Rainfall Infiltration, Drainage, and Load-Carrying Capacity of Pavements

SHANG J. LIU and ROBERT L. LYTTON

ABSTRACT

A systematic analysis is presented that simulates rainfall infiltration into the base course, and subsequently the rate of drainage out the base course into the subgrade and into lateral drainage. The method incorporates the distribution of the amount of rainfall, probabilities of wet and dry days, infiltration of water into the pavement through cracks and joints, and the drainage of a base course. The effects of saturation on the resilient moduli of the base course and the subgrade are calculated. A Gamma distribution is used 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. A new model that uses a parabolic phreatic surface and allows drainage through a permeable subgrade has been developed for computing the drainage of the pavement base and subgrade. Example results indicate that pavement performance is better in a high rainfall area that has a permeable subgrade when compared with the pavement performance in a low rainfall area that has an impermeable subgrade.

In estimating the long-term performance of pavements and in designing pavements to endure the effects of local climate, it is essential to be able to estimate the effect of rainfall on the modulus of the base course and subgrade. In this paper a comprehensive way of making such estimates is described, and the results of example calculations are given.

One cause of excess moisture content in the pavement 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 (1) and Markow (2), 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 model. His model is used in the EAROMAR system, which is a simulation model of freeway performance used by FHWA in conducting economic analyses of various strategies of roadway and pavement reconstruction, rehabilitation, and maintenance. Several improvements can be made on this model, as described later in this paper.

In this paper a stochastic model that consists of five main parts is described:

1. Estimation of the amount of rainfall that falls each day on a pavement,
2. 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. Effect of water saturation on the load-carrying capacity of base courses and subgrades.

Groundwater sources and the side infiltration from pavement shoulders are not considered in this paper.

MODELS OF RAINFALL DISTRIBUTION AND FREQUENCY ANALYSIS

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 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 indicate that the quantity follows a probability density function),
2. The intensity and duration of each rainfall, and
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.

Probability Model of Quantity of Rainfall

Several theoretical probability distribution models of the total quantity of precipitation in a single rainfall have been presented in statistical climatology (3), in which the Gamma distribution has a long history of being used as a suitable theoretical model for frequency distributions of precipitation (4). Because the Gamma distribution has been well accepted as a general model as well as a fairly practical method, it is selected to represent the distribution of the quantity of rainfall.

The probability density function of the Gamma distribution is

$$f(R;\alpha,\beta) = [\beta^{\alpha}/\Gamma(\alpha)]\, e^{-\beta R} R^{\alpha-1},\ R \geqslant 0 \qquad\qquad 0 \quad R < 0 \tag{1}$$

where R is the precipitation quantity, and $\Gamma(\alpha)$ is the Gamma function, where $\Gamma(n + 1) = n!$, $n = 0, 1, 2, \ldots$.

The parameters α and β may be estimated by the moments method:

$$\alpha = \bar{R}^2/S^2 \quad \bar{R} = \text{mean} = \Sigma R_i/n$$

$$\beta = \bar{R}/S^2 \quad S^2 = \text{variance} = \Sigma (R_i - \bar{R})^2/n \tag{2}$$

Models of Intensity and Duration of Rainfall

Storms and floods vary spatially and temporally in magnitude and are often characterized through their peak discharges. The frequently used rainfall intensity-duration-return period equation (5,6) has often been expressed by

$$i = kt_p^x/t_R^n \tag{3}$$

where

t_R = effective rainfall duration (min),
t_p = recurrence interval (years),
i = maximum rainfall intensity (in./hr) during the effective rainfall duration, and
k,x,n = functions of the locality [for example, it was found that in the eastern United States n averaged about 0.75 and x and k were about 0.25 and 0.30, respectively (5)].

The unit hydrograph is a graph of rainfall intensity versus time with a volume of 1 in. 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 (3). In this model 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) (see Figure 1). The deviation between these two functions is fairly small for practical purposes.

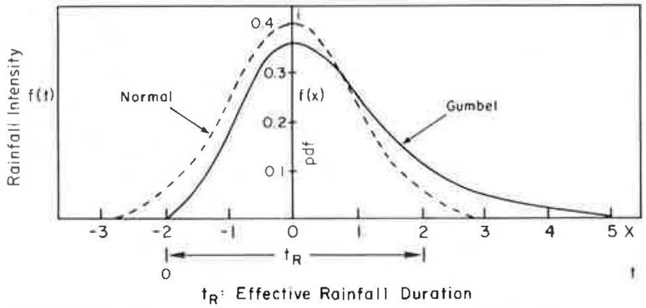

FIGURE 1 Comparison of normal and Gumbel distributions.

