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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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# The System Dynamics of Flooded Pavements

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**FHWA Contact: Amir Golalipour (ORCID: 0000-0001-9932-1127), Infrastructure Analysis and Construction Team, (202) 493-3089, amir.golalipour@dot.gov**

**This TechBrief is part 1 of a two-part series (part 2 is *Evaluating the Load Capacities of Flooded Pavements: Improving Practices and Developing Data-Driven Evaluation* (FHWA-HRT-24-095)). The TechBrief is a technical summary of the Federal Highway Administration (FHWA) report *Developing Procedures for Assessing Flooded Pavements: Evaluating Structural Capacity and Managing Risks* (FHWA-HRT-24-104).**

## INTRODUCTION

### Evaluation of Structural Capacity

Incorporation of flood resilience in road infrastructure is urgently needed to reduce economic losses. Flooded roads may undergo rapid deterioration after being reopened to traffic. Thus, transportation agencies must develop pavement design and management practices and methodologies that account for the likelihood and impacts of flooding, using prior experiences in similar situations and nondestructive testing (NDT) as resources. Additionally, agencies must manage uncertainties associated with these activities to reduce assessment risks, and those should be quantified, especially when data are unavailable. To reduce these risks, agencies should adopt a consistent set of standardized guidelines.

Currently, many agencies primarily use field observations and past experiences to determine suitable pavement evaluations and communicate road reopening decisions for various types of traffic after a flood; some agencies may also include NDT in the decisionmaking process. Minimal guidance is available to inform agencies how field observations, experience, and NDT can be effectively integrated to evaluate the postflooding structural capacity of pavements and make reliable, cost-effective decisions. As a result, agencies are unable to methodologically evaluate all the involved parameters to optimize financial, social, and functional benefits for decisionmakers and users.

This TechBrief summarizes the system dynamics aspects from the report, which was prepared for the Flooded Pavement Assessment project funded through FHWA Project No. DTFH61-13-C-00022.[1] The report, in general, addresses the load-carrying capacity of pavements affected by flooding to provide decisionmakers with quantitative tools to rationally assess and strategize opening roads to traffic after floodwater recedes, considering flooding hydraulics and pavement structural aspects.

## Objective

The objective of this TechBrief is to highlight and summarize the system dynamics models and pavement drainage simulations by presenting this information from two complementary perspectives. First, the TechBrief analyzes preflooding scenarios in terms of the hydraulics of flood-related damage to pavements to evaluate whether a specific pavement is vulnerable to the impacts of flooding. Second, the TechBrief examines postflooding scenarios to determine when different types of vehicles can travel over different types of pavements in accordance with hydraulics and pavement structure behavior, studying methods to monitor pavement structural strength as it recovers over time after floodwaters recede.

# SYSTEM DYNAMICS MODELS AND PAVEMENT-DRAINAGE SIMULATIONS

## Preflooding Evaluation

Flooding-related damage can accumulate in pavements in a variety of pathways, but the controlling factor is pavement moisture susceptibility. Moisture in bound and granular pavement layers may accelerate pavement damage. Damage is usually quantified by evaluating loss of strength or stiffness. In the hot mix asphalt (HMA) layer, strength or stiffness is governed by the resistance of the HMA mix to moisture damage.[1] The flow of water through an HMA layer depends on the layer's permeability as well as surface distresses, such as cracks and joints, whose intensity affects the ingress of water. Furthermore, permeability depends on air void content (which is initially at a maximum) and typically decreases gradually over time due to traffic-related compaction.

Granular layers are usually composed of unbound aggregates or mixes with relatively low asphalt content. The mechanism of moisture damage and the resulting reduction in stiffness are dictated by the pavement's moisture content ($\vartheta$) and saturation level; the permeability of the base course (BC) material is affected by its gradation and density.[2] The chances of water content and saturation level increasing quickly are greater for higher permeabilities. Pavement location, floodwater flow velocity, and erodibility of granular material are also important, because proximity to a stream and floodwater can potentially wash away material.[3]

### *Approach*

The research team developed a framework to predict the likelihood of damage to a flooded HMA pavement considering a specific water depth ($h_L$) and flood duration. A critical time period ($T_{critical}$) was defined, such that, if the duration of flooding was greater than $T_{critical}$, the pavement was assumed to be severely damaged during and immediately after flooding. Damage was defined in terms of saturation. For flooding duration greater than $T_{critical}$, the BC was considered completely saturated and damaged. Researchers accounted for tensile strength deterioration of the HMA by measuring retained tensile strength after inundation—specifically, the rate of change in retained tensile strength over time (RRTS) was measured. Additionally, researchers accounted for the HMA effective permeability ($k_{effective}$) because permeability and the flow of water through the HMA depend on air voids and the presence of cracks. Finally, researchers took into consideration the proximity of the pavement to streams and culverts due to occurrences of roadway sections being washed away in embankments or backfills near bridge abutments.[4]

