Development of an Infiltration-Drainage Model for Saturated and Unsaturated Soils

Chuang Lin, Ph.D., S.M.ASCE[1]; and Xiong Zhang, Ph.D., M.ASCE[2]

[1]Dept. of Civil, Architectural, and Environmental Engineering, Missouri Univ. of Science and Technology, Rolla, MO. E-mail: clnr3@umsystem.edu
[2]Associate Professor, Dept. of Civil, Architectural, and Environmental Engineering, Missouri Univ. of Science and Technology, Rolla, MO. E-mail: zhangxi@umsystem.edu

ABSTRACT

It has long been recognized that excess moisture in the pavement layer when combined with heavy traffic load and moisture-susceptible materials, can significantly reduce the service life of a pavement structure. So far, no pavement design guidelines can provide an accurate, robust, and dynamic infiltration-drainage model that is suitable for both saturated and unsaturated soils under different climatic conditions. This paper aims at proposing a new infiltration-drainage model that is suitable for both saturated and unsaturated soils. The proposed model is based upon Richards' equation to govern the water flow in saturated and unsaturated soils, with an additional water source term to account for the influence of precipitation and the current water state within the soil. The calibrated model was used to evaluate the influence of rainfall intensity and duration on the drainage performance of a pavement structure.

INTRODUCTION

Seasonal variations of unbounded material properties are significant and excess water within pavement structures will decrease the resilient modulus of both base and subgrade (Christopher et al. 2010). In addition, it has long been recognized that excess moisture in pavement layer, when combined with heavy traffic load and moisture-susceptible materials, can significantly reduce the service life of a pavement structure (Christopher and McGuffey 1997). The AASHTO pavement design approach (AASHTO 1993) incorporated an empirical drainage coefficient to increase the awareness of the drainage problems. However, the empirical equations cannot accurately predict the moisture migration within pavement structures. As for the MEPDG (Mechanical-Empirical Pavement Design Guide) approach (ARA 2004), the EICM (Enhanced Integrated Climatic Model) was used to simulate the environmental effect on pavement performance (Larson and Dempsey 1997). However, the EICM model also has its own limitations in simulating the moisture migration within the pavement structure and still needs to be improved in several aspects. Firstly, the EICM model is a one-dimensional model (ARA 2004) which is not accurate enough to evaluate the moisture migrations in a two- or three-dimensional space. Secondly, the infiltration water determined by the EICM model is merely based upon empirical judgment and cannot represent the actual field conditions. Thirdly, the drainage model incorporated in the EICM, also known as DRIP (Drainage Requirements in Pavements) model (Wyatt et al. 1998), is based upon the water flow through saturated soils and is not suitable under unsaturated conditions. Therefore, it is necessary to come up with an accurate, robust, and dynamic infiltration-drainage model that is suitable for both saturated and unsaturated soils under different climatic conditions.

This paper aims at proposing a new infiltration-drainage model that is suitable for both saturated and unsaturated soils. The proposed model is based upon Richards' equation to govern the water flow in saturated and unsaturated soils, with an additional water source term to account for the influence of precipitation and the current water state within the soil. For each step, a water balance analysis is performed to determine the net infiltrating water based upon the precipitation intensity and the water storage capacity of the soil element. During each step, the amount of percolation water, infiltration water, and runoff water are determined and stored for further usage. Then, the proposed model was calibrated using test results from published papers. The simulated and tested results will be compared to evaluate the accuracy of the model. Finally, case studies will be performed to evaluate the influence of rainfall intensity and duration on the drainage performance of a pavement structure.

