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Final Report 615

Best Practice for Assessing Roadway Damages Caused by Flooding

by

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16. Abstract

As a result of a changing climate that is believed to produce more frequent extreme events witnessed in the United States, thousands of roadway lane miles had been inundated in recent years during various storms and hurricanes. Flood-induced damage to roadways is well recognized and documented in both local and national media as well as in the literature. However, the damages to pavement structures that remain visually intact during a flooding event are not well understood, nor is there a guideline for selecting an appropriate engineering tool or procedure to evaluate such structural damage, based on flood characteristics and roadway conditions.

A comprehensive literature review and a national wide questionnaire survey were conducted to identify the best practices for assessing flood-induced roadway damages. The findings indicate: (1) All types of pavements exhibit flood-induced structural damages; however, flexible pavements, particularly those with thin AC layers, are most vulnerable to flood-induced structural damage, relative to rigid and composite pavements; (2) The infiltrated water to unbound pavement layers causes the most damage to the structural loading capacity of flooded roads; (3) The gradation of aggregate base or subbase layers plays a crucial role in defining the resilience of a roadway to flooding by affecting how much time the infiltrated water takes to drain from the flooded roadway; and (4) FWD (falling weight deflectomer), DCP (dynamic cone penetrometer), and GPR (ground penetrating radar) are commonly used in-situ tools for assessing structural damage caused by flooding, with the first sensor deflection, effective structural number, and subgrade resilient modulus as the quantitative indicators.

A holistic framework for evaluating flooding risk is proposed, which considers the degree of hazard (i.e., flooding), vulnerability, and consequence of the flooding of the roadways. A quantitative, composite indicator, risk factor, as a multiplication of hazard factor, vulnerability factor, and consequence factor, can be approximated with storm characteristics, pavement characteristics, and functional class of pavement and traffic volume. A flooding risk map is developed based on the risk fact in a space of criticality factor-consequence factor, which is divided into three different risk zones: high risk zone with a risk factor ranging from 64 to 125; medium risk zone with a risk factor ranging from 27 to 64; and low risk zone with a risk factor smaller than 27. Based on the risk factor, three different levels of engineering procedures are recommended to assess flood-induced damages to roadways:

- Level 1: Hydraulic and pavement performance analyses + Nondestructive testing + Field Reconnaissance (visual inspection-data recording-checking) (for the roadways with High Risk)
- Level 2: Nondestructive testing + Field Reconnaissance (visual inspection-data recording-checking) (for the roadways with Medium Risk)
- Level 3: Field Reconnaissance (visual inspection-data recording-checking) or inferring damage based upon previous engineering studies (for the roadways with Low Risk)

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As a result of a changing climate that is believed to produce more frequent extreme events witnessed in the United States, thousands of roadway lane miles had been inundated in rec years during various storms and hurricanes. Flood-induced damage to roadways is well recognized and documented in both local and national media as well as in the literature. However, the damages to pavement structures that remain visually intact during a flooding event are not well understood, nor is there a guideline for selecting an appropriate engineering tool or procedure to evaluate such structural damage, based on flood characteristics and roadway conditions.

A comprehensive literature review and a national wide questionnaire survey were conducted to identify the best practices for assessing flood-induced roadway damages. The findings indicate: (1) all types of pavements exhibit flood-induced structural damages; however, flexible pavements, particularly those with thin AC (asphalt concrete) layers, are most vulnerable to flood-induced structural damage, relative to rigid and composite pavements; (2) the infiltrated water to unbound pavement layers causes the most damage to the structural loading capacity of flooded roads; (3) the gradation of aggregate base or subbase layers plays a crucial role in defining the resilience of a roadway to flooding by affecting how much time the infiltrated water takes to drain from the flooded roadway; and (4) FWD (falling weight deflectometer), DCP (dynamic cone penetrometer), and GPR (ground penetrating radar) are commonly used in-situ tools for assessing structural damage caused by flooding, with the first sensor deflection, effective structural number, and subgrade resilient modulus as the quantitative indicators.

A holistic framework for evaluating flooding risk is proposed, which considers the degree of hazard (i.e., flooding), vulnerability, and consequence of the flooding of the roadways. A quantitative, composite indicator, risk factor, as a multiplication of hazard factor, vulnerability factors, and consequence factor, can be approximated with storm characteristics, pavement characteristics, and functional class of pavement and traffic volume. A flooding risk map is developed by the research team, on the basis of the risk factor in a space of criticality factor-consequence factor, which is divided into three different risk zones: high risk zone with a risk factor ranging from 64 to 125; medium risk zone with a risk factor ranging from 27 to 64; and low risk zone with a risk factor smaller than 27. Based on the risk factor, three different levels of engineering procedures are recommended to assess flood-induced damages to roadways:

- Level 1: Hydraulic and pavement performance analyses + nondestructive testing + field reconnaissance (visual inspection-data recording-checking) (for the roadways with high risk)
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- Level 3: Field reconnaissance (visual inspection-data recording-checking) or inferring damage based upon previous engineering studies (for the roadways with low risk)

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IMPLEMENTATION STATEMENT

It has been well documented that flooding can cause appreciable structural damage to roadways, which often is undetected from visual inspection and data recording. It is highly recommended that DOTD and local municipalities utilize the composite risk indicator, in combination with flood risk map, to make decisions for long-term planning, immediate post-flood response, and post-flood recovery efforts. In addition, it is beneficial for DOTD and local municipalities to conduct annual or biennial survey of structural capacity of roadways with commonly used in-situ testing devices for providing a benchmark for the before-and-after flooding analysis.

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INTRODUCTION

The United States has witnessed numerous natural disasters in recent years that resulted in the inundation of thousands of roadway lane miles: Hurricanes Harvey, Sandy, and Katrina as well as the unnamed storm in August 2016 in Louisiana, just to name a few (see Figure 1). More recently, Hurricanes Harvey and Irma inundated many streets and roads in Houston and the state of Florida, respectively. Assessing damage to flooded pavements is a challenge that agencies will likely face more often as climatologists predict that the changing climate will produce more frequent extreme events.