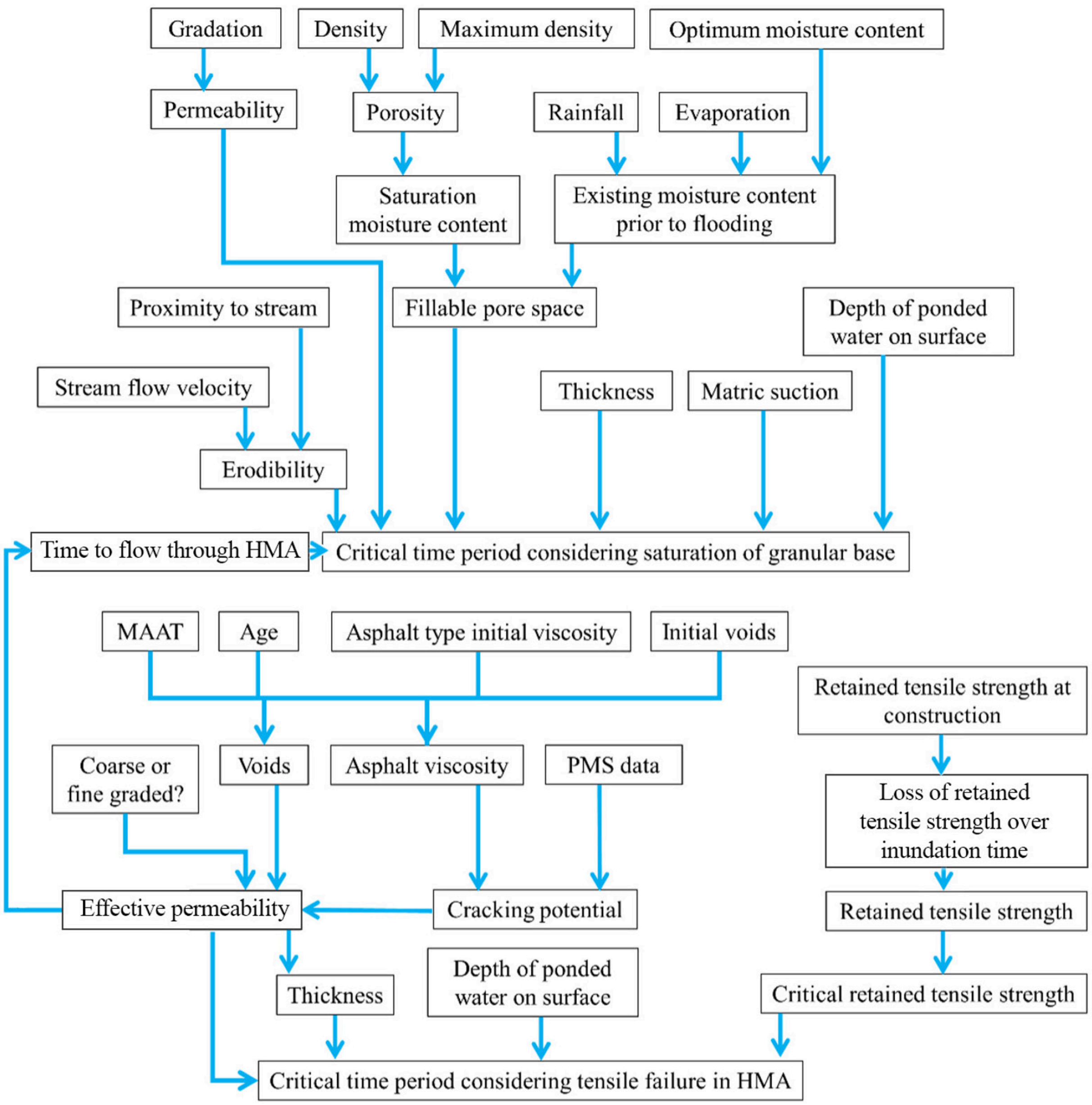
### *Model*

Researchers developed a system dynamics model, based on the framework presented in the "Approach" section, to assess pavement vulnerability to flooding. This model was developed with a strategic view of a pavement system by modeling its different components, simulating the dynamics of interaction, and utilizing numerical integration to evaluate changes in flooding time.[5] The model predicts critical time for saturation, which causes significant loss of support for pavements, by linking material properties to layer properties.[3] Figure 1 shows the assessment framework for the model. Figure 2 shows a Web-based tool with offline capabilities for determining the critical time by simulating the variables that researchers developed from this model.[1,8]

