115 FORMAT(1H1)
STOP
END

C EVAPORATION OF WATER FROM SOIL WITH P. MITCHELL'S SOLUTION

C THIS SUBPROGRAM IS TO COMPARE THE SUCTION LEVELS OF DIFFERENT DEPTH
C AT CERTAIN TIME IN ORDER TO CHECK WITH MITCHELL'S SOLUTION

DIMENSION ASUBN(20),USOIL(50,50),SIGMA(20),ZROOT(20)

UATM : SUCTION OF ATMOSPHERE IN PF (LOG H)
UNOT : INITIAL SUCTION STATE OF SOIL IN PF
DIFC : DIFFUSION COEFFICIENT OF A SOIL (CM**2/SEC)
DEPTH : WATER DEPTH IN SOIL (CM)
YVERT : VERTICAL DISTANCE FROM SOIL BOTTOM (CM)
EVTIME: ELAPSED TIME FOR EVAPORATION (SEC)
HRTIME: ELAPSED TIME FOR EVAPORATION (HOUR)
DYTIME: ELAPSED TIME FOR EVAPORATION (DAYS)
ASUBN : COEFFICIENT OF FOURIER SERIES
SIGMA : EVERY SINGLE TERM OF THE FOURIER SERIES
TSIGMA: TOTAL SUM FOR TEN TERMS OF FOURIER SERIES
USOIL : SOIL SUCTION IN DIFFERENT DEPTH AND TIME (I2:DEPTH,I1:TIME)
ZROOT : ROOTS OF COTAN(Z)=Z/(DEPTH*EVAPC)
EVAPC : EVAPORATION COEFFICIENT IN CM/SEC
DQDU : THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF)

READ(5,305) UATM,UNOT,DIFC,DQDU,EvAPC
305 FORMAT(5E10.3)
WRITE(6,405)UATM,UNOT,DIFC,DQDU,EvAPC,DEPTH
405 FORMAT(1H1,///,T30,'********** EVAPORATION OF WATER FROM SOIL ****',1H1,35 closets
2***','
157
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 I=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
00600
00610
00620
00630
00640
00650
CALL EVROOT(ZROOT,DEPTH,EVAPC)
DO 3000 1=1,10
  ASUBN(I)=2.0*(UNOT-UATM)*SIN(ZROOT(I))/
  (ZROOT(I)+SIN(ZROOT(I))*COS(ZROOT(I)))
3000 CONTINUE
WRITE(6,105)
GO TO 50
121. IF(FOFXM.EQ.0.) ZROOT(I)=XM
122. IF(FOFXL.EQ.0.) ZROOT(I)=XL
123. GO TO 2222
124. XL=XM
125. IF(ABS(XL-XR)-EPSI)
126. CONTINUE
127. GO TO 2222
128. FZROOT=AMPLIT*COTAN(ZROOT(I))-ZROOT(I)
129. CONTINUE
130. RETURN
131. END
132. C
133. C***********************************************************************
134. C WATER AMOUNT EVAPORATED FROM BARE SOIL
135. C***********************************************************************
136. SUBROUTINE EVWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
137. DIMENSION ASUBN(20) ,EVWT(1000) ,SERIES(20) ,ZROOT(20)
138. C COMPUTATION OF AMOUNT OF WATER EVAPORIZED FROM SOIL
139. C EVWT : WATER AMOUNT EVAPORIZED FROM SOIL IN CM
140. C SERIES: SINGLE TERM FOR THE FOURIERS SERIES
141. C TSERIE: SUM OF THE SERIES WHICH IS INTEGRATED FROM SUCTION AT
142. C SPECIFIC TIME
143. C DQDU : THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF)
144. C
145. WRITE(6,405)
146. 405 FORMAT(1H1,2(/) ,T30,'*********** WATER AMOUNT EVAPORIZED FROM SOIL
147. 2 **********' ,3(/),T60,'EVAPORATION TIME(HOUR) , ,T60,'EVAPORATION AM
148. 30UNT (CM)', 3 (/) )
149. DO 4100 IK=1,720
150. TSERIE=O.
151. HRTIME=IK*1-
152. EVTIME=HRTIME*3600.
153. DO 4000 I=1,10
154. POWER=ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2)
155. IF(ABS(POWER).GE.100.) GO TO 4411
156. SERIES(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2))
157. 2
158. TSERIE=TSERIE+SERIES(I)
159. 4000 CONTINUE
160. 4411 EVWT(IK)=(UATM-UNOT+TSERIE)*DEPTH*DQDU
161. OUTPUT THE RESULTS EVERY 2 HOURS
162. I2=IK/2*2
163. IF(I2.NE.IK.AND.EVWT(IK).LT.DEPTH) GO TO 4100
164. WRITE(6,415) HRTIME,EVWT(IK)
165. 415 FORMAT(2(/),T45,Fl0.2,T60,F23.4)
166. IF(EVWT(IK).GE.DEPTH) GO TO 4444
167. 4100 CONTINUE
168. 4444 RETURN
169. END
SUBROUTINE LOWPER(DEPTH,INFILT)

