ENVIRONMENTAL EFFECTS ON PAVEMENTS

Damage Analysis

Shang J. Liu

Robert L. Lytton

Texas Transportation Institute

Texas A&M University Systems

August 1983
This electronic document was created from an original hard-copy.
Due to its age, it may contain faded, cut-off or missing text or low-quality images.
ACKNOWLEDGEMENTS

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

DISCLAIMER

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

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>MODELS OF RAINFALL DISTRIBUTION AND FREQUENCY ANALYSIS</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2.1 Probability Model of Quantity of Rainfall</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2.2 Models of Intensity and Duration of Rainfall</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>2.3 Frequency Models of Rainfall - Markov Chain Method and Dry and Wet Day Probabilities</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>INFILTRATION OF WATER INTO A PAVEMENT THROUGH CRACKS AND JOINTS</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>3.1 Laboratory Studies</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>3.2 Field Observations</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3.3 Low Permeability Base Courses</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.3.1 Water Entry into Low Permeability Bases</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3.3.2 Water Evaporation from the Base Course</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>DRAINAGE OF WATER OUT OF BASE COURSES</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>4.1 Casagrande's and Shannon's Method</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>4.2 Parabolic Phreatic Surface Method with an Impermeable Subgrade</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>4.3 Analysis of Subgrade Drainage</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>4.4 Drainage with a Parabolic Phreatic Surface and a Permeable Subgrade</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>4.5 Application to Pavement Drainage Design</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>4.6 Estimation of Drainability of the Base Course and Evaluation of Drainage Design</td>
<td>52</td>
</tr>
<tr>
<td>5</td>
<td>EFFECT OF WATER SATURATION ON LOAD-CARRYING CAPACITY OF BASE COURSE AND SUBGRADE</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>5.1 Effect of Saturation on Base Course Properties</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>5.2 Effect of Saturation on Subgrade Properties</td>
<td>61</td>
</tr>
</tbody>
</table>
CHAPTER 6 SYNTHESIS OF THE METHODS OF RAINFALL, INfiltration, DRAINAGE, AND LOAD-CARRYING CAPACITY OF A PAVEMENT

6.1 Conceptual Flow Chart for Rainfall, Infiltration and Drainage Analysis

6.2 Synthesis of the Methods of Rainfall Model, Infiltration and Drainage Analysis

6.3 Data Required for Analysis and Sample Results

6.4 An Example of Systematic Analysis of Rainfall Infiltration, Drainage, and Load-Carrying Capacity of Pavements

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

REFERENCES

APPENDICES

A Rainfall Amount Distribution, Rainfall Duration and Markov Chain Model

B Parabolic Phreatic Surface Drain Models for Base Courses with Impermeable Subgrade

C Parabolic Phreatic Surface Drain Models for Base Courses with Subgrade Drainage

D Entry and Evaporation of Water in a Low Permeability Base Course

E Flow Chart, Computer Programming and User's Guide
1. Katz's Model for Computing the Wet Probabilities Associated with Markov Chain Model................................. 19
2. Drainability of Water in the Base Courses from a Saturated Sample................................................................. 54
3. Calculated Elastic Moduli for Materials in the TTI Pavement Test Facility............................................................... 60
4. Regression Coefficients for the Effect of Degree of Saturation on Elastic Moduli of Subgrade Soils......................... 62
5. TTI Drainage Model for an Analysis of a Houston Pavement.................................................................................. 73
6. TTI Drainage Model for Evaluation of a Drainage Design of a Houston Pavement...................................................... 74
7. Markov Chain Model and Katz's Recurrence Equations for Dry Probabilities versus a Drainage Curve of a Houston Pavement........................................................................................................... 76
8. Stochastic Models for a System Analysis of Rainfall Infiltration and Drainage Analysis of a Houston Pavement................................................................................................................................. 77
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Comparison of Normal and Gumble Distributions</td>
<td>16</td>
</tr>
<tr>
<td>2.</td>
<td>Rainfall Infiltration and Evaporation Through Cracks and Joints in a Low Permeability Base</td>
<td>26</td>
</tr>
<tr>
<td>3.</td>
<td>Cross Section of a Pavement</td>
<td>30</td>
</tr>
<tr>
<td>4.</td>
<td>Casagrande-Shannon Model for Base Course Drainage</td>
<td>31</td>
</tr>
<tr>
<td>5.</td>
<td>Variation of Drainage Area with Slope Factor and Time Factor</td>
<td>33</td>
</tr>
<tr>
<td>6.</td>
<td>TTI Model for Base Course Drainage with an Impermeable Subgrade</td>
<td>37</td>
</tr>
<tr>
<td>7.</td>
<td>TTI Drainage Chart with an Impermeable Subgrade</td>
<td>39</td>
</tr>
<tr>
<td>8.</td>
<td>Comparison of Results for an Impermeable Subgrade</td>
<td>40</td>
</tr>
<tr>
<td>9.</td>
<td>Comparison of Results for an Impermeable Subgrade</td>
<td>41</td>
</tr>
<tr>
<td>10.</td>
<td>Comparison of Results for an Impermeable Subgrade</td>
<td>42</td>
</tr>
<tr>
<td>11.</td>
<td>Permeable Subgrade with Casagrande-Shannon Drainage Model</td>
<td>43</td>
</tr>
<tr>
<td>12.</td>
<td>Definition Sketch for Subgrade Drainage Model</td>
<td>44</td>
</tr>
<tr>
<td>13.</td>
<td>Subgrade Drainage Model with Parabolic Phreatic Surfaces</td>
<td>47</td>
</tr>
<tr>
<td>14.</td>
<td>Results of TTI Model with Permeable Subgrade</td>
<td>48</td>
</tr>
<tr>
<td>15.</td>
<td>Results of TTI Model with Permeable Subgrade</td>
<td>49</td>
</tr>
<tr>
<td>16.</td>
<td>Drainage Curves for TTI Model with Permeable Subgrades</td>
<td>51</td>
</tr>
<tr>
<td>17.</td>
<td>Effect of Amount and Type of Fines on the Permeability</td>
<td>53</td>
</tr>
<tr>
<td>18.</td>
<td>Drainage Criteria for Granular Layers</td>
<td>56</td>
</tr>
<tr>
<td>20.</td>
<td>Flow Chart for Conceptual Model of Rainfall Infiltration and Drainage Analysis of Pavements</td>
<td>66</td>
</tr>
</tbody>
</table>
21. Synthesis of Models Used in Systematic Analysis of Rainfall Infiltration and Drainage Analysis of a Pavement

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

23. Definition Sketch of Katz Model

24. Stages of Parabolic Phreatic Surface in a Horizontal Base

25. Stages of Parabolic Phreatic Surface in a Sloping Base

26. Water Penetration into a Subgrade without Lateral Drainage

27. Water Penetration into a Subgrade with Lateral Drainage

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

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

30. Relationship between Suction and Moisture Content in Soil
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

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

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

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

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;

\(SH, J\) = 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;

\[
W_{\text{lane}}' N_{\text{lane}} = \frac{W N}{l} \]

width of lane in feet and number of lanes in roadway, respectively, as input by user;

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

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

\( t_{\text{season}} \) = 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

\[
t_{\text{drain}} = 2.5nL^2 \exp(-2S')/KH
\]  

(1-4)

where

\( n \) = effective porosity of the base course,

\( L \) = the width of the base course,

\( K \) = the permeability of the base course,

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

\( S' \) = an approximate slope factor, assuming a cross slope of 1/2 inch per foot (0.015 ft/ft).
Equation 1-3 applies a time-average correction to the pavement materials properties. Multiplication by 0.5 in Equation 1-3 reflects the assumed loss in material strength under wet condition.

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

The following assumptions are implied.

1. The amount of water inflow into the base courses is a negative exponential function of rainfall quantity. This equation is derived from the data provided by Cedergren (2).

2. The length of the wet period, $t_{wet}$, is linearly related to the time required to drain 80% of the water from the sublayer.

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

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

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

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

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

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

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

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

Infiltration of water into the pavement cracks and joints uses either Ridgeway's (14) rate of infiltration of water through cracks and joints, which was determined in a field experiment, or the regression equations of Dempsey and Robnett (20) which were developed from field measurements, in estimating the amount of free water entering the pavement base course.

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

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

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

The effect of saturation on the resilient modulus of the base course and the subgrade are calculated using relations presented by Haynes and Yoder (26), and Thompson and Robnett (30,33), and these may be used in the prediction of critical stresses and strains in a pavement to determine the amount of traffic it can be expected to carry throughout its useful life.
CHAPTER 2 MODELS OF RAINFALL DISTRIBUTION AND FREQUENCY ANALYSIS

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

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

2. The intensity and duration of each rainfall.

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

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

2.1 PROBABILITY MODEL OF QUANTITY OF RAINFALL

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

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

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

2.2 MODELS OF INTENSITY AND DURATION OF RAINFALL

Hydraulic engineers are concerned mainly with the analysis of annual rainfall and runoff records for trends and cycles. Most records of rainfall and runoff can be generalized with fair success as arithmetically normal series and somewhat better as geometrically normal series (3).

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

\[ i = \frac{kt_x}{t��} e^{-\frac{t}{t_R}} \]  \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)

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

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

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

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

3.1 LABORATORY STUDIES

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

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

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

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

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

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

In the analysis, the following average infiltration rates are chosen for cracks in bituminous concrete pavement,
100 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,

\[ PO = 0.48PV + 0.32 \]

(3-1)

where \( PO \) = Pipe outflow volume \((m^3)\) and \( PV \) = Precipitation volume \((m^3)\).

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

3.3 LOW PERMEABILITY BASE COURSES

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

3.3.1 Water Entry into Low Permeability Bases

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

2. Rain Falls

3. Penetration of Rainfall into Base Course and 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):

\[ x_0 = w \frac{2dl}{\pi} \frac{kh}{kv}, \quad \text{and} \]
\[ y_0 = w \frac{2dl}{\pi} \frac{kv}{kh} \]  

where

- \( x_0 \) = the x-coordinate of the wetting front in the horizontal direction,
- \( y_0 \) = the y-coordinate of the wetting front in the vertical direction,
- \( kh \) = the horizontal coefficient of permeability,
- \( kv \) = the vertical coefficient of permeability,
- \( w \) = the width of cracks or joints, and
- \( l \) = the depth of cracks or joints.

3.3.2 Water Evaporation from the Base Course

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

The general form of the diffusion equation is (21),
\[
\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + \frac{f(x,y,z,t)}{ku} = \frac{1}{k} \frac{\partial u}{\partial t}
\]  \hspace{1cm} (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

\[
\frac{\partial^2 u}{\partial y^2} = \frac{1}{k} \frac{\partial u}{\partial t}
\]  \hspace{1cm} (3-5)

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

An example result is listed in Appendix E-2, where the computer program and output are employed to illustrate the water infiltration and evaporation through the cracks or joints of a low permeability base course.
CHAPTER 4 DRAINAGE OF WATER OUT OF BASE COURSES

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

4.1 CASAGRANDE’S AND SHANNON’S METHOD

The subject of base course drainage has received considerable attention over the last three decades. Casagrande and Shannon (1) made field observations on several airfields in the United States to determine the environmental conditions under which base courses may become saturated. They performed a simplified theoretical analysis of the base course drainage. They assumed symmetry along the axis of the pavement and the equations governing drainage for one half of the cross section of the base course layer ABCD (See Figure 4) were developed. In their analysis, the drainage process was divided into two parts. In the first part shown in Figure 4, the free surface gradually changes from position CD to CA due to free drainage through the open edge CD of the pavement. Darcy's Law and the continuity equation were satisfied to establish a relation among time, \( t \) and \( x(t) \) in terms of \( H, L, \alpha, k_1, \) 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's and Shannon's (1) equations in the form of a dimensionless chart shown in Figure 5. Most recently Cedergren (2) and Moulton (23) have modified the original definition of the slope factor, $S$, as the reciprocal of the one shown in Figure 5 and have presented similar drainage charts in their work on highway subdrainage design.

Drainage of a sloping layer of base course involves unsteady flow with a phreatic surface. The assumptions by Casagrande and Shannon (1) lead to the simple model shown in Figure 4. In this model, the centerline of the base course, AB, and the bottom of the base course, BC, are considered as impervious boundaries. Free discharge is
FIGURE 5. VARIATION OF DRAINAGE AREA WITH SLOPE FACTOR AND TIME FACTOR (1).

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

TIME FACTOR, $T = \frac{tk_{1}H}{n_{1}L^{2}}$

DEGREE OF DRAINAGE, $U = \frac{\text{DRAINED AREA}}{\text{TOTAL AREA}}$
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

Stage 1  \(0 < U < 50\%\)  
\[T = 2U^2\]  

Stage 2  \(50\% < U < 100\%\)  
\[T = \frac{U}{2 - 2U}\]  

(B) Sloping Bases

Stage 1  \(0 < U < 50\%\)  
\[T = 2US - S^2 \ln \left(\frac{S + 2U}{S}\right)\]  

Stage 2  \(50\% < U < 100\%\)  
\[T = S + S \ln \left[\frac{(2S - 2US + 1)}{(2 - 2U)(S + 1)}\right] - S^2 \ln \left[\frac{S + 1}{S}\right]\]  

in which  
Degree of Drainage, \(U = \frac{\text{Drained Area}}{\text{Total Area}}\)  
Slope Factor, \(S = \frac{H}{\text{L} \tan \alpha}\)  
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

\[
\begin{align*}
\text{Stage 1} & \quad 0 \leq U \leq \frac{1}{3} \\
T &= 3U^2 \\
\text{Stage 2} & \quad \frac{1}{3} \leq U < 1 \\
T &= \frac{8}{9} \left( \frac{1}{1-U} \right) - 1
\end{align*}
\]

(B) Sloping Bases

\[
\begin{align*}
\text{Stage 1} & \quad 0 \leq U \leq \frac{1}{3} \\
T &= \frac{3}{2}SU - \frac{3}{8}S^2 \ln \left[ \frac{S+4U}{S} \right] \\
\text{Stage 2} & \quad \frac{1}{3} \leq U < 1 \\
T &= \frac{8}{9} \left( \frac{1}{1-U} \right) - 1
\end{align*}
\]
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,
SLOPE FACTOR, \( S = \frac{H}{L \tan \alpha} \)

TIME FACTOR, \( T = \frac{t k_1 H}{n_1 L^2} \)

DEGREE OF DRAINAGE, \( U = \frac{\text{DRAINED AREA}}{\text{TOTAL AREA}} \)

FIGURE 7. TTI DRAINAGE CHART WITH AN IMPERMEABLE SUBGRADE
\( H = 0.46 \text{ m} \)
\( \tan \alpha = 0.016 \)

\( k_1 = 0.16 \text{ m/min} \)
\( n_1 = 0.07 \)

\( L = 23 \text{ m} \)

**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
Page 43 missing from original
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):

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

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

\( h(t) = \) 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 \( k_2/k_1 = K\cdot0 \) and 0.0002) given by the present model and lies between the two theoretical curves. In this case, the permeable subgrade model with a parabolic phreatic surface yields results that compare well with field data.

In Figure 15, the parabolic model with a permeable subgrade \( K = 0.0001 \) is in closer agreement with the field data than the Casagrande-Shannon model.

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

4.5 APPLICATION TO PAVEMENT DRAINAGE DESIGN

As an illustration of the importance of subgrade drainage, a base course 0.8 m (2.5 ft) thick and 46 m (150 ft) wide with 1% cross slope is considered. The base course has its smallest particles in the medium sand range and has a coefficient of permeability, \( k_1 = 2.4 \text{ m/day (7.8 ft/day)} \), and the porosity, \( n_1 = 0.04 \). It is required to
STAGE 1

STAGE 2

FIGURE 13. SUBGRADE DRAINAGE MODEL WITH PARABOLIC PHREATIC SURFACES
Figure 14. Results of TTI model with permeable subgrades.

