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Comparison of Saturated and Unsaturated Water Flows through Pavement Systems

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Abstract

Most of the current drainage criteria have been developed on the basis of experimental field results and theoretical analyses of infiltration under saturated conditions. The objective of this study is to extend the understanding of pavement drainage systems by considering unsaturated condition in the sublayers. Analyses of unsaturated flows through pavements was performed by running finite element program(SEEP/W) with a range of pavement materials and drainage parameters. Meanwhile, the widely used DRIP program developed by FHWA is based on assumption of saturated condition of pavements. Differences between saturated and unsaturated condition in the sublayers of the pavements are verified. It is verified that for unsaturated conditions time to drain would take longer time compared to saturated condition.

Key words : Pavement Drainage, Finite Element Analysis, Permeability, Unsaturated Flow, Soil Water Characteristic Curve, Infiltration

요 지

현재까지의 일반적인 도로하부 배수설계방법은 구성층이 완전포화 되었다는 가정하에 현장실험결과 및 이론적인 해석해를 바탕으로 개발되었다. 본 연구에서는 포장하부구성층의 불포화상태가 포장체의 배수에 미치는 영향을 분석하였다. 상용의 유한요소해석 프로그램인 SEEP/W를 이용하여 불포화상태에서의 포장하부구성층과 그 투수특성을 달리하여 포장하부층에서의 배수효과를 분석하였다. 반면 현재 포장하부배수해석을 위하여 가장 널리 사용되는 미 연방도로국 개발 DRIP 프로그램은 포장하부구성층이 완전포화 되어있다고 가정한다. 불포화와 포화가정에 따른 배수효과의 차이를 비교, 분석하였으며 불포화가정의 경우 배수시간이 포화에 비하여 크게 오래 걸려 배수효과가 떨어짐이 확인되었다.

핵심용어 : 포장배수, 유한요소해석, 투수, 불포화흐름, 흙-물 특성곡선, 침투

1. Introduction

Pavement is an important component of the transportation infrastructures. The volume and weight of traffic is not the only factors that can cause damage to the pavement. Field data has shown that pavement damage can also be caused by infiltrated water. Water in the pavement system can lead to moisture damage, modulus reduction, and loss of strength.

Most of the current drainage criteria have been developed on the basis of experimental field results and theoretical analyses of infiltration under saturated conditions. Current practice is to use the so called time-to-drain method. The time required to drain a saturated base layer for a given roadway geometry must be calculated. The AASHTO classification of permeable base quality is based on the time required to drain the base from 100 percent saturated condition to 50 percent saturated one. The AASHTO classification divides drainage rating system as "excellent" (time to drain less than 2 hours), "good" (time to drain less than 1 day), "fair" (time to drain less than 7 days), and so on. The FHWA computer program DRIP (Drainage Requirements In Pavements) has been developed to perform the time-to-drain analysis of the pavement(FHWA, 1996).

However, most pavements stay unsaturated most of the time and it is rare to have fully saturated conditions in pavements. When rain follows a dry period, the base and the subbase are usually unsaturated. The amount of water that infiltrates the base and subgrade is not only a function of permeability and the gravitational forces, it is also the function of matric suction of the material. It is well known that permeability of a porous medium varies with its degree of saturation. Hence, it cannot be justified to consider only

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fully saturated condition of the pavement for study of pavement infiltration. Variation of time is another factor that should be considered in addition to unsaturated condition. Transient flow problems are much more complex than the steady state for which classical solutions are available.

Modeling of flow through pavement with an analytical solution can be very complex because of the variability of material properties, geometries, and boundary conditions that can be selected. These complexities make it necessary to use some form of numerical method to analyze the water flow in pavement. Among the numerical methods, finite element method is a suitable and powerful approach for solving this complex problem.

The objective of this study is to extend the understanding of pavement drainage systems to include unsaturated water flow. A more complete understanding of water movement in pavement systems that includes unsaturated flow will permit existing pavement systems to be evaluated and understood better, and to lead to improvements in drainage system designs and subsequent performance.

2. Research Methodology

2.1 The Analysis Methods

2.1.1 Programs DRIP and SEEP/W

Drainage performance of base materials is often measured in terms of the time required to drain a certain amount of water out of the pavement. The two drainage levels that are most often used in design are the time to drain either 50 percent or 90 percent of the water out of the pavement. In this study time-to-drain calculations are performed using two methods: 1) DRIP program which is based on saturated flow theory, 2) SEEP/W which is a commercial finite element analysis program that can consider unsaturated flow theory. The well-known program DRIP(Drainage Requirements In Pavements) developed by FHWA is based on simple analytical prediction model which assumes that pavement systems are only exposed to saturated conditions. SEEP/W can simulate both saturated and unsaturated flow in the media. The overall principles in the SEEP/W program follow Darcy's law. The governing equation used in the SEEP/W program for all the calculations of flow is based on Richards' equation which is easy to represent the unsaturated flow in a more suitable form .