THIS SUBPROGRAM IS USED TO COMPUTE THE WATER DISTRIBUTION IN A LOW PERMEABILITY BASE COURSE FROM THE CRACKS/JOINTS IN A PAVEMENT.

EULER'S METHOD IS APPLIED AS A NUMERICAL ANALYSIS.

UNITS: TIME - HOUR; LENGTH - CENTIMETER; PERMEABILITY - CENTIMETER/HOUR.

UNITS ARE FREE AS LONG AS THEY ARE CONSISTENT. ABOVE IS IN GENER

WC : WIDTH OF CRACKS/JOINTS
TL : DEPTH OF CRACKS/JOINTS
HPERM : HORIZONTAL PERMEABILITY OF BASE
VPERM : VERTICAL PERMEABILITY OF BASE
DPWA : DEPTH OF WATER LEFT IN CRACKS/JOINTS
TIME : TIME PASSED FOR WATER PENETRATION
YOFT : VERTICAL DISTANCE INTO WHICH WATER INFILTRATES
XOFT : HORIZONTAL DISTANCE INTO WHICH WATER FLOWS
POR01 : POROSITY OF BASE SOIL
INFILT: TIME FOR ALL WATER FROM CRACKS/JOINTS INFILTRATES INTO BASE

DIMENSION DPWA(1000),TIME(1000),XOFT(1000),YOFT(1000),DL(1000)

READ(5,25)WC,TL,HPERM,VPERM,POR01,HTCP

WRITE(6,45)

45 FORMAT(lH1,//,T30,'********** WATER DISTRIBUTION OF LOW PERMEABILITY',//)

WRITE(6,55)WC,TL,HPERM,VPERM,POR01,HTCP

55 FORMAT( //,T20,'WIDTH OF CRACK/JOINT (CM) =',E10.3, 0

2 //,T20,'DEPTH OF CRACK/JOINT (CM) =',E10.3, 0

3 //,T20,'VERTICAL PERMEABILITY OF BASE (CM/HR) =',E10.3, 0

4 //,T20,'HORIZONTAL PERMEABILITY OF BASE (CM/HR) =',E10.3, 0

5 //,T20,'POROSITY OF BASE COURSE =',E10.3, 0

6 //,T20,'CAPILLARY HEAD OF BASE (CM) =',E10.3) 0

WRITE(6,65)

65 FORMAT (///,13X,'TIME (HOUR)',5X,'HORIZONTAL DIST.(CM)', 0

27X,'VERTICAL DIST.(CM)',4X,'CRACK WATER DEPTH(CM)://' 0

DPWA(1)=TL
YOFT(1)=0.
TIME(1)=0.
DELY=0.01
DO 100 I=2,1000
IM1=I-1
YOFT(I)=YOFT(IM1)+DELY
DT=POR01*YOFT(I)*DELY/(VPERM*(YOFT(I)+HTCP+TL))
TIME(I)=TIME(IM1)+DT
XOFT(I)=SQRT(2.*HPERM*TIME(I)*(TL+HTCP)/POR01)
DENT=(HPERM*YOFT(I)*(TL+HTCP)/XOFT(I)+2*VPERM*XOFT(I)*YL(T+HTCP)/YOFT(I))*1.5708/POR01
DL(I)=(DENT*DT)/WC
DPWA(I)=DPWA(IM1)-DL(I)

IF(DPWA(I).LE.O.) GO TO 222
ID=IM1/10*10
IF(ID-IDM1)100,111,100
USE INTRAPOLATION TO ENUMERATE THE FINAL DEPTH WHERE WATER WILL REACH