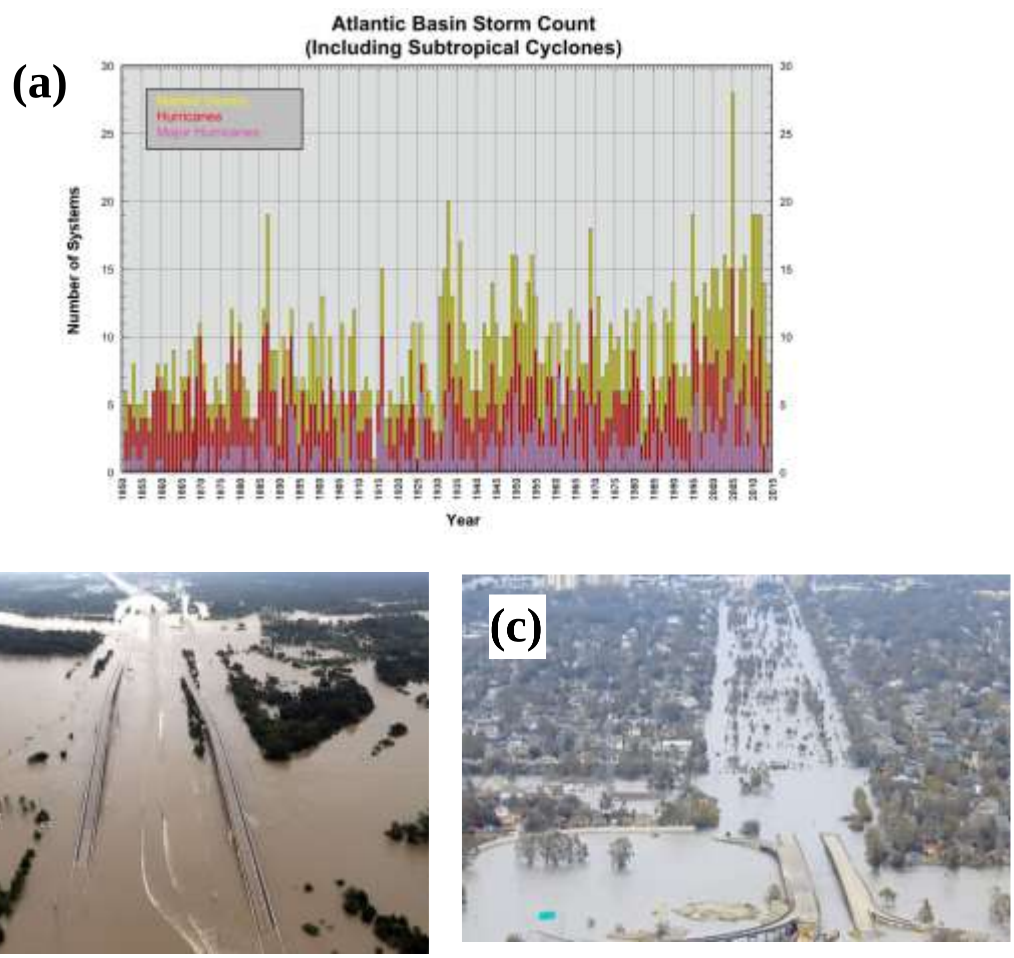

Figure 1
(a) There is a trend towards more tropical storms and hurricanes in the North Atlantic; (b) roadways flooded during Hurricane Harvey, 2017; and (c) roadway flooded during Hurricane Katrina, 2005 *[1-3]*

Over the years, many state and local agencies across the country have used their financial resources to assess and evaluate roadway damages caused by major flooding events with varying degrees of success. There is some guidance for engineers to follow in distinguishing between roadway damage that warrants temporary versus permanent repairs when assessing flooded roadways, but it is primarily based on visual inspection rather than tied to any pavement performance-based properties. A recent survey indicates that more than 90% of the states in the US rely on visual inspection for assessment of damage to flooded pavements, although about 30% conduct nondestructive test also, and about 10% conduct hydraulic analyses [*4*]. For instance, in Louisiana, the Louisiana Transportation Research Center (LTRC) conducted a research project "Impact of Hurricane Katrina on Roadways in the New Orleans Area" on State routes in 2007 [*5, 6*]. In that study, testing protocols were established to assess the damage caused by inundation using pavement engineering techniques and testing equipment commonly used in pavement assessments. Also, the City of New Orleans contracted to conduct a project [*7*], "Quantification of Flood Damage from Hurricane Katrina on the City of New Orleans Pavement Network." In that study, protocols similar to LTRC's research project were used to infer the loss of strength in roadways on the City of New Orleans streets. However, many municipalities, such as smaller cities, towns, villages, and/or parishes (counties) have to assess the roadway damages that occurred during flooding in their jurisdictions but often lack the financial or technical resource to conduct robust engineering studies.

Flooding can cause various degree of damage to roadways, from washing away their structures to indirect damage such as weakening the pavement's strength and stiffness, depending on characteristics of floods and pavement conditions. Flood-induced visual damage to roadways is well recognized and documented in both local and national media as well as in the literature. However, the damages to pavement structures that remain intact (i.e., are not washed out) during a flooding event are not well understood or can go unnoticed. Quite often, flooding results in deterioration or weakening of underlying pavement layers (which could be temporary or long-term), and such damage may not be visible on the surface. The major effect of water is on unbound layers below the bound surface, which is typically hot mix asphalt (HMA) [*5, 8*]. After floodwater has receded, pavement agencies have to make decisions regarding the safety of roadways and the need to repair the flooded pavement, or when to open it to different types of traffic. A severely damaged pavement can cause the surface to fail catastrophically under a relatively heavy vehicle such as a fully loaded truck that is used for removing debris; whereas, a moderately damaged pavement would show signs of structural failure prematurely after the flooding event. Several researchers have underscored the importance of obtaining reliable information regarding flood-induced damage in pavements [*6, 9, 10*]. This is because a wrong decision about after-flooding response can lead to an abrupt shortening of the pavement life and unanticipated repair costs that are most likely not budgeted and potential damage to vehicles. Therefore, it is highly imperative to conduct a study to identify the best practice of assessing flood-induced damages to roadways. The results can help in planning for allocating resources for post-flooding investigative actions and help identify vulnerable sections and allow pre-flood precautions or corrective actions to prevent or minimize damage after flooding.

OBJECTIVES

The major objective of the proposed research was to identify the best practices for assessing roadway damages caused by flooding, through the development of multiple and appropriate levels of roadway damage assessment protocols. A comprehensive literature review and a national survey were conducted to identify the best practices of damage assessment of flooded pavement. In addition, a hierarchical level of flood-induced damage evaluation framework was developed, by holistically considering the characteristics of flood, pavement, and costs associated with damage repairing and mitigation.

