Mechanistic Load Restriction Decision Platform for Pavement Systems Prone to Moisture Variations

National Road Research Alliance

MnDOT Contract 1034192 Task 3: System Dynamics Framework Development

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CHAPTER 1: INTRODUCTION

1.1 RESEARCH PROJECT ABSTRACT AND OBJECTIVES

Excess moisture in base and subgrade soil has detrimental impacts on longevity and serviceability of pavements. Seasonal ground water level fluctuations, inundations due to storms and post-storm recess, frost penetrations and freeze-thaw effects lead to continuous moisture hysteresis and change of stress states in pavement foundation. Current analysis and design procedures rely on approximate empirical approaches, which renders their ability to incorporate moisture-dependency and to conduct real-time and forecasted pavement capacity and load restriction analyses. A load restriction decision platform is proposed to provide a reliable and mechanistically-informed tool for pavement engineers to assess pavement performance and make traffic allowance decision during and after periods of excessive moisture. This platform encompasses three core attributes: (1) A mechanics-based model that correctly captures soil and base response to saturated and unsaturated soil states. It will be validated using actual field pavement tests such as MnROAD and can be further enhanced through the use of physically modelled scaled pavement sections; (2) a system-based approach to integrate impacts of various stressors (soil moisture state, vehicular loads and volume, climatic conditions etc.), current pavement conditions, subgrade properties, hydro-geology, and short-term climate forecast. Due to large number of variables and their inter-dependencies, a system dynamics modelling approach can holistically capture all significant variables and provide a user-friendly system for pavement load restriction decision making; and (3) a policy-informed decision-platform that incorporates inputs from transportation agencies and users to facilitate its implementation and to realize the cost-effectiveness of such mechanistic approach.

1.2 SUMMARY OF RESEARCH METHODOLOGY (SCOPE)

This project is developing a mechanistic pavement load restriction decision framework using system dynamics approach. The main outcome of this project will be a toolkit for pavement engineers to make decisions regarding load restrictions due to seasonal soil moisture variations as well as during post-flooding instances. The use of system-based approach is necessary to integrate impacts of various stressors (soil moisture state, vehicular loads and traffic volume, climatic conditions etc.), current pavement conditions, subgrade properties, hydro-geology, and short-term climate forecast. Due to a very large number of variables and their inter-dependencies, a system dynamics modelling approach can holistically capture all significant variables and provide a user-friendly tool for pavement load restriction (both in current time and for future forecasting) decision making. This research is divided into 10 tasks. The study initiated with development of an initial memo to quantify research benefits and potential implementation steps (Task 1) and literature review (Task 2). This was followed with development of the system dynamics framework to mechanistically evaluate pavement load restrictions (Task 3). This report details the research activities of Task 3. The next steps in this research will be to simultaneously undertake tasks of conducting sensitivity analysis of the system dynamics model (Task 4) and developing a user-friendly toolkit that can be readily implemented for a pavement load restriction decision process

(Task 5). On the basis of sensitivity analysis, the system dynamics model will be refined, and risk quantification feature will be added. Using information from MnROAD (and other agency data if made available to researchers) on pavement sub-surface moisture states and pavement surface deflections (from FWD testing), researchers will calibrate and validate the toolkit in Task 6. Task 8 will finalize the quantification of research benefits and provide guidance on implementation of the research products. Task 7 is out of state travel for researchers to present findings of this project at the annual meeting of the Transportation Research Board and Tasks 9 and 10 will develop and revise the final report for the study.

This report serves as the primary deliverable for Task 3 (system dynamics framework development) of the study.

1.3 ORGANIZATION OF THE REPORT

This report is organized in seven chapters. The subsequent six chapters introduce system dynamics modeling, the embedded system dynamics structures, and the analysis of the developed model for evaluation of pavement deformation under variable soil moisture condition. In order to better introduce the proposed system dynamics framework, the key structures and their performance are discussed through practical examples of a conventional flexible pavement system. Lastly, a summary is provided in chapter 7 that highlights the key findings from the proposed system dynamics framework and briefly describes the on-going and upcoming research tasks in this study.

The key components of this report consist of:

- System dynamics modeling and Vensim Pro® introduction
- Proposed system dynamics framework
- Hydrological structure and variables
- Geotechnical structure and variables
- Pavement response structure and variables
- System dynamics framework summary and conclusions

CHAPTER 2: SYSTEM DYNAMICS MODELING AND VENSIM PRO® INTRODUCTION

2.1 INTRODUCTION

There is a growing recognition of complexities and uncertainties in the management of pavement foundations subjected to moisture variations and, with it, the need for robust policy and decision-making that embraces these complexities and uncertainties. Pavements are dynamic structures and are affected by several complex interdependent parameters such as climatic and mechanical stressors and hydro-geological material properties. To consider this interdependent response, public and private agencies must transition from reductionist empirical approaches to mechanistically informed decision-making processes, as pavements are influenced by a multitude of interacting factors that may not initially appeared to be related.

To date, the majority of the pavement assessment efforts with respect to excess subgrade moisture conditions are based on direct field observation or empirical models, sometimes incorporating soil index parameters or one representative moisture or suction value. Empirical or observation-based methods for complex problems such as flooded pavement systems can be insufficient, limited, and ambiguous, and are often affected by biased evidence-based decision of an expert. Therefore, these methods are often limited in their ability to explain causation and the effect of non-linear interactions and feedback on the behavior of complex systems. This can result in unintended faulty decisions with consequences that create new problems or exacerbate the original problem. Decision-makers are required to integrate scientific and mechanistic-based evidence into decision making.

System dynamics modelling (SDM) is a problem-oriented modelling approach to help agencies better understand complex dynamic problems. The use of system-based approach for pavements subjected to moisture variation is a necessary step to integrate and understand complex interaction of key factors affecting their overall performance. Due to a very large number of variables and their interdependencies, a system dynamics approach can holistically capture all significant variables and provide a user-friendly tool to study and visualize governing factors and their effects on pavement response under variable initial and boundary conditions. The system dynamics modeling can provide engineers with an instructive basis to understand significant factors impacting pavement response to moisture variation and also develop a mechanistic approach for load restriction (both in current time and for future forecasting) decision making. This chapter describes SDM concept and Vensim PRO®, a software utilized to simulate and visualize problems in the context of SDM.

2.2 SYSTEM DYNAMICS MODELING

System dynamics (SD) is a problem-oriented modelling approach originated by Jay Forrester and his colleagues in the late 1950’s, which initiated by applying concepts from feedback control theory to industrial problems (Forrester 1987). It is an approach to study and manage complex systems that change over time. System dynamics modeling has been used to model and understand complex dynamic systems in various fields; some examples include environmental science, management, economics, natural and social sciences, and healthcare systems (Bixler et al. 2019; Currie et al 2018; Forrester 1987). SD involves causal mapping and visualization of behavior of a system as well as interaction between system structures and components with the aid of computer simulation. This provides a strong tool specifically for decision makers to experiment the consequences of their decision before implementation in real world. In addition, while conventional approaches tend to tackle problems by studying individual components of a system (e.g., effect of moisture on subgrade resilient modulus or effect of subgrade resilient modulus on pavement response), a SD approach centers around the idea of integrating dynamic system structures and components considering their interactions over time (e.g., simultaneous evaluation of moisture movement in pavement considering the impact of moisture on hydro-mechanical soil properties as well as pavement response over time).

A SD model consists of three basic elements including (1) level variables, (2) flow variables, (3) information variables. Levels are the key components of each system showing the state of system over time. An example of levels in a flooded pavement system can be the level of ponded water on top of pavement or moisture content in a given layer of soil. Levels can only change through flow variables. Flow variables are defined as the amounts of material added (inflow) or expelled (outflow) from the level. An example of inflow in a pavement system can be the rate of water flowing into the ponded water due to precipitation and an example of outflow can be the rate of water infiltrating into pavement layers from the ponded water. Thus, the level variable in a system is mainly controlled by flow variables and most often are calculated by numerical integration of net flow over time. The quantity and sequence of material flow in a dynamic system is controlled by information variable. An example of information variable in a pavements system can be hydraulic conductivity of soil or precipitation rate and duration which control the rate of inflow and outflow in the system. One key component of SD is causal loop or feedback loop. Causal loop is a closed sequence of material and information flow that establishes the causal effects of different variables in a closed loop (Kirkwood 1998). In recent years several computer programs such as Vensim® and Stella® are developed and employed to simulate and visualize complex system dynamics. The following section describes Vensim PRO®, a system dynamics simulation software utilized in this research to study and simulate the behavior of pavement system under moisture variations.

2.3 VENSIM PRO®

Vensim PRO® (Ventana Systems, Harvard, Massachusetts) is a computer software that allows to conceptualize, document, simulate, visualize, and analyze complex dynamic systems. The software has extensive features including causal loop diagrams, stock and flow diagrams, in built-functions (e.g., if then else, random number generation, etc.), simulation and visual analysis, data use, sensitivity testing, reality check, and more. It is widely used to simulate and visualize complex SD in various fields (e.g., Khan et al. 2009; Rashedi and Hegazy 2016; Whang and Yuan 2017).