### *Simulation Outcomes for Preflooding Evaluation*

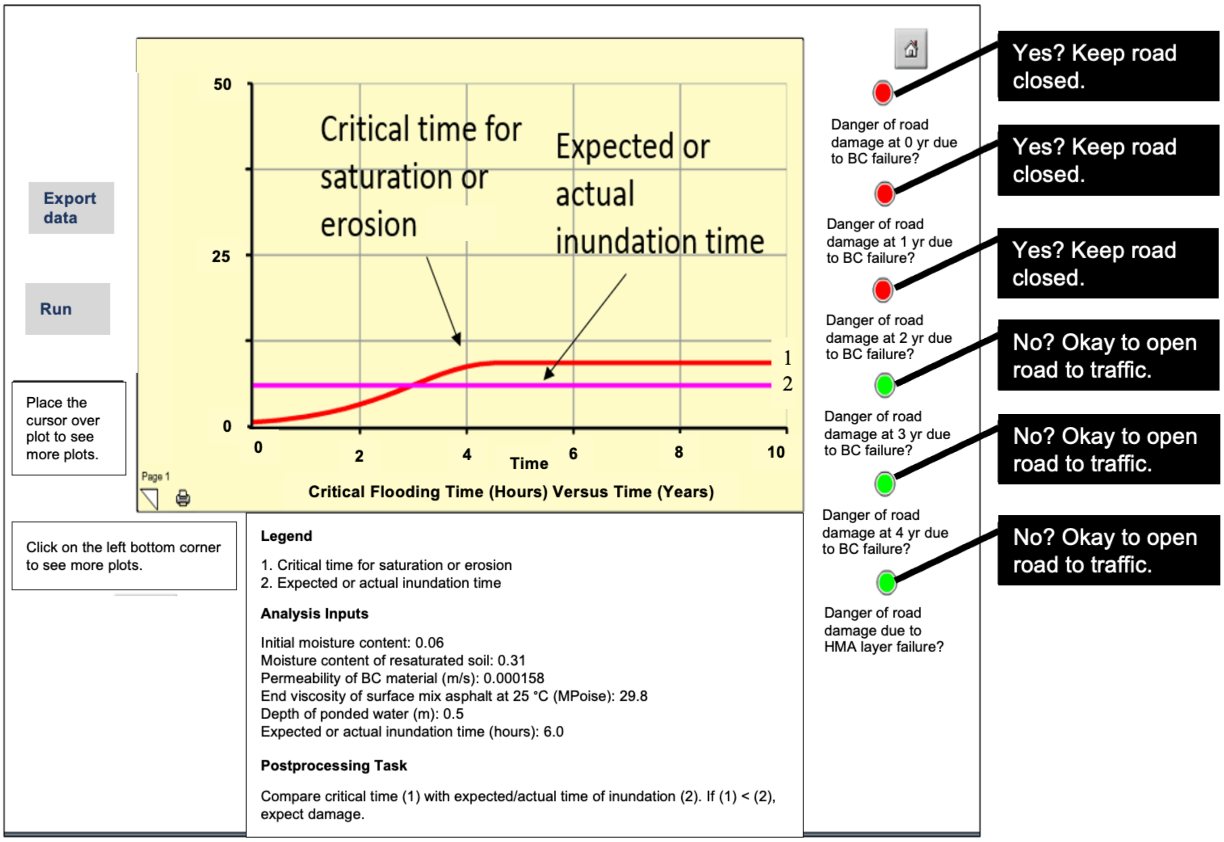
Researchers performed simulations to evaluate the sensitivity of the models to critical factors, including 8 variables and 24 different cases (appendix A of the report).[1] These variables were flood depth (1 m (3.28 ft) in all cases), base thickness, base density, matric suction, asphalt concrete thickness, gradation, air voids, and changes in retained tensile strength versus time. Table 1 encapsulates the general effect of the various parameters on the critical time.

**Figure 1. Flowchart. Framework for model assessment.**




Source: FHWA.
MAAT = mean annual air temperature; PMS = pavement management system.