SCOPE

This report summarizes the best practices used by local, state, and federal highway agencies to evaluate flood-induced damage to roadways, which were collected through a questionnaire survey and a comprehensive literature review. The composite evaluation indicator, Risk Factor, a combination of hazard, vulnerabilities, and consequence factors, is proposed to take into consideration potential of flooding, structural loading capacity, hydraulic conditions, base material properties, and damage-entailed consequence. On the basis of the Risk Factor, a hierarchical engineering evaluation framework was developed to aid decision makers to conduct an appropriate level of evaluation for a specific flooded pavement. Furthermore, recommendations were made on pre-flood planning and post-flooding response and recovery in order to enhance resilience of roadways against flooding events.

METHODOLOGY

Literature Review

It has been well documented and confirmed in the media and literature that flooding has caused various damages to inundated roadways. A comprehensive literature review was performed by the research team to understand the damaging mechanisms to the roadways during flooding and the best practice for assessing structural damages by various agencies.

Damaging Mechanisms During Flooding

During flooding, structural reduction or damages were observed in inundated roadways, which can occur at different roadway locations, pavement layers, and can be caused by different underlying mechanisms. For example, water can erode underlying unbound granular layers, wash out road sections, damage the bituminous layers, reduce the load bearing capacity of the underlying layers, reduce the support in concrete pavements, or cause a combination of all of these effects. The net result is a roadway structure with a significantly reduced load bearing capacity. Such a reduction in the capacity may persist for a short or long period of time, depending on the amount of water and the time it takes for it to drain out. The visually apparent damage related to flooding includes: erosion or washout of road sections and flood debris obstructions on roads and in bridge or culvert openings [*10*]. However, it is the unseen damage that occurs in pavement underlying layers that causes considerable concern to those who manage roadway assets.

One of the primary causes of structural capacity deterioration is the ingress of water into the roadway underlying unbound granular layers, such as granular base, granular sub-base, and subgrade soils, which results in the increases in degree of saturation or reach its maximum value (i.e., 100%) and thus reduces in strength and stiffness in these layers. Consequently, the loading capacity of the flooded pavement is undermined with the reduced stiffness and strength of these pavement layers during flooding. Subjecting the inundated roadways with weakened structural capacity to traffic loading can result in premature rutting, cracking, a reduction of remaining life, or even local structural failure and the impassability of the roadway. On the other hand, the inundated roadway sections can regain their strength and stiffness as the infiltrated water drains out. However, the time required for an inundated roadway to restore its strength and stiffness can vary widely, ranging from days to years, largely depending on the hydraulic permeability of its underlying layers and other hydraulic conditions. Therefore, it is imperative for road authorities to quantitatively evaluate and predict resilient modulus of pavement layers as a function of degree of saturation during flooding for their flood preparedness and response without causing damage to pavements or undermining their structural capacity.

It has long been recognized that the resilient modulus of unbound granular materials decreases as moisture content increases above its optimal value [*11*]. For example, Haynes and Yoder reported that a 50% decrease in resilient modulus in gravel as the degree of saturation increased from 70 to 97% [*12*]. Over the last few decades, numerous research studies were performed to investigate the relationship between moisture content (or degree of saturation) and resilient modulus of both coarse- and fine-grained soils [*13*-*20*]. There also have been many different correlations developed for predicting the influence of moisture content on resilient modulus. Below is a summary of some of these predictive equations reported in the literature.

Drumm et al. observed that an increase in volumetric moisture content (VMC) of 1.5% or an increase in degree of saturation of 4.75% for some Tennessee soils resulted in a decrease in their resilient modulus by a factor of two (e.g., 130 to 70 MPa) [*13*]. On the basis of the testing results of 11 soils throughout Tennessee, they developed a predictive model relating the change in the resilient modulus of fine-grained soils to the increase in degree of saturation, with its value at the optimal condition as a reference (see equations (1a) and (1b)). A linear relationship model and an empirical equation were proposed for the rate of change of resilient modulus with change of degree of saturation, as a function of AASHTO soil classification and the resilient modulus at the optimal condition.

$$M_{r(wet)} = M_{r(opt)} + \frac{dM_r}{dS}\Delta S \tag{1a}$$

$$\frac{dM_r}{dS} = 1690 - 194(CLASS) - 11.2 M_{r(opt)} \tag{1b}$$

where, $M_{r(wet)}$ = resilient modulus at increased post-compaction saturation; dM_r/dS = gradient of resilient modulus with respect to saturation, or the slope of M_r versus degree of saturation curve; and ΔS = change in post-compaction degree of saturation expressed as a decimal. $CLASS$ = AASHTO classification, expressed as a real number (e.g., for A-4, $CLASS$ = 4.0; for A-7-5, $CLASS$ =7.5); and $M_{r(opt)}$ = resilient modulus (MPa) at optimum moisture content and maximum dry density for $\sigma_c = 41\,kPa\ (6\ psi)$ and $\sigma_d = 28\,kPa\ (4\ psi)$.

A sigmoid model was developed by Arizona State University research team and implemented in MEPDG (Mechanistic-Empirical Pavement Design Guide) software for both fine-grained and coarse-grained soils to estimate the effect of change in degree of saturation on their resilient modulus, which is provided below [*14*]:

$$log\frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1+exp\left(\beta+k_s\cdot(S-S_{opt})\right)} \quad (2)$$

where M_R/M_{Ropt}= resilient modulus ratio; M_R= resilient modulus at a given degree of saturation; M_{Ropt}= resilient modulus at optimum moisture content and maximum dry density; a = the minimum of $log\left(M_R/M_{Ropt}\right)$; b = the maximum of $log\left(M_R/M_{Ropt}\right)$; β= location parameter that is obtained as a function of a and b by imposing the condition of a zero intercept: $\beta = ln(-b/a)$; regression parameter; $S - S_{opt}$= variation of degree of saturation in decimal. The resilient modulus predicted using the aforementioned model is only a function of the degree of saturation while the direct effect of the state of stress (or effective stress) is not considered. The fitting parameters for the model, along with their recommended values, are summarized in Table 1.

Table 1
Fitting parameters and their recommended values for the sigmoid model of coarse- and fine-grained soils [*15*]

Parameter	Coarse-grained soils	Fine-grained soils
a	-0.3123	-0.5934
b	0.3	0.4
β	-0.0401	-0.3944
k_s	6.8157	6.1324

Based on the effective stress concept for unsaturated soils, several research groups proposed different stress-matric suction models to indirectly consider the influence of change in moisture content (or degree of saturation) on resilient modulus, with their respective models listed in Table 2. Note that although the stress-matric suction model is based on a more theoretically sound framework, it requires additional information on the relationship between moisture content and matric suction, that is, soil water characteristic curve (SWCC).