Using DRIP and SEEP/W programs, time-to-drain predicted for simulation of flow through pavement systems were analyzed and compared. One is based on saturated condition(DRIP), and the other one is based on unsaturated condition(SEEP/W). At first, a free drainage example is analyzed, and a real pavement drainage example is analyzed separately to investigate differences of time-to-drain due to consideration of unsaturation or matric suction in the sub-layers.

2.1.2 Representative Materials

All element layers included in structure of asphalt pavement are considered for flow analysis in the pavement. However, the asphalt layer was considered as an impervious material. Therefore its properties were not taken into account for the material characterization in finite element modeling of flow analysis in the pavement.

Representative material properties of base, subbase and subgrade were selected from a collected database which is obtained from some test results and published research papers and reports in Korea. While there are a wide range of engineering properties of materials, only those properties that controls flow of water though pavement systems were considered in this analysis. Thus, the material properties included in the analysis are the coefficient of permeability, k_{sat}, at saturation, the effective porosity, n, and hydraulic characteristics in saturated and unsaturated condition such as soil water characteristic curves(SWCC).

Van Genuchten(1980) proposed a model to simulate relation between matric suction(ψ) and normalized volumetric water contents as shown in Eq. (1) which is a function model of SWCC. Only three parameters are required to simulate this model.

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\left[1+\left(\frac{\psi}{\alpha}\right)^n\right]^m} \tag{1}$$

where, θ_w = the volumetric water content
θ_s = the saturated volumetric water content
θ_r = the residual volumetric water content
ψ = the negative pore-water pressure, and
a, n, m = curve fitting parameters

Van Genuchten (1980) proposed also the following closed form equation to describe hydraulic conductivity of a soil as a function of matric suction:

$$k_w = k_s \frac{[1-(\alpha\psi^{(n-1)})(1+(\alpha\psi^n)^{-m})]^2}{\left(((1+\alpha\psi)^n)^{\frac{m}{2}}\right)} \tag{2}$$

where, k_s = saturated hydraulic conductivity
n = 1/(1-m)
ψ = required suction range

The collected material properties used in the analyses for each sublayers of the pavement are shown in Table 1. In order to model representative SWCC of sublayers in unsaturated condition, Van Genuchten(1980) model is adapted since the model need only 3 parameters to complete the model and is simple comparing to other complex models.

Table 1. Material properties

No.	Layer	Material (USCS)		Model	SWCC Parameters					
					k_{sat} (m/s)	θ_r	θ_s	α (kPa)	n	m
1	Subgrade	SC	High	VG	4.94E-06	0.001	0.520	10.5000	2.200	0.545
			Low	VG	9.53E-10	0.020	0.410	10.0000	1.560	0.359
		SM	High	VG	4.94E-07	0.010	0.47	1.8000	1.3500	0.107
			Low	VG	9.53E-10	0.010	0.260	1.6000	1.240	0.193
2	Subbase	SP	High	VG	4.94E-06	0.010	0.330	1.2000	1.450	0.310
			Low	VG	4.94E-09	0.010	0.280	0.8000	1.280	0.219
3	Base	SW	High	VG	4.84E-04	0.001	0.350	2.0000	3.100	0.677
			Low	VG	4.94E-06	0.020	0.280	1.9500	2.000	0.500