Different types of variables such as level variable, rate variable, auxiliary variable, data variable, constant variables are used in Vensim PRO®. Level variables show the current state of dynamics components of the system. The quantity of level at each time step is controlled by the magnitude of cumulative net flow into the level and is computed by numerical integration of difference between inflow and outflow as follows:

$$\boldsymbol{Level(t) = \int_0^t (inflow - outflow)dt + Level(t = 0)}$$

Equation 2-1

Specifically, rate variables control the inflow and outflow into a level. Auxiliary variables are computed through defining analytical equations and functions by using other variables at a given time. Constant variables define constant values for given variables over time. Data variables enable users to define variables that change over time but are independent of changes in the system. Variables in Vensim are connected through arrows indicating that there is either material or information flow between the two given variables. Several numerical integration techniques including Euler and second order and fourth order Runge-Kutta integration are available in the software. The following sections are intended to describe the capabilities of SD modeling in simulating and understanding the system behavior while being presented in a context of a hypothetical one-dimensional (1-D) moisture flow example.

2.4 A SIMPLE EXAMPLE OF SYSTEM DYNAMICS SIMULATION USING VENSIM PRO®

The flow example consists of a fully saturated column of soil subjected to inflow and outflow of water as shown in Figure 2-1 (a). A SD model was developed to simulate the ponded water height and outflow of water to the outflow container using Vensim PRO®. The notations used in Vensim for depicting the defined variables are shown in Figure 2-1 (b). In the software, the material flow is shown by double arrows, information flow is shown by single arrows, level variables are shown in boxes, and auxiliary, constant, and data variables are shown by words. In Figure 2-1 (b), ponded water height (h_p) and accumulated outflow (h_a) are the level variables in the system. Inflow rate (q_{in}), Infiltration rate (q_{out}), and evaporation rate (q_E) are rate variables controlling the rate of water flux to and from the ponded water. The ponded water height can be calculated as an integral of water flux in and out of the soil surface using Equation 2-2.

$$\boldsymbol{h_{p,t} = \int_0^t (q_{in,t} - q_{E,t} - q_{out,t})dt + h_{p,t=0}}$$

Equation 2-2

Vensim PRO® uses numerical integration techniques to compute accumulated level of ponded water at a given time. Inflow can be defined as a constant variable or data variable by defining time dependent data (e.g., providing precipitation time history as an input). Effective soil size for which 10% of soil grains are smaller than that size (D_{10}), soil void ratio (e), and soil thickness (Th) are constant variables. Saturated hydraulic conductivity of soil (k_s) and infiltration rate are examples of auxiliary variables. k_s in this example was calculated based on a semi-empirical equation which uses soil D_{10} and void ratio, e, to estimate hydraulic conductivity of sandy soils (Chapuis 2004).

$$k_s = 2.46[D_{10}^2 \frac{e^3}{(1+e)}]^{0.78}$$

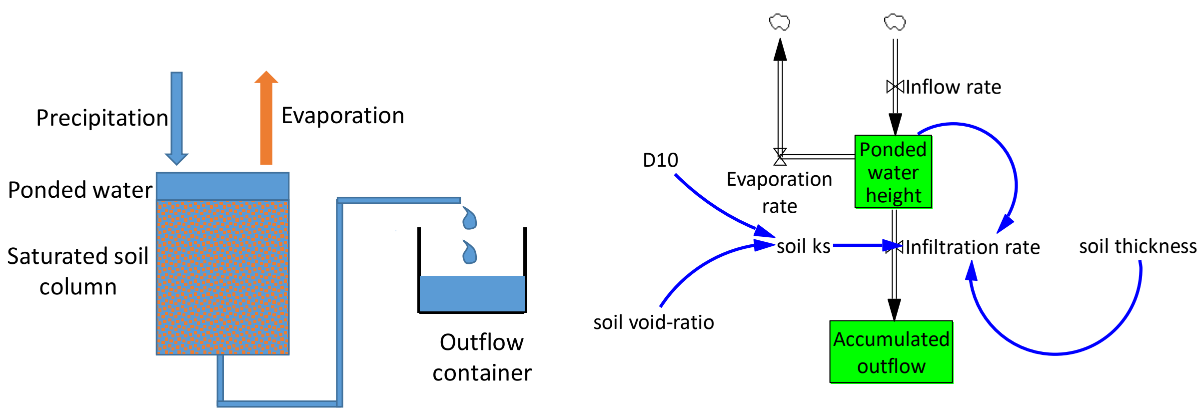
Equation 2-3

Although k_s is an auxiliary variable in this example, its magnitude does not change over time since it is function of two constant variables. However, infiltration rate, the other auxiliary variable changes over time as it is a function of ponded water height, which is a level and time dependent variable. The infiltration rate in this example can be calculated using Darcy's law:

$$q_{out,t} = k_s \frac{\delta h_t}{\delta z}$$

Equation 2-4

where δh_t is the change in total pressure head over a given distance, δz.



(a) (b)

Figure 2-1: (a) Schematic of the example problem, and (b) the system dynamic model of example problem.

Vensim uses the initial and time dependent data to compute auxiliary and time dependent variables at each time step. Results of SD model simulation are produced in terms of time histories. Examples of these results for ponded water height and accumulated outflow are presented in Figure 2-2 in terms of ponded water height and accumulated outflow time series. SD model simulation indicated no ponded water and accumulated outflow at the initial time. This is in agreement with the system's initial condition where total head of water at the soil surface and the end of the outflow tube are the same and the system is at equilibrium. Time history for elevation of ponded water (water height) showed an increasing trend with time, however, with decreasing rate in time. This is because the increase in ponded water height resulted in an increase in hydraulic gradient and subsequently infiltration rate. This is evident in the accumulated outflow curve where the rate of water accumulation was increased with time. Overall, the results of simulation indicated a very good agreement between the SD model predictions and the expected trends. This shows that SD can be a useful tool to model moisture flow through soil systems.

One of the most important advantages of SD modeling using Vensim PRO® is the capability of running sensitivity analysis. This is specifically of great importance for complex systems such as flexible pavements under moisture hysteresis where the existence of complex interdependent components increases the complications of understanding the influential factors governing the system behavior.

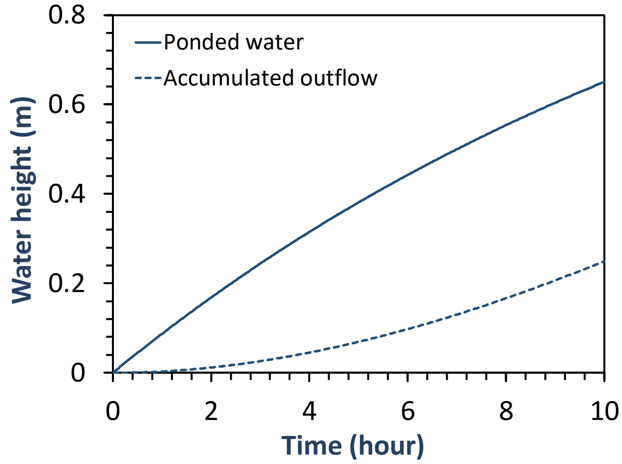


Figure 2-2: Results of system dynamics model simulation using Vensim PRO®.

For the flow example presented herein, the sensitivity of the ponded water height to variations of effective soil particle size (i.e., D_{10}) and soil thickness was examined. The input variables were changed over a range of ±50% and the resulting influence of these changes on the ponded water height over 10 hours were investigated. Figure 2-3 presents the sensitivity of ponded water height to D_{10} and soil thickness variations. Regardless of the type of input variable, a significant change in model response in terms of ponded water height was observed by a change in input variables. The simulation results showed higher sensitivity of ponded water to D_{10} than soil thickness for positive changes in input variables. Overall, results showed that sensitivity analysis of SD model provides a useful tool to understand the significant influence of input variables on model behavior.

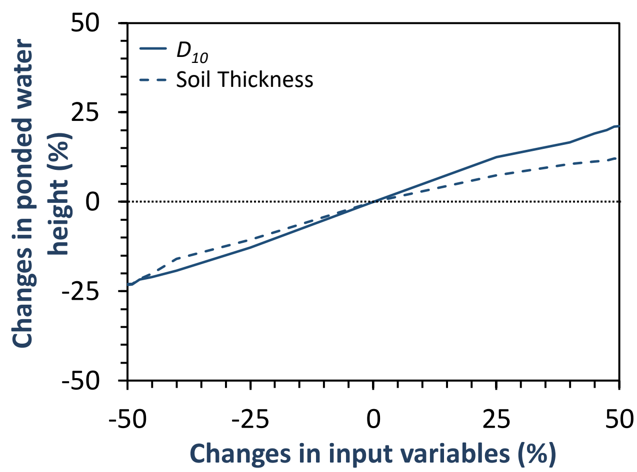


Figure 2-3: Results of SD model sensitivity simulations using Vensim PRO®.