Table 2

Summary of predictive equations relating resilient modulus of unbound geomaterials with their moisture content

Author	Year	Model	Parameters
		Models with Saturation Effects	
Drumm et al. [*13*]	1997	$M_{r(wet)} = M_{r(opt)} + \frac{dM_r}{dS} \Delta S$ $\frac{dM_r}{dS} = 1690 - 194(CLASS) - 11.2M_{r(opt)}$	$M_{r(wet)}$ = wet resilient modulus $M_{r(opt)}$ = resilient modulus at optimum moisture content dM_r/dS = gradient of resilient modulus ΔS = change in degree of saturation $CLASS$ = AASHTO classification
Ceratti et al. [*15*]	2004	$M_R = 142 + 16.9(u_a - u_w)$	$(u_a - u_w)$ = matric suction
MEPDG model [*14*]		$log \frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1 + exp\left(\beta + k_s \cdot (S - S_{opt})\right)}$	M_{Ropt} = resilient modulus at optimum moisture content a, b, β = fitting parameters $S - S_{opt}$ = variation of degree of saturation in decimal; k_s = gradient of log resilient modulus ratio to change in degree of saturation
Yang et al.[*17*]	2005	$M_R = k_5(\sigma_d + \chi(u_a - u_w))^{k_6}$	k_5, k_6 = fitting parameter σ_d = deviator stress $(u_a - u_w)$ = matric suction χ = saturation function
Liang et al. [*16*]	2008	$M_R = k_1 p_a \left(\frac{\theta + \chi_w \psi_m}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$	K_1, k_2, k_3 = fitting parameters ψ_m = matric suction χ_w = Bishop's effective stress parameter Pa = atmospheric pressure
Gupta et al. [*19*]	2007	$M_R = k_1 p_a \left(\frac{\theta - 3k_6}{p_a}\right)^{k_2} \left(\frac{\tau}{p_a} + k_7\right)^{k_3} + \alpha_1 (u_a - u_w)^{\beta_1}$	k_1, k_2, k_3, k_6, k_7, α_1, β_1 = fitting parameters $(u_a - u_w)$ = matric suction

Author	Year	Model	Parameters
Cary and Zapata [18]	2010	$$M_R = k'_1 p_a \left(\frac{\theta_{net} - 3\Delta u_{w-sat}}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k'_3} + \left(\frac{(\psi_{m0} - \Delta\psi_m)}{p_a} + 1\right)^{k'_4}$$	K'1, k'2, k'3 , k'4 = fitting parameter Δu_{w-sat}: pore pressure build up under saturation condition θ_{net} = net bulk stress ψ_{m0} = initial matric suction $\Delta\psi_m$ = suction change due to pore pressure build up in unsaturated condition
		Models with Saturation Hysteresis Effects	
Khoury et al.[20]	2011	$$M_R = \left[\left(k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}\right) + (\psi - \psi_0)\left(\frac{\theta_d}{\theta_s}\right)^{\frac{m}{a}}\right]\left(\frac{\theta_d}{\theta_w}\right)$$	k_1, k_2, k_3 = fitting parameters Pa = atmospheric pressure Θ = bulk stress τ_{oct} = octahedral shear stress θ_d = volumetric water content along drying θ_w = volumetric water content along wetting corresponding the same suction as in θ_d ψ_0 = initial matric suction ψ = matric suction m relates to soil's residual water content a relates to soil's AEV

Hydraulic Analysis on Water Movement in Flooded Roadway Structures

During a flooding, it is imperative for road authorities to have the knowledge of the temporal variation of structural loading capacity of inundated roadways in making rational decisions regarding immediate response and post-flooding recovery strategy. As reviewed in the preceding sections, moisture content of unbound granular layers plays an important role in their resilient modulus and thus affects the structural capacity of the roadway. Therefore, it is important to conduct hydraulic analysis of inundated roadways for predicting the degree of saturation or moisture content of their underlying layers during flooding. Literature studies on predicting water movement in pavement structures through numerical simulations were reviewed and summarized in the following sections.

Stormont and Zhou performed hydraulic analysis on a generic pavement section (shown in Figure 2) using an open-source software package (VS2DHI) [*21*]. The pavement model consists of a 3.6-m wide pavement section, a 1-m wide shoulder and a surface water drainage ditch, was a generic pavement section with a drainage system according to conventional design guidance. VS2DH is a finite difference model that solves Richard's equation for flow in one or two dimensions, under both unsaturated and saturated flow conditions.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z}\left[K(\theta)\left(\frac{\partial \varphi}{\partial z} + 1\right)\right] \qquad (3)$$

where, θ= volumetric water content; $K(\theta)$= unsaturated hydraulic conductivity as a function of soils' water content; φ= suction of the soil; t = time; and z = vertical coordinate taken positive downward.

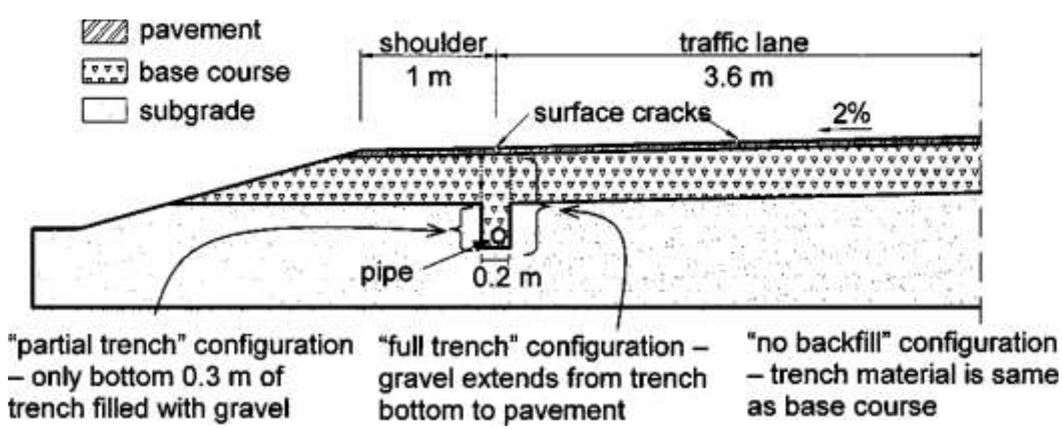

Figure 2
Configuration of modeled pavement section [*21*]

Their simulation results indicate that: (1) realistic hydraulic analysis of roadways should consider unsaturated flow since it is the dominant flow pattern of the water movement in the pavement section from the surface infiltration; (2) the drainage efficiency depends on the base course, edgedrain configurations, and trench backfill materials; and (3) it is necessary to design for unsaturated flow in order to achieve great drainage efficiency of roadways.