DEVELOPMENT OF AN INFILTRATION-DRAINAGE MODEL

The governing equation (the water continuity equation) for the proposed infiltration-drainage model was modified from Richard's equation, as expressed in Equation 1.

$$\frac{1}{\gamma_w}\left(\frac{\partial}{\partial x}(k\frac{\partial(-u_w)}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial(-u_w)}{\partial y})+\frac{\partial}{\partial z}(k\frac{\partial(-u_w)}{\partial z}+1)\right)=m_1^w\frac{\partial\sigma_m}{\partial t}+m_2^w\frac{\partial(-u_w)}{\partial t}+S \qquad (1)$$

Where, u_w = pore water pressure; γ_w = unit weight of water; k = coefficient of permeability; t = time; σ_m = mean stress; m_1^w = coefficient of pore-water volume change due to the change in mechanical stress; m_2^w = coefficient of pore-water volume change due to the change in pore water pressure, $m_2^w = \rho_d C_w$; ρ_d = soil dry density; C_w = specific water capacity, or the slope of the soil water characteristic curve (SWCC); and S = water generation term.

The value m_1^w is much smaller compared with the m_2^w and S terms. Therefore, m_1^w assumes to be zero for preliminary simulations. The last term, *S*, is the water source term which depends upon the ambient climatic conditions, such as precipitation and evapotranspiration and will be discussed in detail in the following section.

SOIL-CLIMATE INTERACTIONS

The ground surface relies on a moisture flux boundary condition (or Neumann boundary condition) which interacts with the ambient atmospheric environment (Wilson et al. 1994). The ground surface boundary conditions must be described in terms of moisture flux so that the moisture exchange between the saturated/unsaturated soil and the surrounding environment can be quantified. The roadway embankment is always hydro-seeded after construction to prevent erosion and dust contamination. Water is either entering into the pavement structure via precipitation infiltration process or leaving the pavement structure via evapotranspiration (ET) process. Figure 1 shows the water balance analysis of a soil element within the grass root zone. At the top surface of the soil element, the water may leave the soil via evapotranspiration process or infiltrate into the soil through the precipitation process. If the rainfall intensity was high, not all water will infiltrate into the soil element and most of the water will be considered as runoff water. Meanwhile, at the bottom of the soil element, water may also percolate to the underlying soil or wicking to the overlying soil via capillary action. Therefore, to evaluate the interactions between the soil infrastructure and the ambient environment, it is necessary to accurately quantify the amount of water that the soil element may lose or gain.

There are several critical water contents representing different soil water states and need to be defined (see in Figure 1), namely saturation water content, field capacity (FC), threshold water content, and wilting point (WP). According to Allen et al. (1998), the total available water

(TAW) represents the capacity of soil to retain water available to plants. After heavy rainfall events, water in the soil will be drained under the influence of gravity and the soil water content decreases from the saturation water content to the field capacity, which is defined as the amount of water a well-drained soil should hold against gravitational forces. As the water continued to drain and the soil water content becomes lower than the threshold value, the absence of water supply renders increasing soil stress against the water uptake by the grass and the remaining water is held to the soil particles with greater force. At this moment, not all the TAW will be available for the grass to extract, the actual amount of available water will be denoted as the readily available water (RAW), which is a fraction of the TAW. If the soil water content continued to reduce, the grass will permanently wilt if the water content is lower than the wilting point (WP). In other words, if the soil water content is lower than the wilting point, the vegetation will not survive.

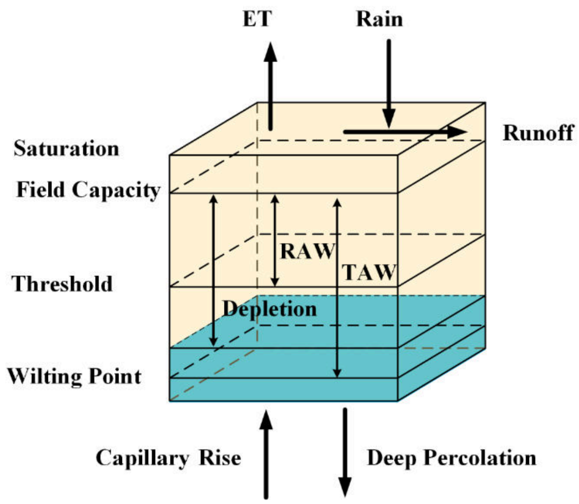

Figure 1. Water balance analysis.