**Figure 2. Screenshot. Simulation of interface for Web-based tool.[1,8]**




Source: FHWA.

**Table 1. Preflooding evaluation variable effects on $T_{critical}$.[1]**

| Variable Change Effect | General Effect on $T_{critical}$ |
|---|---|
| Air voids increase. | Higher permeability; hence, decrease in $T_{critical}$. |
| Number of years after construction. | Increasing compaction due to traffic, resulting in air void decrease and lower permeability; hence, increase in $T_{critical}$. |
| HMA layer thickness increase. | Increase in $T_{critical}$. |
| HMA gradation. | Lower $T_{critical}$ for fine-graded compared to coarse-graded. |
| Base thickness increase. | Moderate increase in $T_{critical}$. |
| Matric suction increase. | Insignificant increase in $T_{critical}$. |
| RRTS increase. | Significant decrease in $T_{critical}$. |

Based on simulations in the study, researchers recommended the use of certain design methodologies, construction materials, and pavement material properties to help ensure roadway pavements close to streams or in frequently flooded, low-lying areas avoided failure during flooding.[1] For pavements without cracks, researchers recommended properties, such as a finely graded HMA seal, a well-compacted HMA layer, an adequately thickened HMA layer over unbound aggregates, and a protectively geared riprap material. For pavements with cracks, researchers assumed $T_{critical}$ was zero, which implied the pavement had been unserviceable since the commencement of flooding. Additionally, researchers conducted evaluations for a scenario in which insufficient crack-related information was available and estimation of cracking was required. In the cases in this scenario, researchers used parameters, such as global aging system and MAAT, to back-calculate values where pavement property data were insufficient.

### *Preflooding Evaluation Implications*

In a typical pavement with reduced-strength BC, tensile strength when the HMA layer is fully saturated is critical because the bottom of the HMA layer can be in tensile mode. The tensile strengths for different types of HMA layers at various moisture conditioning ranges (and hence, saturation levels) should be determined with varying voids and thicknesses. The research team made the following recommendations for using data appropriately in this type of pavement evaluation: [1]

- Pavements with full base saturation having greater than 90-percent retained tensile strength for HMA layers can be assumed to be in serviceable condition.
- Pavements with 70- to 90-percent retained tensile strength can be considered in fair condition but requiring repairs and should be reopened only for emergency vehicles until repairs can be made.
- Pavements with less than 70-percent tensile strength need emergency repairs involving replacement of BC materials and repaving before any vehicles can be allowed access.

Table 2 contains a recommended preflooding evaluation method for pavements based on general findings; table 3 shows further treatments from the developed tool.

**Table 2. Recommended preflooding evaluation method.[1]**

| Property | Effect on Pavement | Effect on $T_{critical}$ | Treatment, as Applicable |
|---|---|---|---|
| Air voids in HMA. | The higher the air voids, the higher the permeability, which implies faster ingress of water in unbound base, hastening deterioration. | Lowers as air voids increase. | — |
| Time since construction. | Air voids are at their highest immediately after construction and subsequently decrease due to traffic loading-related compaction. | Lowers. | — |
| Cracks in thin HMA layer. | Faster ingress of water occurs i n the underlying, unbound layer. | Lowers. | Age-resistant binders. |
| Cracks in thick HMA layer. | Water is trapped in the HMA for a longer duration, even in the case of short-duration floods. | Lowers. | High retained strength in terms of percentage of dry value and high absolute value of tensile strength.<br><br>Low rate of retained tensile strength (or low slope). |
| Coastal region pavements or pavements in river flood plains. | Pavements are more prone to flooding and are vulnerable to future flooding. | Same as the general case in the study: always between 2 h and 6 h. | — |

—Not applicable.

**Table 3. Recommended preflooding evaluation method from a developed tool.[1]**

| Property | Effect on Pavement | Effect on *Tcritical* | Treatment, as applicable |
|---|---|---|---|
| $T_{flood}$ less than $T_{critical}$ and pavement appears intact with visual examination. | — | — | Minimum required tests to validate pavement layer stiffnesses. |
| $T_{flood}$ more than $T_{critical}$ and pavement appears intact with visual examination. | — | — | Detailed subsurface investigation. |
| Analyses conducted before initial evaluation. | Identify vulnerable stretches/sections of highway. | — | Road improvement and then monitoring. |
| Analyses conducted during initial evaluation. | Check pavement vulnerability. | — | Preventive action.<br>Evaluation of damage potential. |

—Not applicable.