Ariza and Birgisson first verified the capacity of SEEP/W to model unsaturated flow through layered systems such as pavements under complex boundaries, by comparing with the results from three laboratory and analytical experiments reported in the literatures [*22*]. The authors then used SEEP/W and FHWA DRIP software to analyze data collected at the Minnesota Road Research project (Mn/ROAD Cell 33, Cell 34, and Cell 35). SEEP/W is a commercial finite element CAD software package for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock [*23*]. DRIP is a windows-based program developed by Federal Highway Administration (FHWA) for pavement infiltration and drainage analyses [*24*]. It calculates the time to drain in the drainage layer of a pavement based on simple analytical prediction methods and under the assumption of saturated flows in the pavement [*25, 26*]. Therefore, DRIP is unable to consider unsaturated conductivity characteristics of pavement layers or simulate unsaturated flow that is believed to be the dominant flow patterns in pavement systems.

These pavement sections consist of a layer of hot mix asphalt, a Mn/DOT Class 6 Special base course, consisting of 100% crushed granite, an R-12 silty clay subgrade. Figure 3 shows the thickness of each of base and hot mix asphalt layers for Cells 33-35 while the pavement configuration at these sections is shown in Figure 4. The authors compared the time-to-drain, which is the time required to drain a certain amount of water out of a pavement, predicted by SEEP/W and DRIP in unsaturated and saturated conditions, respectively. Two drainage levels often used are the time to drain 50 and 90% of the water out of the pavement. Their simulation results indicated that most modeled materials would drain under saturated conditions in just a few minutes while it would take days or is unachievable under unsaturated conditions. Their study also indicated that SWCC, hydraulic conductivity curve, and air entry potential of pavement materials, play important roles in governing flows throughout pavement systems.

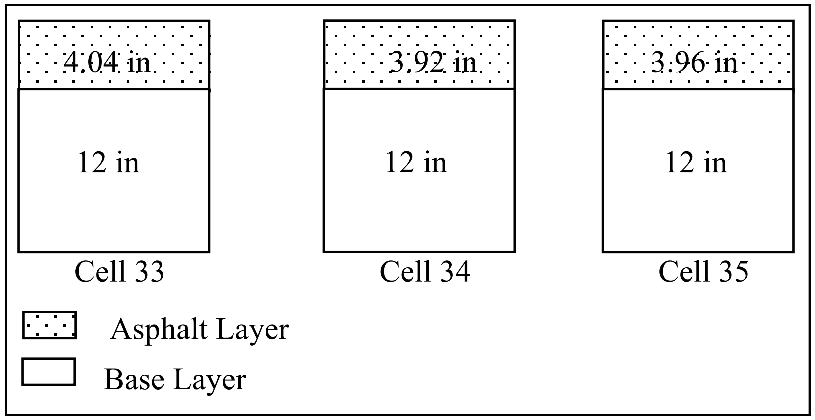

Figure 3
Thickness of base and hot mix asphalt layers for Mn/ROAD Cells 33-35 [*22*]

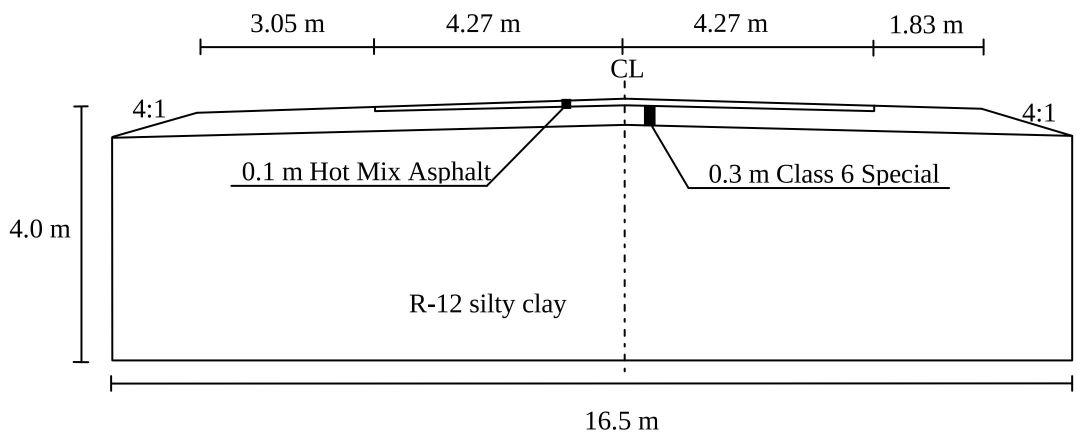

Figure 4
Pavement geometry and dimensions for Cells 33, 34, and 35 [*22*]

Hasson et al. investigated the feasibility of using HYDRUS-2D in predicting unsaturated flow paths in pavements, with a focus on the following three specific processes: (1) the surface runoff followed by infiltration through an asphalt fracture zone; (2) the surface runoff with subsequent infiltration in the embankment; and (3) capillary barrier effects between layers within the road [*27*]. In addition, they also examined the influence of variations in precipitation and fracture conductivity on the above processes. HYDRUS-2D is capable of simulating the movement of water, heat, and multiple solutes in variably saturated media. The model includes a parameter optimization algorithm for inverse estimation of a variety of soil hydraulic and/or solute transport parameters.

The pavement section used in their simulations was a multilayered flexible pavement often used in Sweden (Figure 5). HYDRUS-2D does not explicitly consider fractures that are often developed in surface asphalt layer and are the main pathways for water infiltrating into pavement structures. However, the program can practically take into account the facture effect based on the concept of the effective hydraulic conductivity of a facture zone and the parallel plate model proposed by Freeze and Cherry [*28*]. Hasson et al. confirmed that HYDRUS-2D is mostly appropriate in predicting the above processes anticipated during the infiltration of surface runoff throughout pavement systems [*27*]. They also pointed out that numerical difficulties might arise largely due to the strongly nonlinear hydraulic properties of the coarse materials.