The precipitation infiltration process can be accurately determined given the infrastructure geometry and the local precipitation data. The evapotranspiration process can be reasonably simulated using the *FAO 56 PM* method, which was proposed by the *United Nations Food and Agriculture Organization* (FAO) (Allen et al. 1998). Soil evaporation is strongly influenced by the net radiation from the sun and the movement of air above the ground surface (Tran et al. 2015). The FAO 56 PM method requires measurements of air temperature, relative humidity, wind speed, and solar radiation to determine the reference evapotranspiration, as expressed in Equation 2. For this paper, the field site was selected to be at Kirkwin, Kansas, and the local meteorological data of the year 2016 was obtained from WRCC (West Regional Climate Center) (WRCC 2017)

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{2}$$

Where, ET_0 = reference evapotranspiration; Δ = slope of vapor pressure curve; R_n = net radiation at the crop surface; G = soil heat flux density, which is assumed as zero for daily calculations; γ = psychometric constant; T = mean daily air temperature at a height of 2 m; e_s and e_a = saturation and actual vapor pressure, $\left(e_s - e_a\right)$ is the saturation vapor pressure deficit

(VPD); and u_2 = wind speed at 2 m.

To further demonstrate the water exchange between the vegetated soil and the ambient environment, Figure 2 shows the flow chart of the water balance analysis and was coded into a user subroutine for numerical simulations. In total, there are three inputs that will be passed to the subroutine at the beginning of each time step, including the precipitation (Rain), ET (determined by Equation 2), and the suction value (a field variable that was stored at the end of the previous time step). Firstly, the actual water stress coefficient, AKS, was determined based upon Equation 4, and the actual evapotranspiration, AET, was calculated according to Equation 5. Then, the actual net water loss (ANWL) value was calculated based upon the water balance analysis shown in Figure 2. If the $ANWL \geq 0$, the soil element is essentially losing water and there shall be no runoff water. The water source term, S, is determined based upon the comparison of the values for $ANWL$ and $(h_w - h_{WP})$. The $ANWL$ term indicates the calculated net water loss while the $(h_w - h_{WP})$ term indicates the maximum available amount of water could be lost in the soil. If the $ANWL \geq (h_w - h_{WP})$, the soil element cannot provide sufficient water to be evaporated and the water source term shall be determined based upon the value of $(h_w - h_{WP})$. On the other hand, if the $ANWL < (h_w - h_{WP})$, the water source term shall be calculated based upon the $ANWL$ term.