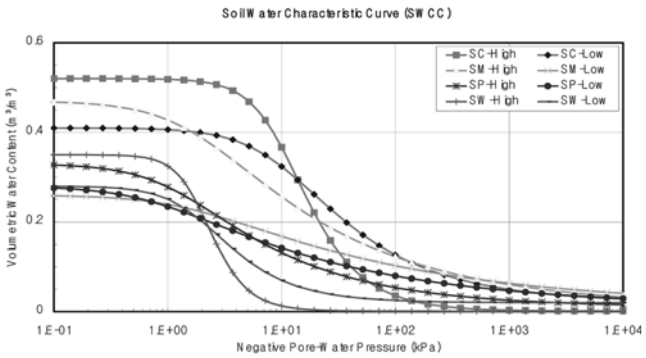

Fig 1. Soil-Water chracteristic curves(SWCC) used for analyses

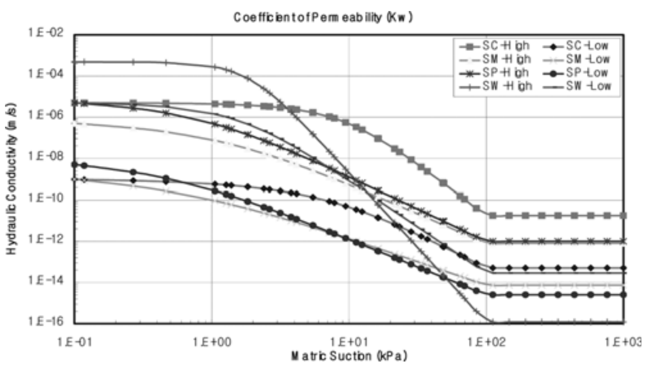

Fig 2. Obtained coefficient of permeability curves with suction

SWCCs of sublayers in unsaturated condition are collected from the database and analyzed to get typical models that can be used to represent upper and lower bounds of SWCCs in the sublayers as shown in Fig 1. Most subgrade soils used in the road construction are grouped into SC and SM in USCS. Most subbase soils are grouped into SP. Most base materilas are grouped into SW.

All curve fitting parameters (α, n, m) and the saturation and residual volumeteric water contents(θ_s, θ_r) required to complete Van Genuchten model in the materials used in the pavement sublayers are decided from the database as shown in Table 1. and Fig 1.

In order to simulate permeability of a sublayer in unsaturated condition, the Eq. (2) is adapted as a function of matric suction. Permeability variations of sublayers in unsaturated condition with matric suction are collected from the database and analyzed to get typical models that can be used to represent upper and lower bounds of permeability curves in the sublayers. as shown in Fig 2.

3. Verification of SEEP/W for Pavement Application

SEEP/W program is verified first for checking the capability and reliability of simulating the flow of water through simplified pavement system. SEEP/W predictions are compared to the results obtained from an infiltration test incited in a published paper performed by Vauclin (1979).

Vauclin (1979) performed an infiltration test in the laboratory with a layer of soil 3 m long, 2 m high and 0.05 m thick, in order to study the changes of water content and water pressure occurring in the flow in soil. The soil was packed as homogeneously as possible between two rigid walls supported by a frame resting on an impervious horizontal boundary. One of the vertical ends of the slab was connected to a constant head reservoir, and a water table was imposed at the depth of H_o=1.35 m. There was no flow through the vertical left hand side of the slab. A constant flux corresponding to q_0=4.1111×10^{-5} m/s was applied on the soil surface over a width of L_o=0.50 m as shown in Fig. 3.

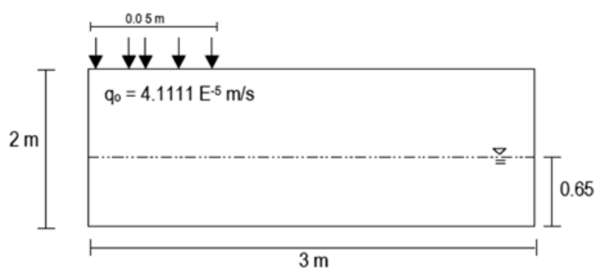

Fig 3. Simple model for analysis of infiltration

Table 2. Soil hydraulic parameters

Brutsaert			Gardner		
α	β	θ_S	A	β	K_s (m/s)
40,000	2.9	0.30	2.99E+06	5.0	9.72E-05

3.1 Soil Hydraulic Parameters

For getting hydraulic parameters of soil, Vauclin(1979) had determined suction and hydraulic conductiviy curves of the soil from the laboratory tests that can be fitted to Brutsaert(1966)'s SWCC model and Gardner(1956)'s hydraulic conductivity model. The parameters obtained from the regression analysis are shown in Table 2. Brutsaert(1966)'s SWCC model can be expressed as Eq. (3). Gardner(1956)'s hydraulic conductivity model can be expressed as Eq. (4).

$$\theta = \theta_s \frac{\alpha}{\alpha + |h|^{\beta}} \tag{3}$$

where α, β = empirical parameters and h = negative pore pressure (suction)

$$k = k_s \frac{A}{A + |h|^{\beta}} \tag{4}$$

where A, β = empirical curve fitting coefficients obtained by the method of least squares.

Using soil hydraulic parameters of Brutsaert (1966) and Gardner(1956)'s models obtained by Vauclin(1979), SWCC and hydraulic conductivity curve generated internally from SEEP/W are shown in Fig 4.

3.2 Finite Element Mesh

SEEP/W Finite Element Mesh used in analysis of the simple infiltration experiment performed by Vauclin(1979) is shown in Fig 5. The mesh is composed of 0.1×0.1 m quadrilateral elements available in the library of SEEP/W program.