C

DEPT=YOFT(I)-(YOFT(I)-YOFT(IM1))/(DPWA(I)-DPWA(IM1))*DPWA(I)
YOFT(I)=DEPT
DELY2=DEPT-YOFT(IM1)
DT=POR01*DEPT*DELY2/(VPERM*(DEPT+HTCP+TL))
TIME(I)=TIME(IM1)+DT
INFILT=TIME(I)
XOFT(I)=SQRT(2.*HPERM*TIME(I)*TL+HTCP)/POR01
DENT=(HPERM*DEPT*(TL+HTCP)/XOFT(I)+
2
VPERM*XOFT(I)*(DEPT+TL+HTCP)/DEPT)*1.5708/POR01
DL(I)=(DENT*DT)/WC
DPWA(I)=DPWA(IM1)-DL(I)
WRITE(6,75) TIME(I),XOFT(I),DEPTH,DPWA(I)
RETURN
### 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

<table>
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<tr>
<th>Time (Hour)</th>
<th>Horizontal Dist. (cm)</th>
<th>Vertical Dist. (cm)</th>
<th>Crack Water Depth (cm)</th>
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<td>0.846E-04</td>
<td>0.332E 00</td>
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<td>0.715E-03</td>
<td>0.964E 00</td>
<td>0.300E 00</td>
<td>0.248E 02</td>
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<td>0.126E-02</td>
<td>0.128E 01</td>
<td>0.400E 00</td>
<td>0.246E 02</td>
</tr>
<tr>
<td>0.196E-02</td>
<td>0.160E 01</td>
<td>0.500E 00</td>
<td>0.244E 02</td>
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<tr>
<td>0.281E-02</td>
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<td>0.700E 00</td>
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<td>0.254E 01</td>
<td>0.800E 00</td>
<td>0.234E 02</td>
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<td>0.100E 01</td>
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<td>0.130E 01</td>
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****** 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 ******

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<th>SOIL DEPTH (CM)</th>
<th>SUCTION (PF)</th>
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<td>t</td>
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<td>y2</td>
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<td>EVAPORATION TIME (HOUR)</td>
<td>EVAPORATION AMOUNT (CM)</td>
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<td>-------------------------</td>
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</table>
E-3. GUIDE FOR DATA INPUT TO COMPUTER PROGRAM

(a) Simulation Model of Rainfall Infiltration and Drainage Analysis

1. Identification Card (I5, I3, I8A4)

   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 α = 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 5-1)

1. Crushed limestone+4% cement
2. Crushed limestone+2% lime
3. Crushed limestone
4. Gravel
5. Sand clay
6. Embankment-compacted plastic clay

**cc 5-8 ITYPE** Pavement type (PCC or BCP)

**cc 9-16 ASOIL** Types of subgrade soils classified by "AASHO" or Unified (see Table 3)

**cc 17-20 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 (5F10.0) (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)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc 1-10</td>
<td>Width of Crack/Joint (cm)</td>
<td>WC</td>
</tr>
<tr>
<td>cc 11-20</td>
<td>Depth of Crack/Joint (cm)</td>
<td>TL</td>
</tr>
<tr>
<td>cc 21-30</td>
<td>Permeability of Horizontal</td>
<td>Hperm</td>
</tr>
<tr>
<td>direction in Base Course</td>
<td>(cm/hr)</td>
<td></td>
</tr>
<tr>
<td>cc 31-40</td>
<td>Permeability of Vertical</td>
<td>Vperm</td>
</tr>
<tr>
<td>direction in Base Course</td>
<td>(cm/hr)</td>
<td></td>
</tr>
<tr>
<td>cc 41-50</td>
<td>Porosity of Base Course</td>
<td>Pror</td>
</tr>
<tr>
<td>(dimensionless)</td>
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<td></td>
</tr>
<tr>
<td>cc 51-60</td>
<td>Capillary head in Base Course</td>
<td>Htcp</td>
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<tr>
<td>(cm)</td>
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2. Characteristics of water evaporation from the base course and boundary conditions (5E 10.3)

<table>
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<th>Code</th>
<th>Description</th>
<th>Units</th>
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</thead>
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<td>Suction of atmosphere (pF)</td>
<td>Uatm</td>
</tr>
<tr>
<td>cc 11-20</td>
<td>Initial suction of base soil</td>
<td>Unot</td>
</tr>
<tr>
<td>(pF)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cc 21-30</td>
<td>Diffusion Coefficient</td>
<td>Difc</td>
</tr>
<tr>
<td>(cm²/sec)</td>
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<tr>
<td>cc 31-40</td>
<td>Slope ratio between water</td>
<td>Qdu</td>
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<td>content and suction</td>
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<tr>
<td>cc 41-50</td>
<td>Evaporation Coefficient</td>
<td>Evapc</td>
</tr>
<tr>
<td>(cm/sec)</td>
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</tr>
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