The equation relating the duration of rainfall and its quantity is derived as

$$t_R = (1.65R/kt_p^x)^{1/1-n} \tag{4}$$

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 wet days on which the quantity of precipitation is greater than 0.01 in. have been used in a variety of weather-related research fields. However, the Markov process has been regarded as the basic general method. To simplify the modeling, the first-order Markov chain model was selected as an estimation of the rainfall occurrence probability.

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

$$P(t) = [p_{ij}(t)] = \begin{bmatrix} p_{00}(t) & p_{01}(t) \\ p_{10}(t) & p_{11}(t) \end{bmatrix} \tag{5}$$

where p_{ij} represents the probability that the Markovian system is in state j at time t given that it was in state i at time 0; the subscript 0 stands for dry, and a subscript of 1 stands for wet. Thus $p_{10}(t)$ represents the probability of having a dry day at time t when time 0 is a wet day; 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 number of wet or dry days in a sequence follows a negative exponential distribution:

$$f(x) = \lambda e^{-\lambda x} \quad \begin{cases} x > 0, \lambda > 0 \\ x = \text{number of wet or dry days in sequence} \end{cases} \tag{6}$$

The variable λ is the reciprocal of the average dry or wet days per period: $\lambda_d = 1/\bar{x}_{dry}$ and $\lambda_w = 1/\bar{x}_{wet}$, where $\bar{x}_{dry}$ is the average number of dry days in a given period, and $\bar{x}_{wet}$ is the average number of wet days in that same period. Therefore, the transition matrix is derived as (7)

$$P(t) = [1/(\lambda_w + \lambda_d)] \times \begin{bmatrix} \lambda_w + \lambda_d e^{-(\lambda_w + \lambda_d)t} & \lambda_d[1 - e^{-(\lambda_w + \lambda_d)t} \\ \lambda_w[1 - e^{-(\lambda_w + \lambda_d)t}] & \lambda_d + \lambda_w e^{-(\lambda_w + \lambda_d)t} \end{bmatrix} \tag{7}$$

Associated with the Markov chain model (Equation 7) is a recurrence relation for computing the probabilities of dry and wet days that was derived by Katz (8):

$$\begin{bmatrix} W_0(k;N) \\ W_1(k;N) \end{bmatrix} \underbrace{\begin{bmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{bmatrix}}_{\text{Transition Matrix}} \begin{bmatrix} W_0(k;N-1) \\ W_1(k-1;N-1) \end{bmatrix} \tag{8}$$

where W_0 (k;N) is the probability of k wet days during N consecutive days when the 0th day is dry (the subscript 0 stands for when the 0th day is dry and the subscript 1 stands for when the 0th day is wet), and the transition matrix is derived from the Markov chain method (Equation 7). Because the recurrence relation is applied 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 (8)

$$W(k;N) = (1 - p_0)W_0(k;N) + p_0 W_1(k;N) \tag{9}$$

where W(k;N) is the probability of having k wet days during N consecutive days, and p_0 is the initial probability of having a wet day in a season or a year (e.g., if there are usually 45 wet days during a 92-day fall season, p_0 is 45/92 or 0.49).

An example of the probabilities of having k wet days in 5 consecutive days is given in Table 1. Based on the data for May 1970 from the Houston Intercontinental Airport, the probability of having 5 consecutive dry days is 0.264, that of having 1 wet day is 0.301, that of having 2 wet days is 0.236, and so forth.

In summary, the Gamma distribution is used 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 4 is used to estimate the duration of rainfall. The Gamma distribution leads to an estimate of the distribution of the amount of rainfall that falls on a pavement. Estimation of rainfall duration is used for evaluating the total amount of precipitation that infiltrates into the

TABLE 1 Katz's Model for Computing the Wet Probabilities Associated with Markov Chain Model

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

Note: Data are from Houston Intercontinental Airport for May 1970. $p_0 = 0.71$, $p_{00} = 0.78$, $p_{01} = 0.22$, $p_{10} = 0.54$, and $p_{11} = 0.46$, where N = number of consecutive days, k = number of wet days, W_0 = wet probabilities when 0th day is dry, W_1 = wet probabilities when 0th day is wet, W = probability of having k wet days in 5 consecutive days, p_{ij} = transitional probabilities from Markov chain model; and p_0 = initial wet probability.

base, and the Markov chain method and Katz's recursive model are adopted for computing the probabilities of having dry periods during which a pavement can drain out all of the excess water. These results are used for further analysis, as described subsequently.