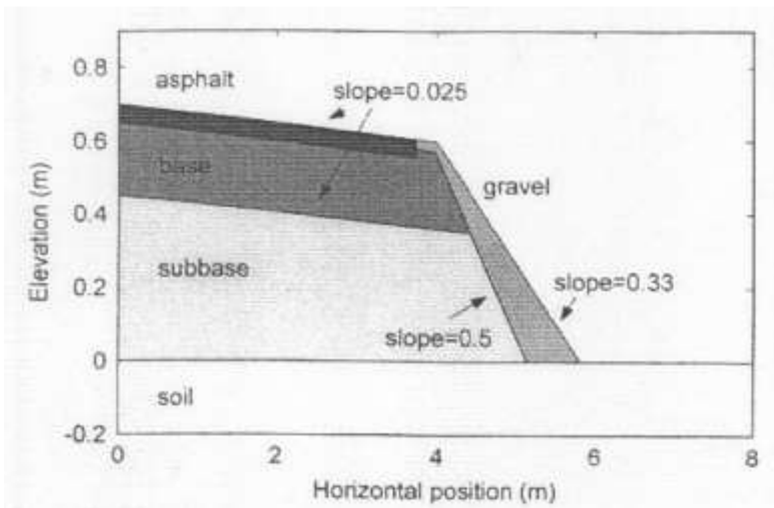

Figure 5

Cross-section of the modeled pavement section [*27*]

Techniques and Methods Used to Evaluate Flood-induced Roadway Damage

During Hurricane Katrina in August 2005, approximately 2,000 miles of roadways in the Greater New Orleans area were inundated for up to 5 weeks, including 500 miles of the federal-aid highway systems and 1,500 miles local routes [*5*, *6*]. A research study was conducted to assess the flooding-induced structural damage to the inundated roadways in New Orleans, St. Bernard, and Jefferson parishes, using several commonly used pavement assessment devices, including Falling Weight Deflectometer (FWD), Dynaflect, ground penetrating radar (GPR), and dynamic cone penetrometer (DCP). In addition, sample coring was performed to determine the type and thickness of the pavement and base layer and to validate GPR readings. Because there was lack of “before and after” data of flooding structural conditions for most of the inundated roadways, FWD testing results were compared and contrasted among the testing locations on the basis of flooding vs. nonflooding, short vs. longer flooding durations, shallow flooding vs. deep flooding, and thick vs. thin pavement sections, with the aid of a geographical information system and flood maps made available through NOAA and FEMA (Federal Emergence Management Agency).

For LA 46 with a composite pavement configuration where “before and after” flooding structural condition data were available, the flooding water-induced structural damage was equivalent to approximately 3 in. of AC. For the other routes in the flooded area, a statistical network analysis indicated that: (1) all the submerged pavements, regardless of pavement types, were weaker than their non-submerged counterparts, on the basis of the first sensor deflection (D_1), effective structural number (SN_{eff}), and subgrade resilient modulus (M_r); (2) the overall average strength loss for asphalt pavements was found to be equivalent to 2 inches of AC, which was attributed to the reduce in the stiffness of both the AC layer and subgrade; (3) for a Portland Cement Concrete (PCC) pavement, thicker pavements had no loss of strength, although in some cases voids at joints and loss of joint transfer efficiencies were observed. The thinner (<270 mm) PCC pavements had an average structural loss of 0.43 in. and 0.47 in. in terms of the equivalent thickness of AC layer, for pavement and subgrade, respectively; (4) although no conclusion could be drawn with respect to flooding damage on composite pavement due to the variety of pavement structure, composition, and materials in that group, composite pavements had twice as much subgrade structural loss, equivalent to 0.9 in. of AC; and (5) thinner pavements that are under jurisdiction of local municipalities were most vulnerable to flooding-induced structural damages, compared to their thicker, more robust counterparts.

In a separate study after Hurricanes Katrina and Rita, Helali et al. assessed flood-induced damage to pavements and roadways in Jefferson Parish, by comparing “before and after” functional and structural data, with extensive field-testing to evaluate roughness, distresses, deflection, and coring/boring, as well as with the aid of the historical data in pavement management system [*9*]. The authors performed damage analysis at three different spatial levels: the network level, the section level, and the roadway level.

The comparison based on the functional analysis indicates that the flooded roadway sections were on average significantly worse than the non-flooded counterparts at 95% confidence level, with the more pronounced weakening observed in flooded asphalt pavement than PCC pavement sections. Similarly, the structural analysis indicates that the flooded roadway sections suffered from different extent of reduction in their structural capacity, from higher deflection values or reduced effective structural numbers, relative to the nonflooded roadway sections. In addition, Helali et al. pointed out that: (1) it is important to have the historical pavement condition data, especially the structural data, because it provides a benchmark in the assessment of flood-induced damage through the before-and-after forensic analysis; and (2) the road network inventory, including the road network definition, road sections location information, geometry information, jurisdiction information, information (functional class) information, and as-built data, is also essential for the structural back-calculation analysis and for preparing the claims made to FEMA federal emergency programs [*9*].

Vennapusa et al. carried out a study to evaluate flooding-induced damage to roadways with gravel (unpaved), AC, chip sealed, and PCC surfaces in western Iowa after the 2011 Missouri River flooding, using the combination of visual inspection, destructive and non-destructive techniques, including FWD, DCP, GPR, 3-D laser scanning, and hand auger borings [*10*].

Voids were formed at both shallow and deep depths of both asphalt and PCC pavement sections due to the erosion of underlying base and subsurface materials while erosion of gravel surface was observed for unpaved roadways. On gravel roads, FWD testing results indicated that the flooded sections were significantly weaker than the non-flooded ones upon the statistical analysis. In addition, significant rutting up to 4.9 in. was observed in some locations of the unpaved roadways, whose subgrade had California bearing ratio (CBR) readings of less than two derived from DCP testing that was likely contributed to the rutting.

On the one tested AC pavement that consists of 14 in. AC layer and 12 in. base layer, FWD testing results also indicate that it suffered from structural damage during the flooding, based on the fact that: (1) FWD-based moduli of the AC and subgrade were approximately 1.35 times higher in the non-flooded area as compared to the flooded area 6 months after the flooding event; and (2) CBR values in the subgrade were around 10 times higher in the non-flooded areas relative the flood area. For the only one PCC pavement that was evaluated, it was subjected to fast water flows that caused the erosion of the base course and embankment beneath the pavement. Longitudinal cracks were observed in some panels where the base course was weakened due to erosion. Another important finding is that both unpaved and asphalt pavement sections showed recovery of the weakened structural capacity post the flooding, based on FWD testing results that show insignificant difference between some flooded areas and their respective non-flooded counterparts several months after the flooding. In addition, the authors provided a catalog of different available evaluation and assessment techniques and a framework for the selection of assessment and mitigation techniques.