2.5 SUMMARY

Pavements are dynamic structures that are affected by several complex interdependent stressors and material properties. The use of a system-based approach for pavements subjected to moisture variations that integrates these interactions is needed. SDM, an approach to study and manage complex systems which change over time, is an approach that can address this challenge. This approach holistically captures all significant variables and provide a user-friendly tool to study and visualize the pavement response. In this chapter, Vensim PRO®, was successfully used to model 1-D flow through a saturated soil system while demonstrating some of the SD capabilities.

CHAPTER 3: PROPOSED SYSTEM DYNAMICS FRAMEWORK

3.1 INTRODUCTION

The first step in modeling any dynamic system in the context of SD is the identification of influential factors and establishing the relationship between them. In the case of pavements with moisture variations, several parameters such as climate conditions, hydro-geological properties, loading patterns, and pavement structural properties contribute to overall pavement system response. A complete SD model should incorporate all influential variables as well as their interdependency to capture overall pavement system response to moisture movement in real time. This chapter focuses on identification of different system dynamics structures and variables contributing to overall pavement system response to moisture variation.

3.2 SYSTEM DYNAMICS MAIN STRUCTURES

Previous studies have shown that about 80% of pavement damage is directly or indirectly influenced by the presence pore water especially in subgrade soil (e.g. Sultana et al. 2016; Mndawe et al. 2015) while the quality and type of base, subbase, and subgrade layers control the overall performance of pavement system (Santero et al. 2011, Mallick and El-Korchi 2013, Elshaer et al. 2018a). Moisture movement in pavement structure and subsurface layers can significantly affect the soil and unbound aggregate layers' mechanical properties and thus pavement response to traffic loading (Sauer and Monismith 1968, Edris and Lytton 1976, Fredlund and Morgenstern 1977, Noureldin 1994, Drumm et al. 1997, Ceratti et al. 2004, Yang et al. 2005, Khoury and Khoury 2009, Sawangsuriya et al. 2009, Khoury et al. 2010, Cary and Zapata 2010, Han and Vanapalli 2015). Thus, modeling moisture movement and factors affecting its mechanism is the first step in mechanistic pavement response assessment in the context of SDM.

Heavy storm precipitation and low permeability of subgrade soil result in ponding water on top of natural subgrade. In the case of highly permeable base and subbase material, the floodwater easily permeates through these layers which results in inundation of layers within ponded water depth. The level of ponded water depends on climatic conditions (i.e., precipitation and evaporation rates), the topography of pavement, and rate of water infiltration to subsurface soil. The infiltration of water into the subsurface is highly affected by subsurface hydro-geological conditions including soil moisture/suction profile in depth, hydraulic conductivity, and elevation of groundwater table. Thus, a well-designed, mechanistic pavement response assessment protocol requires a robust hydrological analysis of water flow through pavement layers in real time. Moisture movement in the proposed system dynamics framework is conducted under a hydrological structure, while the details of the hydrological structure and its components are elaborated in chapter 4.

The next step in the mechanistic assessment of pavement response to moisture variation is the analysis of the impact of moisture variation on the mechanical properties of various pavement layers and subgrade layers. This analysis should incorporate the soil moisture/suction profile time series obtained from hydrological analysis as inputs and estimates the mechanical properties of pavement layers in real time as an output. This is performed using a geotechnical structure as the second main structure in the SD model. The details of geotechnical structure and its components are elaborated in chapter 5.

The final step in the proposed SD framework is the estimation of pavement structural response to traffic loading. It is well established that weakening of pavement layers due to moisture variation and excessive deformations is the main cause of damage to pavement systems (Gaspard et al., 2007; Helali et al., 2008; Zhang et al., 2008; Vennapusa et al., 2013). The analysis of pavement response should consider the variable, moisture-dependent mechanical properties of pavement layers, pavement current conditions due to existing distresses, and vehicular axle loads and configuration. The pavement response can be analyzed in terms of vertical deflection and peak stresses. This is performed using a pavement response structure, which incorporates the results of analysis of hydrological and geotechnical structures, and pavement and traffic inputs to estimate pavement response in real time. The details of pavement response structure and its components are elaborated in chapter 6.

These three major structures of the SD model will be integrated while each structure contains multiple interrelated variables. Figure 3-1 provides a snapshot of how these three structures work within the SD model.

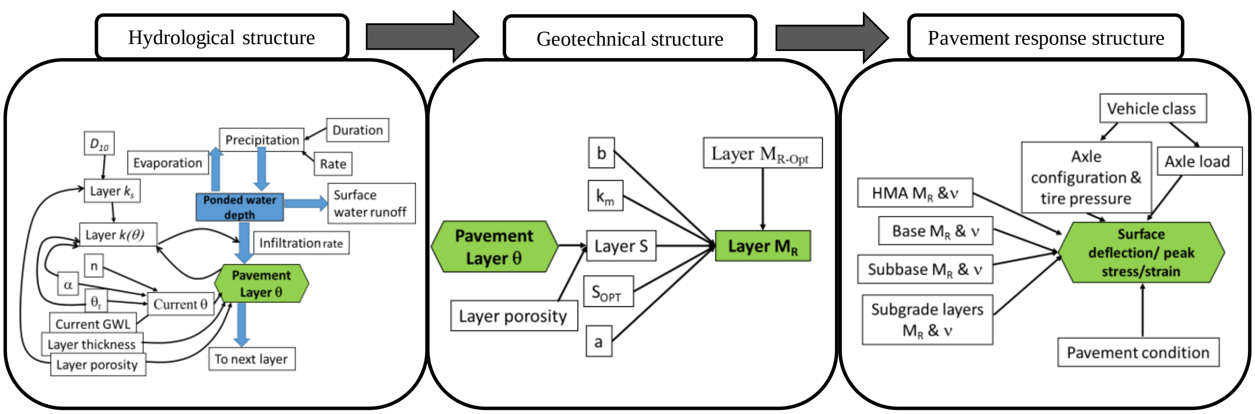


Figure 3-1: A conceptual schematic of the SD model structures and their variables.

3.3 EXAMPLE CONVENTIONAL FLEXIBLE PAVEMENT PROPERTIES

In order to better explain the application of the SD, the framework development process is discussed by evaluating the response of a conventional flexible pavement system with hypothetical material properties and given hydrological and climate conditions. Figure 3-2 presents the schematic of this conventional flexible pavement example which consists of a 0.1 m (~4 inch) thick Hot Mix Asphalt (HMA) layer, 0.3 m (~12 inch) thick base, and 0.1 m (~4 inch) thick subbase placed on top of natural subgrade. Ground water table (GWT) is assumed to be located 2 m (~6.56 ft.) deep from natural ground surface and bedrock is at a depth of 10 m (~32.8 ft.) from natural ground surface. Since different physical and mechanical characteristics of subgrade soil is depth-dependent, the subgrade above GWT is divided to 10 layers. The normal seasonal ground water level is assumed to be 2 m deep.

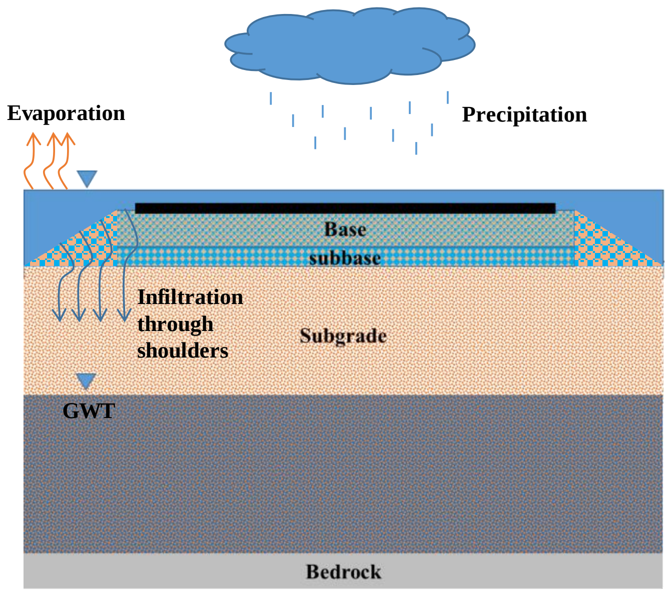


Figure 3-2: The conventional flexible pavement example.

3.4 SUMMARY

Any SD framework for pavement response analysis during moisture hysteresis should include three general structures, (1) a hydrological structure, (2) a geotechnical structure, and (3) a pavement response structure. Such framework should be able to model the interaction between these three structures. The overall pavement response during moisture variation depends on the concurrent interactions between the three structures and their components over time. Each of these structures are described in following chapters.

CHAPTER 4: HYDROLOGICAL STRUCTURE MODEL

4.1 INTRODUCTION

The hydrological structure of the proposed SD model simulates the moisture flux in and out of pavement layers due to precipitation, evaporation, or ground water level (GWL) fluctuation. This is governed by complex interaction of two main components including climate information (e.g., precipitation duration and rate, evaporation rate, surface water runoff) and unsaturated soil hydraulics (e.g., moisture-dependent hydraulic properties of soil layers, current moisture state of the soil, and subsurface GWL). The hydrological structure models the complex interaction between these components to capture variation of moisture content and soil suction profiles during a period of time for consequent geotechnical and pavement response assessment. The following sections are intended to describe each component and related variables of hydrological structure. To better understand the function of each variable, their performance is discussed using the conventional flexible pavement example introduced in Chapter 3.