INFILTRATION OF WATER INTO A PAVEMENT THROUGH CRACKS AND JOINTS

Ridgeway (9) and Dempsey and Robnett (10) conducted research in determining the amount of water entering pavement structures. Ridgeway's studies and Dempsey and Robnett's field observations are selected as the basis for the analytical model presented herein.

Ridgeway's Studies

Ridgeway (9) made measurements in Connecticut of free water infiltration rates on portland cement concrete and bituminous concrete pavements using several methods. He 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, and
2. An infiltration rate of 0.1 $ft^3/hr/ft$ of crack (100 $cm^3/hr/cm$) can be used for design purposes.

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

Dempsey and Robnett's Observations

Dempsey and Robnett (10) 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 flow meters. The rainfall data were obtained from nearby weather stations.

Regression equations were obtained from their field studies for both sealed and unsealed conditions in the test area. 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

$$PO = 0.48PV + 0.32 \tag{10}$$

where PO is the pipe outflow volume (m^3), and PV is the precipitation volume (m^3).

Nonetheless, Dempsey and Robnett (10) pointed out that the infiltration rates predicted by their regression analyses were considerably less than those estimated by using Ridgeway's tests. In the simulation model used in this paper, Ridgeway's model is furnished as an analytical tool if data on the length of cracks and joints are provided by the user. If no data for cracks and joints are 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.

DRAINAGE OF WATER OUT OF BASE COURSE

The subject of base course drainage has received considerable attention during the past three decades. Casagrande and Shannon (11) made field observations on several airfields in the United States to determine the environmental conditions under which base courses may become saturated. In addition, Casagrande and Shannon performed a simplified theoretical analysis of base course drainage. They assumed the phreatic surface is a straight line and the subgrade is impervious.

It was noted in the paper by Casagrande and Shannon (11) that as the slope of the pavement became flatter or the depth of the base became greater, their theoretical predictions differed more widely from actual observations. The differences between theory and field results are primarily caused by the assumptions (i.e., a linear free surface and an impermeable subgrade) in their model. This model is used in the Highway Subdrainage Design manual (12).

The theoretical analyses reported by Wallace and Leonardi (13) 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 (14), also suggested that a parabolic phreatic surface would yield more realistic results for drainage calculations.

To develop better analytical procedures for pavement drainage design, a parabolic phreatic surface and a permeable subgrade were used to derive a new model (15,16). This model is called Texas Transportation Institute (TTI) drainage model, and the analyses appear to fit the field data better than Casagrande and Shannon's model. The TTI drainage model is applied to compute the rate of drainage of water out of the base course into the subgrade and into lateral drainage.

The degree of drainage (U) that is used in the previous sections of this paper can be readily converted to the saturation level. The relationship between saturation (S_a) and the degree of drainage is

$$S_a = 1 - P.D. \times U \tag{11}$$

where P.D. is a percentage indicating the amount of water that can be drained from a sample, which is determined by the mixture of materials [Table 2 (17)].

A drainage time of 5 hr to a saturation level of 85 percent is set for an acceptable material based on studies done at the Georgia Institute of Technology and the University of Illinois (17). A drainage time between 5 and 10 hr is marginal, and greater

TABLE 2 Drainability of Water in the Base Courses from a Saturated Sample (*17*).

	Drainability (%) by Amount and Type of Fines								
	<2.5 Percent Fines			5 Percent Fines			10 Percent Fines		
	Inert Filler	Silt	Clay	Inert Filler	Silt	Clay	Inert Filler	Silt	Clay
Gravel[a]	70	60	40	60	40	20	40	30	10
Sand[b]	57	50	35	50	35	15	25	18	8

Note: Gap-graded material will follow the predominant size.

[a] Gravel, 0 percent fines, 75 percent greater than No. 4: 80 percent water loss.

[b] Sand, 0 percent fines, well graded: 65 percent water loss.

than 10 hr is unacceptable. A base course with granular materials that are classified as unacceptable will hold more water and allow excessive deformations and pumping in the pavements.

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

Effect of Saturation on Base Course Properties

Haynes and Yoder (18) performed a laboratory investigation of the behavior of the AASHTO Road Test gravel and crushed stone mixtures subjected to repeated loading. A series of repeated triaxial tests was 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 2), especially when saturation is greater than 85 percent, where total deformation begins to increase, thus accelerating fatigue damage.