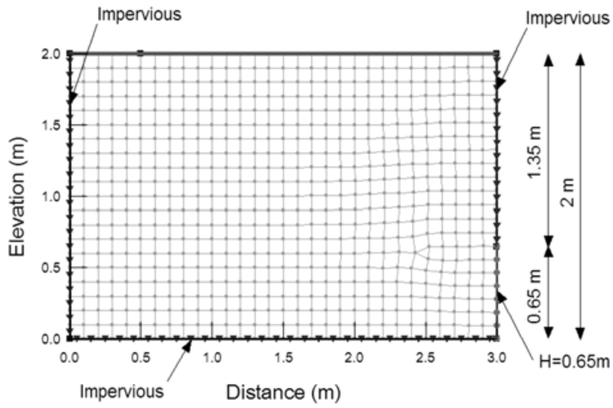

Fig 5. Finite element mesh

3.3 Comparison of Computed Results by SEEP/W to Measured Values

As shown in Fig 6., the SEEP/W simulation for the simple infiltration experiment by Vauclin(1979) showed a slightly higher water table under the section where the constant flux was applied. However, the predicted values are in good matching with the measure values mostly. In addition, the differences between the measured and predicted water table are reduced with time until the water table reached its steady state.

In addition it is proved that patterns of fluxes and contours of water content calculated by SEEP/W at given different times after start of infiltration as wn in Fig 7 are well-matched with predicted ones by Vauclin(1979) using his own numerical technique.