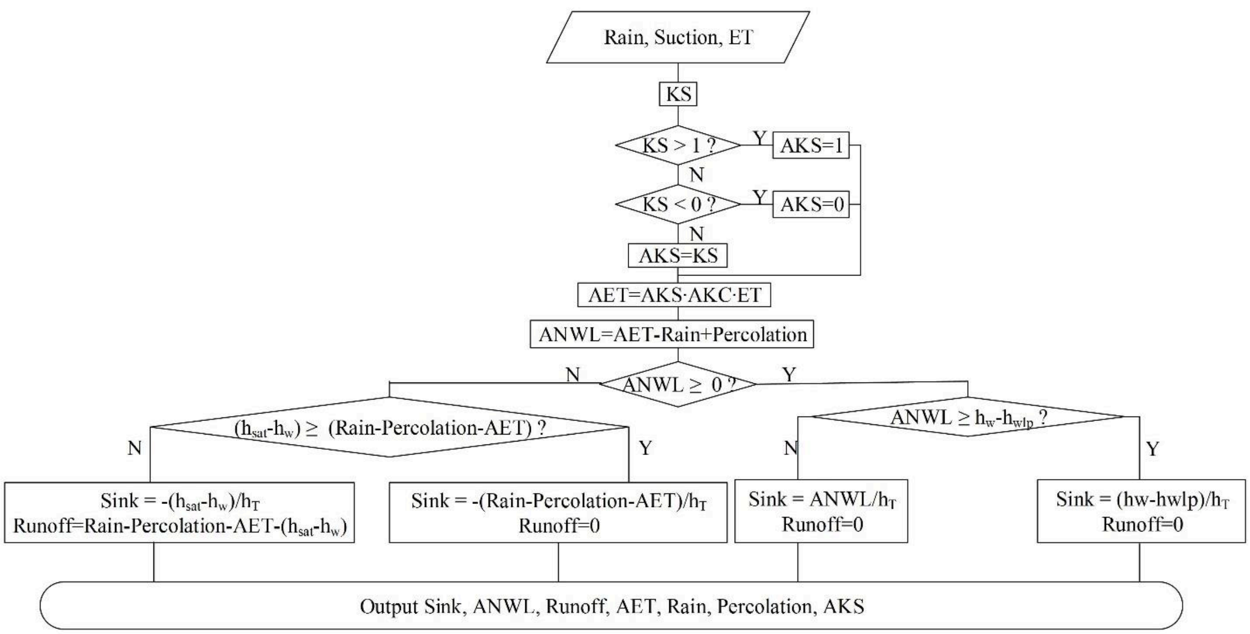

Figure 2. Flow chart for water balance analysis.

In comparison, if $ANWL < 0$, water is expected to flow into the soil element and the rainfall event dominates the water balance analysis. Similarly, the $(h_{sat} - h_w)$ term indicates the maximum amount of water the soil can absorb and the $(Rain - Percolation - AET)$ term represents the calculated amount of water flowing into the soil element. If $(h_{sat} - h_w) \geq (Rain - Percolation - AET)$, the soil element can absorb all the amount of water and the source term shall be calculated based upon the calculated value of $(Rain - Percolation - AET)$. However, if

$(h_{sat} - h_w) < (Rain - Percolation - AET)$, the soil element cannot absorb the entire amount of water and the amount of runoff water shall be the difference between the two terms. Finally, the terms of S, ANWL, Runoff, AET, Rain, Percolation, and AKS will be stored as solution dependent variables for future usage.

MODEL VALIDATION

The laboratory test performed by Leung et al. (2015) was used as a reference to calibrate the proposed numerical model. During the drying test, the readings from the four suction sensors at the beginning of the test were used as the initial condition and a constant ET value of 1.225×10^{-4} m/hour (Rain=0 during the drying test) was used as the external input for the water balance analysis. The numerical model simulated the entire 12-hour drying period and the suction distribution at the end of the simulation was extracted to be compared with the laboratory test results, as shown in Figure 3. The dash lines represent the laboratory test results for the initial and final suction distributions. The solid lines represent the suction distributions at the end of the drying test based on the proposed model by the authors and from Leung et al. (2015). At the starting point of the drying test (right after the wetting test), the soil with an elevation greater than 0.15 m had smaller suction values, indicating that this part of the soil was relatively wet compared with the underlying soil. For the simulation result provided by Leung et al. (2015), it significantly deviated from the laboratory test results and their model could not catch the phenomena of the increasing suction at the top of the soil due to the imposed solar radiation boundary. In comparison, the simulation results based upon the authors' proposed model reasonably matched with the laboratory test results. However, the simulated suction values between 0.07 and 0.20 m were higher than the laboratory test results, indicating that the provided soil permeability in the reference was lower than the actual value, and the excess water did not percolate to the underlying soil. In summary, the simulation results of the proposed FEM model matched well with the laboratory test results and the simulation results could be more accurate when given reasonable soil permeability data.