In the simulation model presented here, the moduli of different base course materials must be furnished. In simulating the influence of the degree of saturation on the base moduli, the lower part of Figure 2 is applied. In the range of degree of saturation from 0 to 60 percent, the elastic moduli are assumed to be constant. Between 60 and 85 percent saturated the slope between deflection measurements and saturation levels is 0.24. At degrees of saturation greater than 85 percent, the slope is 3.5. To estimate the average base modulus during any specific season, the cumulative probabilities of each section of the elastic modulus, as well as the dry and wet probabilities of the base course, are incorporated into the model.

Effect of Saturation on Subgrade Properties

Thompson and Robnett (19) conducted research identifying and quantifying the soil properties that control the resilient behavior of Illinois soils. They concluded that the degree of saturation is a factor that reflects the combined effects of density and moisture content. Their analyses indicated a highly significant relation between the resilient modulus and the degree of saturation of the subgrade. A set of regression equations was developed for various soil classification groups. The equations developed are used to predict the resilient moduli of different soil groups.

The depth of the base course and subgrade is assumed to be 70 in. in order to evaluate the degree

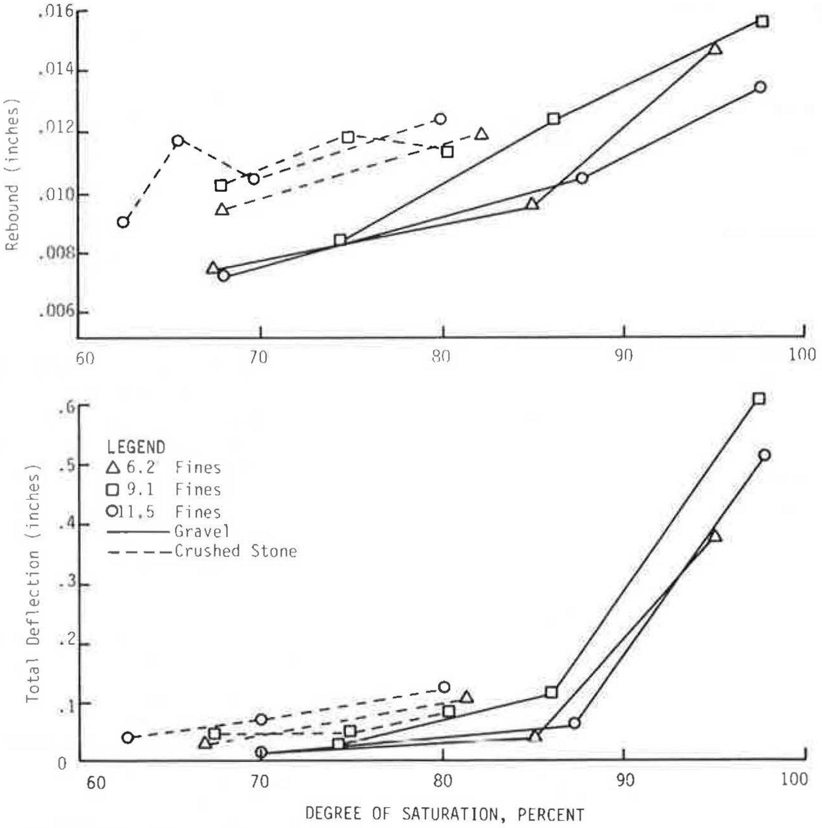

FIGURE 2 Effect of degree of saturation on the repeated-load deformation properties of AASHTO granular materials.

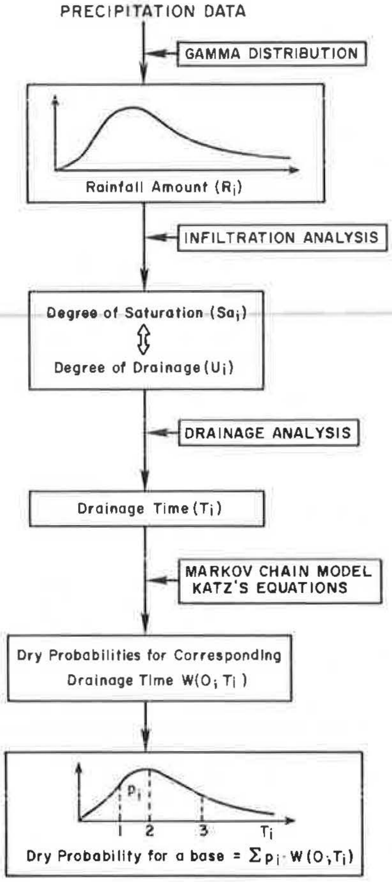

FIGURE 3 Synthesis of models used in systematic analysis of rainfall infiltration and drainage analysis of a pavement.