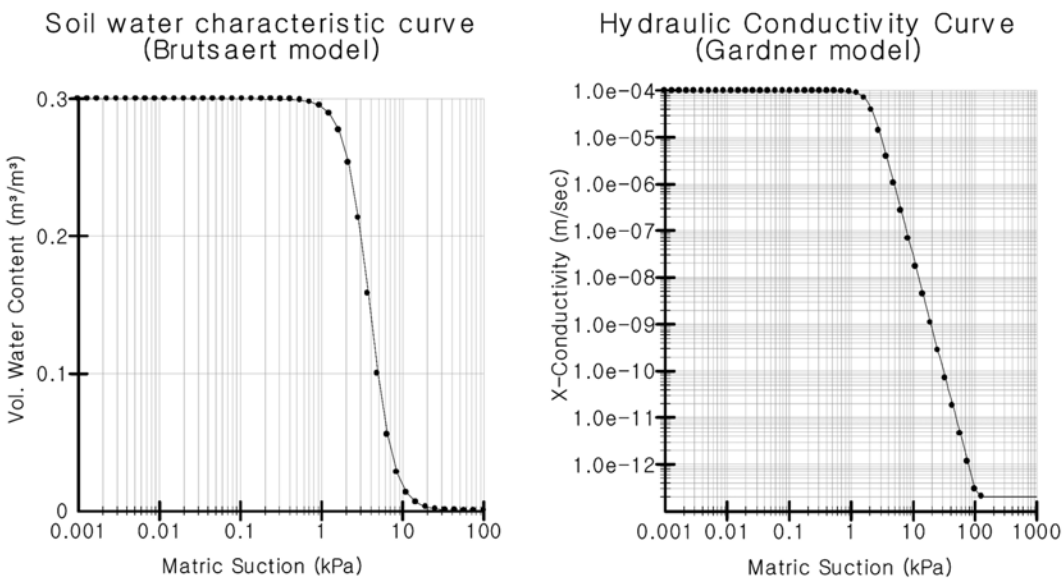

Fig 4. SWCC and hydraulic conductivity curve generated from SEEP/W

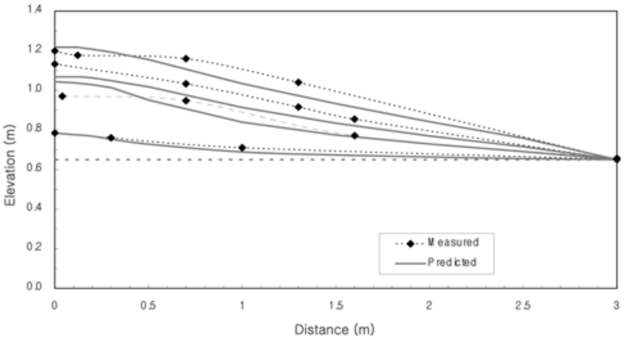

Fig 6. Comparison of water table positions at different times

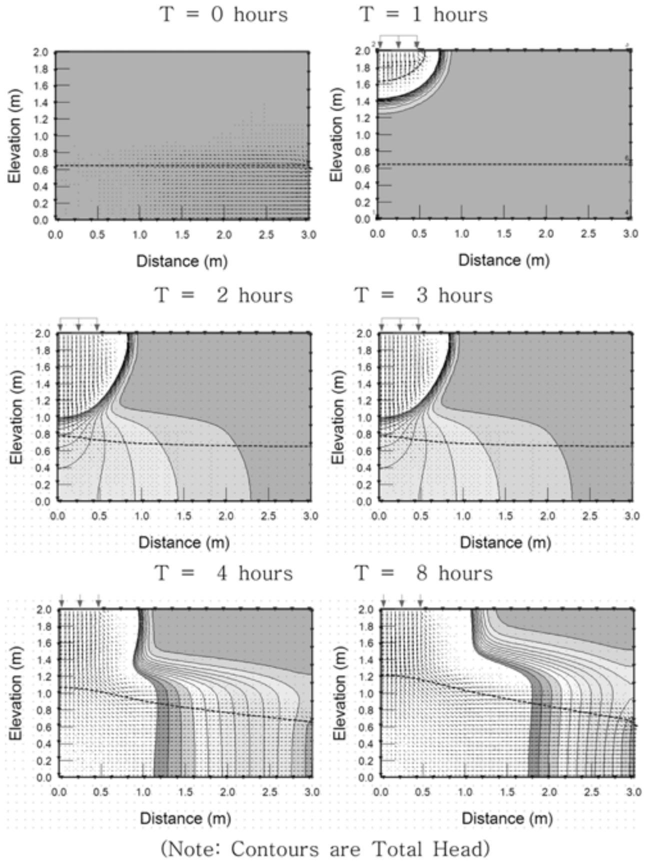

Fig 7. Patterns of fluxes and contours of water content calculated at given different times after start of infiltration

4. Evaluation Methods of Time to Drain

4.1 Free Drainage Example

4.1.1 SEEP/W Analysis of Unsaturated Flow Condition

A one-dimensional finite element-based flow example was selected as shown in Fig. 8. The example problem is simulated by using SEEP/W under unsaturated condition. The finite element model consisted of a 1 meter tall column that had a 0.4 m by 0.4 m cross section, with 0.05×0.05 m quadrilateral elements. The composed material of the column was fully saturated initially so that no water table was set. Lateral sides were considered impervious (q=0 m/s per square meter). Subsequently, the bottom of the column was

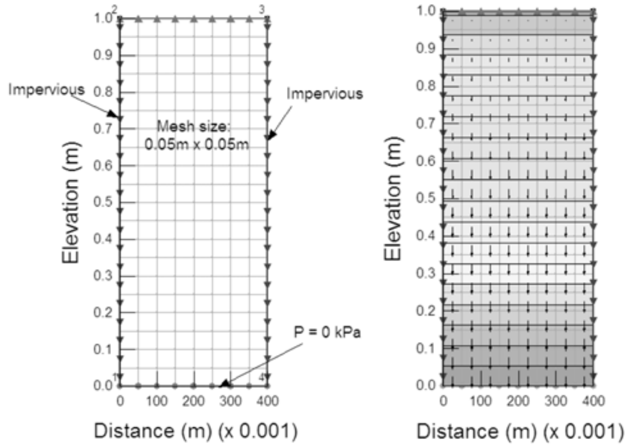

Fig 8. Finite element mesh and a typical seepage pattern

subjected to atmospheric conditions, and the column was allowed to drain freely.

The evolution of the volumetric water content at the top of the soil column at selected times is shown in Fig 9.

The percent of drainage of the soil column at selected times is shown in Fig 10.

Due to the geometry of the finite element model, the maximum suction that can be achieved is 9.8 kPa. The total height of the mesh is 1 m, therefore, if the water table reaches the bottom of the mesh, the pressure head created above the water table is equal to 1 m. This suction head corresponds to a suction pressure of 9.8 kPa. The materials will only show significant drainage if the air entry potential is considerably less than the maximum suction sustained by the height of the soil column. Hence, the results from the finite element analyses for all 8 materials showed a negligible to small change in volumetric water content, meaning that the times to drain to 50 and 90 percent were also affected greatly. For example, according to the SC-High soil water characteristic curve, at pressure of 10 kPa the soil water content (θ_w=0.367) is higher than θ_r=0.001, a pressure higher than 10 kPa is needed to have a reduction of volumetric water content. Because the system's maximum developed suction is 9.8 kPa, this material never achieves 50 percent drainage, even with 90 percent drainage. This phenomenon was also observed with subgrade and subbase materials, meaning that the SC, SM, SP materials never drain fully.

Comparing SW-High soil against the others, it is possible to see that the K_{sat} is highest value among the soils. Therefore, the SW-High soil should be drained faster than others. The calculated results from the numerical simulations using SEEP/W with full-unsaturated conditions show that with the similar permeability of K_{sat} (SC-High, SP-High, SW-Low) = 4.94E-06 m/s, the compared soils with the similar hydraulic properties all result in very different maximum percent of drainage or the times to drain. This observed phenomena is considered due to undrained condition.