Field data from Casagrande & Shannon

CASAGRANDE-SHANNON MODEL

K = 0.0002

K = 0

L = 23 m
H = 0.5 m
tan α = 0.015
k₁ = 9.6 m/min
n₁ = 0.43
K = k₂/k₁
U - DEGREE OF DRAINAGE (%) vs. TIME (MINUTES)

FIELD DATA FROM CASAGRANDE & SHANNON

CASAGRANDE-SHANNON MODEL

K = 0.0001
K = 0

L = 23 m  k_1 = 7.8 m/min
H = 0.15 m  n_1 = 0.4
\tan \alpha = 0.015
K = \frac{k_2}{k_1}

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.
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 affect 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 Youder \(27\) 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>INERT FILLER</td>
<td>SILT</td>
<td>CLAY</td>
</tr>
<tr>
<td>GRAVEL</td>
<td>70</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>SAND</td>
<td>57</td>
<td>50</td>
<td>35</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

\[ S_a = 1 - \text{P.D.} \times U \]  \hspace{1cm} (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 (32), the moisture content is determined primarily by the seasonal variation of rainfall. In this report, the location of the water table is not taken into account.

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

<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)

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

where

- $E_s =$ calculated total subgrade modulus,
- $d =$ depth of subgrade,
- $E_1 =$ subgrade modulus under 100% saturated condition, which is evaluated from Thompson and Robnett equations (33),
- $d_1 =$ average depth of water penetrating into subgrade from the base course,
- $E_2 =$ subgrade modulus under dry condition, and
- $d_2 =$ average depth of dry portion of the subgrade.
CHAPTER 6  SYNTHESIS OF THE METHODS OF RAINFALL INFILTRATION, DRAINAGE, AND LOAD-CARRYING CAPACITY OF A PAVEMENT

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

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

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

3. The TTI drainage model (25), which uses a parabolic phreatic surface and permits subgrade drainage, was developed for base course and subgrade drainage analysis.

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

5. Evaluation of base course (26) and subgrade moduli (31,33) as they are affected by moisture contents in the materials.
A conceptual flow chart is drawn in Figure 20 to give a clear profile of the entire model, and a synthesis of the various models mentioned above into a systematic analysis of the rainfall, infiltration and drainage analysis of a pavement is sketched in Figure 21.

6.1 CONCEPTUAL FLOW CHART FOR RAINFALL, INFILTRATION AND DRAINAGE ANALYSIS

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

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

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

Rainfall Frequency → Markov Chain Method → Dry & Wet Probabilities

Rainfall Amount → Gamma Distribution

B. Water Infiltration

No

Cracks & Joints Data

Dempsey's Field Test (Regression Analysis)

Yes

Ridgway's Lab. Results (Infiltration Data)

Water Amount in Pavement

C. Drainage Analysis

Parabolic free surface & subgrade drainage → Average drainage time

t_1.0 > 1

Base Course Properties → Base Drainage Design Evaluation

t_1.0 < 1

Base saturation Distribution

t_0.5

Base wet Probability

Base & Subgrade Elastic Moduli

FIGURE 20. Flow Chart for Conceptual Model of Rainfall Infiltration and Drainage Analysis of Pavements
FIGURE 21. Synthesis of Models Used in Systematic Analysis of Rainfall Infiltration and Drainage Analysis of a Pavement
Katz's recurrence equations (13), which are associated with the Markov chain model, together with the gamma distribution for the quantity of rainfall, the infiltration of water into the base course and the drainage analysis, are applied to estimate the probability of a base course remaining dry or wet. After taking the climatic condition, water penetration and drainage design of a base course into consideration, the distribution of various saturation levels in a base and a subgrade is then used for predicting the elastic moduli of these pavement layers.

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

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

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

As a result, the amount of rainfall is transformed into the corresponding drainage time in terms of days. This transformation is not linear due to the fact that the drainage curves of the TTI model are approximately a reverse S shape (see Chapter 4), while the conversions of the amount of rainfall into a degree of saturation and further into a degree of drainage are linearly correlated. In spite of this nonlinear relation between the amount of rainfall and the drainage time, the gamma distribution is used to estimate the probability of requiring a given amount of time in days to drain out a specified amount of water that infiltrates. This estimate of the probabilities of having a specific required drainage time is found by integrating the areas under the Gamma distribution curve between 0 to 1, 1 to 2, 2 to 3 days, etc.

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

$$BC_{\text{dry}} = P_i \times W(0; T_i) \quad \text{for} \quad t_{1.0} > 1 \quad (6-1)$$

where

- $BC_{\text{dry}} = \text{the probability of a base course being dry,}$
- $P_i = \text{the cumulative probability of required drainage time from i-1 days to i days, which corresponds to a certain degree of water saturation,}$
- $W(0; T_i) = \text{the probability of T_i consecutive dry days from Katz's model (13), and}$
- $t_{1.0} = \text{the time, in days, required to drain 100}\% \text{ of free water from a base course.}$

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

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

where

- $BC_{\text{dry}}$ and $t_{1.0}$ defined as in Equation 6-1.
- $P_{\text{wet}} = \text{the probability of wet days in the season concerned, and}$
\( t_{0.5} \) = 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 \( t_{1.0} \geq 1 \) and Equation 6-2 for \( t_{0.1} < 1 \), respectively.

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

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

Based on the weather data and pavement structure, the drainage time, degree of drainage and corresponding
TABLE 5. TTI DRAINAGE MODEL FOR AN ANALYSIS OF A HOUSTON PAVEMENT

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

System Analysis of Rainfall Infiltration and Drainage

<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>10.00000</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
probabilities are calculated in Table 7. Table 8 gives the characteristics of gamma distribution and related material properties under local rainfall conditions, and Table 9 shows the rainfall effect on the base and subgrade moduli.

6.3 DATA REQUIRED FOR ANALYSIS AND SAMPLE RESULTS

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

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

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

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

(3) Pavement structure and materials data, which include the total area of cracks and joints, the pavement type (portland cement concrete or asphalt concrete), base materials (Table 3), the soil type and horizon of subgrades (Table 4), and total length surveyed.
### TABLE 7. MARKOV CHAIN MODEL AND KATZ'S RECURRENCE EQUATIONS FOR DRY PROBABILITIES VERSUS A DRAINAGE CURVE OF A HOUSTON PAVEMENT

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Average Free Water in Base (Sq Feet) = 1.07</td>
</tr>
<tr>
<td>Duration of Average Rainfall Amount (Hours) = 0.08</td>
</tr>
<tr>
<td>Average Rainfall Amount Per Day (Inches) = 0.479</td>
</tr>
<tr>
<td>Average Base Course Modulus in Wet State (ksi) = 41.45</td>
</tr>
<tr>
<td>Average Base Course Modulus (ksi) = 53.41</td>
</tr>
<tr>
<td>Average Subgrade Modulus (ksi) = 27.30</td>
</tr>
</tbody>
</table>
(4) Climatic data, which include: intended evaluation period, rainfall amount of every rainy day (precipitation \( \geq 0.01 \text{ inch} \)) 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 (\( \alpha \)) and beta (\( \beta \)) 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
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


APPENDIX A

Rainfall Amount Distribution, Rainfall Duration
and Markov Chain Model

A-1. RAINFALL AMOUNT DISTRIBUTION

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

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

\[ 0, \quad R < 0 \] (A-1)

where

\[ R \] = precipitation amount and \n\[ \Gamma(\alpha) \] = Gamma function where \( (n+1) = n! \), \( n = 0, 1, 2, \ldots \).

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

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

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

where

\[ \bar{R} \] = precipitation amount and \n\[ \Gamma(\alpha) \] = Gamma function where \( (n+1) = n! \), \( n = 0, 1, 2, \ldots \).
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)

\[
i = \frac{k t_p x}{t_n^n} \tag{A-4}
\]

where

- \( t_R \) is the effective rainfall duration in minutes,
- \( t_p \) is the recurrence interval in years,
- \( i \) is the maximum rainfall intensity, inches per hour, during the effective rainfall duration,

and

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

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

Using the standard normal distribution, a rainfall duration, \( t_R \), was chosen from -1.96 to 1.96 which made the area under the curve to be 0.95. Furthermore, \( i \) corresponds
to 0.3989 in the standard normal distribution curve. Therefore, the ratio between the product \((t_R)i\) and the total amount of rainfall during effective duration, \(R\), is

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

(A-5)

which is called the shape factor (SF).

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

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

\[
= (t_R) (kt_{tp}^x)/(t_R^n)(SF)
\]

\[
= k t_R^{(1-n)} t_{tp}^x/(SF)
\]

(A-6)

Thus, \(t_R = \left[\frac{R(SF)}{k t_{tp}^x}\right]^{1/(1-n)} \)

(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.

\[
P(t) = [p_{ij}(t)] = \begin{bmatrix}
p_{00}(t) & p_{01}(t) \\
p_{10}(t) & p_{11}(t)
\end{bmatrix}
\]  \hspace{1cm} (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.
\[ x > 0, \quad x > 0, \text{ and} \]

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

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

The variable \( \lambda \) is the reciprocal of the average dry or wet days per period,

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

where \( \bar{x}_{\text{dry}} \) = the average number of dry days in a given period

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

So that the transition matrix is derived as \((34)\)

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

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

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

Transition Matrix

where

\[ W_0(k;N) = \text{the probability of } k \text{ wet days during } N \]

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

\[ W(k;N) = (1-p_0)W_0(k;N) + p_0 W_1(k;N) \]  

(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) \( W_0(k;N) \)

For \( N \) days:  
- Zeroth day

(2) \( W_1(k;N) \)

For \( N-1 \) days:  
- Zeroth day

First day

N-1 days

FIGURE 23. Definition Sketch of Katz Model
probability of the first day remaining dry from zero-th day 
\(p_{00}\) multiplied by the probability of having \(k\) wet days 
of the remaining \(N-1\) days, \(W_0(k;N-1)\), plus the 
probability of changing from a dry zero-th day to a wet 
first day (\(p_{01}\)) multiplied by the probability of having 
k-1 wet days in the remaining \(N-1\) days, \(W_1(k-1;N-1)\); so 
that

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

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

\[
W_1(k;N) = p_{10}W_0(k;N-1) + p_{11}W_1(k-1;N-1) \quad (A-15)
\]

Equation A-12 is simply a matrix form of Equations A-14 
and A-15. The total probability of having \(k\) wet days out of 
\(N\) consecutive days is further dependent on the initial 
probability of having a wet day (\(p_0\) of Equation A-13).
APPENDIX B
Parabolic Phreatic Surface Drain Models
for Base Courses with Impermeable Subgrades

B-1. Analysis of Horizontal Bases with Impervious Subgrades

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

\[ y = \sqrt{ax} \]  \hspace{1cm} (B-1)

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

Drained Area = \( A' = \frac{Hx_1}{3} \) \hspace{1cm} (B-2)

The rate of water amount \( (q) \) change is

\[ dq = n_1 \cdot \frac{dA}{dx_1} \cdot dx_1 = \frac{n_1H}{3} \cdot dx_1 \]  \hspace{1cm} (B-3)

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

\[ \frac{dq(x)}{dt} = k_1 iy = k_1 \cdot \frac{dy}{dx} \cdot y = \frac{k_1}{2x_1} H^2 \]  \hspace{1cm} (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 (1), 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 \( 0 < U < \frac{1}{3} \) 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)

\[ \frac{dq}{dt} = -\frac{2}{3} n_1 L dh \]  

(B-10)

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

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

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

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

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

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

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

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

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

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

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

which are valid for \( \frac{1}{3} \leq U < 1 \) of horizontal bases.
B-2. Analysis of Sloping Bases with Impervious Subgrades

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

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

Stage 2. $\frac{1}{3} \leq U < 1$
\[ y = \sqrt{ax} + x \tan \alpha \]
\[ a = \frac{H^2}{x_1} \]
\[ y = \frac{H}{\sqrt{x_1}} \sqrt{x} + x \tan \alpha \]

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

\[ dq = n_1 \frac{dA'}{dx_1} \cdot dx_1 = \frac{n_1 H}{3} \cdot dx_1 \]

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

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

Let \( T = t \frac{k_1 H}{n_1 L^2} \)
Since \( U = \frac{x_1}{3L} \) and \( S = \frac{H}{Ltana} \)

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

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

\[
= HL - \frac{2}{3} hL
\]  \hspace{1cm} (B-22)

\[
dq = n_1 \frac{dA'}{dh} \ dh = - \frac{2}{3} n_1 Ldh
\]  \hspace{1cm} (B-23)

Using Darcy's law,

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

\[
= k_1 \left( \frac{h^2}{2L} + \frac{htan \alpha}{\sqrt{L}} \right) \ \sqrt{x}
\]  \hspace{1cm} (B-24)

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

\[
= k_1 \left( \frac{h^2}{2L} + \frac{2}{3} h \tan \alpha \right)
\]  \hspace{1cm} (B-25)
From Equations B-23 and B-24

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

\[ \Delta t = \Delta t \]

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

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

\[ = S \ln \left[ \frac{9S - 9US + 8}{3(1-U)(3S+4)} \right] \quad (B-26) \]

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

Maximum \( T_1 = S \frac{2}{2} - \frac{3}{8} S^2 \ln \left( \frac{3S+4}{3S} \right) \)

\[ T_{II} = T_{I, \text{maximum} + \Delta T} \]

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

104
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.
Subgrade

\[ n = \text{porosity} \]
\[ k = \text{permeability} \]
\[ t = \text{time} \]

**FIGURE 26.** Water Penetration into a Subgrade without Lateral Drainage
FIGURE 27. Water Penetration into a Subgrade with Lateral Drainage
The parabola drawn here is only to be consistent with the previous derivations. The datum is located at point \( 0 \) in Figure 26.

The velocity of water is generally defined as

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

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

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

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

\[
\phi_1 = -k_1 \left( \frac{P_1}{\gamma_w} - y \right), \quad v_1 = \frac{d\phi_1}{dy} \quad \phi_1 = v_1y + c_1 \quad \text{(C-4)}
\]

\[
\phi_2 = -k_2 \left( \frac{P_2}{\gamma_w} - y \right), \quad v_2 = \frac{d\phi_2}{dy} \quad \phi_2 = v_2y + c_2 \quad \text{(C-5)}
\]
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), \( y=H \),

\[
v_1 = v_2 = v, \text{ and thus}
\]

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

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

In order to solve for \( c_1 \) and \( c_2 \) in terms of the parameters which we have been using, two points \( y=H-h \) and \( y=y_0 \) (the wetting front) are chosen.

at \( y=H-h \), \( P=0 \)

\[
\phi_1 = -k_1 (-y) = k_1 y = k_1 (H-h) = v_1 (H-h) + c_1, \text{ so that}
\]

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

at \( y=y_0 \), \( P=0 \)

\[
\phi_2 = v_2 y_0 + c_2 = k_2 y_0, \text{ so that}
\]

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

Substituting Equations C-7 and C-8 into Equation C-6, we find the velocity that water penetrates from the base course into the subgrade:
\[
\frac{vH+(H-h)(k_1-v)}{k_1} = \frac{vH+(k_2-v)y_0}{k_2} \quad \text{and}
\]

\[
v = \frac{y_0 - H+h}{\frac{h}{k_1} + \frac{y_0-H}{k_2}} \quad \text{(C-9)}
\]

Furthermore, the wetting front \( y_0 \) must be determined.