4.2 CLIMATE INFORMATION VARIABLES

The climate information provides material and information data that controls water flux into and out of the soil surface (i.e., flows associated with water infiltration and discharge). Climate information variables include evaporation rate, initial post flooding ponded water height, rate of surface run-off, and precipitation rate. The initial post flooding ponded water height can be treated as a constant variable based on forecasted data. It can also be estimated from subtraction of evaporation, surface runoff, and infiltration rates from precipitation rate. The surface water runoff depends on the location of pavement and it can be assumed to be zero for “flat areas” and equals precipitation minus infiltration and evaporation for pavements with significant grades. The evaporation/precipitation can be treated as constant input based on average regional evaporation/precipitation rate. Also, the short-term climate forecast can be directly utilized as an input. The SD model has the capability to utilize past precipitation time series for calibration and validation purposes. Figure 4-1 presents the defined climate information variables in the SD model.

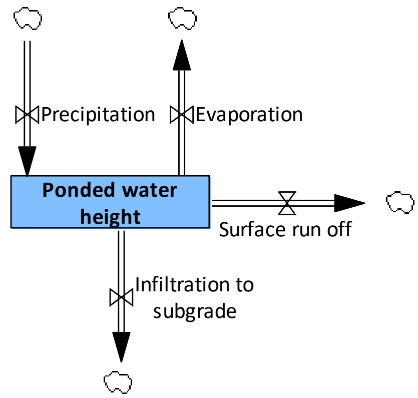


Figure 4-1: Climate information variables in the system dynamics model.

4.3 HYDRAULICS OF UNSATURATED SUBSURFACE SOIL

The water flux out and into unsaturated subgrade layers can be estimated by Richards' equation (Richards 1931). Richards' equation for the one-dimensional transient unsaturated flow through subgrade layers to the ground water table in an isotropic soil deposit can be expressed as follows:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}[K_{(\theta)}(\frac{\delta h}{\delta z} + 1)]$$

Equation 4-1

where, θ is the volumetric water content, *z* is the depth from the subgrade surface, *h* is the soil pressure head, *t* is time, and $K_{(\theta)}$ is the moisture dependent hydraulic conductivity of soil. The initial volumetric water content profile of subgrade can be estimated using Soil Water Retention Curve (SWRC) predictive models. Several SWRC predictive models including Brooks and Corey Model (Brooks and Corey 1964), van Genuchten (VG) Model (van Genuchten 1980), and Fredlund and Xing Model (Fredlund and Xing 1994) were introduced in Task 2 deliverable report. The van Genuchten's formula was implemented in the current SD model due to its accuracy in predicting SWRC and its common use. The model has the following form:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha h)^{n_{vG}}}\right]^{m_{vG}}$$

Equation 4-2

where θ_r is residual volumetric water content, θ_s is saturated volumetric water content, and m_{vG} and n_{vG} are VG model fitting parameters ($m_{vG} = 1 - 1/n_{vG}$). The moisture-dependent hydraulic conductivity at each soil layer soil can, then, be calculated according to Mualem (1976):

$$K(\theta) = K_{sat}(\frac{\theta - \theta_r}{\theta_s - \theta_r})^{0.5}[1 - \left(1 - (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{\frac{1}{m_{vG}}}\right)^{m_{vG}}]^2$$

Equation 4-3

where K_{sat} is the hydraulic conductivity of soil at fully saturated state. The hydraulic conductivity of fully saturated soil layer can be obtained from field tests or be estimated by semi-empirical equations. Table 4-1 summarizes some empirical equations for estimating the hydraulic conductivity of soils in fully saturated state.

Table 4-1: Empirical relations for estimation of hydraulic conductivity of fully saturated soils.

Reference	Equation number	Hydraulic conductivity (cm/s)	Notation	Remarks
Hazen (1911)	Equation 4-4	$k_s = cD_{10}^2$	c= constant.	c ≈1, applicable for fairly uniform sand
Chapuis (2004)	Equation 4-5	$k_s = 2.46[D_{10}^2 \frac{e^3}{(1+e)}]^{0.78}$	e= void ratio of soil	Applicable for uniform gravel and sand and non-plastic silty sands
Mbonimpa et al. (2002)	Equation 4-6	$k_s = C_p \frac{\gamma_w}{\mu_w} \frac{e^{3+x}}{(1+e)} \frac{1}{\rho_s^2 w_L^{2x}}$	γ_ω=unit weight of water (kN/m3) μ_ω= Water dynamic viscosity (Pa·s) ρ_s= Density (kg/m^3) of solids W_L= Liquid limit (%) x= $7.7w_L^{-0.15}-3$	Applicable for plastic soils, γ_ω ≈9.8, μ_ω≈10^{-3}, χ=1.5

While Richards' equation is one of the most accurate methods to model the moisture infiltration into unsaturated soils, it requires a numerical solution due to the challenges in setting the initial and boundary conditions. Yang et al. (2009) suggested a simple numerical solution of Equation 4-1 for water movement in unsaturated soils and demonstrated that the solution works satisfactorily. The solution uses the integration of Equation 4-1, vertically, over the soil layer to simulate moisture movement in unsaturated soil layers (Yang et al. 2009):

$$\Delta\theta = (\frac{v_{wi} - v_{wi+1}}{\Delta z})\Delta t$$

Equation 4-7

where i is the number of layer, Δt is time step, Δz is the soil layer thickness, v_{wi} and v_{wi+1} are the water flow rate from layer i to $i+1$. The flow rate at each layer is calculated based on the volumetric water content, moisture dependent hydraulic conductivity, and soil pressure head at a given time step:

$$v_{wi} = K_{(\theta_i)}(\frac{\Delta h_{i,i-1}}{\Delta z} + 1)$$

Equation 4-8

$$v_{wi+1} = K_{(\theta_{i+1})}(\frac{\Delta h_{i,i+1}}{\Delta z} + 1)$$

Equation 4-9

where $\Delta h_{i,i-1}$ and $\Delta h_{i,i-1}$ represent the differences in soil total head between the given layer and its adjacent top and bottom layers. In order to simulate water movement in subgrade layers, the simplified numerical solution of Equation 4-1 was formulated into the SD model. The SD model incorporates the climate variables and variables related to the flow in unsaturated soil layers to simulate the moisture movement in real time. Figure 4-2 presents the interrelation of these variables in the hydrological structure of SD model.

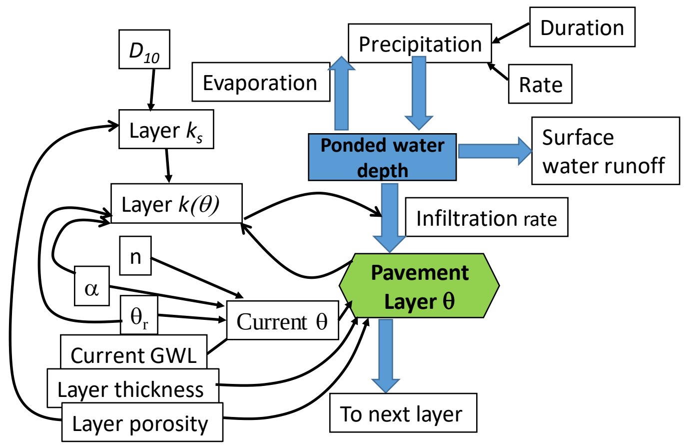


Figure 4-2: Hydrological structure of flooded pavement SD model.

4.4 WATER MOVEMENT SIMULATION WITHIN THE CONVENTIONAL FLEXIBLE PAVEMENT EXAMPLE

In order to highlight the capability of the SD model to simulate moisture movement in pavement layers, the conventional flexible pavement example (described in Chapter 3) was simulated in Vensim PRO®. In this regard, a hypothetical climate scenario was defined in the software. It was assumed that the pavement section with the given initial and boundary condition would be subjected to two discrete periods of heavy precipitation; first with a rate of 0.2 m per hour for 10 hours and second with a rate of 0.1 m per hour for 5 hours while they occur 20 hours apart. The evaporation rate and run off were assumed to be negligible during the period of simulation. This hypothetical precipitation time history is shown in Figure 4-3, it was used as an input to the SD model demonstrated in this report.