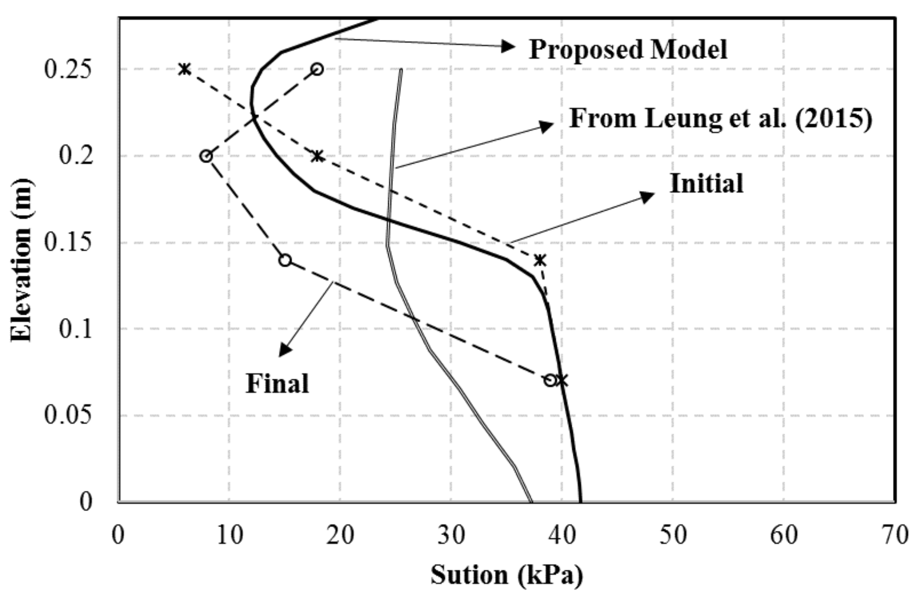

Figure 3. Comparisons of simulation and laboratory test results.

CASE STUDY

To reduce the complexity of the numerical model and evaluate the capabilities of the model, a simple soil column model was established, as shown in Figure 4. The height of the soil column was 2.0 m with the top 0.1 m was used to simulate the grass root zone. The water table was located 1.8 m below the ground level. The soil used in the numerical model was assumed to be the Aggregate Base Class 3 (AB3), which was a typical aggregate used as base course materials in Kansas and the detailed properties could be found in a companion paper (Lin et al. 2018). For the completeness, the soil water characteristic curve and the unsaturated hydraulic conductivity function are provided as in Equations 3-4. Zhang et al. (2005) performed the analogue analysis between thermal-stress and consolidation problems and used the thermodynamic analysis in Abaqus software to simulate the consolidation theory for saturated-unsaturated soils. This paper adopted this method and only considered hydraulic performance (soil moisture migration). Therefore, a used 8-node 3D solid element for heat transfer problems (DC3D8). As for the initial condition, the soil was at the optimum water content of 8.5 % and the corresponding suction was 15.0 kPa. Since the water table was 0.2 m above the bottom of the soil column, the suction at the bottom of the soil column was maintained at 2.0 kPa throughout the simulation. At the top of the soil column, the net water loss/gain was imported to the grass root zone as a boundary condition so that the climatic effect on the soil water content variations could be determined.

$$w = 12.50 \times C(\psi)\left\{1/\ln\left[2.718 + \left(\psi/2.35\right)^{1.241}\right]\right\}^{0.412} \tag{3}$$

Where, w = soil water content, %; $C(\psi) = 1 - \ln(1+\psi/\psi_r)/\ln(1+10^6/\psi_r)$; ψ = suction, kPa.; and ψ_r = residual suction, kPa.

$$k = 10^{\left(-0.0727\cdot\log_{10}(\psi)^4 + 0.6053\cdot\log_{10}(\psi)^3 - 1.7158\cdot\log_{10}(\psi)^2 - 0.6322\cdot\log_{10}(\psi) - 5.2956\right)} \tag{4}$$

Where k = permeability of the AB3; and ψ = suction.

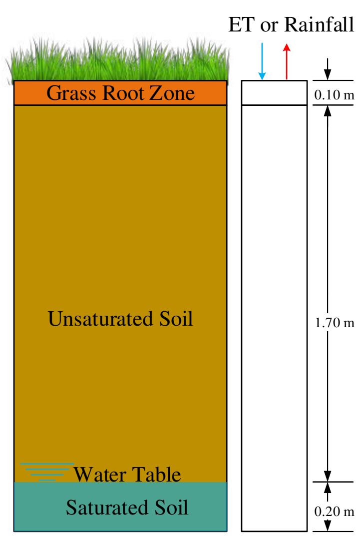

Figure 4. The geometry of the numerical model.