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

\[
n_2 \int_0^y dy_0 = -n_1 \int_0^h dh, \quad \text{we have}
\]

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

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

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

\[
\frac{h}{k_1} + \frac{\frac{n_1}{n_2} (H-h)}{k_2} \quad \text{(C-11)}
\]
C-2. Parabolic Phreatic Surface with Subgrade Drainage

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

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

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

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

\[
\text{Stage 1} \quad dq_x = k_1 \left( \frac{h_0^2}{2x_1} + \frac{2}{3} h_0 \tan \alpha \right) dt \quad (C-12)
\]

\[
\text{Stage 2} \quad dq_x = k_1 \left( \frac{h^2}{2L} + \frac{2}{3} h \tan \alpha \right) dt \quad (C-13)
\]
FIGURE 28. Stages of Parabolic Phreatic Surface with both Lateral and Subgrade Drainage for a Sloping Base
The water quantity flowing through subgrade is

\[
dq_y = n_2 dy_0 \, dx
\]

\[
= v \cdot x \, dt
\]

In Stage 1,

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

\[v = \sqrt{ax} + xtan\alpha \text{ for parabolic free surface}\]

on Figure 28

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

\[dq_y (0-x_1) = v \, dx \, dt \quad \dot{y} (1 - \frac{n_1}{n_2}) + \frac{n_1H}{n_2} \]

\[= k_2 \frac{k_2 - \frac{n_1}{n_2}}{\dot{y}} \frac{n_1}{n_2} \, dx \, dt \quad (C-15a)\]

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

\[dq_y (x_1-L) = \frac{h_0}{\frac{k_2}{k_1} - \frac{n_1}{n_2}} + \frac{n_1H}{n_2} \]

\[\quad \frac{k_2 - \frac{n_1}{n_2}}{\dot{y}} \frac{n_1}{n_2} \, dx \, dt \quad \cdot \quad (C-15b)\]

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

\[= \frac{1}{L} \int_{0}^{x_1} \dot{y} (1 - \frac{n_1}{n_2}) + \frac{n_1H}{n_2} \, dx \]

\[+ \frac{k_2 - \frac{n_1}{n_2}}{\dot{y}} \frac{n_1}{n_2} \, (L-x_1) \quad (C-16)\]
In Stage 2,

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

Total \( \frac{dq}{dt} = k_2 \int_0^L \frac{h}{\sqrt{L}} \sqrt{x} \left( \frac{1}{n_2} - \frac{n_1}{n_2} \right) + \frac{1}{n_0} dx \) \hspace{1cm} (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 $0$ 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 $0$.

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,

\[ \frac{dg}{dt} = w \frac{d\ell}{dt} = \frac{dA}{dt} = \frac{\pi}{2} b \left( \frac{dx}{dt} \right) + \frac{\pi}{2} a \left( \frac{dy}{dt} \right) \]  

(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.

\[ v_y = \frac{dy}{dt} = \frac{-k_v}{n} \frac{\partial h}{\partial y} = \frac{-k_v}{n} \frac{\partial}{\partial y} \left( \frac{p}{\gamma} - y \right) \]  

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

and \( y = y_0, h = a_1 y_0 + c_1 \)

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

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

\[ a_1 = \frac{-y_0 - h_k - \ell}{y_0} \]  

(D-6)
where \( h_k \) is the capillary head.

Thus

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

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

From Eq. D-1

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

therefore,

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

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

Assume \( h = a_2x + c_2 \)

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

and \( x = x_0 \)  \( h = ax_0 + \ell = h_k \)

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

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

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

therefore,

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

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

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

This differential equation is accompanied by the initial conditions

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

\[ \omega = \frac{\pi}{2} x_0 y_0 \]

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

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

\[ y_0 = \sqrt{w} \frac{2\omega}{\pi} \frac{k_v}{k_h} \quad \text{(D-18)} \]
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: \( \frac{\partial u}{\partial t} = \kappa \frac{\partial^2 u}{\partial y^2} \) \hspace{1cm} (D-19)

Initial Condition: \( u(y,0) = u_0 \) \hspace{1cm} (D-20)

Boundary Conditions: \( \frac{\partial u(0,t)}{\partial x} = 0 \) \hspace{1cm} (D-21)

\[ \frac{\partial u(y_0,t)}{\partial x} = -\beta \{ u(y_0,t) - h_0 \} \] \hspace{1cm} (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):

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

where \( A_n = \frac{2(u_0 - u_a) \sin y_n}{y_n + \sin y_n \cos y_n} \) \hspace{1cm} (D-24)

\( y_n = \) solution of \( \cot y = \frac{y}{\beta Y_0} \)

\( u_a = \) suction of atmosphere,

\( u_0 = \) original suction throughout soil,

\( Y_0 = \) wetting front of water penetration,

\( \beta = \) evaporation constant, and

\( \kappa = \) 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:

\[ \Delta w = \int_0^{Y_0} \Delta u(y,t_f) \left[ \frac{\partial \bar{u}}{\partial u} \right] dy, \] \hspace{1cm} (D-25)
where

$$\Delta u(y, t_f) = u(y, 0) - u(y, t_f)$$

$$= u_0 - u(y, t_f), \text{ and}$$

$$t_f \text{ is the time when evaporation stops.}$$

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.
START

Input
Length, Height, Slope, Permeability, Porosity

Base Course Drainage Computation

Output

TTI Drainage Model

Drainage Design Evaluation

A
Time for 50% of Water to Drain

Parameters (α, β) of Gamma Distribution

Markov Chain Model

Probability of Wet and Dry Days

Water Infiltration into Pavement

Is Area of Joints and Cracks Provided?

Dempsey's Equation

Ridgeway's Lab Results

Rainfall Amount / Wet and Dry Day Frequency

Output

Joints and Cracks Data / Total Area Surveyed
Water Carrying Capacity of Base Course (CC)

PCC: 0.03 ft³/hr/ft

BCC: 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

Yes

Katz's Model

No

t₀.5

D
Dry and Wet Probabilities of a Base Course

Types of soil and Pavement, Horizon Data

Elastic Moduli of Base Course and Subgrade

Output the Effect of Rainfall on Loading Capacity

STOP
(a) Simulation Model for Rainfall Infiltration and Drainage Analysis of Pavement
1. C
2. C************************************************************************************
3. TEXAS TRANSPORTATION INSTITUTE
4. SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND PAVEMENT DRAINAGE
5. AUGUST, 1983
6. C************************************************************************************
7. C************************************************************************************
8. C************************************************************************************
9. C************************************************************************************
10. C************************************************************************************
11. C************************************************************************************
12. C************************************************************************************
13. C************************************************************************************
14. C************************************************************************************
15. C************************************************************************************
16. C************************************************************************************
17. C************************************************************************************
18. C************************************************************************************
19. C************************************************************************************
20. C************************************************************************************
21. C************************************************************************************
22. C************************************************************************************
23. C
24. INTEGER N, NA, NB, NC
25. COMMON LA, HE, TA, K1, K2, N1, N2, A1, B1, B2, C1, G1, G2, G3, R1
26. COMMON CASE, HED, HSDA, HSDB, NUM, S
27. COMMON /RAW/ XTIME(120, 10), YAREA(120, 10), INDS, TIMAX(10), UMAX(10)
28. COMMON /TNUM/ INABT
29. DIMENSION UAREA(120, 10)
30. DIMENSION LOGTIM(120, 10)
31. DIMENSION ITITLE(18)
32. DATA UDRAN/0.5/
33. C
34. C UDRAN : 50 PERCENT DRAINAGE
35. C INDS : NUMBER OF DATA SET
36. C NA : NO. OF SECTORS IN RUNGE-KUTTA METHOD FOR CASE 1
37. C NB : NO. OF SECTORS IN DIVIDING HEIGHT FOR CASE 2
38. C N : NO. OF SECTORS IN SIMPSON'S RULE
39. C INABT : SUM OF NA AND NB
40. C LA : LENGTH OF BASE (FEET)
41. C HE : HEIGHT OF BASE (FEET)
42. C TAPER : SLOPE RATIO OR THE VALUE OF TANGENT ALPHA (IN PERCENT)
43. C K1 : PERMEABILITY OF BASE COURSE (FEET PER HOUR)
44. C K2 : PERMEABILITY OF SUBGRADE (FEET PER HOUR)
45. C N1 : POROSITY OF BASE COURSE
46. C N2 : POROSITY OF SUBGRADE
47. C TA : SLOPE RATIO (IN DECIMAL POINTS), TAPER/10J.
48. C
49. C INEEED : 0 DRAINAGE ANALYSIS ONLY
50. C 1 DRAINAGE ANALYSIS AND EVALUATION OF DRAINAGE DESIGN
51. C 2 SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINAGE
52. C
53. NA=30
54. NB=30
55. INT=NA+NB
56. INABT=INT
57. N=10
58. DO 300 INDS=1,10
59. 130
C  INPUT THE DATA

READ(5,55555,END=99999) IPROB, INEEED, ITITLE

55555 FORMAT(I5, I3, 18A4)

WRITE(6,55556) IPROB, ITITLE

55556 FORMAT(1H1, 2(/), 5X, 'PROBLEM NUMBER', I5, 2X, 18A4)

IF(INEED.EQ.0) WRITE(6,55557)
IF(INEED.EQ.1) WRITE(6,55558)
IF(INEED.EQ.2) WRITE(6,55559)

55557 FORMAT(3(/) ,5X, 'DRAINAGE ANALYSIS USING TITI DRAINAGE MODEL')

55558 FORMAT(3(/), 5X, 'DRAINAGE ANALYSIS AND DESIGN EVALUATION')

55559 FORMAT(3(/), 5X, 'SYSTEM ANALYSIS OF RAINFALL INFILTRATION AND DRAINAGE')

IA=INDS
READ(5,15)LA,HE,TAPER,K1,K2,N1,N2

15 FORMAT(7(F10.0))

TA=TAPER/100.

HORIZONTAL BASE COURSE

IF(TA.LE.O.) TA=0.1E-06
IF(N2.LE.O.) CALL POR02
IF(N1.EQ.N2.AND.K2.EQ.K1) K2=K2*1.0001
WRITE(6,25)

25 FORMAT(3(/), 5X, 'LENGTH', 4X, 'HEIGHT', 4X, 'SLOPE%', 
+4X, 'PERM.1', 4X, 'PERM.2', 4X, 'PORO.1', 4X, 'PORO.2')

WRITE(6,55)LA,HE,TAPER,K1,K2,N1,N2

55 FORMAT(1X,3(F10.2), 2(F10.5), 2F10.4)

TWETA=LA*HE
S=HE/(LA*TAP)
WRITE(6,35)S

35 FORMAT(I5, 'SLOPE FACTOR=', F6.3)

WRITE(6,255)

255 FORMAT(3X, 'NOTE: THE FOLLOWING ANALYSIS IS BASED ON PARABOLIC SHAPE')
+E PLUS SUBGRADE DRAINAGE'

C  RUNGE-KUTTA METHOD FOR PARABOLIC(DQX) AND HORIZONTAL(DQY) EQUATION OF CA01010

WRITE(6,115)

115 FORMAT(6(/), 5X, 'HEAD ON X COOR.', ' HT.(SUB.DRAIN ONLY)' 
+1.6X, 'AVG. HEIGHT.', 7X, 'TIME(1ST STAGE)', 7X, 'DRAINAGE DEG.')

TIME=0.

106.

XM=0.

107.

AKL=0.

108.

DELT=LA/NA

109.

CASE=1.

110.

DO 700 I2=1, NA

700.

TIME2=TIME+AKL

112.

XM=XM+DELT

113.

NUM=2.

114.

CALL SUBHT(TIME2, HSUB2)

115.

HSUB=HSUB2

116.

CALL CONSFC(XM, A)

117.

DDTDX=DUMMYF(XM)

118.

AK2=DDTDX*DELT

119.
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*XK/3.

UE1=WET1/TWETA

HAVG1=(TWETA-WET2)/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

C

WRITE(6,45)

45 FORMAT(1H1,6(/), 5X,'HEAD ON Y COOR.' ', ' HT.(SUB.DRAIN ONLY)',
+6X,'AVG. HEIGHT',7X,'TIME(STAGE 2)',7X,'DRAINAGE DEG.'//)

CASE=2.

HMAX=HSUBA

HMAX2=HMAX

DELT=HMAX/NB

DO 800 I3=1,NB

HMIN=HMAX2-DELT*I3

CASE=I3+NA

IF(I3.EQ.NB.OR.HMIN.LE.0.) HMIN=HMAX*0.5

CALL CONSFC(XM,HMIN)

CALL SIMPSN(AREA,DUMMYF,HMIN,HMAX,N)

TIME=TIME+AREA

CALL SUBHT(TIME,HTSU)

WET2=TWETA-2.*HMIN*LA/3.

UE2=WET2/TWETA

HAVG2=(TWETA-WET2)/LA

IF(HTSU.LE.0.OR.HTSU.LE.HAVG2) HTSU=HAVG2

WRITE(6,135)HMIN,HTSU,HAVG2,TIME,UE2

800 CONTINUE

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) UMAX(IA)=UE2

900 CONTINUE

IMAX=TIMAX(IA)/24.+0.5

CALL INPOLA(TDRAN,UDRAN,IA,LOGTIM)

IF(INEED.NE.0)

1CALL JUDGE(IA,INT,ITYPF1,IOFINE,GRAVPC,SANDFC)

IF(INEED.EQ.2) CALL RAIN(TDRAN,IMAXD)

CONTINUE

125 FORMAT(1H1)

STOP

END

C

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,NJONT,NLANE
COMMON LA,HE,IA,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1
COMMON CASE,HED,HSUBA,HSUBB,NUM,S
IF(NUM.EQ.1.) HSUB=HSUBA
IF(NUM.EQ.2.) HSUB=HSUBB
IF(CASE.EQ.2.) HSUB=HMIN
IF(CASE.EQ.2.) XM=LA
A1=HSUB/SQRT(XM)
B1=A1*(1.-N1/N2)
B2=A1*(K2/K1-N1/N2)
C1=N1*HE/N2
G1=B1/B2
G2=C1*(1.-G1)/G2
G3=C1*G2
R1=G3/B2
RETURN
END

SUBROUTINE DRYDAY(IMAXD,YDRA,WP)
IMAXD=IDRY
IF(IMAXD.GE.39) IMAXD=39
YDRAN(IMAXD)=100.
WRITE(6,6005)
6005 FORMAT(1H1,5(/),T34,'PROBLEM NO.',5X,'TIME(DAYS)',4X,'DRAINAGE(%')
2,2X,'PROB(CONSECUTIVE DRY DAYS)',5(/))
IN=1
DO 6600 I=1,IMAXD
IN=IN+1
WRITE(6,6010)IA,I,YDRAN(I),WPROB(1,IN)
6010 FORMAT(T30,Il5,I15,F15.2,20X,F8.3,5(/))
6600 CONTINUE
RETURN
END
C***********************************************************************
C*
C* ROUTINE FOR COMPUTING ALL THE FUNCTIONS
C*
C* 02520
C*
C* X: MAXIMUM X VALUE FOR CASE 1; X=LA FOR CASE 2;
C* X: MINIMUM X VALUE FOR CASE 3;
C* C*
C* 02530
C*
FUNCTION DUMMYF(X)
IMPLICIT REAL(J-Z)
INTEGER N,NA,NE,NC,NJONT,NLANE
COMMON LA,HE,TA,K1,K2,N1,N2,A1,E1,B2,Cl,Gl,G2,G3,R1
COMMON CASE,HED,HSUBA,HSUBB,NUM,S
IF(NUM.EQ.1.) HSUB=HSUBA
IF(NUM.EQ.2.) HSUB=HSUBB
IF(CASE.EQ.2.) AE=X
IF(CASE.EQ.2.) X=LA
IF(CASE.EQ.2.) HSUB=AE
HED=HSUB
IF(N2.GT.0.1E-05.AND.K2.NE.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=O.
IF(N2.GT.O.1E-05)DQY=(HSUB*(l.-Nl/N2)+Cl)/(HSUB*(K2/K1-Nl/N2)+Cl)
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*********************X***********************************************
C*
C* EVALUATE THE MODULI OF BASE AND SUBGRADE BY DISTRIBUTION
C* 02990
C* 02990
300. C* OF MATERIAL SATURATION FROM THE RAINFALL  * 03000