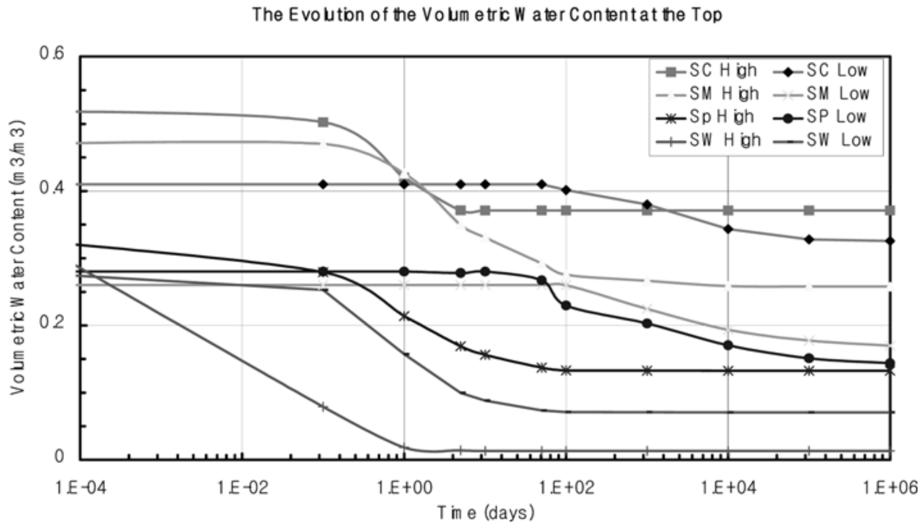

Fig 9. Evolution of the volumetric water content at the top

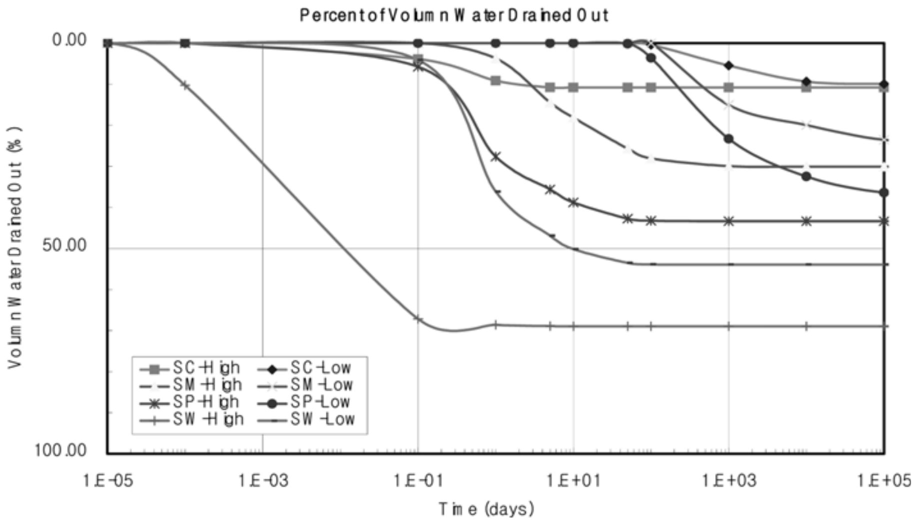

Fig 10. Percent of drained water

4.1.2 Time to Drain from Saturated Flow Theory

The DRIP(Drainage Requirements In Pavement) computer program developed by FHWA can analyze and design flow problem in pavements. DRIP can calculate the time to drain in the drainage layer of a pavement system with full saturation condition. DRIP is developed using simple analytical prediction models such as Barber and Sawyer (1952) and Casagrande and Shannon (1952). In the Barber and Sawyer (1952) method the required time (t) to drain U % of water from the drainage layer is as follows:

$$t = \frac{T n_e L^{2}_{R}}{kH} \quad (5)$$

where n_e = the effective porosity of the drainage layer, L_R = the resultant length of the drainage layer, k = permeability of the drainage layer, H = the thickness of the drainage layer, T = time factor offered by Barber and Sawyer (1952).

In Casagrande and Shannon (1952) method, with using the same time to drain equation as Eq. (5) time factor T is offered separately as follows:

$$T = \frac{c}{2}\left\{ S_R + S_R \cdot ln\left[\frac{2S_R - 2US_R + 1}{(2-2U)(S_R+1)}\right] - S_R^2 \cdot ln\left[\frac{S_R+1}{S_R}\right]\right\} \quad (U>50\%) \qquad (6)$$

$$T = \frac{c}{2}\left\{ 2US_R - S_R^2 \cdot ln\left[\frac{S_R+2U}{S_R}\right]\right\} \quad (U\leq 50\%) \qquad (7)$$

where, $c = 2.4 - \frac{0.8}{S_R^{1/3}}$

DRIP program assumes that full saturation is attained through analysis because the drainage layer is saturated 100%. This means that the hydraulic conductivity is constant all the way through the analysis.