In order to enhance flooding resilience of roadways in Queensland, Australia, Khan et al. have developed road deterioration (RD) models that are related to flooding characteristics (probability or return period, period of flooding), flood-induced loss of subgrade resilient modulus, to pavement performance indicators (e.g., rutting and IRI) [*29*-*31*]. Their models predicted that PCC and robust asphalt pavements are the most flood resilient, which qualitatively agree with the findings in the literature. However, given that it is already technically challenging to predict the pavement deterioration in terms of IRI or rutting without considering the detrimental effect of flooding, it is even harder to develop a robust quantitative RD model with the flooding effect.

Some deterministic RD models were also proposed to relate pavement performance indicators (e.g., rutting and IRI) to characteristics of pavement sections and climatic conditions, with the aim of predicting the influence of flooding on the functional performance of roadways [*32*-*34*].

Sultana et al. present the effects of flood on the structural performance of pavements after floods occurred in 2010 and 2011 in Southeast Queensland, Australia [*33*]. Their study indicated a consistent trend with increased FWD deflection and reduced structural strength immediately after the flood events, with the reduction of structural numbers in different pavement sections ranging from 1.5% to 50%. Sultana et al. developed a model for predicting post-flood short-term structural condition of flexible pavements, on the basis of their work with southeast Queensland roadways in Australia that were flooded extensively in 2011 [*34*]. The model was presented as a ratio of the post and pre-flood Modified Structural Number (SNC) that considers the structural capacity contribution from subgrade layer, as follows,

$$SNC_{ratio f} = 1.032 - 0.034 * \exp^{(t/21.5)}, \quad (4)$$

where, t = time after flooding, upto 42 days.

However, the model does not include parameters relating to pavement configurations or properties of pavement layers; its applicability is limited to the pavement sections on which it was developed. Other limitations of the model include: (1) its incapability of reflecting which pavement sublayer contributes most to the structural capacity loss during the flooding; and (2) its incapability of considering the post-flooding recovery of lost structural capacity, as confirmed by the Iowa study by Vennapusa et al. [*10*].

Wang et al. estimated the loss of flexible pavement life caused by the reduced subgrade resilient modulus during flooding [*35*]. Based on the mechanistic empirical pavement design method transfer functions, they estimated the damage due to a reduction in allowable traffic under saturated subgrade conditions. The loss of service life in days was quantified with a ratio of allowable traffic under normal conditions to that when the subgrade is highly saturated after flooding. Their simulation results indicated that a flood event can cause a damage in an asphalt pavement with 80 mm of hot-mix asphalt (HMA) layer that is equivalent to an additional 32 days of damage by traffic under normal conditions.

Mallick et al. developed a system dynamics based model to evaluate the vulnerability of asphalt pavements to flooding, on the basis of the time required for unbound base layer to reach full saturation and the time for the bound surface layer to fail by tension [*36*]. The simulations showed that impermeable surfaces and thicker layers make pavements more resilient to flooding. The web-based simulation tool that is freely available to the public at http://goo.gl/1esRKC, can aid the decision makers in selecting the most appropriate post-flooding response that is required to evaluate potential structural damage by the flooding. In addition, the tool can help the users to identify most vulnerable sections of roadways prior to flooding and either take proactive action to strength them or perform in-situ pavement condition testing annually that can be used for "before-and-after" flooding analysis for future flooding events.

Mallick et al. presented a framework and a tool for estimating the structural condition of pavements after flooding by using a combined hydraulic and structural analysis [*37*]. They estimated the flow conditions through the underlying layers, utilized the hydraulic conductivity to estimate the degree of saturation of the base layer at different times, and finally used the resilient modulus-saturation relationships to predict the overall structural capacity of the pavement in terms of predicted deflection under various types of loads. Their results showed a reduction capacity to different extents and for different periods of time, depending on the hydraulic conductivities of the underlying layers. The tool can be utilized by road authorities to predict the condition of roads after flooding and make appropriate decisions regarding opening it, posting load restrictions or closing and testing it for evaluation of structural damage.

Elshaer et al. have conducted parametric studies to evaluate the load bearing capacity of inundated pavements using multi-layer elastic analysis [*38*]. The weakened structural capacity of inundated roadway sections was simulated through the relationship between degree of saturation and resilient modulus of unbound material layers with matric suction as an intermediary variable. The pavement response was quantified with the maximum surface deflection, horizontal strain at the bottom of asphalt layer, and vertical strain at the top of subgrade layer, under different moisture conditions ranging from unsaturated to fully saturated condition, by manually varying ground water level. Variable considered in their numerical parametric study include three different asphalt pavement sections (thin, intermediate, and thick) and three different types of subgrade soils (A-2-4, A-4, and A-7-5). The results of their simulations showed a significant decrease in the structural capacity of pavements during the time when the base and subgrade layers are fully saturated and the inundated roadway sections can regain structural loading capacity after flooding water recedes. Since the authors controlled the moisture content of unbound material layers by manually lowering ground water level without performing hydraulic analysis, the simulation cannot predict the temporal variation of moisture contents in unbound material layers after the flooding water recedes.

Qiao et al. developed a Bayesian Decision Trees based approach for making decisions to open or close a road after flooding, on the basis of probabilities and assumed risks and payoffs for specific events [*39*]. Their tool could be utilized by road authorities to consider different options such as conduct hydraulic analysis or nondestructive testing of pavement after flooding, compare the relative merits and demerits and then select the option with the most payoff potential. The approach is based on minimizing the risk of opening the road when it is in a damaged or unsafe condition or closing the road when it is in an undamaged condition, based on visual inspection only. Users can modify the tool on the basis of their confidence levels and risks for the use of specific techniques for the evaluation of pavements – such as visual, hydraulic or nondestructive testing.

Nivedya et al. developed a framework for quantitatively assessing the resilience of flexible pavements to flooding [*40*]. The different interlinked steps consist of utilizing unsaturated flow through the different layers to estimate drainage, interpretation of the results in terms of stiffness of the relevant layers, estimation of the impact of the change in stiffness on the overall structural condition of the pavement and then translating that change to a resilience index. The paper provides an illustrative example of such an estimation of resilience for a pavement. The results demonstrate the need for providing base course materials with appropriate gradation to ensure adequate hydraulic conductivity, and/or thicker surface layer, to avoid a reduction in service quality and loss of resilience for an extended period of time, in flood-prone areas.