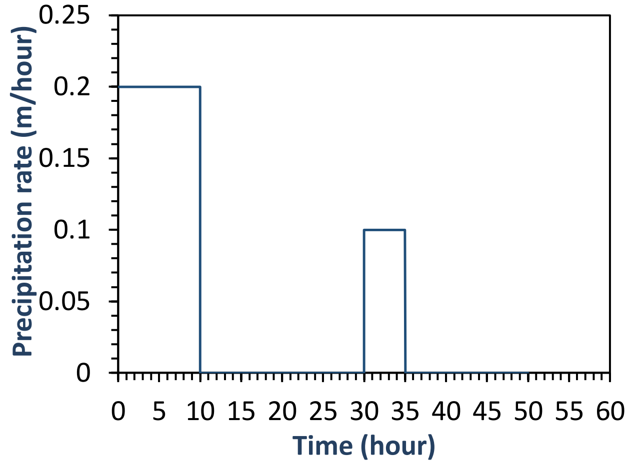
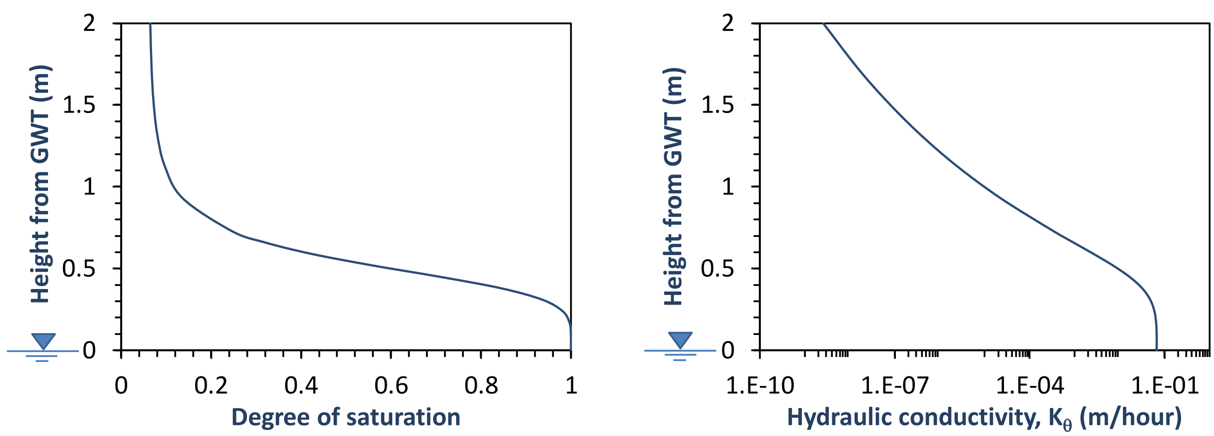


Figure 4-3: Precipitation rate time history.

In order to simulate the moisture flow in subsurface, physical properties were assumed for the pavement layers (as shown in Table 4-2). The SD model used the input information and Equation 4-2 and Equation 4-3 to estimate initial soil degree of saturation, $S = \theta/n$ (n= soil porosity), and hydraulic conductivity profile. These are shown in Figure 4-4.



(a) (b)

Figure 4-4: (a) Initial degree of saturation and (b) moisture dependent hydraulic conductivity profile.

Table 4-2: Physical and hydraulic properties of hypothetical subgrade.

Properties	Attributes/Value
Soil type	Silty sand
Void ratio (e)	0.5
Effective grain size (D_{10})	0.035 (mm)
n_{vG}	5
a_{vG}	2
Residual volumetric water content (θ_r)	0.02
Saturated water content (θ_s)	0.3

The SD model incorporated the input climate data, unsaturated soil hydraulic variables, and formulations to simulate moisture movement through pavement layers and to estimate the degree of saturation of each layer in time steps. It is noteworthy that pavement base and subbase layers typically consist of granular material with relatively very high permeability and very low water retainability. Therefore, for the case of flooded pavement with granular base and subbase layers, it is reasonable to assume free water movement in these layers. Accordingly, the degree of saturation in these layers is assumed to be a function of the ponded water height and the total layer thickness, i.e., degree of saturation is calculated by dividing the portion of the layer under the ponded water to the total thickness of the layer. Figure 4-5 presents the SD simulation results (in form of degree of saturation for various layers) associated with the conventional flexible pavement example using the proposed hydrological structure. Figure 4-6 illustrates the moisture profiles within the pavement layers at different periods of time. Subgrade layer 1 presented in Figure 4-5 was located at the natural soil surface (0 to 0.2m) and subgrade layer 5 was 1 meter deep from the surface (1 to 1.2m) (i.e., 1 meter to GWL). The SD simulation indicated that after approximately 2.5 hours from the first period of precipitation the subbase and base layers become fully saturated. The 20 hours stop in precipitation resulted in full desaturation recovery of both layers. However, 5 hours of rain, even in a lower rate was enough to re-saturate both layers. The infiltration of rainwater into subgrade layers resulted in gradual saturation of the subgrade layers. The full saturation of layer 1 and layer 5 occurred in about 5 and 8 hours, respectively, after the first period of precipitation. Both layers remained fully saturated for more than 40 hours. Then, the recession of ponded water resulted in desaturation of both base and subbase layers and also redistribution of water in subgrade layers. This resulted in a gradual reduction in subgrade layers' degree of saturation toward their initial value (i.e., SWRC equilibrium level). In general, results show expected trends in pavement layers' degree of saturation due to the precipitation. This provides confidence in the suitability of hydrological structure of the SD model to capture moisture movement in pavement systems.

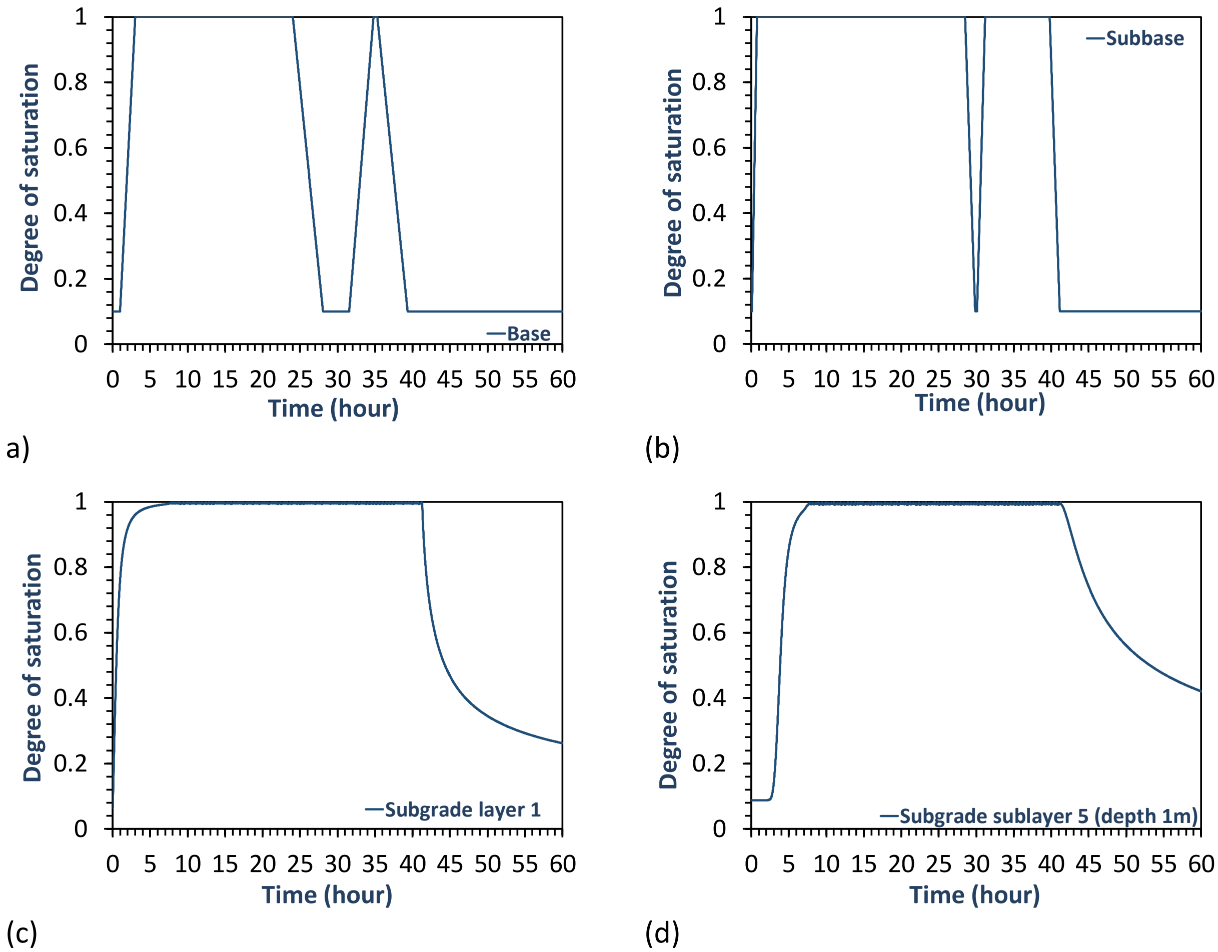


Figure 4-5: Typical results of moisture movement simulation using the SD model formulated in Vensim PRO® in terms of saturation time histories for (a) base (averaged for whole layer), (b) subbase (averaged for whole layer), (c) subgrade layer 1, and (d) subgrade layer 5.