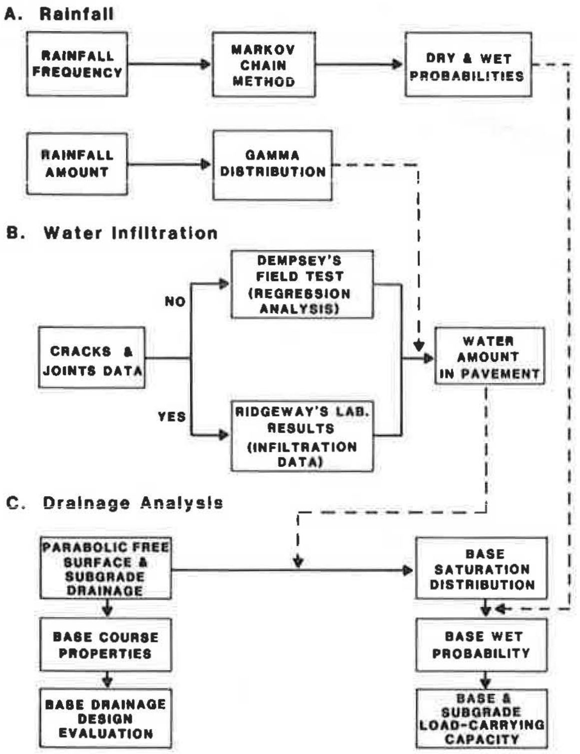

FIGURE 4 Flowchart for conceptual model of rainfall infiltration and drainage analysis of pavements.

TABLE 3 TTI Drainage Model for Analysis of a Houston Pavement

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

Note: The data in this table are from an analysis of a pavement in Houston in May 1970. The data for the system analysis of rainfall infiltration and drainage are as follows: length = 50.00, height = 0.50, slope% = 1.50, perm.1 = 10.00000, perm.2 = 0.00100, poro.1 = 0.2000, and poro.2 = 0.0500 (note that 1 and 2 stand for base course and subgrade, respectively). The analysis in this table is based on parabolic phreatic surface plus subgrade drainage.

TABLE 4 TTI Drainage Model for Evaluation of a Drainage Design of a Houston Pavement

Parameter	Value
Water drained due to gravel (%)	80.00
Gravel in sample (%)	70.00
Water drained due to sand (%)	65.00
Sand in sample (%)	30.00
Water that will be drained (%)	75.50
Critical degree of drainage (%) (85 percent saturation)	19.87
Draining time for 85 percent saturation (hr)	2.79

Note: This drainage design is satisfactory.

TABLE 5 Markov Chain Model and Katz's Recurrence Equations for Dry Probabilities Versus a Drainage Curve of a Houston Pavement

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

TABLE 6 Stochastic Models for System Analysis of Rainfall Infiltration and Drainage Analysis of a Houston Pavement: Parameters of Gamma Distribution and Markov Chain Model

Parameter	Value
Rainfall, average per wet day (in.)	1.649
Variance of rainfall amount	2.341
Alpha of Gamma distribution	1.161
Beta of Gamma distribution	0.704
Lambda of dry days (Markov process)	0.409
Lambda of wet days (Markov process)	1.000
Sum of lambda of dry and wet days	1.409
Probability of dry days	0.710
Probability of wet days	0.290
Water-carrying capacity of base (ft^2)	5.000
Average degree of drainage per hour (%)	3.303
Overall probability of saturated base	0.225
Dry probability of base course	0.817
Wet probability of base course	0.183

Note: The analysis for water entering pavement is based on Dempsey's field equation.