Figure 5 shows the simulation results. Figure 5a shows the soil water content variations with time within the grass root zone (top 0.1 m of the soil column) during the simulated one-year period. Meanwhile, the precipitation data is also presented in the figure as a reference. The water generation term in Equation 1 reflected the actual amount of water infiltrated into or evaporated out of the grass root zone and it depended not only on the magnitudes of rainfall and ET, but also relied on the current state of water storage. In addition, Figure 5b further showed the relationship among rainfall, runoff, and ET during a heavy rainfall event. Before the rainfall started, the evaporation rate was relatively high and the values were zero for both rainfall and runoff. When the rainfall was introduced as the boundary condition at the top of the soil column, the time step automatically decreased to adjust the significant decreasing in soil suction. The runoff water gradually increased and then maintained at a constant value. The difference between rainfall and runoff was the actual amount of water that percolated to the underlying soils (beneath the grass root zone). As the soil gradually changed from unsaturated condition to saturated conditions, the amount of water flowed into the soil gradually became constant. As the soil became saturated, even though the rainfall intensity increased, the total amount of water can be infiltrated into the soil was the same and the rest of the water would be considered as runoff.

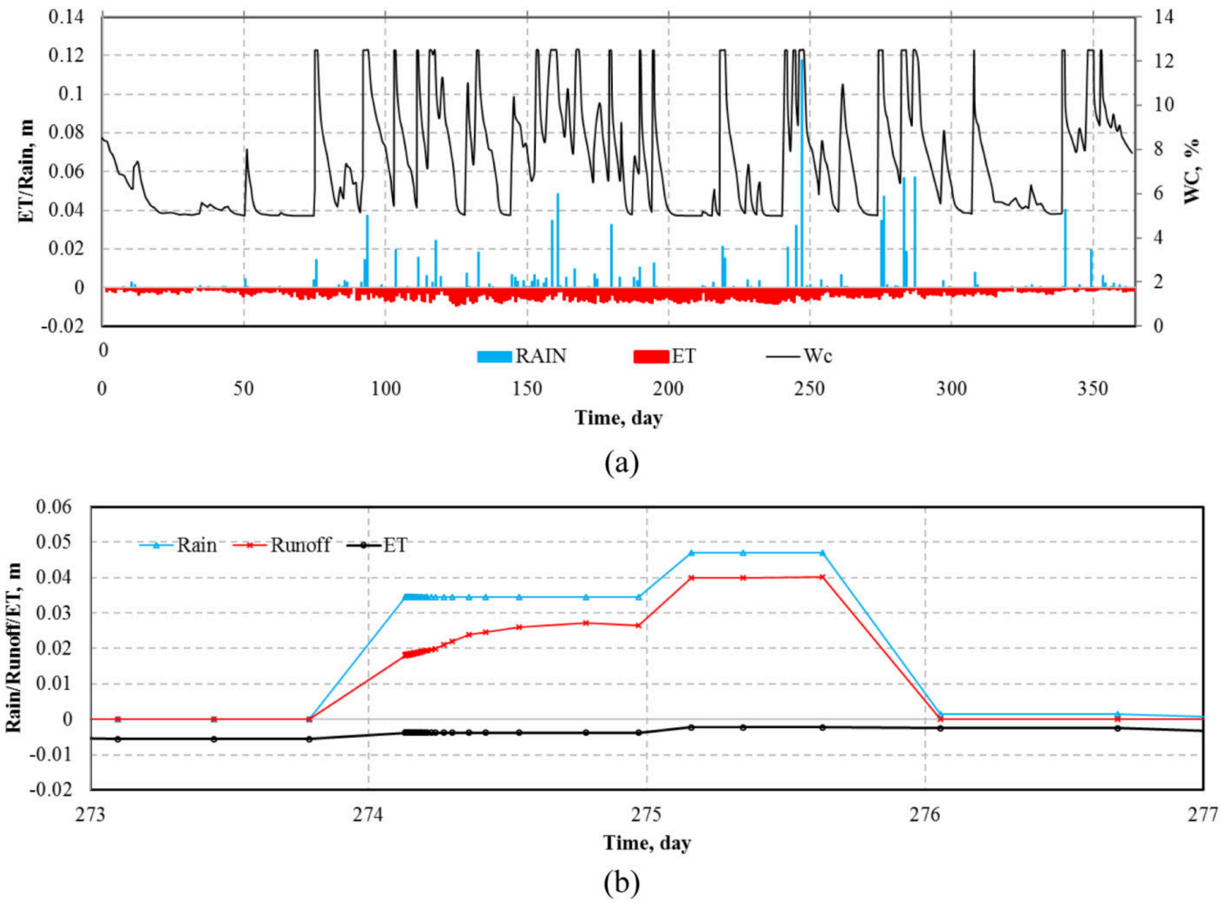

Figure 5. Simulation results: (a) soil water content variations, and (b) comparisons of rainfall, runoff, and ET.

The proposed model is essentially a coupled hydro-mechanical model with considerations of climatic effects. Different from conventional hydro-mechanical models, which could only predict the soil characteristics under the influence of the variations in mechanical stress and pore water pressure, the proposed model was able to take another critical factor – climate – into consideration. As for the applications of the model in predicting the pavement performance, it can be used to predict soil behavior under saturated and unsaturated conditions. If the S term in Equation 1 was excluded in the model, the model could be used to simulate the soil behavior within the road embankment where the climatic effect is negligible. If the climatic effect is considered but the evapotranspiration portion is excluded, then the model can be used to simulate