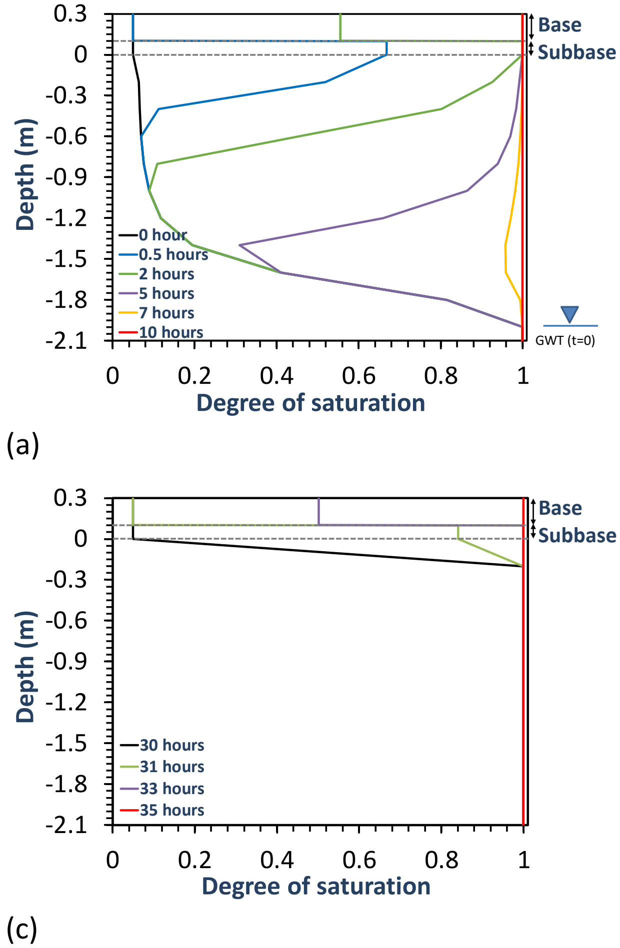


Figure 4-6: Moisture profile of pavement layers (a) during first period of precipitation, (b) between two periods of precipitation, (c) during the second period of precipitation, and (d) after the second period of precipitation.

CHAPTER 5: GEOTECHNICAL STRUCTURE MODEL

5.1 INTRODUCTION

Excessive moisture in pavement systems especially in subgrade soils reduces the pavement foundation stiffness and results in surface deflection and cracking. This has been shown through numerical modeling (e.g., Elshaer et al. 2017, Haider and Masud 2018), physical small-scale and full-scale modeling (e.g., Amiri 2004, Saevarsdottir and Erlingsson 2013), and field performance assessment (e.g., Zhang et al. 2008, Sultana et al. 2016). Geotechnical properties of soils play a key role in pavement response; thus, accurate assessment of these properties under various degrees of water saturation is crucial. Resilient modulus of subgrade soil is one of the most influential factors that controls the overall stiffness of the pavement system. Developing moisture-dependent resilient modulus has been in the forefront of transportation geotechnics research. Especially, with the advancement of unsaturated soil mechanics, significant efforts have been made to correlate soil suction and state of stress to resilient modulus in a more mechanistic setting. The geotechnical structure of the proposed SD model incorporates the moisture/suction variation of soil layers obtained from the hydrological structure at each time step to estimate resilient modulus of the pavement layer subjected to moisture variations. The following sections discuss the variables used in the geotechnical structure of the SD model.

5.2 GEOTECHNICAL STRUCTURE VARIABLES FOR ESTIMATION OF RESILIENT MODULUS

Several analytical and empirical models have been proposed to estimate the resilient modulus, M_R, of soil under various moisture and stress states; some being simple and empirical whereas other being complex and mechanistic (e.g., Yang et al. 2005, Liang et al. 2008, Cary and Zapata 2010, Seed et al. 1967, Khoury and Zaman 2004, Khosravifar et al. 2015). To date, the most commonly used equation is the extended version of Mechanistic-Empirical Pavement Design Guide (MEPDG) equation for resilient modulus at optimum water content from the results of extensive experimental material evaluation (Zapata et al. 2007). In this method, Equation 5-1 is used to determine resilient modulus at any degree of saturation by adjusting the resilient modulus at optimum water content.

$$\boldsymbol{log\left(\frac{M_R}{M_{R-OPT}}\right) = a + \frac{b-a}{1+exp\left[ln\left(-\frac{b}{a}\right)+k_m(S-S_{OPT})\right]}}$$

Equation 5-1

where S_{OPT}= degree of saturation at optimal water content (in decimals); a= minimum of log (M_R/M_{R-OPT}); b= maximum of log-log (M_R/M_{R-OPT}); and k_m= regression parameter. Parameter values a= −0.5934, b= 0.4, and k_m= 6.1324 are suggested for fine-grained soils, and parameter values a= −0.3123, b= 0.3, and k_m= 6.8157 are suggested for coarse-grained soils. M_{R-OPT} can be estimated based on soil type and properties, laboratory tests, or back calculated from field tests (e.g., Falling Weight Deflectometer, FWD) (Christopher et al. 2006).

Equation 5-1was impleneted in the SD model to capture the moisture variation impacts on the resilient modulus of base, subbase and subgrade layers. The proposed geotechnical structure for a given layer of pavement is presented in Figure 5-1. The proposed SD model uses the estimated values of degree of saturation from hydrological analysis and $M_{R\text{-}OPT}$ and fitting parameters in Equation 5-1 to estimate moisture-dependent M_R for each pavement layer and at each time step.

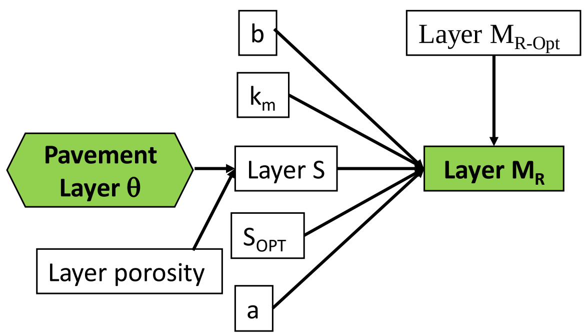


Figure 5-1: The geotechnical structure of the proposed SD model.

5.3 SIMULATION OF GEOTECHNICAL STRUCTURE FOR THE CONVENTIONAL FLEXIBLE PAVEMENT EXAMPLE

The conventional flexible pavement example introduced in Chapter 3 in conjunction with the hydrological solution presented in Chapter 4 under the given precipitation scenario was simulated in Vensim PRO®. This will highlight the capability of the proposed SD model to estimate M_R variation with moisture movement in pavement layers. In this regard, a set of typical mechanical properties were assigned to the pavement layers (as presented in Table 5-1). The initial moisture-dependent properties were estimated according to the initial moisture distribution in Chapter 4 and were concurrently updated throughout the simulation as moisture moved through the soil layer.

Table 5-1: Mechanical properties of pavement layers.

Property/parameter	value
Base optimum resilient modulus ($M_{R,B\text{-}OPT}$)	200 MPa (~30 ksi)
Subbase optimum resilient modulus ($M_{R,SB\text{-}OPT}$)	137 MPa (~20 ksi)
Subgrade optimum resilient modulus ($M_{R,Sg\text{-}OPT}$)	70 MPa (~10 ksi)
a	−0.3123
b	0.3
K_m	6.8157

Figure 5-2 illustrates the results of SD simulation for analysis of moisture-dependent resilient modulus variation with moisture movement in the conventional flexible pavement example. The resilient modulus time histories are presented along with the degree of saturation time histories for the base layer and the 5th subgrade layer (located 1 m above the seasonally normal GWT). A comparison of the resilient modulus time histories with moisture showed good agreement between the trends observed in both figures. This suggests that the SD model could successfully capture the interaction between geotechnical and hydrological structures. The resilient modulus of the base layer decreased to almost a quarter of its initial value when the first period of raining resulted in full saturation of the base from its initial degree of saturation. The SD model predicted full recovery of the base layer's resilient modulus after approximately 16 hours from the end of the first period of precipitation followed by a sudden drop during the second period of raining. This was in a very good agreement with the degree of saturation variation with time. Similar results were also observed for the selected subgrade layer. In general, results showed the capability of geotechnical structure to capture the effect of moisture movement on the subgrade resilient modulus. Specifically, simultaneous simulation of hydrological and geotechnical structures enabled real time prediction of moisture movement as well as resilient modulus variations based on climate forecast.