TABLE 7 Stochastic Models for System Analysis of Rainfall Infiltration and Drainage Analysis of a Houston Pavement: Probability Distribution of Modulus of Base Course

	Saturation Level (%)									
Parameter	10	20	30	40	50	60	70	80	90	100
Water in base (ft^2)	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
Rainfall quantity (in.)	0.19	0.44	0.69	0.94	1.19	1.44	1.69	1.94	2.19	2.44
Rain duration (hr)	0.00	0.06	0.35	1.21	3.09	6.62	12.54	21.76	35.31	54.37
Base moduli (ksi)	64.60	64.60	64.60	64.60	64.60	64.60	29.36	19.00	5.07	2.14
Ratio of dry modulus	1.00	1.00	1.00	1.00	1.00	1.00	0.45	0.29	0.08	0.03
Subgrade moduli (ksi)	30.71	30.71	29.61	29.01	28.36	27.18	25.68	23.61	20.17	12.70
Probability density	0.48	0.46	0.41	0.37	0.32	0.27	0.24	0.20	0.17	0.15
Probability	0.08	0.12	0.11	0.10	0.09	0.07	0.06	0.05	0.05	0.04
Cumulative probability	0.08	0.20	0.31	0.41	0.50	0.57	0.63	0.69	0.74	0.78

TABLE 8 Evaluation of Rainfall Effect on Pavement Performance of a Houston Pavement

Distribution Characteristics of Rainfall Effect	Value
Average free water in base (ft^2)	0.92
Duration of average rainfall amount (hr)	0.040
Average rainfall amount per day (in.)	0.403
Average base course modulus in wet state (ksi)	41.45
Average base course modulus (ksi)	60.36
Average subgrade modulus (ksi)	30.31

of saturation in the subgrade. The average wetting front of water penetration from the base course into the subgrade is calculated by estimating the proportions of water in the base flowing into the subgrade from the TTI drainage model. 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 (20)

$$E_s = (E_1 d_1^3 + E_2 d_2^3)/d^3 \qquad (12)$$

where

E_s = calculated total subgrade modulus;
d = depth of a subgrade (= $d_1 + d_2$);
E_1 = subgrade modulus under 100 percent saturated condition, which is evaluated from Thompson and Robnett's equations (19);
d_1 = average depth of water penetrating into subgrade from the base course;
E_2 = subgrade modulus under dry conditions; and
d_2 = average depth of dry portion of the subgrade.

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

The following models are used as analytical procedures to estimate rainfall infiltration, drainage analysis, and load-carrying capacities of base courses and subgrades:

1. The Gamma distribution (4) for the distribution of rainfall quantity;
2. Dempsey and Robnett's (10) regression equations as well as Ridgeway's (9) results are used for infiltration analysis together with an estimate of the amount of rainfall that, in turn, permits an estimate of the duration of the rainfall;
3. The TTI drainage model (15)--the parabolic phreatic surface with subgrade drainage--as developed for base course and subgrade drainage analysis;
4. Markov chain model (7) and Katz's (8) recurrence equations for the calculation of dry and wet day probabilities; and
5. Evaluation of base course (18) and subgrade moduli (19) as they are affected by moisture contents in the materials.

A synthesis of these various models into a systematic analysis of rainfall infiltration and drainage analysis of a pavement is shown in Figure 3, and a conceptual flowchart is shown in Figure 4 for a clear profile of the entire model.

A series of sample calculations from the computer program is given in Tables 3-8. The rainfall data are for Houston Intercontinental Airport for May 1970, and a pavement structure is assumed for illustration. The pavement is 100 ft wide on one side, the base course is 6 in. thick, and the subgrade is permeable. The data in Table 3 give 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 (17) is given in Table 4.

Based on the weather data and pavement structure, the drainage time, degree of drainage, and corresponding probabilities are calculated in Table 5. The characteristics of the probability distributions and related material properties under local rainfall conditions are given in Tables 6 and 7, and data on the effect of rainfall on the base and subgrade moduli are given in Table 8.

APPLICATION TO SYSTEMATIC ANALYSIS OF RAINFALL INFILTRATION, DRAINAGE, AND LOAD-CARRYING CAPACITY OF A PAVEMENT

An example is presented of the effects of the amount of rainfall and subgrade drainage on the load-carrying capacity of a pavement. It is assumed that a base course is 70 percent gravel and 30 percent sand, 100 ft wide, 6 in. deep, 1.5 percent slope, the coefficient of permeability of the base course is 10 ft/hr, the drainable porosity is 0.1, and the subgrade is assumed to be impermeable. The drainage design used is considered marginally acceptable because the drainage time of 6.35 hr that is required to reach a saturation level in the base is less than 85 percent.