For each soil water characteristic curve(SWCC), the effective porosity (n_e) is determined from the difference between θ_{sat} and θ_R. The calculations of time-to-drain obtained from

Table 3. Comparison of drainage time under saturated vs. unsaturated flow conditions

Layer	Material		Unsaturated condition SEEP/W			Saturated condition DRIP			
			Vol. Free Water m^3	Vol. Drainage m^3	Percent Drainage (at 10^6days)	Barber and Sawyer		Casagrande & Shannon	
						T50	T90	T50	T90
Subgrade	SC	High	0.208	0.022	10.8	2.6	23.8	2.6	23.0
		Low	0.156	0.016	9.9	3,418.5	123,196.4	13,482.5	119,384.8
	SM	High	0.184	0.055	30.1	22.9	210.6	23.1	204.1
		Low	0.100	0.024	24.1	6,463.7	59,343.2	6,494.5	57,507.1
Subbase	SP	High	0.128	0.055	43.3	1.6	14.7	1.6	14.2
		Low	0.108	0.040	36.9	1,346.7	12,364.0	1,353.1	11,981.5
Base	SW	High	0.140	0.096	69.0 (*)	0.02	0.16	0.02	0.15
		Low	0.104	0.056	53.9 (**)	1.30	11.91	1.30	11.54

Note: *T_{50} = 0.12 days (2.88 hrs), **T_{50} = 8.90 days

DRIP were performed by both the Barber and Sawyer method (1952) and the Casagrande and Shannon method (1952). All calculation results are compared in Table 3.

The comparison in Table 3. shows that most materials would drain under saturated conditions in all cases, while for unsaturated conditions it would not be achieved except SW materials. Although saturated flow theories adapted in DRIP consider the material characterization and geometry of the system, it does not take into account the variation of the hydraulic conductivity with volumetric water content or suction that represents the true behavior of the material under field conditions. Therefore, considering only permeability at saturation (k_{sat}) and using that throughout the flow analysis in order to characterize the drainage of materials is to make the time to drain be obviously significantly shorter (6-7 times) than those of the more realistic unsaturated conditions. In the drainage layer of unsaturated condition, the hydraulic conductivity is a function of the suction experienced in the material.

4.2 Real Pavement Drainage Example

4.2.1 Time to Drain in Case of Unsaturated Condition

Geometry attributed to a drainage base layer used to generate a FE mesh is 0.5 m tall and 6.5 m long, with a slope of 2% as shown in Fig 11. The FE mesh is composed of quadrilateral elements. The layer was set up so that the material was fully saturated initially, the right side was subjected to atmospheric conditions, and the layer was allowed to drain freely. The layer was considered impervious on left and bottom sides. Fig 12 is a typical seepage pattern performed by SEEP/W using the mesh and geometry and boundary condition given in Fig. 11.

Due to the geometry of the layer under unsaturated conditions, the maximum suction pressure that can be obtained is approximately 1.5 kPa. When the water table reaches the layer bottom, the maximum pressure head developed is 0.15 m. This is equivalent to 1.5 kPa of suction. Therefore, only a small reduction in the volumetric water content will occur according to the characterization of the all layer mate-

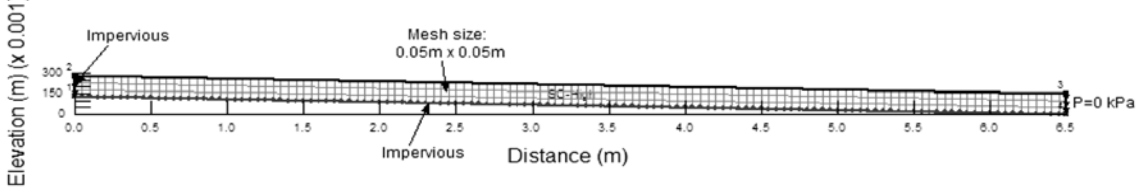

Fig 11. Geometry and boundary conditions real pavement drainage example

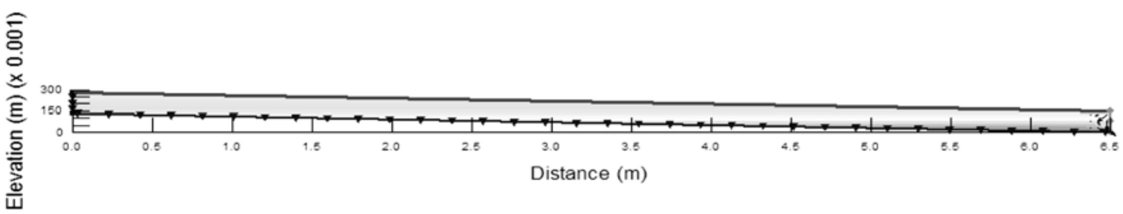

Fig 12. Seepage pattern after t=1 day for SC-High material

Table 4. Comparison of drainage times under saturated vs unsaturated flow conditions