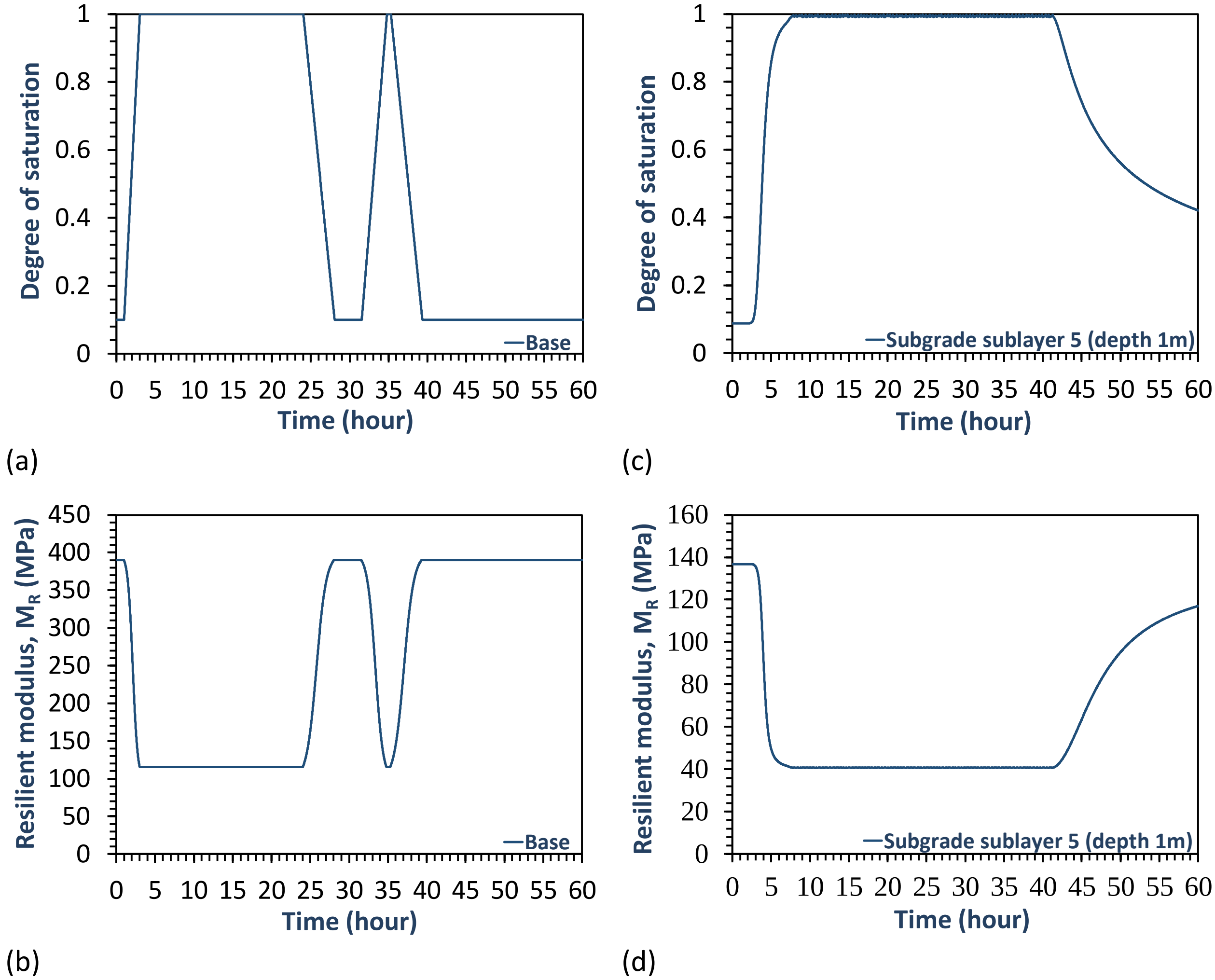


Figure 5-2: Results of geotechnical structure simulation using the SD model formulated in Vensim PRO®. Results show (a) base saturation; (b) base resilient modulus time history; (c) subgrade layer 5 saturation; and (d) subgrade layer 5 resilient modulus time history.

CHAPTER 6: PAVEMENT RESPONSE STRUCTURE MODEL

6.1 INTRODUCTION

In the proposed framework, the pavement surface deflection will be considered as an indicator of the overall pavement load carrying capacity. This choice was based on the literature review, pavement surface deflection under loading is often able to quickly discern safe passage of a vehicle versus of that where unsafe conditions in terms of pavement failure may prevail. Furthermore, pavement surface deflection has been shown in other previous researches on post-flooding assessment as a reliable indicator of damage potential to roadways due to allowance of traffic before full recovery. Deflection of pavement surface layer during moisture variation requires real time information on moisture-dependent mechanical properties of pavement layers, current pavement condition (i.e., age and distresses), and traffic information. The pavement response structure considers the interaction between all these components to estimate real-time surface deformation of pavement considering moisture movement in pavement layers. Therefore, a pavement structure should incorporate the real time moisture movement and pavement layers' mechanical variables from hydrological and geotechnical structures to estimate surface deflection based on traffic and current pavement condition information. This chapter describes the main components of pavement structure and the methodology to estimate the pavement surface deflection during moisture variation.

6.2 MAIN COMPONENTS OF PAVEMENT RESPONSE STRUCTURE

6.2.1 Traffic information

There are two approaches to determine the expected loads on the given pavement over its entire design life. One approach is to convert all magnitudes of loading and repetitions of loading to an equivalent unit using approaches such as equivalent damage; a commonly used example for this is equivalent single axial load (ESAL). The other approach is to use a load spectrum, which characterizes loads directly by number of axles, configuration, and weight. The latter method is typically more complex since the structural analysis requires the use of each vehicular combination to be evaluated to obtain relevant responses. Both methods follow standard equations and/or procedures that have been well laid out in the literature (such as, AASHTO, 1993 and FHWA, 2019). For the proposed SD framework, the use of ESAL approach is not appropriate, since the damage potential from each vehicle type needs to be evaluated. Thus, vehicle class-based traffic inputs can be more appropriate for the current system. In this regard, the 13-category FHWA vehicle classification was adopted (FHWA, 2014). The traffic variables include axle loads, axle configurations, and tire pressures.

6.2.2 Pavement structural performance

Historically, different methods have been proposed to analyze the structural performance of pavement systems. The use of multilayer analysis, specifically layered elastic analysis, is the current state-of-the-practice in the majority of flexible pavement analysis and design systems (such as, MnPAVE, PavementME, CalME etc.). However, the use of these methods requires an iterative numerical scheme, which is not easily implementable in Vensim Pro®. Thus, the use of a closed form solution such as Boussinesq (1885)'s theory for an elastic half-space was considered in this research. In this regard, Odemark's Equivalent Thickness Method (ETM) was employed to reduce the multilayer elastic pavement system to an equivalent single half-space layer (Ullidtz 1987). ETM is also used in MnPAVE to reduce multiple asphalt concrete layers into single layer. ETM uses each layer's elastic modulus (*E*) and Poisson ratio (ν) to convert the layered pavement system to a single homogenous half-space layer according to Equation 6-1:

$$\mathrm{H_{Eq}} = H_n + \sum_{i}^{n} C_i H_i \ \left[\frac{\mathrm{E}_i(1-\nu_n{}^2)}{\mathrm{E}_n(1-\nu_i{}^2)}\right]^{1/3}$$

Equation 6-1

Where H_{Eq}, is the equivalent thickness of pavement layers, H_n is the thickness of layer *n* with young's modulus= E_n and Poisson ratio= ν_n, and H_i is the thickness of layer i with young's modulus= E_i and Poisson ratio= ν_i, and C_i is a fitting parameter and depends on the ratio of modulus of the equivalent pavement (E_n) and the pavement layer thickness (E_i). Preliminary analyses using Equation 6-1 and layered elastic analysis software (e.g., WinJULEA) indicated less than 20% error in stress distribution estimations when $E_n = E_{Subgrade}$, $\nu_n = \nu_{Subgrade}$, and C_{HMA}= 0.5, C_{Base}= 0.7, $C_{Subbase}$= 0.85, and $C_{subgrade}$= 1. Equation 6-1 converts each pavement layer to a new layer with equivalent thickness and mechanical properties to ones in layer *n*. The total equivalent pavement thickness is obtained by summation of equivalent thicknesses of all the layers. The stress distribution and deflection in each layer can then be calculated using Boussinesq (1885) theory for a homogenous and isotropic linear elastic half-space system in axisymmetric condition (Equation 6-2, Equation 6-3, and Equation 6-4):

$$\sigma_z = q\left(1 - \frac{z^3}{(a^2+z^2)^{1.5}}\right)$$

Equation 6-2

$$\sigma_r = \frac{q}{2}\left[1 + 2\mu_i - \frac{2(1+\mu_i)z}{(a^2+z^2)^{0.5}} - \frac{z^3}{(a^2+z^2)^{1.5}}\right]$$

Equation 6-3

$$\epsilon_z = \frac{1}{E_z}[\sigma_z - \mu_z(2\sigma_r)]$$

Equation 6-4

where *a* is the equivalent tire radius and is calculated based on wheel load and tire pressure (*q*), ε_z is the vertical strain at depth z, σ_r is the horizontal stress, and E_z and ν_z are the young modulus and Poisson ratio of layer i located at depth z. The SD model calculates the deflections imposed by each wheel to estimate maximum deflection using the superposition principle. The conceptual structure for simulation of pavement response is shown in Figure 6-1.

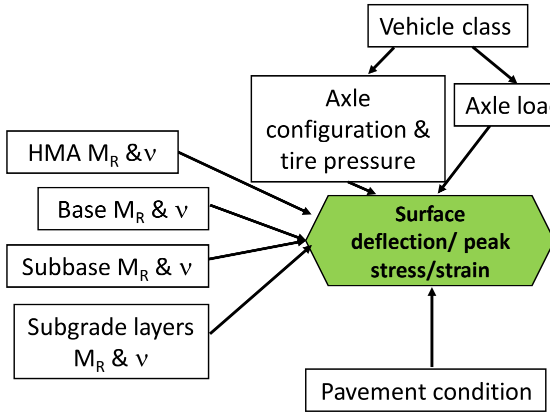


Figure 6-1: Surface deflection simulation using the SD model in Vensim PRO®.