301. C*  * 03010

302. C* ALPHA,BETA: PARAMETERS OF GAMMA DISTRIBUTION  * 03020

303. C* PWET,PDRY : PROBABILITY OF WET AND DRY DAYS IN STEADY STATE  * 03030

304. C* HALFT : TIME OF 50% DRAINAGE(HOUR);  * 03040

305. C*  * 03050

306. C*  * 03060

307. C****************************************************************** 03070

308. C 03080

309. C 03090

310. C SUBROUTINE FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE, 03100

311. 2ASOIL,BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPROB,IMAXD) 03110

312. C 03120

313. C GAMDIS: GAMMA DISTRIBUTION AS A FUNCTION 03130

314. C AINTER,BSLOPE: INTERCEPT AND SLOPE OF THE LINEAR FUNCTION OF BASE COUR 03140

315. C MODULUS VS. WATER SATURATION DEGREE 03150

316. C EMPDF : PROBABILITY DENSITY FUNCTION OF BASE COURSE MODULUS IN WET 03160

317. C PAVE : INFILTRATION RATE OF PCC(1) OR BCP(2),UNIT=FT**3/(HOUR*FT) 03170

318. C FLOAVG: INFILTRATION RATE SELECTED ACCORDING TO PAVEMENT TYPE 03180

319. C PVA,PVB: THE INTERCEPT AND SLOPE OF REGRESSION EQUATION IN DEMPSEY'S TE 03190

320. C C****************************************************************** 03200

321. C CFHALF : THE AVERAGE DEGREE OF FREE WATER DRAINAGE PER HOUR 03210

322. C DEFL : DEFLECTION OF BASE MATERIALS (INCHES) 03220

323. C DERATE : RATIO OF BASE MODULUS OF ELASTICITY 03230

324. C BCRATE : BASE MODULUS OF ELASTICITY (KSI) 03240

325. C BCRATE: SLOPE OF DEFLECTION CHANGE WITH RESPECT TO DEGREE OF SATURATION 03250

326. C TURNPT: 1. DEFLECTION OF DRY BASE MATERIAL 03260

327. C 2. DEFLECTION OF 85% SATURATION LEVEL 03270

328. C 03280

329. C REAL LA,K1,K2,N1,N2 03290

330. C EXTERnal GAMDIS 03300

331. C COMMON LA,HE,Tk,K2,N1,N2,A1,B1,B2,C1,G1,G2,R1 03310

332. C COMMON CASE,HE,DSUBA,HSUBB,NUM,S 03320

333. C COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE 03330

334. C COMMON /RAW/ XTME(120,10),YAREA(120,10),INDS,TINAX(10),UENAX(10) 03340

335. C COMMON /TNUM/ INAPT 03350

336. C COMMON /SGWET/ SGWET(100),SGDRY(100),SGW(100),SGD(100) 03360

337. C COMMON /NOGAMA/ LIGHWET,AVGM',TS!'St!!{ 03370

338. C DIMENSION EMPDF(100),EMPDF(100),AIN(2,9),BSLOPE(2,9) 03380

339. C DIMENSION PAVE(2),SOIL(9),HORIZ(2),PTYPE(2),FREE(100) 03390

340. C DIMENSION PX(100),DURAT(100),SECT(20),CDF(20),IIA(100) 03400

341. C DIMENSION DEFL(100),DERATE(100),BCRATE(2),BCMAT(6),TURNPT(2), 03410

342. C ZBCMAT(100) 03420

343. C DIMENSION FREEZ(100),DURATB(100),FZB(100),SECTB(50) 03430

344. C DIMENSION YDRAN(100),WPROB(50,50) 03440

345. C INTEGER PTYPE,'PCC', 'BCP'/ 03450

346. C DATA PAVE/0.03,0.11/ 03460

347. C DATA PVA,PVB/0.32,0.48/ 03470

348. C DATA BCMAT/425.3,236.3,209.3,64.6,29.8,17.1/ 03480

349. C DATA BCMAT/24.3,5.3,236.3,209.3,64.6,29.8,17.1/ 03490

350. C REAL*8 SOIL/'A-7-5','A-4','A-7-6','A-6','CL','ML-CL', 03500

351. C 'CH','ML','MH'/,ASOIL 03510

352. C INTEGER HORIZ,'ABC', 'BC',BHORIZ 03520


354. 2 31.89,32.13,31.89,32.13,21.93,23.02,31.39,29.01, 03540

355. 3 31.39,29.01/ 03550

356. C DATA BSLOPE/0.450,0.266,0.158,0.146,0.294,0.196,0.362,0.354, 03560

357. 2 0.312,0.311,0.312,0.311,0.151,0.161,0.331,0.284, 03570

358. 3 0.311,0.284/ 03580

359. C IF(IMAXD.GE.39) IMAXD=39 03590
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 FLOWMX: THE MAXIMUM AMOUNT WHICH WATER WOULD ENTER THE PAVEMENT
 C CC : CARRYING CAPACITY OF WATER IN BASE COURSE (N1*L*H)
 CC=N1*LA*HE
 CFHALF=(0.5/HALFT)*100.
 C DISTRIBUTION OF PAVEMENT MODULI AND DRY, WET PROBABILITIES
 C FREE : AMOUNT OF FREE WATER IN PAVEMENT (FEET**2)
 C DURAT : DURATION OF SPECIFIC RAINFALL AMOUNT (HOURS)
 C ITEST : 1 USING RIDGEWAY'S EQUATION; 2 USING DEMPESY'S FOR NO CRACKS
 C DATA AND WHEN RIDGEWAY'S METHOD TURNS OUT TO BE UNREASONABLE
 IF(NUMWET-1)33333,22222,11111 PX1=0.
 K=0
 CDFSUM=0.
 DO 7000 I=5,100,5
 FREE(I)=CC*I*0.01
 SGWET SGDRY SGD SGEM
 SGW(I)=(AINTER(INDEXA,INDEXB)-(BSLOPE(INDEXA,INDEXB)*100.))
 2 *(SGWET(I)**3)
 IF(SGW(I).LE.0.) SGW(I)=0. 
 SGD(I)=AINTER(INDEXA,INDEXB)*(SGDRY(I)**3)
 SGEM(I)=(SGW(I)+SGD(I))/((5.83333-HE)**3)
 IF(SGEM(I).LE.0.) SGEM(I)=0.
 IF(CRKJON.EQ.0.) GO TO 7777
 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=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
7788 ITEST=2
 PX(I)=((FREE(I)*FTLONG**0.02832-PVA)/(PVB**0.02832*FTLONG*LA))**12.
 IF(PX(I).LE.0.) PX(I)=0.
 DURAT(I)=((PX(I)*SHAPE)/(CONST*(YEAR**RECPOW)))**(1./(1.-DURPOW))
 2 /60.
 PX2=PX(I)
 EXPDF(I)=GAMDIS(PX2,ALPHA,BETA)
 EXPDF(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)*C.01*(I-60)
 DERATE(I)=TURNPT(1)/DEFL(I)
BCEM(I)=BCMAT(IBC)*DERATE(I)
GO TO 7766
7744  BCEM(I)=BCMAT(IBC)
DERATE(I)=1.0
GO TO 7766
7755  DEFL(I)=TURNPT(2)+BCRATE(2)*0.01*(I-85)
DERATE(I)=TURNPT(1)/DEFL(I)
BCEM(I)=BCMAT(IBC)*DERATE(I)
7766  IIB=I/10*10
IF(IIB.NE.I) GO TO 7000
CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA)
K=K+1
IF(SECTOR.LE.0.) SECTOR=0.
IF(SECTOR.GT.1.0) SECTOR=1.0
SECT(K)=SECTOR
CDFSUM=CDFSUM+SECT(K)
IF(CDFSUM.GE.1.0) CDFSUM=1.0
CDF(K)=CDFSUM
PX1=PX2
7000 CONTINUE

CALCULATE THE PART WHICH IS BEYOND THE FIELD CAPACITY IN GAMMA DISTRIBUTION
PX2 IS THE MAXIMUM INFILTRATION AMOUNT AFTER THE ABOVE LOOP

TAILPT=1.0-CDFSUM
THE DRY AND WET PROBABILITIES OF THE PAVEMENT
PAVDRY: THE DRY PROBABILITY OF PAVEMENT
PAWET: THE WET PROBABILITY OF PAVEMENT

IF(TIMAX(INDS)/24.LT.1.) GO TO 8833
PX1=0.
K=0
DO 8000 I=1,IMAXD
FREE2(I)=CC*0.01*YDRAN(I)
IF(CRKJON.EQ.0.) GO TO 8777
ISTEST=1
DURATB(I)=(FREE2(I)*FTLONG)/(CRKJON*FLCAVG)
PXB(I)=(60.*DURATB(I))**(1.-DURPOW)*CONST*(YEAR**RECPOW)/SHAPE
RIDGE=BETA*PB2(I)
IF(RIDGE.GE.174.) GO TO 8777
PX2=PXB(I)
GO TO 8788
8777 ISTEST=2
PX2=PXB(I)
CALL SIMP2(SECTOR,GAMDIS,PX1,PX2,60,ALPHA,BETA)
K=K+1
IF(SECTOR.LE.0.) SECTOR=0.
IF(SECTOR.GT.1.0) SECTOR=1.0
SECT(K)=SECTOR
PX1=PX2
8000 CONTINUE
PAVDRY=0.
IN=1
DO 8100 K=1,IMAXD
IN=IN+1
PAVDRY = PAVDRY + SECTB(K) * WPROB(1, IN)  
CONTINUE  
PAVDRY = PAVDRY + WPROB(1, IN) * TAILPT  
GO TO 8844  
DHALF = HALFT / 24.  
PAVDRY = 1. - PWET * DHALF  
GO TO 8844  
PAWET = 1. - PAVDRY  
C  
CALCULATE THE PROBABILITIES OF SATURATION LEVELS:  
SECT1: 0-60%; SECT2: 60-85%; SECT3: 85-100%  
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  
I TEST = 1  
IF(CRJKON.EQ.0.) GO TO 9191  
AVGDUR = (AVGRAS * 0.08333 * LA * FTLONG) / (CRJKON * FLOAVG)  
AVGFLO = ((60. * AVGDUR) ** (1. - DURPCW) * CONST * (YEAR ** RECPOW) / SHAPE  
GO TO 9292  
9191 I TEST = 2  
AVGDUR = ((SHAPE * AVGRAS / (CONST * (YEAR ** RECPOW))) ** ((1. / (1. - DURPCW)) / 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  
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(I2, IND)  
TRAIN1 = CONCOE + REGCOE * YRAIN1  
GO TO 9933  
9922 TRAIN1 = TIMAX(IND)  
9933 PAWET = TRAIN1 / (TOTSUM * 24.)  
PAVDRY = 1. - PAWET  
IF(YRAIN1 - 0.85) 9944, 9944, 9955  
9944 SECT3 = 0.  
GO TO 9966  
9955 SECT3 = XTIME(103, IND) / TOTSUM  
9966 IF(YRAIN1 - 60.) 9988, 9988, 9977  
9977 SECT2 = (XTIME(103, 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
DERATE(73)=TURNPT(1)/DEFL(73) 05400
DEFL(93)=TURNPT(2)+BCRATE(2)*0.075 05410
DERATE(93)=TURNPT(1)/DEFL(93) 05420
AVBCEM=BCMAT(IBC)*(1.*SECT1+DERATE(73)*SECT2+DERATE(93)*SECT3) 05430
GEBCEM=AVBCEM*PAWET+BCMAT(IBC)*PAWDRY 05440
C 05450
AVBCM: AVERAGE BASE MODULI IN WET STATE 05460
GEBCM: TOTAL AVERAGE OF BASE MODULI 05470
C 05480
AVGDUR=DURATION CORRESPONDING TO THE AVERAGE RAINFALL AMOUNT 05490
AVGFLO: FREE WATER IN PAVEMENT DUE TO AVERAGE RAINFALL AMOUNT 05490
GESGEM=TOTAL AVERAGE OF SUBGRADE MODULI 05500
AVBCEM: AVERAGE BASE MODULI IN WET STATE 05510
GEBCEM: TOTAL AVERAGE OF BASE MODULI 05520
C 05530
AVGDUR=(SHAPE*AVGRAS/(CONST*(YEAR**RECPOW)))**((1./(1.-DURPOW))/60. 05540
IF(ITEST.EQ.2) GO TO 8888 05550
AVGFLO=FLOAVG*AVGDUR*CRKJON/FTLONG 05560
GO TO 8899 05570
8888 AVGFLO=(PVB*AVGRAS*0.08333*FTLONG*LA*0.02832+PVA)/(0.02832*FTLONG) 05580
8899 IF(AVGFLO.GE.CC) AVGFLO=CC 05590
CALCULATE SUBGRADE MODULI 05600
EXACT2=AVGFLO/CC 05610
DO 9100 I2=1,100 05620
IF(EXACT2.GE.1.) GO TO 9222 05630
IF(YAREA(I2,INDS).GT.EXACT2) GO TO 9111 05640
9100 CONTINUE 05650
9111 I1=I2-1 05660
IF(I1.LE.0) GO TO 9001 05670
PEGCOE=(XTIME(I2,INDS)-XTIME(I1,INDS)) 05680
(YAREA(I2,INDS)-YAREA(I1,INDS)) 05690
INCEPT=XTIME(I2,INDS)-PEGCOE*YAREA(I2,INDS) 05700
TSGAVW=INCEPT+PEGCOE*EXACT2 05710
GO TO 9333 05720
9001 TSGAVW=XTIME(I1,INDS)*EXACT2/YAREA(I1,INDS) 05730
GO TO 9333 05740
9222 TSGAVW=TIMAX(INDS) 05750
9333 CALL SUBHT(TSGAVW,HSUBEM) 05760
C 05770
SGWETD: AVERAGE WET DEPTH OF SUBGRADE DURING THE SEASON 05780
SGDRYD: AVERAGE DRY DEPTH OF SUBGRADE 05790
SG1 : FACTOR OF SUBGRADE MODULUS FOR WET ZONE (El**3) 05800
SG2 : FACTOR OF SUBGRADE MODULUS FOR DRY ZONE 05810
SGWETD=(HE-HSUBEM)*N1/N2 05820
IF(SGWETD.LE.0.OR.K2.EQ.0.) SGWETD=0. 05830
SGDRYD=5.83333-HE-SGWETD 05840
SG1=(AINTER(INDEXA,INDEXB)-3SLOPE(INDEXA,INDEXB)**100.)*(SGWETD**3) 05850
IF(SG1.LE.0.) SG1=0. 05860
SG2=AINTER(INDEXA,INDEXB)**(SGDRYD**3) 05870
GESGEM=(SG1+SG2)/((5.83333-HE)**3) 05880
C 05890
IF(NUMWET.LE.1) GO TO 55555 05900
WRITE(6,735)CC,CFHALF,TAILPT,PAWDRY,PAWET 05910
735 FORMAT(3(/),T40,'WATER CARRYING CAPACITY OF BASE(SQ.FT)=' ,F10.3,/, 05920
2 T40,'AVERAGE DEGREE OF DRAINAGE PER HOUR =',F10.3,/, 05930
3 T40,'OVERALL PROBABILITY OF SATURATED BASE=' ,F10.3,/, 05940
4 //,T40,'DRY PROBABILITY OF BASE COURSE =',F10.3,/, 05950
5 T40,'WET PROBABILITY OF BASE COURSE =',F10.3) 05960
IF(ITEST.EQ.2) WRITE(6,745)
745 FORMAT(/>T30,'THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED ON DEMPSEY'S FIELD EQUATION')
IF(ITEST.EQ.1) WRITE(6,755)
755 FORMAT(/>T30,'THE ANALYSIS FOR WATER ENTERING PAVEMENT IS BASED ON RIDGEWAY'S LAB EQUATION')
WRITE(6,705)
705 FORMAT(/>T35,'**********PROBABILITY DISTRIBUTION OF MODULUS OF BASE COURSE**********',///)
DO 7200 I=1,10
IIA(I)=I*10
WRITE(6,715)(IIA(I),I=1,10),(FREE(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
775 FORMAT(/>T40,'***** DISTRIBUTION CHARACTERISTICS OF RAINFALL EFFECT: *****',///,
T30,'AVERAGE FREE WATER IN BASE (SQ.FT)=' ,10F7.2,///,
T30,'DURATION OF AVERAGE RAINFALL ll.M.JOUNT (HOURS)=',10F7.3,///,
T30,'AVERAGE RAINFALL AMOUNT PER DAY (INCHES)=',10.2,///,
T30,'AVERAGE BASE COURSE MODULUS IN WET STATE (KSI)=',10.2,///,
T30,'AVERAGE BASE COURSE MODULUS (KSI)=',10.2)
RETURN
C A SEASON IS COMPLETE DRY
PAVDRY=1.
PAWET=0.
AVGRAS=0.
AVGDUR=0.
AVGFLO=.
AVBCEM=BCMAT(IBC)
GEBCEM=AVBCEM
AVGECM=AINIER(INDEXA,INDEXB)
GESGEM=AINIER(INDEXA,INDEXB)
C PRINTOUT FOR ONLY ONE RAINY DAY OR A COMPLETE DRY SEASON
WRITE(6,785)
785 FORMAT(3(/)/T40,'***************************************',///)
WRITE(6,715)(IIA(I),I=1,10),(FREE(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)
CPRINTOUT FOR ONLY ONE RAINY DAY OR A COMPLETE DRY SEASON
COMPUTING PROBABILITIES OF CONSECUTIVE DRY DAYS BY KATZ'S METHOD