the performance of the surface course in which precipitation infiltration is critical. Moreover, if all the components shown in Figure 2 are considered with all the parameters well defined, the model can be used to simulate the soil performance at the slopes of the road where the water balance is controlled by the soil-vegetation-climate interactions. In summary, the proposed model can be used to simulate the performance of the surface course, the base course, and the vegetation covered area (depending how the parameters in the water balance analysis are defined).

CONCLUSIONS

This paper proposed an infiltration-drainage model that was suitable for both saturated and unsaturated soils. The model was based on Richard's equation and was able to predict soil-climate interactions. The calibrated model was able to capture the effects of rainfall intensity and duration on the soil moisture variations. The vegetation (grass root zone) effectively served as a protective layer to prevent excess water from infiltrating into the base course. The precipitation and evapotranspiration data served as the lower and upper limit for soil water storage and played important roles in keeping the water balance within the grass root zone.

REFERENCES

Christopher, B. R., Schwartz, C. W., and Boudreau, R. L. (2010). *Geotechnical aspects of pavements: Reference manual*, US Department of Transportation, Federal Highway Administration.

Christopher, B.R. and McGuffey, V.C. (1997). "*Pavement subsurface drainage systems"* 239, Transportation Research Board.

AASHTO (1993). "*Guide for Design of Pavement Structures",* AASHTO.

Abaqus, V. (2014). "6.14 Documentation." *Dassault Systemes Simulia Corporation*.

ARA, I., ERES Consultants Division. (2004). "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures." *Final Rep., NCHRP Project 1-37A*.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56." *FAO, Rome*, 300(9), D05109.

Larson, G., and Dempsey, B. J. (1997). "Enhanced integrated climatic model, Version 2.0." *Department of Civil and Environmental Engineering, University of Illinois.*

WRCC (2017). <https://raws.dri.edu/>. (latest access on June 15, 2018)

Wyatt, T., W. Barker, and J. Hall. "Drainage requirements in pavements user manual." *Rep. FHWA-SA-96-070. Federal Highway Administration, US Department of Transportation, Washington, DC* (1998).

Wilson, G. W., Fredlund, D., and Barbour, S. (1994). "Coupled soil-atmosphere modeling for soil evaporation." *Canadian Geotechnical Journal*, 31(2), 151-161.