Layer	Material		Unsaturated condition SEEP/W			Saturated condition DRIP			
			Vol. Free Water (m^3)	Vol. Drainage (m^3)	Percent Drainage at 10^6days	Barber and Sawyer		Casagrande & Shannon	
						T_{50}	T_{90}	T_{50}	T_{90}
Subgrade	SC	High	0.506	0.001	0.3	2.2E+03	8.4E+03	2.2E+03	1.0E+04
		Low	0.380	0.007	1.7	8.5E+06	3.3E+07	8.5E+06	4.0E+07
	SM	High	0.449	0.030	6.8	1.9E+04	7.4E+04	1.9E+04	9.2E+04
		Low	0.244	0.042	17.2	5.4E+06	2.1E+07	5.4E+06	2.6E+07
Subbase	SP	High	0.312	0.038	12.0	1.3E+03	5.2E+03	1.3E+03	6.4E+03
		Low	0.263	0.095	36.2	1.1E+06	4.4E+06	1.1E+06	5.4E+06
Base	SW	High	0.340	0.032	9.5	1.6E+01	6.2E+01	1.6E+01	7.7E+01
		Low	0.254	0.020	8.0	1.2E+03	4.6E+03	1.2E+03	5.7E+03

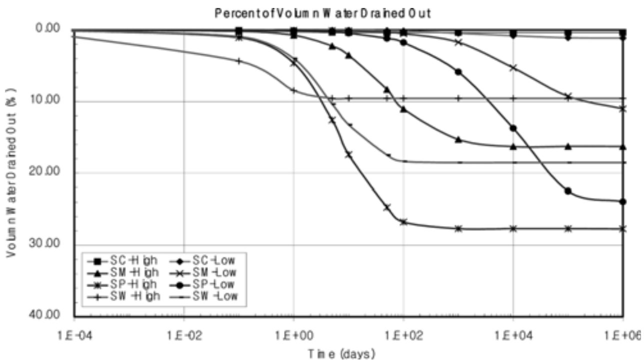

Fig 13. Percent of volume of water drained out

rials. Fig. 13 shows the percent of volume of water drained out obtained from SEEP/W program using the conditions given in Fig. 11. As described in flow analysis of simple flow problem and anticipated, there are large differences in soils for percent of volume of water drained out. Even SP-High soil which produced the largest percent of volume of water drained out among the soils compared in the analysis could be drained approximately only 28 percent at 100 days after drainage started.

4.2.2 Time to Drain in Case of Saturated Condition

Using the geometry condition given in Fig. 11 of real flow example of the drainage layer, time to drain in case of full saturated condition was calculated using DRIP program. The height (H) of the model is 0.15 m. The width of the drainage path (W) is 6.5 m. The resultant length of the drainage path (L_R) is 6.5 m.

The calculations of time-to-drain obtained from DRIP were performed by both the Barber and Sawyer method (1952) and the Casagrande and Shannon method (1952). All calculation results are compared in Table 4.

The comparison in Table 4. shows that most materials would drain under saturated conditions in all cases, while for unsaturated conditions it would not be achieved in most soils. Subbase material with SP-Low hydraulic conductivity could be drained out only 36.2 percent of the volume of water at 1,000,000 days after drainage started which is the best drainage material among the compared soils.

Although saturated flow theories adapted in DRIP consider the material characterization and geometry of the system, it does not take into account the variation of the hydraulic conductivity with volumetric water content or suction that represents the true behavior of the material under field conditions. Therefore, considering only permeability at saturation (k_{sat}) and using that throughout the flow analysis in order to characterize the drainage of materials is to make the time to drain be obviously significantly shorter (6-7 times) than those of the more realistic unsaturated conditions. In the drainage layer of unsaturated condition, the hydraulic conductivity is a function of the suction experienced in the material.

5. Conclusions

Although saturated flow theories adapted in DRIP consider the material characterization and geometry of the system, it does not take into account the variation of the hydraulic conductivity with volumetric water content or suction that represents the true behavior of the material under field conditions. Therefore, considering only permeability at saturation (k_{sat}) and using that throughout the flow analysis in order to characterize the drainage of materials is to make the time to drain be obviously significantly shorter (6-7 times) than those of the more realistic unsaturated conditions. In the drainage layer of unsaturated condition, the hydraulic conductivity is a function of the suction experienced in the material.

Comparisons between the results obtained by DRIP with saturated conditions and SEEP/W with unsaturated conditions show that most materials would drain under saturated conditions, while for unsaturated conditions it would take longer time or not be achieved.

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