6.3 SIMULATION OF PAVEMENT RESPONSE STRUCTURE FOR THE CONVENTIONAL FLEXIBLE PAVEMENT EXAMPLE

The previously described pavement system example is used to evaluate the ability of the pavement response structure to simulate the impact of moisture movement on pavement deflection under traffic load. In this regard, the pavement response structure was incorporated in the SD model to connect all three structures (i.e., hydrological, geotechnical, and pavement response) and simultaneously evaluate the impact of moisture variations on different variables in the system. The mechanical properties of the pavement layers for the deflection analysis were assumed to be as shown in Table 6-1. The effect of pavement age and existing distresses will be accounted for by adjusting these mechanical properties. In the current example, no adjustments were made.

Table 6-1: Mechanical properties of pavement layers.

properties	value
AC resilient modulus ($M_{R,AC}$)	2500 MPa (~360 ksi)
AC Poisson ratio (μ_{AC})	0.35
Base Poisson ratio (μ_B)	0.3
Subbase Poisson ratio (μ_{Sb})	0.3
Subgrade Poisson ratio (μ_{Sg})	0.4

Table 6-2: Traffic load information for the pavement example.

Traffic information	Value
Tire pressure	550 kPa (80 psi)
Wheel load	45 kN (10 kips)

The flexible pavement system's surface deflection was analyzed in Vensim PRO® under the given precipitation scenarios in Chapter 4. The analysis was performed for a single tire with loading characteristics presented in Table 6-2. The SD model used the moisture-dependent properties of pavement layers obtained from hydrological and geotechnical structures to simulate deflection of pavement surface at each time step using the assumed traffic and mechanical material properties. Figure 6-2 presents results of surface deflection simulation of the flexible pavement example. Results showed a very good agreement between trends in surface deflection and moisture and resilient modulus variations in the pavement layers. The full saturation of the pavement layers resulted in almost a 150% increase in surface deflection during both periods of raining. The results showed that although the surface deflection partially recovers after 20 hours from the first period of precipitation, the second period of precipitation, even with a lower rate and duration, could result in full saturation of pavement layers and significant increase in deflection and thus vehicular traffic during this duration can potentially damage the pavement foundation. This highlighted the significant importance of simulating pavement systems in context of SD to capture real time, post-inundation pavement response using forecasted climate data.

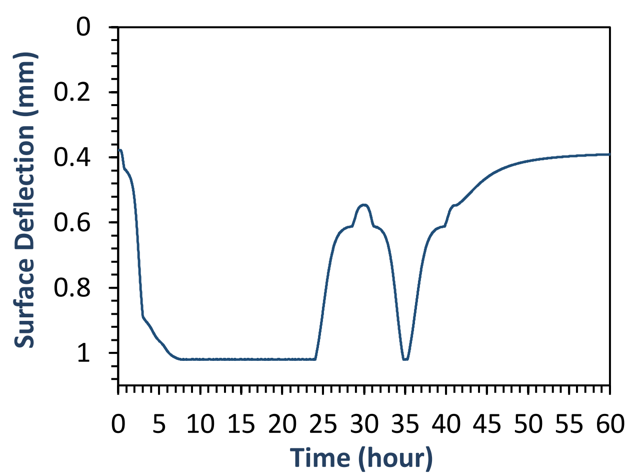


Figure 6-2: Surface deflection simulation using the example pavement SD model.

CHAPTER 7: SYSTEM DYNAMICS FRAMEWORK SUMMARY AND CONCLUSIONS

7.1 SUMMARY

A SD model was developed to simulate the real time behavior of pavement systems due to moisture variations. Three main structures including hydrological, geotechnical, and pavement response structures were identified to be crucial in order to develop the SD model. A detailed discussion on components and variables required to model each structure and the interaction between them was provided in this report. A practical example of a conventional flexible system, simulated using the developed SD model, was also provided to highlight the suitability of the SD model to address this problem. Figure 7-1 illustrates a big picture of the SD model structures and variables along with the typical results of the conventional flexible pavement example. The new SD model could holistically incorporate pavement structure, climatic forecast, traffic loads, and moisture movement processes within a pavement system. The comparison between input variables and output charts using the developed SD model indicated the capability of the model to simultaneously model interactions between hydrological, geotechnical, and pavement response structures. The SD model would be able to address the sensitivity of pavement foundation response to each contributing factor and how these factors would interact under different state conditions, which will be evaluated in the next Task of the project.

7.2 FUTURE WORK

In future, the SD framework will be continuously improved to update the structures based on the state-of-the-art and practice. The developed framework provided a tool to simulate moisture movement in pavement systems and assess its impact on hydrological, geotechnical, and pavement response. The developed SD model will be implemented to assess sensitivity of pavement response to various variables defined in the system.

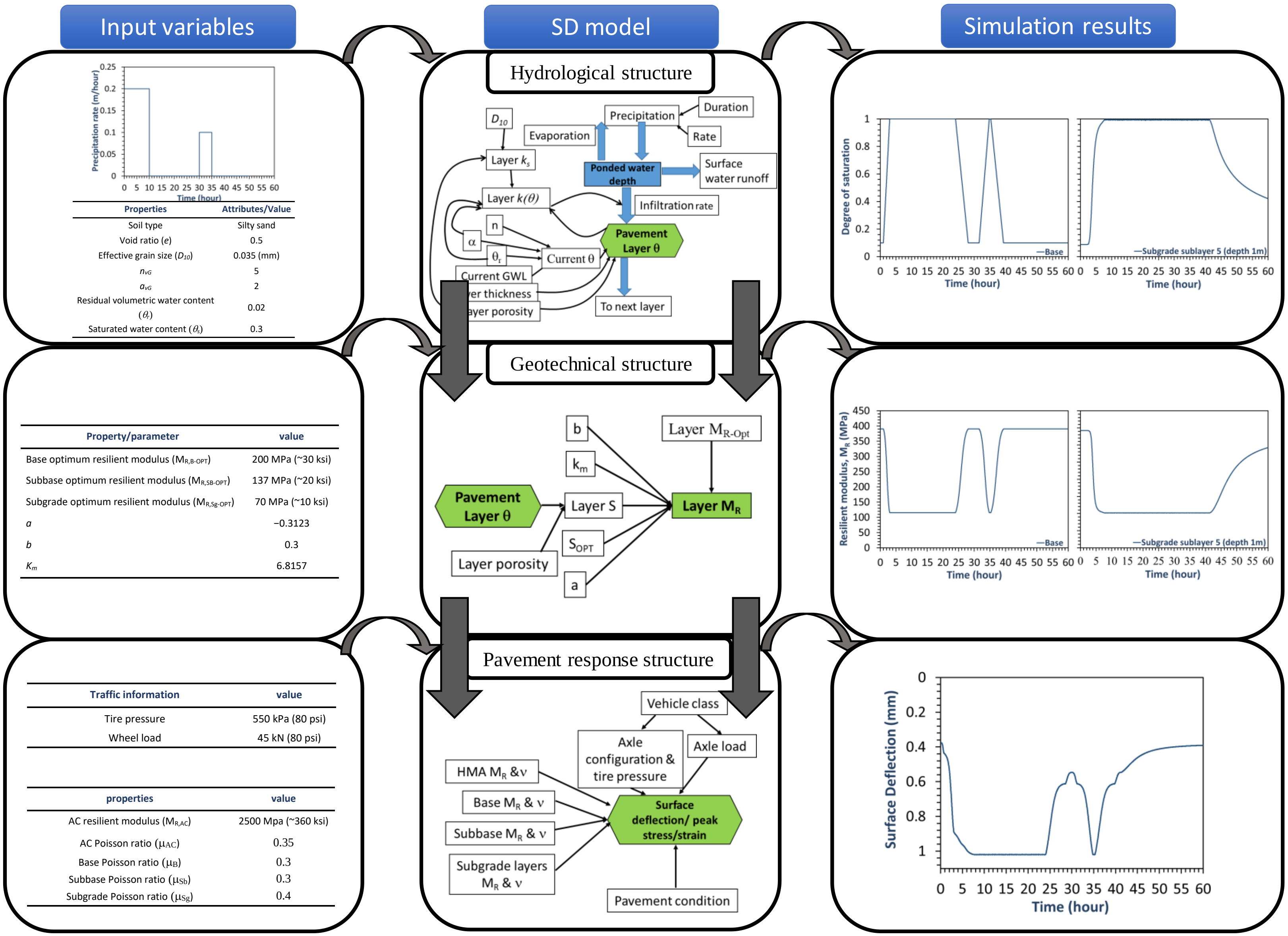


Figure 7-1: A big picture of the SD model structures and variables along with the typical results of the conventional flexible pavement.

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