Tran, D. T., Fredlund, D. G., and Chan, D. H. (2015). "Improvements to the calculation of actual evaporation from bare soil surfaces." *Canadian Geotechnical Journal*, 53(1), 118-133.

Leung, A.K., Garg, A., and Ng, C.W.W. (2015). "Effects of Plant Roots on Soil-Water Retention and Induced Suction in Vegetated Soil." Engineering Geology, 193, 183-197.

Lin, C., Zhang, X., and Han, J. (2018). "Comprehensive material characterization of pavement structure installed with wicking fabrics." Journal of Materials in Civil Engineering, 31(2), 04018372.

Zhang, X., Lytton, R., and Briaud, J. (2005). "Coupled consolidation theory for saturated-unsaturated soils." *Proc., Proc., 3rd Biot Conf. on Poromechanics (Biot Centennial)*, Univ. of Oklahoma, 323-330.

Use of Wicking Fabric to Reduce Pavement Pumping

Javad Galinmoghadam, S.M.ASCE[1]; and Xiong Zhang, Ph.D., P.E., M.ASCE[2]

[1]Graduate Research Assistant, Dept. of Civil, Architectural and Environmental Engineering, Missouri Univ. of Science and Technology, Rolla, MO. E-mail: jgtb5@mst.edu
[2]Associate Professor, Dept. of Civil, Architectural and Environmental Engineering, Missouri Univ. of Science and Technology, Rolla, MO. E-mail: zhangxi@mst.edu

ABSTRACT

Pumping is among the leading distresses in both flexible and rigid pavement. Pumping is defined as the ejection of water and fine materials of the pavement system under pore water pressure generated by repetitious traffic loading through larger voids or cracks. Pumping can significantly reduce the overall strength of the pavement, clogging the course material and eventually affecting pavement performance. Pumping requires heavy traffic loads, water, fine content in the lower layer, and no fine particles in the upper layer. Methods of limiting pumping include removing water, reducing pore water pressure, and separation of fine content from upper layers. The latter is investigated extensively in the literature. In this study, the reduction of water content as a means to reduce pumping is investigated. The drainage performance of a newly developed geotextile that can drain water both in saturated and unsaturated conditions has been compared to conventional drainage systems being used in pavements. For this purpose, a box filled with a granular pavement base material was instrumented and measurements of volumetric water contents were made to compare the effectiveness of each studied case. Results showed that the drainage ability of the newly developed geotextile is significant, specifically in an unsaturated condition, compared to conventional drainage methods being used in practice.

INTRODUCTION

Pavements typically consist of a surface layer (asphalt or concrete), and underlying granular layers (subbase and/or base), placed on top of a subgrade. Pumping (also known as fines migration) has been a problem since the 1940s with an increase in traffic load since World War II (Van Wijk and Lovell 1986) and still is considered a common problem related to pavement support (Kermani et al. 2018a; Bhatti et al. 1996). Pumping is defined as the displacement and/or ejection of water and/or fine materials of the pavement system under pore water pressure generated by repetitious traffic loading through larger voids/cracks. Alobaidi and Hoare (1996) pointed out that the presence of subgrade soil with a high amount of fines, overlying granular layers lacking fine particles, heavy load repetition, and free water at the subgrade-subbase interface is essential for pumping. Different climatic region, varying temperature, precipitation, groundwater table, topography/terrain, availability of construction material, and subgrade material contribute to challenges in comprehending, quantifying and mitigating pavement pumping. This variety of contributing factors to pumping implies that pumping is very common both in flexible (Kermani et al. 2018a) and rigid pavements (Kermani 2018) as well as railways (Chawla and Shahu 2016).

Pumping has been observed in both the laboratory (Alobaidi and Hoare 1996, 1998; Chapuis et al. 2008; Dempsey 1982; Grau 1984; Henry et al. 2013; Huang et al. 2018; Kermani 2018; Kermani et al. 2018a, 2019b; Tosti and Benedetto 2012; Van Wijk and Lovell 1986) and the field (Black and Holtz 2002; Collins et al. 2005; Dempsey 1982; Hansen et al. 1991; Hufenus et