SUBROUTINE KATZ(IMAXD,W)

DIMENSION WZERO(50,50),WONE(50,50),W(50,50)
COMMON /DRYW:TLAMDA,DRY,LAM, WET LAM, 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 I-10 WET DAYS IN J CONSECUTIVE DAYS

WHEN THE ZEROITH DAY IS DRY

WONE (I,J): THE PROBABILITY OF I-10 WET DAYS IN J CONSECUTIVE DAYS

WHEN THE ZEROITH DAY IS WET

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

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

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

WRITE(6,45) POO,P01,P10,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)

46 FORMAT(5(/),T30, '********** PROBABILITY MATRIX **********
2**,3(/),T40,'P00=',F5.3,10X,'P01=',F5.3,10X,
3 T40,'P10=',F5.3,10X,'P11=',F5.3)
WZERO(K9,NJ9)=P00*WZERO(K9,NJ8)+P01*WONE(K8,NJ8)
WONE(K9,NJ9)=P10*WZERO(K9,NJ8)+P11*WONE(K8,NJ8)
W(K9,NJ9)=(1.-PWET)*WZERO(K9,NJ9)+PWET*WONE(K9,NJ9)

100 CONTINUE
200 CONTINUE
C
C CONVERT THE I+10 SEQUENCE TO LOWER SERIES STARTING FROM 1
C WHICH STANDS FOR DRY DAY, 2 FOR 1 WET DAY........

DO 500 I=1,MXWTPl
DO 500 J=1,I
II0=I+9
JJ0=J+9
WONE(J,I)=WONE(JJ0,II0)
WZERO(J,I)=WZERO(JJ0,II0)
IF(I.GT.1)W(J,I)=W(JJ0,II0)
500 CONTINUE

WRITE(6,:35)
35 FORMAT(1H1,5X,1********** PROBABILITIES OF K WET DAYS IN COSECUTIV
2E N DAYS ****************,5(/),T40,45(''),/T40,4X,'N',4X,'K',
C +3X,'W0(K;N)',3X,'W1(K;N)',4X,'W(K;N)'
DC 400 J2=1,IMAXD
C
J3=J2+1
WRITE(6,25)
FORMAT(///,T40,45(''),///)
DO 300 I2=1,J3
J210=J2+1
I29=I2
II=I2+1
C
WRITE(6,15)J2,II,II,WZERO(I29,J210),WONE(I29,J210),
W(I29,J210)
C
2
C 15 FORMAT(T40,15,15,3F10.3)
C 300 CONTINUE
C 400 CONTINUE
RETURN
END
C
C***************************************************************************
SUBROUTINE INPOLA(TDRAN,UDRAN,IA,LOGTIM)
IMPLICIT REAL(J-Z)
COMMON /RAW/ XTIME(l20,10),YAREA(l20,10),INDS,TIMAX(10),UEMAX(10)
COMMON /TNUM/ INABT
COMMON LA,HE,TA,K1,K2,H1,N2,A1,B1,B2,C1,G1,G2,G3,R1
C
C***************************************************************************
720. WZERO(K9,NJ9)=P00*WZERO(K9,NJ8)+P01*WONE(K8,NJ8) 07200
721. WONE(K9,NJ9)=P10*WZERO(K9,NJ8)+P11*WONE(K8,NJ8) 07210
722. W(K9,NJ9)=(1.-PWET)*WZERO(K9,NJ9)+PWET*WONE(K9,NJ9) 07220
723. 100 CONTINUE 07230
724. 200 CONTINUE 07240
725. C 07250
726. C 07260
727. C CONVERT THE I+10 SEQUENCE TO LOWER SERIES STARTING FROM 1 07270
728. C WHICH STANDS FOR DRY DAY, 2 FOR 1 WET DAY........ 07280
729. C 07290
730. C 07300
731. DO 500 I=1,MXWTPL 07310
732. DO 500 J=1,I 07320
733. I10=I+9 07330
734. J10=J+9 07340
735. WONE(J,I)=WONE(J10,I10) 07350
736. WZERO(J,I)=WZERO(J10,I10) 07360
737. IF(I.GT.1)W(J,I)=W(J10,I10) 07370
738. 500 CONTINUE 07380
739. C 07390
740. C 07400
741. C WRITE(6,35) 07410
742. C 35 FORMAT(1H1,5X,'********** PROBABILITIES OF K WET DAYS IN COSECUTIV
743. C 2E N DAYS ***********',5(/),T40,45(''),/T40,4X,'N',4X,'K',
744. C +3X,'W0(K;N)',3X,'W1(K;N)',4X,'W(K;N)'
DC 400 J2=1,IMAXD
745. C
J3=J2+1
746. C
WRITE(6,25)
747. C 25 FORMAT(///,T40,45(''),///)
748. DO 300 I2=1,J3
749. C
J210=J2+1
750. C I29=I2
751. C II=I2+1
752. C
WRITE(6,15)J2,II,II,WZERO(I29,J210),WONE(I29,J210),
753. C 2
W(I29,J210)
754. C 15 FORMAT(T40,15,15,3F10.3)
755. C 300 CONTINUE
756. C 400 CONTINUE
757. C RETURN
758. END
759. C 07590
760. C 07600
761. C 07610
762. C***************************************************************************
763. C* CALCULATE THE DESIRED DRAINING AREA BY INTRAPOLATION 07640
765. C* 07650
766. C* XTIME: TIME ( X COORDINATE ) ; 07660
767. C* YAREA: DRAINING AREA ( Y COORDINATE ) ; 07670
768. C* TDRAN: TIME OF 50 PERCENT DRAINAGE; 07680
769. C* UDRAN: 50 PERCENT DRAINAGE; 07690
770. C* TIMAX: MAXIMUM VALUE FOR TIME; 07700
771. C* UEMAX: MAXIMUM VALUE FOR DRAINAGE; 07710
772. C* 07720
773. C***************************************************************************
774. C 07730
775. C SUBROUTINE INPOLA(TDRAN,UDRAN,IA,LOGTIM) 07750
776. IMPLICIT REAL(J-Z) 07760
777. COMMON /RAW/ XTIME(120,10),YAREA(120,10),INDS,TIMAX(10),UEMAX(10) 07770
778. COMMON /TNUM/ INABT 07780
779. COMMON LA,HE,TA,K1,K2,H1,N2,A1,B1,B2,C1,G1,G2,G3,R1 07790
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
COMMON /SGWET1/ SGWET(100), SGDRY(100), SGW(100), SGD(100)
DIMENSION LOGTIM(120,10), YAPER(120,10)
DATA IPT/20/
REAL INCEPT
TOTAL SUBGRADE MODULUS
WET DEPTH OF SUBGRADE
DRY DEPTH OF SUBGRADE
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 I2=1,100
IF(I2.EQ.INABT) GO TO 2222
IF(YAREA(I2,IA).GT.EXACT) GO TO 1111
1100 CONTINUE
1111 Il=I2-1
IF(I1.LE.0) GO TO 1001
REGCOE=(XTIME(I2,IA)-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA))
INCEPT=XTIME(I2,IA)-REGCOE*YAREA(I2,IA)
IlOO=I+100
XTIME(I100,IA)=INCEPT+REGCOE*EXACT
YAREA(I100,IA)=EXACT
CALL SUBHT(XTIME(I100,IA),HSUBX)
SGWET(IX)=(HE-HSUBX)*N1/N2
IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
IF(SGWET(IX).LE.0. OR.K2.EQ.0.) SGWET(IX)=0.
SGDRY(IX)=5.83333-HE-SGWET(IX)
IF(IX EQ. IX
TDRAN=XTIME(IX)
GO TO 1000
1001 IlOO=I+100
XTIME(I100,IA)=XTIME(I2,IA)*EXACT/YAREA(I2,IA)
YAREA(I100,IA)=EXACT
CALL SUBHT(XTIME(I100,IA),HSUBX)
SGWET(IX)=(HE-HSUBX)*N1/N2
IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
IF(SGWET(IX).LE.0. OR.K2.EQ.0.) SGWET(IX)=0.
SGDRY(IX)=5.83333-HE-SGWET(IX)
1000 CONTINUE
2222 IMAX=IlOO+1
XTIME(IMAX,IA)=TIMAX(IA)
YAREA(IMAX,IA)=UEMAX(IA)
CALL SUBHT(XTIME(IMAX,IA),HSUBX)
SGWET(IX)=(HE-HSUBX)*N1/N2
IF(SGWET(IX).GE.SGDEP) SGWET(IX)=SGDEP
IF(SGWET(IX).LE.0. OR.K2.EQ.0.) SGWET(IX)=0.
SGDRY(IX)=5.83333-HE-SGWET(IX)
WRITE(6,2)
FORMAT(1H1,5(/) ,T30,'DRAINAGE%',11X,'TIME' ,5X,'PROBLEM NO.'
DO 1200 I7=101, IMAX
YAPER(I7,IA)=YAREA(I7,IA)*100.
1200 CONTINUE
2 FORMAT(1H1,5(/) ,T30,'DRAINAGE%',11X,'TIME' ,5X,'PROBLEM NO.'
DO 1200 I7=101, IMAX
WRITE(6,2)
FORMAT(1H1,5(/) ,T30,'DRAINAGE%',11X,'TIME' ,5X,'PROBLEM NO.'
DO 1200 I7=101, IMAX
WRITE(6,2)
FORMAT(1H1,5(/) ,T30,'DRAINAGE%',11X,'TIME' ,5X,'PROBLEM NO.'
DO 1200 I7=101, IMAX
WRITE(6,2)
FORMAT(1H1,5(/) ,T30,'DRAINAGE%',11X,'TIME' ,5X,'PROBLEM NO.'
DO 1200 I7=101, IMAX
SUBROUTINE JUDGE(IA,INT,ITYPF1,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 REAL INCEFT+REGCOE*UCRIT

REGCOE=(XTIME(I2,IAJ-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA))

Il=I2-1

IF(YAREA(I2,IA).LT.UCRIT) GO TO 400

11=I2-1

RECOE=(XTIME(I2,IA)-XTIME(I1,IA))/(YAREA(I2,IA)-YAREA(I1,IA))

INCEPT=XTIME(I2,IA)-RECOE*YAREA(I2,IA)

TCRIT=INCEPT+RECOE*UCRIT

IF(YAREA(I2,IA).GE.UCRIT) GO TO 4411

400 CONTINUE

4411 WRITE(6,415)GRAVEL(ITYPF1,IQFINE),GRAVPC,SAND(ITYPF1,IQFINE),

1 SANDPC,PERIND

415 FORMAT(6/,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.) GO TO 4444

WRITE(6,425)UCRPER,TCRIT

425 FORMAT(6/,T30,'CRITICAL DRAINAGE DEGREE (85% SATURATION)=',F11.2,

2/T30,'DRAINING TIME FOR 85% SATURATION (HOURS) =',F11.2,3(/)

IF(TCRIT,GT.10.) WRITE(6,11115)