## Postflooding Evaluation

In the study, researchers developed a framework and a tool for helping State agencies make decisions regarding roadway safety, the necessity of repairs, and whether to open roadways to different types of traffic.[1] The guidelines available for evaluating flooded pavements had a major limitation, in that the variation of the strength of the pavement after flooding could not be captured as a function of the drainage of the pavement layers. However, the strength and structural condition of pavement must be determined over time, as well as the fluctuation of the degree of saturation ($s$), to understand whether materials, structural condition, and drainage conditions are sufficient to ensure the pavement has adequate load-bearing capacity. Moreover, if pavement strength is compromised temporarily during or immediately after flooding, all the data described in this subsection can be used to help determine when loading capacity is restored. Using existing test methods, researchers can only ascertain the condition of a pavement by testing in specific conditions—and thus, the fact that pavement strength is a dynamic parameter is not accounted for.

### Approach

The problem was formulated as a combination of two major subject areas: hydraulics and structural analysis. As floodwater drains through pavement layers, moisture content, degree of saturation, and hydraulic conductivity ($K$) decrease with time. As a result, the base layer gains strength, improving the structural capacity. Researchers assumed the base layer was fully saturated as an initial condition and then used an existing procedure formulated by Mallick et al. to estimate the degree of saturation of the base layer.[6] Additionally, researchers used a model to simulate conditions, such as duration and depth of flooding.

To quantify the recovery of postflooding pavement strength, researchers first determined the variation of hydraulic conductivity and saturation with time over the course of floodwater recession. Second, researchers determined the time-versus-strength relationship and estimated predictions of pavement responses to traffic loads. Finally, researchers combined the results of simulations from these first two steps and determined pavement responses for various factors, including different types of vehicles, soils, thicknesses, and drainage conditions.

In this study, researchers used a pavement structure with three layers: an HMA surface layer, an aggregate BC, and a subgrade. Researchers selected surface deflection as the performance indicator and computed the surface deflections for different pavement conditions and loading combinations. Surface deflection is an ideal performance indicator because failure by excessive deflection can be catastrophic and is related to pavement condition.[6,7] Furthermore, pavement condition can be determined relatively easily using a falling weight deflectometer (FWD) without back calculation of moduli. Additionally, researchers carried out structural analysis of pavement response under loading using layered elastic analysis (LEA).