This same design of a base course is used in two climatic regions: Abilene and Houston, Texas, which 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 5) indicate that the

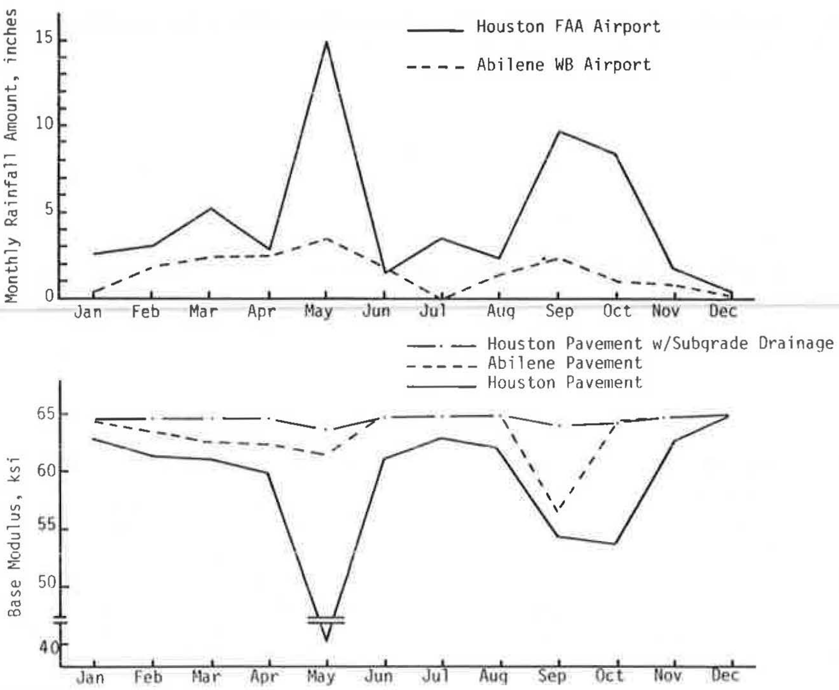

FIGURE 5 Effects of rainfall quantity and subgrade drainage on load-carrying capacity of pavements.

precipitation quantity affects the elastic moduli of the base course. If the water in the base course can drain into a subgrade with a permeability of 0.01 ft/hr and a porosity for freely draining water of 0.01 in a higher rainfall area (i.e., Houston), the load-carrying capacity could be improved significantly. It indicates that the pavement performance may be better in a high rainfall area that has a permeable subgrade, when compared with the pavement performance in a low rainfall area where there is an impermeable subgrade.

CONCLUSIONS AND RECOMMENDATIONS

A systematic analysis of rainfall infiltration into and drainage from a base course is constructed that incorporates a probability distribution of the amount of rainfall, the probabilities of dry and wet days, estimates of water infiltration into pavements, drainage analysis of pavements, and load-carrying capacities of base courses and subgrades. This comprehensive analysis of the effect of rainfall on pavement structures is recommended as an effective approach for future evaluation of the climatic effects on pavements.

ACKNOWLEDGMENT

This research has been funded by FHWA, U.S. Department of Transportation, and by a subcontract from the University of Illinois at Urbana. The authors gratefully acknowledge the support received from these sources.

REFERENCES

1. H.R. Cedergren. Drainage of Highway and Airfield Pavements. Wiley, New York, 1974.
2. M.J. Markow. Simulating Pavement Performance Under Various Moisture Conditions. In Transportation Research Record 849, TRB, National Research Council, Washington, D.C., 1982, pp. 24-29.
3. K.T. Kottegoda. Stochastic Water Resources Technology. Wiley, New York, 1980.
4. E. Suzuki. A Summarized Review of Theoretical Distributions Fitted to Climatic Factors and Markov Chain Models of Weather Sequences, with Some Examples. In Statistical Climatology, Elsevier, Amsterdam, Netherlands, 1980, pp. 1-20.
5. R.K. Linsley, Jr., and J.B. Franzini. Elements of Hydraulic Engineering. McGraw-Hill, New York, 1955.
6. R.G. Kazmann. Modern Hydrology. Harper and Row, New York, 1965.
7. H.A. Taha. Operations Research, 2nd ed. Macmillan, New York, 1976.
8. R.W. Katz. Computing Probabilities Associated with the Markov Chain Model for Precipitation. Journal of Applied Meteorology, Vol. 13, 1974, pp. 953-954.
9. H.H. Ridgeway. Infiltration of Water Through the Pavement Surface. In Transportation Research Record 616, TRB, National Research Council, Washington, D.C., 1976, pp. 98-100.
10. B.J. Dempsey and Q.L. Robnett. Influence of Precipitation, Joints, and Sealing on Pavement Drainage. In Transportation Research Record 705, TRB, National Research Council, Washington, D.C., 1979, pp. 13-23.
11. A. Casagrande and W.L. Shannon. Base Course Drainage for Airport Pavement. Proc., ASCE, Vol. 77, June 1951.
12. L.K. Moulton. Highway Subdrainage Design. Report FHWA-TS-80-224. FHWA, U.S. Department of Transportation, 1980.
13. K. Wallace and F. Leonardi. Theoretical Analyses of Pavement Edge Infiltration and Drainage. Research Report 6. Department of Civil Engineering, James Cook University of North Queensland, Townsville, Australia, 1975.
14. P. Ya. Polubarinova-Kochina. Theory of Ground Water Movement (translated by J.M. Roger De