111
1115 FORMAT(///,T30,'$$$$ THIS DRAINAGE DESIGN IS NOT ACCEPTABLE $$$')
09000
901. IF(TCRIT.GE.5.AND.TCRIT.LE.10.) WRITE(6,1125) 09010
902. IF(TCRIT.LE.5.) WRITE(6,1125) 09020
903. 1125 FORMAT(///,T30,'$$$$ THIS DRAINAGE DESIGN IS NOT ACCEPTABLE $$')
09030
904. IF(TCRIT.GE.5.AND.TCRIT.LE.10.) WRITE(6,1135) 09040
905. IF(TCRIT.LE.5.) WRITE(6,1135) 09050
906. 1135 FORMAT(///,T30,'$$$$ THIS DRAINAGE DESIGN IS NOT ACCEPTABLE $$')
09060
907. GO TO 4455 09070
908. 4444 WRITE(6,1145) 09080
909. 1145 FORMAT(///,T40,'!!!! THIS DRAINAGE DESIGN WOULD NOT ALLOW THE SATURATION LEVEL REACH OR LOWER THAN 85% !!!!')
09090
910. GO TO 4455 09100
911. END 09110
912. C 09120
913. C 09130
914. C****************************************************************************************** 09140
915. C* 09150
916. C* COMPUTE THE N2 VIA KNOWN K1,K2,N1 WITH NEWTON-RAPHSON'S METHOD 09160
917. C* 09170
918. C* EQUATION: K*(1-N)**2/(N**3) = CONSTANT 09180
919. C* K: PERMEABILITY; N: POROSITY 09190
920. C* 09200
921. C****************************************************************************************** 09210
922. C 09220
923. SUBROUTINE POR02 09230
924. IMPLICIT REAL(J-Z) 09240
925. INTEGER N,NA,NB,NC,NJONT,NLANE 09250
926. COMMON LA,HE,T1,K1,K2,N1,N2,A1,B1,B2,C1,G1,G2,G3,R1 09260
927. COMMON CASE,ED,EED,HSUBA,HSUBB,NUM,S 09270
928. DATA EPSI/0.1E-03/ 09280
929. DELK=0.10 09290
930. IF(K2.LE.K1) GO TO 455 09300
931. N2=N1 09310
932. GO TO 999 09320
933. 455 IF(K2.GT.0.) GO TO 555 09330
934. N2=0.1E-05 09340
935. GO TO 999 09350
936. 555 AFCTR=((1.-N1)**2)*K1/(K2*(N1**3)) 09360
937. K=K2*0.1/K1 09370
938. FOFK1=AFCTR*K**3-K**2+2.*K-1. 09380
939. KN=K+DELK 09390
940. FOFKN=AFCTR*KN**3-KN**2+2.*KN-1. 09400
941. IF(FOFK1*FOFKN)206,205,207 09410
942. 204 CONTINUE 09420
943. IF(FOFK1.EQ.0.) N2=K 09430
944. IF(FOFKN.EQ.0.) N2=KN 09440
945. RETURN 09450
946. 207 K=KN 09460
947. FOFK1=FOFKN 09470
948. GO TO 204 09480
949. 206 N21=KN 09490
950. 208 FOFN=AFCTR*N21**3-N21**2+2.*N21-1. 09500
951. DFDN=3.*AFCTR*N21**2-2.*N21+2. 09510
952. N2=N21-FOFN/DFDN 09520
953. IF(ABS(N2-N21)-EPSI)210,210,209 09530
954. 209 N21=N2 09540
955. GO TO 208 09550
956. 210 FOFN=AFCTR*N2**3-N2**2+2.*N2-1. 09560
957. RETURN 09570
958. 999 END 09580
959. C 09590
SUBROUTINE Rain(HALFT,IMAXD)
IMPLICIT INTEGER (I-N)
DIMENSION ITITL2(20)
DIMENSION AMT(5,300),SUM(10),N-M(10),YDRAN(100),WPROE(50,50)
COMMON /EDR/CONST,RECPOW,DURPOW,SHAPE
COMMON /DRYWET/
TLAMDA,DRYLAM,WE~LAM,PWET
COMHON
/X'IM:C: (120, 10), YAREA (120, 10), INDS, TIMAX(10), UEMA.l{ (10)
COHMON /NOGAMA/
NUMWE~,AVGAMT,TOTSUM
READ THE RAINFALL AMOUNT DATA IN AND COUNT THE NUMBER OF WET DAYS
AMT(1): THE RAINFALL AMOUNT DURING THE PERIOD IS CONCERNE (IN INCHES)
AMT(2): THE SEQUENCE OF DRY DAYS
AMT(3): THE SEQUENCE OF WET DAYS
TYPE: TYPE OF PAVEMENT, EITHER FCC OR BCP
ASOIL: SOIL TYPES CLASSIFIED BY 'AASHTO' OR 'UNIFIED'.
BORIZ: HORIZON (ABC OR BC). P.36,ASCE TRANS. 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-RECURRENCE EQUATION
DEFAULT = 0.3
RECPOW: POWER OF RECURRENCE INTERNAL (PERIOD EVALUATED)
DEFALT = 0.25
DURPOW: POWER OF RAINFALL DURATION
DEFALT = 0.75
SHAPE : THE CONSTANT DUE TO CURVE SHAPE OF RAINFALL INTENSITY VS. PERIOD
DEFAULT = 1.65 (GAUSSIAN CURVE)
REAL*8 ASOIL
INTEGER BORIZ
C
INPUT MATERIAL PROPERTIES OF BAE AND SUBGRADE
READ(5,445)IBC,ITYPE,ASOIL,BHORIZ
READ(5,485)CRKJON,FTLONG
READ(5,475)YEAR,CCNST,RECPOW,DURPOW,SHAPE
IF(CONST.EQ.0.) CONST=0.3
IF(RECPOW.EQ.0.) RECPOW=0.25
IF(DURPOW.EQ.0.) DURPOW=0.75
1021.
IF(SHAPE.EQ.0.) SHAPE=1.65
1022.
WRITE(6,955)
1023.
955 FORMAT(1H1,T30,'***** PAVEMENT TYPES DATA AND PERIOD *****'/,1X,
1024. 2T30,'PVMT TYPE ',5X,'SOIL CLASS',5X,' HORIZON',6X,' CRK.JT. FT.'),
1025. 35X,' SURVEYED FT',5X,' PERIOD(YEAR)'//)
1026.
WRITE(6,965)ITYPE,ASOIL,BHORIZ,CRKJON,FTLONG,YEAR
1027.
965 FORMAT(T20,A10,7X,A8,11X,A4,2(5X,F13.1),5X,F13.0,//)
1028.
WRITE(6,455)
1029.
455 FORMAT(T30,'*****CHARACTERISTICS OF RAINFALL INTENSITY-DURATION-RE
1030. 2CURRENCE EQUATION*****'//,T30,
1031. 3'K(I-D-R EQ)' , ' REC. POWER', ' DUR. POWER', '
1032. 4' CURVE SHAPE',//)
1033.
WRITE(6,465)CONST,RECPOW,DURPOW,SHAPE
1034.
465 FORMAT(T30,4F13.2)
1035.
READ(5,985)IRAIN
1036.
985 FORMAT(I3)
1037.
DC 77777 ITIME=1,IRAIN
1038.
READ(5,405) ITTL2
1039.
405 FORMAT(2GA4)
1040.
WRITE(6,495) ITITL2
1041.
495 FORMAT(1H1,T30,20A4)
1042.
DO 100 I...=l,20
1043.
INT=(L-1)*16H
1044. IEN=(L-l)rl6+l6
1045.
READ(5,415) (AMT(ISEQ,I) ,I=INT,IEN)
1046.
Fom:AT(16F5.C)
1047.
DO 800 I...=2.,3
1048. K=NUM( IJ) (K)
1049.
IF(K.EQ.O) K=1
1050.
WRITE(6,915) NUM(1)
1051. IF(IJ.EQ.1) WRITE(6,925) NUM(2)
1052.
1053.
915 FORMAT(16F5.0)
1054.
DC 200 I=INT, IEN
1055.
IF(AMT(ISEQ,I).E~.O.) GO TO 500
1056.
200 NUM(ISEQ)=I
1057.
100 CONTINUE
1058.
500 CONTINUE
1059.
DO 800 IJ=1,3
1060.
K=NUM(IJ)
1061.
IF(K.EQ.0) K=1
1062.
IF(IJ.EQ.1) WRITE(6,915) NUM(1)
1063. IF(IJ.EQ.2) WRITE(6,925) NUM(2)
1064.
995 FORMAT(T40,16I5)
1065.
995 FORMAT(T40,16F5.2)
1066.
1067.
915 FORMAT(/,T40,'***** RAINFALL AMOUNT DATA*****'//,
1068. 2 T40,'NO. OF COUNTS=',I5,//)
1069.
925 FORMAT(/,T40,'***** SEQUENCE OF DRY DAYS *****'//,
1070. 2 T40,'NO. OF COUNTS=',I5,//)
1071.
935 FORMAT(/,T40,'***** SEQUENCE OF WET DAYS *****'//,
1072. 2 T40,'NO. OF COUNTS=',I5,//)
1073.
IF(IJ.NE.1) WRITE(6,995) (IFIX(AMT(IJ,I)) ,I=1,K)
1074.
1075.
1076.
1077.
800 CONTINUE
1078.
C TOTAL NUMBER OF DAYS IN A PERIOD
1079.
C TOTUM: TOTAL NUMBER OF COUNTS FROM DRY AND WET DAYS' SEQUENCE
1080.
1081.
1082.
C THE AVERAGE AND VARIANCE
1083.
1080. C
1081. DO 600 IB=1,3
1082. SUM(IB)=0.
1083. IVALUE=NUM(IB)
1084. IF(IVALUE.EQ.0) IVALUE=1
1085. DO 300 J=1,IVALUE
1086. SUM(IB)=SUM(IB)+AMT(IB,J)
1087. 300 CONTINUE
1088. 600 CONTINUE
1089. NUMWET=NUM(1)
1090. IF(NUMWET.EQ.0) GO TO 333
1091. AVGAMT=SUM(1)/NUM(1)
1092. GO TO 444
1093. 333 AVGAMT=0.
1094. 444 TOTNUM=NUM(2)+NUM(3)
1095. TOTSUM=SUM(2)+SUM(3)
1096. AVGRAS=SUM(1)/TOTSUM
1097. IF(NUMWET.LE.1) GO TO 888
1098. DRYLAM=TOTNUM/SUM(2)
1099. WETLAM=TOTNUM/SUM(3)
1100. TLAMDA=DRYLAM+WETLAM
1101. FWET=DRYLAM/TLAMDA
1102. PDRY=WETLAM/TLAMDA
1103. C
1104. C AVGAMT: AVERAGE OF RAINFALL AMOUNT PER RAINY DAY
1105. C AVGRAS: AVERAGE OF RAINFALL AMOUNT PER DAY
1106. C WETLAM: RECIPROCAL OF THE AVERAGE OF WET DAYS
1107. C DRYLAM: RECIPROCAL OF THE AVERAGE OF DRY DAYS
1108. C
1109. SSAMT=0.
1110. DO 400 K=1,NUMWET
1111. 400 SSAMT=SSAMT+(AMT(1,K)-AVGAMT)**2
1112. VARA~T=SSAMT/NUMWET
1113. C
1114. C PARAMETERS OF GAMMA DISTRIBUTION
1115. C
1116. C ALPHA=AVGAMT**2/VARAMT
1117. C BETA=AVGAMT/VARAMT
1118. C
1119. C THE DURATION OF RAINFALL(HOURS) CORRESPONDING TO AVERAGE RAINFALL AMOUNT
1120. C
1121. WRITE(6,945)
1122. 945 FORMAT(/,T30,'***** PARAMETERS OF GAMMA DISTRIBUTION AND MARKOV
1123. 2CHAIN MODEL *****')
1124. WRITE(6,435)AVGAMT,VARAMT,ALPHA,BETA
1125. 2,DRYLAM,WETLAM,TLAMDA,PDRY,PWET
1126. 435 Format(3//), T40,'AVERAGE RAINFALL PER WET DAY(INCHES)','=F10.3//
1127. 2 T40,'VARIANCE OF RAINFALL AMOUNT','=F10.3//
1128. 3 //,T40,'ALPHA OF GAMMA DISTRIBUTION','=F10.3//
1129. 4 T40,'BETA OF GAMMA DISTRIBUTION','=F10.3//
1130. 5 //,T40,'LAMDA OF DRY DAYS (MARKOV PROCESS')','=F10.3//
1131. 6 T40,'LAMDA OF WET DAYS (MARKOV PROCESS')','=F10.3//
1132. 7 T40,'SUM OF LAMDA OF DRY AND WET DAYS','=F10.3//
1133. 8 //,T40,'PROBABILITY OF DRY DAYS','=F10.3//
1134. 9 T40,'PROBABILITY OF WET DAYS','=F10.3//
1135. IF(TIXMAX(INDS)/24.LT.1.) GO TO 888
1136. CALL KATZ(IMAXD,WPBRO)
1137. CALL DRYDAY(IMAXD,YDRAN,WPBRO)
1138. 888 CALL FLOWIN(ALPHA,BETA,PDRY,PWET,HALFT,CRKJON,IBC,ITYPE,ASOIL,
1139. 2BHORIZ,FTLONG,YEAR,AVGRAS,YDRAN,WPBRO,IMAXD)
CONTINUE
RETURN
END
C***************************************************************
C  SIMPSON'S RULE USED TO INTEGRATE THE GAMMA DISTRIBUTION
C***************************************************************
SUBROUTINE SIMP2(area2, gamdis, xmin, xmax, n, alpha, beta)
  h = (xmax - xmin) / n
  sum = 0.0
  x = xmin + h
  do 4 i = 2, n
    if (mod(i, 2)) 2, 2, 3
    2 sum = sum + 4.0 * gamdis(x, alpha, beta)
    go to 4
    3 sum = sum + 2.0 * gamdis(x, alpha, beta)
  4 x = x + h
  area2 = h / 3.0 * (gamdis(xmin, alpha, beta) + sum + gamdis(xmax, alpha, beta))
return
end
FUNCTION GAMDIS(x, alpha, beta)
  if (x .le. 0.0 .and. alpha .le. 1.0) go to 3333
  gamma = x**(alpha - 1.) * exp(-x*beta) * (beta**alpha) / (gamma(alpha))
return
3333 gamma = 10.
end
C***************************************************************
C  SIMPSON'S RULE FOR INTEGRATION
C***************************************************************
SUBROUTINE SIMPSN(area, dummyf, xmin, xmax, n)
  integer n, na, nb, nc, njont, nlane
  real la, k1, k2, n1, n2
  common la, he, ta, k1, k2, n1, n2, a1, b1, b2, c1, g1, g2, g3, r1
  common case, hed, hsuba, hsubb, num, s
  h = (xmax - xmin) / n
  sum = 0.0
  x = xmin + h
  do 4 i = 2, n
    if (mod(i, 2)) 2, 2, 3
C
C
C
C
C***************************************************************
C*             12000
C*               12010
C*                 12020
C*                   12030
C*                      12040
C*                           12050
C*                               12060
C*                                   12070
C*                                       12080
C*                                             12090
C*                                                12100
C*                                                   12110
C*                                                       12120
C*                                                           12130
C*                                                               12140
C*                                                                     12150
C*                                                                            12160
C*                                                                                   12170
C*                                                                                             12180
C*                                                                                                   12190
C*                                                                                                         12200
C*                                                                                                               12200
C*                                                                                                                   12200
C*                                                                                                                             12220
C*                                                                                                                               12230
C*                                                                                                                                   12240
C*                                                                                                                                 12250
C*                                                                                                                                     12260
C*                                                                                                                                                 12270
C*                                                                                                                                             12280
C*                                                                                                                                                    12290
C*                                                                                                                                                 12300
**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>75.00</td>
<td>0.50</td>
<td>1.50</td>
<td>10.0000</td>
<td>0.0000</td>
<td>0.1000</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