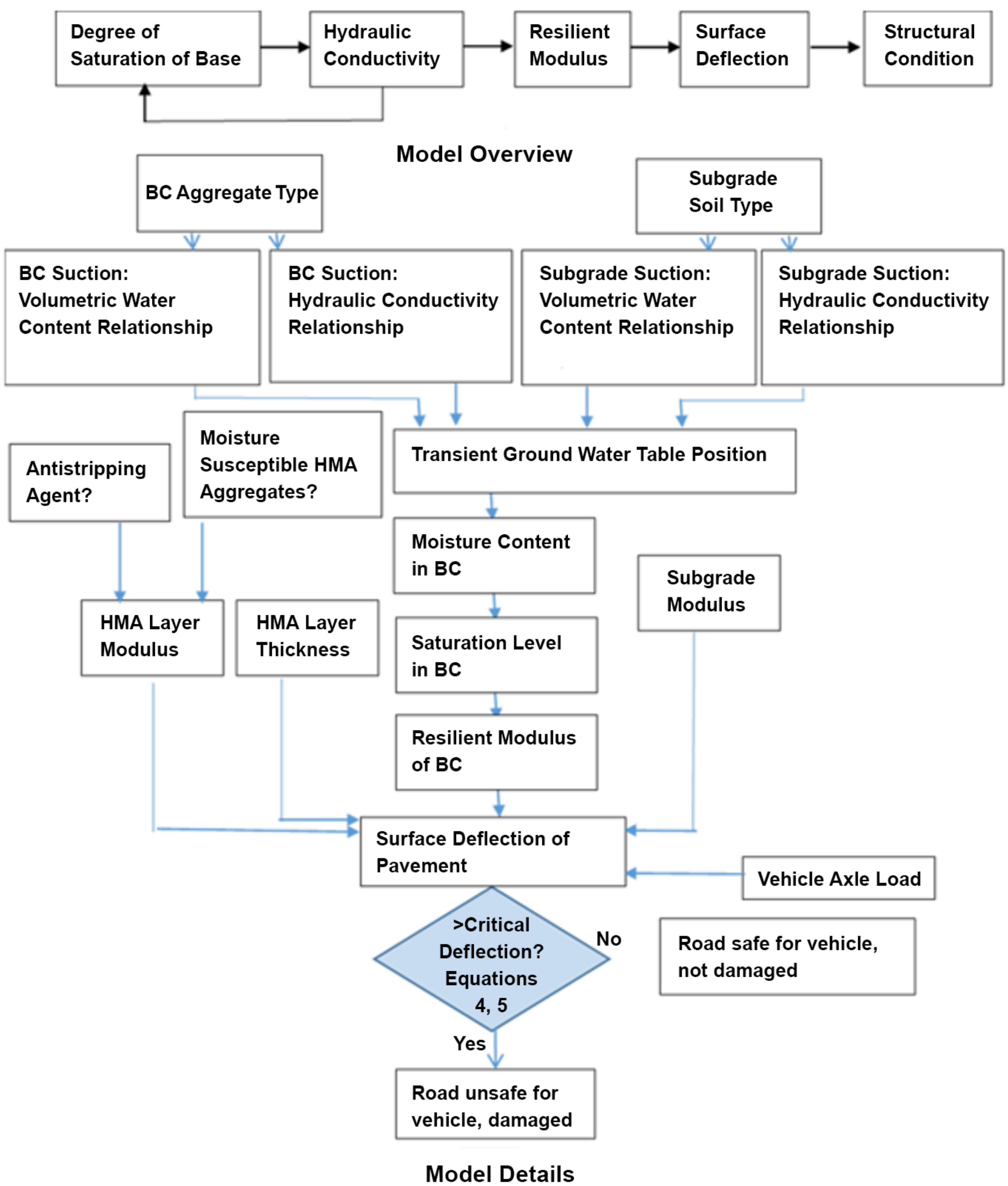
### Model

Researchers combined the results from the structural analyses with the results from the preflooding evaluation using a model.[8] Researchers determined the rate of change for the degree of saturation in the base layer ($dS/dt$) from the hydraulic analysis. The moduli of the base layer were related to saturation level, and the surface deflection was related to the base layer moduli (and the moduli of the other layers). For each 15-min base-saturation value, researchers updated five variables—saturation, base moduli, surface deflection, damage factor (DF), and safety factor (SF)—and obtained the variables' time histories. Figure 3 shows an overview of the approach and expanded details in a flowchart. The postflooding analysis tool is an interactive simulation program that is available online.[9,10]

Researchers carried out parametric studies to evaluate the effects of several key variables on damage and SFs. Simulations ran for 3 w (504 h) after flooding. The following terminology for DF and SF values is used to summarize researchers' observations:[1]

- If SF is greater than 1, the pavement is called "safe."
- If DF is greater than 1, the pavement is called "damaged."
- If DF is greater than 1 for only part of the total simulation time after flooding, the pavement is called "susceptible to damage."

**Figure 3. Flowcharts. Diagram of an overview of the model and the details of the model.[8]**




Source: FHWA.
For equations 4 and 5, see the report.[1]

### *Simulation Outcomes for Postflooding Evaluation*

The simulation's results and outcomes document effects of changes in the variables over the periods since the complete recession of floodwaters (table 4 and table 5).

**Table 4. Simulation results and outcomes—part 1.**

| Parameter | Conditional and Type of Variations With Time | Specific Condition |
|---|---|---|
| Subgrade modulus. | — | — |
| SF. | Yes. | — |
| DF. | Yes. | — |
| Deflection and other related variables. | Change and stabilize after 50 h. | Depends on: <br>• Rate of change of saturation. <br>• Effect of saturation on modulus. |
| Modulus of subgrade less than or equal to 7.25 ksi (50 MPa). | Susceptible to damage. | — |
| Modulus of subgrade more than 17.4 ksi (120 MPa). | Not susceptible to damage. | — |
| Moisture susceptible HMA with thickness less than 8 inches (200 mm). | Susceptible to damage. | — |
| Moisture susceptible HMA with thickness between 1.2 and 2 inches (30 and 50 mm). | Unsafe even after 3 w of flooding. | — |
| BC with thickness less than 24 inches (600 mm). | Likely to be damaged. | — |

—No data.