Wiest). Princeton University Press, Princeton, N.J., 1962.
15. S.J. Liu, J.K. Jeyapalan, and R.L. Lytton. Characteristics of Base and Subgrade Drainage of Pavements. In Transportation Research Record 945, TRB, National Research Council, Washington, D.C., 1983, pp. 1-10.
16. S.J. Liu and R.L. Lytton. A Simulation Model for Rainfall Infiltration, Drainage Analysis, and Load-Carrying Capacity of Pavements. Texas Transportation Institute, Texas A&M University, College Station, Aug. 1983.
17. S.H. Carpenter, M.I. Darter, and B.J. Dempsey. A Pavement Moisture Accelerated Distress (MAD) Identification System--Volume 2. Report FHWA-RD-81-080. FHWA, U.S. Department of Transportation, 1981.
18. J.H. Haynes and E.J. Yoder. Effects of Repeated Loadings on Gravel and Crushed Stone Base Course Materials Used in the AASHTO Road Test. In Highway Research Record 39, HRB, National Research Council, Washington, D.C., 1963, pp. 82-96.
19. M.R. Thompson and Q.L. Robnett. Resilient Properties of Subgrade Soils. ASCE, Journal of Transportation Engineering, 1979, pp. 71-89.
20. R.L. Lytton and C.H. Michalak. Flexible Pavement Deflection Equation Using Elastic Moduli and Field Measurements. Research Report 207-7F. Texas Transportation Institute, Texas A&M University, College Station, Aug. 1979.

Publication of this paper sponsored by Committee on Subsurface Drainage.

Implementation of Internal Road Drainage Design and Application

GEORGE S. KOZLOV

ABSTRACT

As a result of more than 5 years of research, which culminated in the construction of two experimental, internally drainable road sections, it is now possible to present engineers with procedures for the design, construction, and maintenance of adequately drainable roads. These procedures are offered as a guide until their further application would provide additional data for improvements. It is suggested that adequate surface drainage, combined with appropriate internal drainage, is the most advantageous solution to the problem of water buildup beneath a roadway.

Research by the New Jersey Department of Transportation (NJDOT) has established that improved pavement durability can be realized if water is not allowed to accumulate within the structural section of a pavement. Therefore use of a drainage layer immediately below the lower bound layer of a pavement has been found to be the most effective means of achieving the necessary degree of internal drainage. This system is designed to handle surface infiltration water only.

However, groundwater drainage systems will be used only when groundwater is deemed to be a problem. It can be in the form of longitudinal or transverse drains to intercept flow, or drainage blankets or well systems to lower the water table and relieve pore water pressure. In this way the two internal water drainage sources previously mentioned call for two totally and distinctly different drainage approaches and solutions.

SUMMARY OF SUPPORTING RESEARCH

As part of the research study, a field investigation of the existing underdrainage conditions of New Jersey highways was performed. The field surveys indicated a definite need for better internal drainage solutions. Subsurface drainage failure under portland cement concrete pavements was found to be manifested by pumping, cracking, and eventual disintegration of the surfacings. Water-related deterioration of bituminous concrete pavements appeared to occur no less often; however, the relationship was often not visually apparent. It appeared that the type of surfacing had little effect on the moisture conditions immediately below a pavement.

The survey of New Jersey highways included a performance evaluation of several previous subsurface drainage solutions. The conclusion, in essence, was that longitudinal pipe drains, after-the-fact solutions, or even initial installations apparently are not adequate to handle the subsurface drainage of infiltrated roofwater. Thus the objective of this project became the development of the pavement design process.

Specifically, it was intended that the research formulate the design methods and the construction