**SLOPE FACTOR= 0.444**

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

<table>
<thead>
<tr>
<th>HEAD ON X COOR. HT. (SUB.DRAIN ONLY)</th>
<th>AVG. HEIGHT</th>
<th>TIME(STAGE 1)</th>
<th>DRAINAGE DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2500E 01 0.5000E 00</td>
<td>0.4944E 00</td>
<td>0.3788E-01</td>
<td>0.1111E-01</td>
</tr>
<tr>
<td>0.5000E 01 0.5000E 00</td>
<td>0.4888E 00</td>
<td>0.1452E 00</td>
<td>0.2222E-01</td>
</tr>
<tr>
<td>0.7500E 01 0.5000E 00</td>
<td>0.4814E 00</td>
<td>0.3108E 00</td>
<td>0.3333E-01</td>
</tr>
<tr>
<td>0.1000E 02 0.5000E 00</td>
<td>0.4778E 00</td>
<td>0.5268E 00</td>
<td>0.4444E-01</td>
</tr>
<tr>
<td>0.1250E 02 0.5000E 00</td>
<td>0.4722E 00</td>
<td>0.7839E 00</td>
<td>0.5556E-01</td>
</tr>
<tr>
<td>0.1500E 02 0.5000E 00</td>
<td>0.4671E 00</td>
<td>0.1079E 01</td>
<td>0.6667E-01</td>
</tr>
<tr>
<td>0.1750E 02 0.5000E 00</td>
<td>0.4612E 00</td>
<td>0.1407E 01</td>
<td>0.7778E-01</td>
</tr>
<tr>
<td>0.2000E 02 0.5000E 00</td>
<td>0.4556E 00</td>
<td>0.1764E 01</td>
<td>0.8888E-01</td>
</tr>
<tr>
<td>0.2250E 02 0.5000E 00</td>
<td>0.4500E 00</td>
<td>0.2146E 01</td>
<td>1.0000E 00</td>
</tr>
<tr>
<td>0.2500E 02 0.5000E 00</td>
<td>0.4444E 00</td>
<td>0.2552E 01</td>
<td>1.1111E 00</td>
</tr>
<tr>
<td>0.2750E 02 0.5000E 00</td>
<td>0.4389E 00</td>
<td>0.2978E 01</td>
<td>1.2222E 00</td>
</tr>
<tr>
<td>0.3000E 02 0.5000E 00</td>
<td>0.4333E 00</td>
<td>0.3424E 01</td>
<td>1.3333E 00</td>
</tr>
<tr>
<td>0.3250E 02 0.5000E 00</td>
<td>0.4278E 00</td>
<td>0.3887E 01</td>
<td>1.4444E 00</td>
</tr>
<tr>
<td>0.3500E 02 0.5000E 00</td>
<td>0.4222E 00</td>
<td>0.4365E 01</td>
<td>1.5556E 00</td>
</tr>
<tr>
<td>0.3750E 02 0.5000E 00</td>
<td>0.4167E 00</td>
<td>0.4858E 01</td>
<td>1.6667E 00</td>
</tr>
<tr>
<td>0.4000E 02 0.5000E 00</td>
<td>0.4111E 00</td>
<td>0.5365E 01</td>
<td>1.7778E 00</td>
</tr>
<tr>
<td>0.4250E 02 0.5000E 00</td>
<td>0.4056E 00</td>
<td>0.5884E 01</td>
<td>1.8888E 00</td>
</tr>
<tr>
<td>0.4500E 02 0.5000E 00</td>
<td>0.4000E 00</td>
<td>0.6414E 01</td>
<td>2.0000E 00</td>
</tr>
<tr>
<td>0.4750E 02 0.5000E 00</td>
<td>0.3944E 00</td>
<td>0.6955E 01</td>
<td>2.1111E 00</td>
</tr>
<tr>
<td>0.5000E 02 0.5000E 00</td>
<td>0.3889E 00</td>
<td>0.7505E 01</td>
<td>2.2222E 00</td>
</tr>
<tr>
<td>0.5250E 02 0.5000E 00</td>
<td>0.3833E 00</td>
<td>0.8065E 01</td>
<td>2.3333E 00</td>
</tr>
<tr>
<td>0.5500E 02 0.5000E 00</td>
<td>0.3778E 00</td>
<td>0.8634E 01</td>
<td>2.4444E 00</td>
</tr>
<tr>
<td>0.5750E 02 0.5000E 00</td>
<td>0.3722E 00</td>
<td>0.9211E 01</td>
<td>2.5556E 00</td>
</tr>
<tr>
<td>0.6000E 02 0.5000E 00</td>
<td>0.3667E 00</td>
<td>0.9796E 01</td>
<td>2.6667E 00</td>
</tr>
<tr>
<td>0.6250E 02 0.5000E 00</td>
<td>0.3611E 00</td>
<td>1.0399E 02</td>
<td>2.7778E 00</td>
</tr>
<tr>
<td>0.6500E 02 0.5000E 00</td>
<td>0.3556E 00</td>
<td>1.0999E 02</td>
<td>2.8888E 00</td>
</tr>
<tr>
<td>0.6750E 02 0.5000E 00</td>
<td>0.3500E 00</td>
<td>0.1159E 02</td>
<td>0.3000E 00</td>
</tr>
<tr>
<td>0.7000E 02 0.5000E 00</td>
<td>0.3444E 00</td>
<td>0.1220E 02</td>
<td>0.3111E 00</td>
</tr>
<tr>
<td>0.7250E 02 0.5000E 00</td>
<td>0.3389E 00</td>
<td>0.1281E 02</td>
<td>0.3222E 00</td>
</tr>
<tr>
<td>0.7500E 02 0.5000E 00</td>
<td>0.3333E 00</td>
<td>0.1344E 02</td>
<td>0.3333E 00</td>
</tr>
<tr>
<td>HEAD ON Y COORD. (SUB.DRAIN ONLY)</td>
<td>AVG. HEIGHT</td>
<td>TIME(STAGE 2)</td>
<td>DRAINAGE DEG.</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-------------</td>
<td>--------------</td>
<td>---------------</td>
</tr>
<tr>
<td>0.4833E 00 0.5000E 00</td>
<td>0.3222E 00</td>
<td>0.1472E 02</td>
<td>0.3556E 00</td>
</tr>
<tr>
<td>0.4667E 00 0.5000E 00</td>
<td>0.3111E 00</td>
<td>0.1605E 02</td>
<td>0.3778E 00</td>
</tr>
<tr>
<td>0.4500E 00 0.5000E 00</td>
<td>0.3000E 00</td>
<td>0.1744E 02</td>
<td>0.4000E 00</td>
</tr>
<tr>
<td>0.4333E 00 0.5000E 00</td>
<td>0.2889E 00</td>
<td>0.1890E 02</td>
<td>0.4222E 00</td>
</tr>
<tr>
<td>0.4167E 00 0.5000E 00</td>
<td>0.2667E 00</td>
<td>0.2043E 02</td>
<td>0.4444E 00</td>
</tr>
<tr>
<td>0.4000E 00 0.5000E 00</td>
<td>0.2556E 00</td>
<td>0.2203E 02</td>
<td>0.4667E 00</td>
</tr>
<tr>
<td>0.3833E 00 0.5000E 00</td>
<td>0.2333E 00</td>
<td>0.2738E 02</td>
<td>0.4889E 00</td>
</tr>
<tr>
<td>0.3667E 00 0.5000E 00</td>
<td>0.2167E 00</td>
<td>0.2936E 02</td>
<td>0.5056E 00</td>
</tr>
<tr>
<td>0.3500E 00 0.5000E 00</td>
<td>0.2000E 00</td>
<td>0.3147E 02</td>
<td>0.5222E 00</td>
</tr>
<tr>
<td>0.3333E 00 0.5000E 00</td>
<td>0.1889E 00</td>
<td>0.3371E 02</td>
<td>0.5400E 00</td>
</tr>
<tr>
<td>0.3167E 00 0.5000E 00</td>
<td>0.1778E 00</td>
<td>0.3667E 02</td>
<td>0.5556E 00</td>
</tr>
<tr>
<td>0.3000E 00 0.5000E 00</td>
<td>0.1667E 00</td>
<td>0.4142E 02</td>
<td>0.5778E 00</td>
</tr>
<tr>
<td>0.2833E 00 0.5000E 00</td>
<td>0.1556E 00</td>
<td>0.4439E 02</td>
<td>0.5999E 00</td>
</tr>
<tr>
<td>0.2667E 00 0.5000E 00</td>
<td>0.1444E 00</td>
<td>0.4762E 02</td>
<td>0.6222E 00</td>
</tr>
<tr>
<td>0.2500E 00 0.5000E 00</td>
<td>0.1333E 00</td>
<td>0.5113E 02</td>
<td>0.6444E 00</td>
</tr>
<tr>
<td>0.2333E 00 0.5000E 00</td>
<td>0.1222E 00</td>
<td>0.5499E 02</td>
<td>0.6666E 00</td>
</tr>
<tr>
<td>0.2167E 00 0.5000E 00</td>
<td>0.1111E 00</td>
<td>0.5926E 02</td>
<td>0.6889E 00</td>
</tr>
<tr>
<td>0.2000E 00 0.5000E 00</td>
<td>0.1000E 00</td>
<td>0.6402E 02</td>
<td>0.7111E 00</td>
</tr>
<tr>
<td>0.1833E 00 0.5000E 00</td>
<td>0.8889E-01</td>
<td>0.6940E 02</td>
<td>0.7333E 00</td>
</tr>
<tr>
<td>0.1667E 00 0.5000E 00</td>
<td>0.7778E-01</td>
<td>0.7557E 02</td>
<td>0.7556E 00</td>
</tr>
<tr>
<td>0.1500E 00 0.5000E 00</td>
<td>0.6666E-01</td>
<td>0.8276E 02</td>
<td>0.7778E 00</td>
</tr>
<tr>
<td>0.1333E 00 0.5000E 00</td>
<td>0.5556E-01</td>
<td>0.9135E 02</td>
<td>0.8000E 00</td>
</tr>
<tr>
<td>0.1167E 00 0.5000E 00</td>
<td>0.4444E-01</td>
<td>1.020E 03</td>
<td>0.8222E 00</td>
</tr>
<tr>
<td>0.1000E 00 0.5000E 00</td>
<td>0.3333E-01</td>
<td>1.158E 03</td>
<td>0.8444E 00</td>
</tr>
<tr>
<td>0.0833E-01 0.5000E 00</td>
<td>0.2222E-01</td>
<td>0.1356E 03</td>
<td>0.8667E 00</td>
</tr>
<tr>
<td>0.0666E-01 0.5000E 00</td>
<td>0.1111E-01</td>
<td>0.1697E 03</td>
<td>0.8889E 00</td>
</tr>
<tr>
<td>0.0500E-01 0.5000E 00</td>
<td>0.5556E-02</td>
<td>0.2041E 03</td>
<td>0.9111E 00</td>
</tr>
<tr>
<td>0.0333E-01 0.5000E 00</td>
<td></td>
<td></td>
<td>0.9333E 00</td>
</tr>
<tr>
<td>DRAINAGE%</td>
<td>TIME</td>
<td>PROBLEM NO.</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.655E 00</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.215E 01</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td>0.413E 01</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>0.641E 01</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>0.892E 01</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>0.116E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>35.0</td>
<td>0.144E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td>0.174E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>45.0</td>
<td>0.208E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>50.0</td>
<td>0.246E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>55.0</td>
<td>0.289E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>0.337E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>65.0</td>
<td>0.394E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>70.0</td>
<td>0.460E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>75.0</td>
<td>0.540E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>80.0</td>
<td>0.640E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>85.0</td>
<td>0.774E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>90.0</td>
<td>0.967E 02</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>95.0</td>
<td>0.131E 03</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>98.9</td>
<td>0.204E 03</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

****** EVALUATION OF DRAINAGE DESIGN ******

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

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

$$$$ THIS DRAINAGE DESIGN IS IN THE MARGINALLY ACCEPTABLE REGION $$$$
***** 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-RECURRANCE EQUATION *****

<table>
<thead>
<tr>
<th>K(I-D-R EQ)</th>
<th>REC. POWER</th>
<th>DUR. POWER</th>
<th>CURVE SHAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>0.25</td>
<td>0.75</td>
<td>1.65</td>
</tr>
</tbody>
</table>
RAINFALL DATA AND ANALYSIS OF HOUSTON FAA AIRPORT; MAY, 1970.

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

NO. OF COUNTS = 9

1.65 0.01 4.20 0.45 4.22 0.01 1.04 2.25 1.01

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

NO. OF COUNTS = 4

8 4 4 6

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

NO. OF COUNTS = 5

1 1 2 3 2

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

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

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

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

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

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

P00=0.781  P01=0.219
P10=0.536  P11=0.464
<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

(The 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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Base Moduli (KSI)</th>
<th>64.60</th>
<th>64.60</th>
<th>64.60</th>
<th>64.60</th>
<th>64.60</th>
<th>64.60</th>
<th>29.36</th>
<th>19.00</th>
<th>5.07</th>
<th>2.14</th>
</tr>
</thead>
<tbody>
<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>1.00</td>
<td>1.00</td>
<td>0.45</td>
<td>0.29</td>
<td>0.08</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 *****

<table>
<thead>
<tr>
<th>Average Free Water in Base (SQ.FEET)</th>
<th>1.55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of Average Rainfall Amount (HOURS)</td>
<td>0.080</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>25.84</td>
</tr>
<tr>
<td>Average Base Course Modulus (KSI)</td>
<td>39.55</td>
</tr>
<tr>
<td>Average Subgrade Modulus (KSI)</td>
<td>31.22</td>
</tr>
</tbody>
</table>
(b) Water Penetration Into and Evaporation from a Low Permeability Base Course
C WATER INFILTRATION AND EVAPORATION OF A LOW PERMEABLE BASE COURSE

C TEXAS TRANSPORTATION INSTITUTE

C AUGUST 1983

C***********************************************************************

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

CALL LOWPER(DEPTH, INFILT)

CALL EVAPOR(ZROOT, ASUBN, UATM, UNOT, DIFC, DEPTH, DQDU)

CALL EVWET(ZROOT, ASUBN, UATM, UNOT, DIFC, DEPTH, DQDU)

WRITE(6,115)

115 FORMAT(1H1)

STOP

END

C***********************************************************************

C 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

SUBROUTINE EVAPOR(ZROOT, ASUBN, UATM, UNOT, DIFC, DEPTH, DQDU)

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**Z/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 ***', 2H2*, 00010
0020
0030
0040
0050
0060
0070
0080
0090
0100
0110
0120
0130
0140
0150
0160
0170
0180
0190
0200
0210
0220
0230
0240
0250
0260
0270
0280
0290
0300
0310
0320
0330
0340
0350
0360
0370
0380
0390
0400
0410
0420
0430
0440
0450
0460
0470
0480
0490
0500
0510
0520
0530
0540
0550
0560
0570
0580
0590
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)

105 FORMAT(///,T30,'********** SUCTION DISTRIBUTION IN SOIL DUE TO EVAPORATION **********',3(/),T40,' TIME (DAYS)',5(/),T80, 'SOIL DEPTH (CM) I',T80, 'SUCTION (PF) I',3(/))

DO 3300 I2=1,10
  TSIGMA=0.
  YVERT=DEPTH/10.*I2
  DO 3100 1=1,10
    POWER=ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2)
    IF(ABS(POWER).GE.100.) GO TO 3333
    SIGMA(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2))*COS(ZROOT(I)*YVERT/DEPTH)
    TSIGMA=TSIGMA+SIGMA(I)
  CONTINUE
  USOIL(I2,I1)=UATM+TSIGMA
  WRITE(6,205)
  DYTIME,YVERT,USOIL(I2,I1)
205 FORMAT(2(/),T40,F15.3,T60,F15.3,T80,E12.5)
3300 CONTINUE
RETURN
END

C**********************************************************************
c
C**********************************************************************
SUBROUTINE EVROOT(ZROOT,DEPTH,EVAPC)
C BISECTION METHOD TO SOLVE FOR ROOTS OF 'DEPTH*EVAPC*COT(Z)-Z=0'
C DEPTH: LENGTH OF SOIL COLUMN IN CENTIMETER
C EVAPC: EVAPORATION COEFFICIENT IN CM/SEC

DIMENSION ZROOT(20)
DATA EPSI/0.1E-05/
DO 1000 I=1,10
  AMPLIT=EVAPC*DEPTH
  XL=3.1416*(I-1)+0.1
  XR=3.14*I
  DO 1000 I2=1,10
    XM=(XL+XR)/2.
    FOFXL=AMPLIT*COTAN(XL)-XL
    FOFXM=AMPLIT*COTAN(XM)-XM
    IF(FOFXL*FOFXM).LE.0. ) GO TO 1010
    IF(ABS(FOFXL).LE.EPSI.) GO TO 1010
    IF(ABS(FOFXM).LE.EPSI.) GO TO 1010
    IF(ABS(FOFXL*FOFXM).LE.EPSI.) GO TO 1010
    XM=(XM+XM)/2.
  100 CONTINUE
1010 CONTINUE
RETURN
END
GO TO 50
30 IF(FOFXM.EQ.0.) ZROOT(I)=XM
 IF(FOFXL.EQ.0.) ZROOT(I)=XL
 GO TO 2222
40 XL=XM
50 IF(ABS(XL-XR)-EPSI) 210,210,100
100 CONTINUE
210 ZROOT(I)=XM
2222 FZROOT=AMPLIT*COTAN(ZROOT(I))-ZROOT(I)
1000 CONTINUE
RETURN
END

C***********************************************************************
c
C WATER
C***********************************************************************
c
SUBROUTINE EVWET(ZROOT,ASUBN,UATM,UNOT,DIFC,DEPTH,DQDU)
DIMENSION ASUBN(20) ,EVWT(1000) ,SERIES(20) ,ZROOT(20)
C
COMPUTATION OF AMOUNT OF WATER EVAPORATED FROM SOIL
C EVWT WATER AMOUNT EVAPORATED FROM SOIL IN CM
C SERIES: SINGLE TERM FOR THE FOURIES SERIES
C TSERIE: SUM OF THE SERIES WHICH IS INTEGRATED FROM SUCTION AT
C SPECIFIC TIME
C DQDU: THE RATE OF WATER CONTENT CHANGE PER UNIT SUCTION (PF)
C
WRITE(6,405)
405 FORMAT(1H1,2(/)
   T30,'*********** WATER AMOUNT EVAPORATED FROM SOIL ',3(/)
   T60,'EVAPORATION TIME(HOUR) ',T60,'EVAPORATION AMOUNT  (CM) ')
DO 4100 IK=1,720
   TSERIE=0.
   HRTH!E=IK*1.
   EVTIME=HRTIME*3600.
   DO 4000 I=1,10
      POWER=ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2)
      IF(ABS(POWER).GE.100.) GO TO 4411
      SERIES(I)=ASUBN(I)*EXP(-ZROOT(I)**2*EVTIME*DIFC/(DEPTH**2))
      TSERIE=TSERIE+SERIES(I)
   4000 CONTINUE
   4411 EVWT(IK)=(UATM-UNOT+TSERIE)*DEPTH*DQDU
   C
   I2=IK/2*2
   IF(I2.NE.IK.AND.EVWT(IK).LT.DEPTH) GO TO 4100
   WRITE(6,415) HRTIME,EVWT(IK)

415 FORMAT(2(/),T45,F10.2,T60,F23.4)
   IF(EVWT(IK) .GE.DEPTH) GO TO 4444
4100 CONTINUE
4444 RETURN
END
C***********************************************************************
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 GENERATOR.