**Table 5. Simulation results and outcomes—part 2.**

| Parameter | Conditional and Type of Variations With Time | Specific Condition |
|---|---|---|
| BC with thickness between 6 and 8 inches (150 and 500 mm). | Unsafe after 3 w of flooding. | — |
| HMA modulus less than or equal to 145 ksi (1,000 MPa). | Unsafe for about 5 h after floodwater recedes. | — |
| Vehicle load 18,000 to 34,000 lbf (80 to 150 kN) per axle. | Damage 3 w after floodwater recedes. | HMA thickness 1.2–8 inches (30–200 mm); modulus 145–580 ksi (1,000–4,000 MPa).<br>BC thickness 6–24 inches (150–600 mm).<br>Subgrade modulus 1.4–22 ksi (10-150 MPa). |
| Vehicle load 18,000 lbf (80 kN) per axle. | Safe any time after flooding. | |
| Vehicle load 22,500 lbf (100 kN) per axle. | Safe after 20 h. | |
| Vehicle load 27,000 to 33,700 lbf (120 to 150 kN) per axle. | Unsafe even after 3 w. | |
| Antistripping agent. | No significant effect. | — |
| Loam-sand and clay subgrades. | DF below critical and SF above critical. | — |
| Clay performance levels postflooding. | Three times longer than loam-sand to attain same performance levels. | — |

—Not applicable.
lbf = pound-force.

### *Postflooding Evaluation Implications*

For the typical structure considered in this analysis, researchers expected pavement damage under heavy vehicles (i.e., vehicles used for debris removal or other postflooding maintenance activities) due to resulting deflections. To prevent such damage, pavement designers and managers should consider higher structural strength when designing new or rehabilitated pavements. Owners and operators can expect enhanced, premature pavement damage for structures with very poor-quality subgrade, thin BC, and thin HMA layers. Depending on the type of material in the base and subgrade, surface deflection will stabilize with time to a constant value and then decrease slowly. Based on the stabilization time, owners and operators can conduct FWD tests to determine the long-term condition or residual life of the pavement; testing should be completed after a pavement's stabilization date for this purpose. If deflections lead to damage and safety levels beyond acceptable thresholds—even after a sufficiently long stabilization period—then owners and operators must take appropriate actions to repair and rehabilitate the flooded pavement.

Table 6 shows an example of critical times for a selected set of pavements for SFs. The most critical factor is the thickness of the HMA layer (i.e., the SF remains less than 1 even after 3 w). As the table indicates, the SF for pavement with HMA-layer thickness of 1.2 inches (30 mm) remains less than 1 for a period of up to 3 w. Notably, the results are from simulations in which no edge drain was considered; removal of the water through edge drains will lower the saturation level further and lead to an SF greater than 1.

**Table 6. Examples of critical times for an SF less than 1 for five types of pavements and a heavy vehicle load.[1]**

| Pavement Type (Characteristics) | $T_{critical}$ for SF (SF less than 1) (hours) |
|---|---|
| Low subgrade resilient modulus ($M_R$) (1.45 ksi (10 MPa)). | 20 |
| Low HMA layer thickness (1.2 inches (30 mm)). | >504 (3 w) |
| Low base layer thickness (8 in (200 mm)). | 50 |
| Low HMA layer modulus (145 ksi (1,000 MPa)). | 30 |
| High vehicle load (22,500 lbf (100 kN) per axle). | 20 |

Some other findings in this study that are not included in table 6 indicate that the SFs for 1.2- and 2-inch (30- and 50-mm-) thick HMA pavements increase from 0.78 to 0.92 and 0.82 to 0.97 in 3 w.[1] In pavements with HMA thicknesses of 4 and 8 inches (100 and 200 mm), the minimum SF is always either close to 1 or greater than 1 (0.2 for 4-inch (100-mm) thickness and 1.23 for 8-inch (200-mm) thickness). This SF indicates that the safety of pavements with HMA layers with thickness greater than 4 inches (100 mm) is never compromised, even if the base is completely saturated.

The results presented in this study (as examples) are valid only for the default values of the other variables. One recommended use for the framework presented in this study is to develop tables of the critical periods for different types of pavements that highway agencies can use in decisionmaking.

## SUMMARY

This TechBrief first highlights a hydraulics-based preflooding evaluation in which researchers developed a framework to predict the likelihood of damage to a flooded asphalt pavement, given $h_L$ and flood duration, and defined a critical time ($T_{critical}$). Researchers considered this parameter to be a predictor of pavement damage severity and propounded a system dynamics model that links material and layer properties to predict $T_{critical}$ based on the parameter. Researchers developed a Web-based tool for simulations from this model and conducted simulations to analyze the effect of eight variables—flood depth (1 m (3.28 feet) in all cases), base thickness, base density, matric suction, asphalt concrete thickness, gradation, air voids, and changes in retained tensile strength versus time—on $T_{critical}$.[1]