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
25 FORMAT(6(E10.3))
WRITE(6,45)
45 FORMAT(1H1,//,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,
//,T20, 'DEPTH OF CRACK/JOINT (CM) =',E10.3,
//,T20, 'VERTICAL PERMEABILITY OF BASE (CM/HR) =',E10.3,
//,T20,'HORIZONTAL PERMEABILITY OF BASE (CM/HR) =',E10.3,
//,T20, 'POROSITY OF BASE COURSE =',E10.3,
//,T20, 'CAPILLARY HEAD OF BASE (CM) =',E10.3)
WRITE(6,65)
65 FORMAT(///,13X,'TIME (HOUR)',5X,'HORIZONTAL DIST.(CM)',
27X,'VERTICAL DIST.(CM)',4X,'CRACK WATER DEPTH(CM)',//)

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
YOFT(I)=SQRT(2.*HPERM*TIME(I)*T(L+HTCP)/POR01)
DENT=(HPERM*YOFT(I)*(T(L+HTCP)/YOFT(I))+
2*VPERM*YOFT(I)*(YOFT(I)+T(L+HTCP))/YOFT(I))*1.5708/POR01
DL(I)=(DENT*DT)/WC
DPWA(I)=DPWA(IM1)-DL(I)

OUTPUT ONE SET OF RESULTS OUT OF EVERY TEN CALCULATIONS
IF(DPWA(I).LE.0.) GO TO 222
ID=IM1/10*10
IF(ID-IM1)100,111,100

162
USE INTRAPOLATION TO ENUMERATE THE FINAL DEPTH WHERE WATER WILL REACH

```fortran
    222  DEPTH=YOFT(I)-(YOFT(I)-YOFT(IM1))/(DPWA(I)-DPWA(IM1))*DPWA(I)
    241.  YOFT(I)=DEPTH
    244.  DELY2=DEPTH-YOFT(IM1)
    245.  DT=POR01*DEPTH*DELY2/(VPERM*(DEPTH+HTCP+TL))
    246.  TIME(I)=TIME(IM1)+DT
    247.  INFILT=TIME(I)
    248.  XOFT(I)=SQRT(2.*HPERM*TIME(I)*(TL+HTCP)/POR01)
    249.  DENT=(HPERM*DEPTH*(TL+HTCP)/XOFT(I)+
    250.  VPERM*XOFT(I)*(DEPTH+TL+HTCP)/DEPTH)*1.5708/POR01
    251.  DL(I)=(DENT*DT)/WC
    252.  DPWA(I)=DPWA(IM1)-DL(I)
    253.  WRITE(6,75) TIME(I),XOFT(I),DEPTH,DPWA(I)
    254.  RETURN
    255. END
```
********** WATER DISTRIBUTION OF LOW PERMEABILITIY 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 = 0.000E 00
CAPILLARY HEAD OF BASE (CM) = 0.300E 03

<table>
<thead>
<tr>
<th>TIME (HOUR)</th>
<th>HORIZONTAL DIST.(CM)</th>
<th>VERTICAL DIST.(CM)</th>
<th>CRACK WATER DEPTH(CM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.846E-04</td>
<td>0.332E 00</td>
<td>0.100E 00</td>
<td>0.250E 02</td>
</tr>
<tr>
<td>0.323E-03</td>
<td>0.648E 00</td>
<td>0.200E 00</td>
<td>0.249E 02</td>
</tr>
<tr>
<td>0.715E-03</td>
<td>0.964E 00</td>
<td>0.300E 00</td>
<td>0.248E 02</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>0.281E-02</td>
<td>0.191E 01</td>
<td>0.600E 00</td>
<td>0.241E 02</td>
</tr>
<tr>
<td>0.382E-02</td>
<td>0.223E 01</td>
<td>0.700E 00</td>
<td>0.238E 02</td>
</tr>
<tr>
<td>0.498E-02</td>
<td>0.254E 01</td>
<td>0.800E 00</td>
<td>0.234E 02</td>
</tr>
<tr>
<td>0.629E-02</td>
<td>0.286E 01</td>
<td>0.900E 00</td>
<td>0.230E 02</td>
</tr>
<tr>
<td>0.775E-02</td>
<td>0.317E 01</td>
<td>0.100E 01</td>
<td>0.225E 02</td>
</tr>
<tr>
<td>0.937E-02</td>
<td>0.349E 01</td>
<td>0.110E 01</td>
<td>0.220E 02</td>
</tr>
<tr>
<td>0.111E-01</td>
<td>0.381E 01</td>
<td>0.120E 01</td>
<td>0.214E 02</td>
</tr>
<tr>
<td>0.131E-01</td>
<td>0.412E 01</td>
<td>0.130E 01</td>
<td>0.208E 02</td>
</tr>
<tr>
<td>0.151E-01</td>
<td>0.444E 01</td>
<td>0.140E 01</td>
<td>0.201E 02</td>
</tr>
<tr>
<td>0.174E-01</td>
<td>0.475E 01</td>
<td>0.150E 01</td>
<td>0.194E 02</td>
</tr>
<tr>
<td>0.198E-01</td>
<td>0.507E 01</td>
<td>0.160E 01</td>
<td>0.186E 02</td>
</tr>
<tr>
<td>0.223E-01</td>
<td>0.538E 01</td>
<td>0.170E 01</td>
<td>0.178E 02</td>
</tr>
<tr>
<td>0.250E-01</td>
<td>0.570E 01</td>
<td>0.180E 01</td>
<td>0.169E 02</td>
</tr>
<tr>
<td>0.278E-01</td>
<td>0.601E 01</td>
<td>0.190E 01</td>
<td>0.160E 02</td>
</tr>
<tr>
<td>0.308E-01</td>
<td>0.633E 01</td>
<td>0.200E 01</td>
<td>0.150E 02</td>
</tr>
<tr>
<td>0.339E-01</td>
<td>0.664E 01</td>
<td>0.210E 01</td>
<td>0.140E 02</td>
</tr>
<tr>
<td>0.372E-01</td>
<td>0.696E 01</td>
<td>0.220E 01</td>
<td>0.130E 02</td>
</tr>
<tr>
<td>0.407E-01</td>
<td>0.727E 01</td>
<td>0.230E 01</td>
<td>0.118E 02</td>
</tr>
<tr>
<td>0.443E-01</td>
<td>0.759E 01</td>
<td>0.240E 01</td>
<td>0.107E 02</td>
</tr>
<tr>
<td>0.480E-01</td>
<td>0.790E 01</td>
<td>0.250E 01</td>
<td>0.095E 02</td>
</tr>
<tr>
<td>0.519E-01</td>
<td>0.822E 01</td>
<td>0.260E 01</td>
<td>0.089E 02</td>
</tr>
<tr>
<td>0.560E-01</td>
<td>0.853E 01</td>
<td>0.270E 01</td>
<td>0.088E 02</td>
</tr>
<tr>
<td>0.602E-01</td>
<td>0.884E 01</td>
<td>0.280E 01</td>
<td>0.055E 01</td>
</tr>
<tr>
<td>0.645E-01</td>
<td>0.916E 01</td>
<td>0.290E 01</td>
<td>0.041E 01</td>
</tr>
<tr>
<td>0.690E-01</td>
<td>0.947E 01</td>
<td>0.300E 01</td>
<td>0.026E 01</td>
</tr>
<tr>
<td>0.737E-01</td>
<td>0.979E 01</td>
<td>0.310E 01</td>
<td>0.013E 01</td>
</tr>
<tr>
<td>0.772E-01</td>
<td>0.100E 02</td>
<td>0.317E 01</td>
<td>0.012E-03</td>
</tr>
</tbody>
</table>
********** 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 **********

<table>
<thead>
<tr>
<th>TIME (DAYS)</th>
<th>SOIL DEPTH (CM)</th>
<th>SUCTION (PF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>0.317</td>
<td>0.43524E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>0.635</td>
<td>0.43822E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>0.952</td>
<td>0.44319E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>1.269</td>
<td>0.45011E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>1.586</td>
<td>0.45896E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>1.904</td>
<td>0.46970E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>2.221</td>
<td>0.48224E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>2.538</td>
<td>0.49650E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>2.855</td>
<td>0.51233E 01</td>
</tr>
<tr>
<td>1.000</td>
<td>3.173</td>
<td>0.52958E 01</td>
</tr>
<tr>
<td>2.000</td>
<td>0.317</td>
<td>0.48874E 01</td>
</tr>
<tr>
<td>Value</td>
<td>Column 1</td>
<td>Column 2</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>2.000</td>
<td>0.635</td>
<td>0.49105E</td>
</tr>
<tr>
<td>2.000</td>
<td>0.952</td>
<td>0.49487E</td>
</tr>
<tr>
<td>2.000</td>
<td>1.269</td>
<td>0.50017E</td>
</tr>
<tr>
<td>2.000</td>
<td>1.586</td>
<td>0.50688E</td>
</tr>
<tr>
<td>2.000</td>
<td>1.904</td>
<td>0.51493E</td>
</tr>
<tr>
<td>2.000</td>
<td>2.221</td>
<td>0.52425E</td>
</tr>
<tr>
<td>2.000</td>
<td>2.538</td>
<td>0.53474E</td>
</tr>
<tr>
<td>2.000</td>
<td>2.855</td>
<td>0.54627E</td>
</tr>
<tr>
<td>2.000</td>
<td>3.173</td>
<td>0.55874E</td>
</tr>
<tr>
<td>3.000</td>
<td>0.317</td>
<td>0.52835E</td>
</tr>
<tr>
<td>3.000</td>
<td>0.635</td>
<td>0.53003E</td>
</tr>
<tr>
<td>3.000</td>
<td>0.952</td>
<td>0.53281E</td>
</tr>
<tr>
<td>3.000</td>
<td>1.269</td>
<td>0.53667E</td>
</tr>
<tr>
<td>3.000</td>
<td>1.586</td>
<td>0.54155E</td>
</tr>
<tr>
<td>3.000</td>
<td>1.904</td>
<td>0.54742E</td>
</tr>
<tr>
<td>3.000</td>
<td>2.221</td>
<td>0.55420E</td>
</tr>
<tr>
<td>3.000</td>
<td>2.538</td>
<td>0.56183E</td>
</tr>
<tr>
<td>3.000</td>
<td>2.855</td>
<td>0.57022E</td>
</tr>
<tr>
<td>3.000</td>
<td>3.173</td>
<td>0.57929E</td>
</tr>
<tr>
<td>4.000</td>
<td>0.317</td>
<td>0.55717E</td>
</tr>
<tr>
<td>Value</td>
<td>Column 1</td>
<td>Column 2</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>4.000</td>
<td>0.635</td>
<td>0.55839E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>0.952</td>
<td>0.56041E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>1.269</td>
<td>0.56322E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>1.586</td>
<td>0.56677E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>1.904</td>
<td>0.57104E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>2.221</td>
<td>0.57597E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>2.538</td>
<td>0.58151E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>2.855</td>
<td>0.58762E 01</td>
</tr>
<tr>
<td>4.000</td>
<td>3.173</td>
<td>0.59421E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>0.317</td>
<td>0.57812E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>0.635</td>
<td>0.57901E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>0.952</td>
<td>0.58049E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>1.269</td>
<td>0.58252E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>1.586</td>
<td>0.58511E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>1.904</td>
<td>0.58821E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>2.221</td>
<td>0.59180E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>2.538</td>
<td>0.59583E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>2.855</td>
<td>0.60027E 01</td>
</tr>
<tr>
<td>5.000</td>
<td>3.173</td>
<td>0.60506E 01</td>
</tr>
<tr>
<td>Evaporation Time (Hours)</td>
<td>Evaporation Amount (CM)</td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>0.5339</td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>0.9948</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>1.4172</td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>1.8123</td>
<td></td>
</tr>
<tr>
<td>10.00</td>
<td>2.1860</td>
<td></td>
</tr>
<tr>
<td>12.00</td>
<td>2.5422</td>
<td></td>
</tr>
<tr>
<td>14.00</td>
<td>2.8837</td>
<td></td>
</tr>
<tr>
<td>16.00</td>
<td>3.2123</td>
<td></td>
</tr>
</tbody>
</table>
E-3. GUIDE FOR DATA INPUT TO COMPUTER PROGRAM

(a) Simulation Model of Rainfall Infiltration and Drainage Analysis

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

cc 1-5 IPROB Problem Number (< 10)
cc 6-8 INEED Analytical procedures required
0: Drainage analysis only
1: Drainage analysis and drainage design evaluation
2: System analysis of rainfall infiltration and drainage

cc 11-80 ITITLE Problem title

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

cc 1-10 LA One side width of base (feet)
cc 11-20 HE Depth of base (feet)
cc 21-30 TAPER Slope ratio or value of tan of base (%) e.g., tan 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

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

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

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

3. Material types of base course (215, 2F10.0)

cc 5 ITYPE Types of fines added*
1. Inert filler
2. Silt
3. Clay

cc 6-10 IQFINE Amount of fines added*
1. 0%
2. 2.5%
3. 5%
4. 10%

*see Table 2

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

cc 21-30 SANDPC Percentage of Sand in sample

NOTE: If INEED=0 or 1, skip the following cards.
4. Material properties of base and subgrade (I4, A4, A8, A4)

cc 4 IBC  Index of base course material which corresponds to the elastic modulus (see Table 3)

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

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

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

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

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

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

cc 11-20 FTLONG Surveyed field length (feet)
*If cracks and joints are not available input 0.0 for CRKJON, the model will use Dempsey and Robnett's regression equation to calculate the amount of water flowing into base course.

6. Parameters of intensity-duration-recurrence equation (5F10.0) (see Appendix A-2)

cc 1-10 YEAR Evaluated period (years)
cc 11-20 CONST Constant K (default=0.3)
c c 21-30 RECPOW Power of recurrence interval (default=0.25)
c c 31-40 DURPOW Power of rainfall duration (default=0.15)
c c 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>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 WC</td>
<td>Width of Crack/Joint (cm)</td>
</tr>
<tr>
<td>11-20 TL</td>
<td>Depth of Crack/Joint (cm)</td>
</tr>
<tr>
<td>21-30 HPERM</td>
<td>Permeability of Horizontal direction in Base Course (cm/hr)</td>
</tr>
<tr>
<td>31-40 VPERM</td>
<td>Permeability of Vertical direction in Base Course (cm/hr)</td>
</tr>
<tr>
<td>41-50 POR01</td>
<td>Porosity of Base Course (dimensionless)</td>
</tr>
<tr>
<td>51-60 HTCP</td>
<td>Capillary head in Base Course (cm)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 UATM</td>
<td>Suction of atmosphere (pF)</td>
</tr>
<tr>
<td>11-20 UNOT</td>
<td>Initial suction of base soil (pF)</td>
</tr>
<tr>
<td>21-30 DIFC</td>
<td>Diffusion Coefficient (cm²/sec)</td>
</tr>
<tr>
<td>31-40 DQDU</td>
<td>Slope ratio between water content and suction</td>
</tr>
<tr>
<td>41-50 EVAPC</td>
<td>Evaporation Coefficient (cm/sec)</td>
</tr>
</tbody>
</table>