Researchers followed this preflooding analysis with a postflooding evaluation, combining the hydraulic concepts from the preflooding phase with structural analyses. Researchers developed a framework for evaluating the condition of the road after flooding. The basis was to evaluate and monitor the decrease in pavement saturation with time, coupled with gain in strength and stiffness in the postflooding phase. The key parameters included soil-water characteristic-curve variables, such as suction, moisture content, and hydraulic conductivity, and the saturation-versus-resilient-modulus relationship for BC materials. Researchers used LEA to predict pavement responses under different hydraulic conditions. Researchers used the relationship between surface deflection and pavement condition to develop a DF—indicating potential damage—and an SF. Researchers used the results from this framework to create a model and software simulation tool with offline capabilities to assess how pavement parameters changed over time and with the recession of floodwaters.[1]

## RECOMMENDATIONS

The recommendations presented are based on results of the illustrative example outputs from the simulation tool, and not all likely cases have been included. Suggested improvements for the postflooding period are as follows:

- Incorporate realistic conditions, including edge drains and partially blocked edge drains.
- Conduct hydraulic analysis using dynamic water levels.
- Vary soil types for subgrade, and vary other materials for BC and other layers.
- Consider appropriate loss of modulus in HMA (specific to the mix used for initial paving) due to moisture damage.

- Use appropriate relationships between surface deflection and condition for different types of pavements (such as those with and without stabilized base and/or subgrade layer).
- Validate safety and damage conditions, as defined in this study, with in-place data—data from testing flooded pavements, in particular—and update the model.

Additionally, pavement professionals should consider the following:

- Multiple appropriate criteria for evaluation of structural conditions, in addition to surface deflection.
- Different layers, in addition to granular base, such as a subbase.
- Stabilized base or subbase layers.
- Short- and long-term effects of traffic loading on pavements with various structural capacities (various degrees of saturation levels in the BC).

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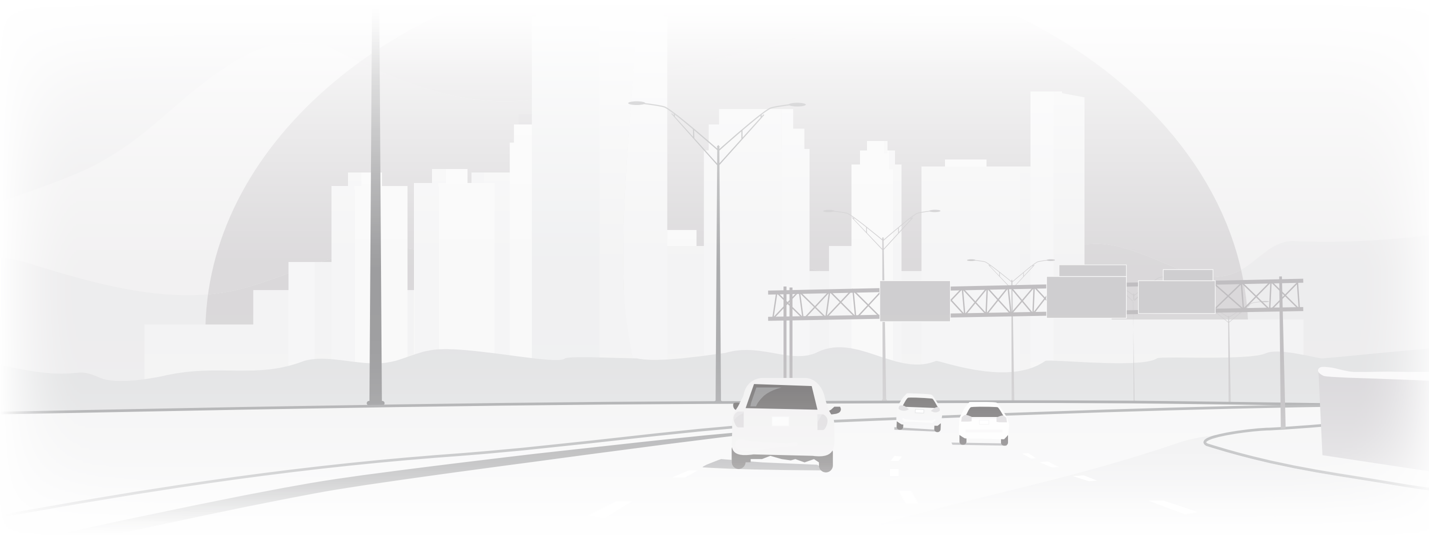

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