Questionnaire Survey

The research team conducted a national questionnaire survey to discover which agencies [federal, state, city, or counties] have conducted and completed engineering studies to assess and determine the damages caused by roadway submergence. A copy of the questionnaire survey is included as an Appendix.

Engineering Protocol Levels for Assessing Flood-induced Damage

Some road sections are more vulnerable to the effects of flooding than others, due to the high likelihood of flooding, unfavorable hydraulic conditions, pavement structure, material type, drainage, and surface permeability. In addition, the consequence of flood-induced damages to different roadways depends on the traffic volume, the class of roadways, and the costs and traffic delay associated with flood-induced damages and their repair.

Therefore, it is logical to utilize evaluation methods for flood-induced damage to roadways at a level that is commensurate with the corresponding degree of hazard (i.e., flood in this case), vulnerability, and consequence. A composite evaluation indicator, Risk Factor (RF), which is a combination of hazard, vulnerabilities, and consequence factors (given in equation (5)) was used to rank the relative risk associated with flood of various roadways from a holistic point of view *[41]*. Hazard, vulnerability, criticality factor (the product of hazard and vulnerability factors), and consequence factors associated with flood-induced damage, as well as the corresponding criteria for determining their numerical values, are described in the following sub-sections. The RF can be used to guide highway agencies and decision makers for the selection of appropriate level of engineering evaluation of flood-induced damage for a given roadway, as illustrated schematically in Figure 6.

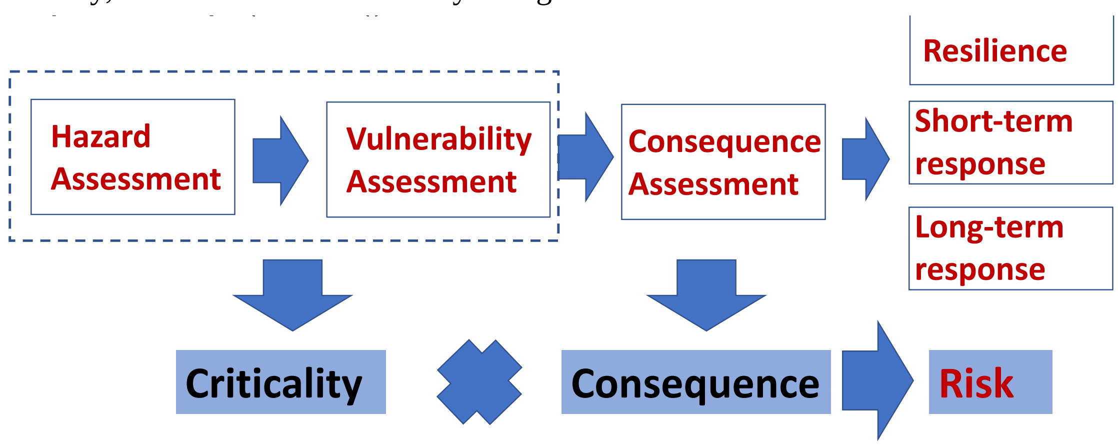

Figure 6

Flowchart illustrating that the composite indicator, Risk Factor as a multiplication of hazard, vulnerability, and consequence factors, is proposed to evaluate flooding risk for pavements

$$RF = Harzard\ Factor\ \times\ Vulnerability\ Factor\ \times\ Consequence\ Factor \qquad (5)$$

Each of the above factors and how its values are determined are explained in the following sections. Note: The variables and methods in equation (5) should be considered theoretical and in need of validation with subsequent refinements from actual inundation events prior to being considered for adoption by any agency.

<u>**A hazard factor**</u> is a qualitative score used to quantify a hazard, taking into account both its probability and magnitude. For the case of flood, its hazard factor depends on such characteristics as flood intensity, duration and conditions of ponding water (e.g., depth and duration). In hydrology, the peak discharge, which is the peak volume of water per unit time passing a specific point on a stream, is often used to quantify the size of a flood and thus governs the extent of the floodplain to be inundated. Flood discharges for a given stream are collected over a long time period to predict the recurrence intervals, flood probability, and flooding risk (see Figure 7). For example, a 100-year flood for a stream means that the flood of certain size (or corresponding to a given peak discharge) has a recurrence interval of 100 years or has a 1% chance of happening in any year. Therefore, it is logical to approximate hazard factor of a flood based on its size or its recurrence interval. Table 3 summarizes the recommended criteria for determining hazard factor of floods, ranging from 1(the least severe hazard) to 5 (the most severe hazard). As expected, the larger the size of a flood, more of the floodplain is likely to be inundated and thus higher is the hazard factor.

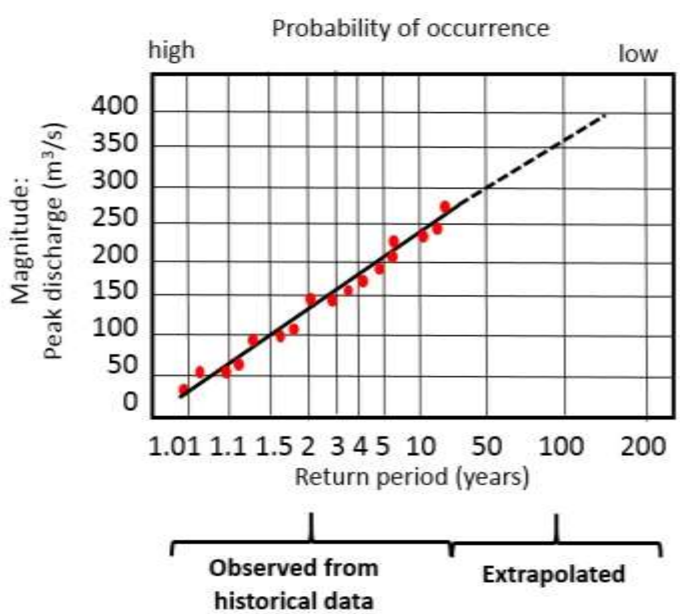

Figure 7

An example of relationship between peak discharge and recurrence interval of floods for a given stream [*42*]

Table 3
Criteria and typical indicator and their values for quantifying risk of floods

Flood characteristics	Hazard factor
100-year flood	5
50-year flood	3
10-year flood	1

A vulnerability factor is a score for quantifying the sensitivity to a specific source of risk (i.e., hazard) that can induce an event with a consequence. The location, topographic, structural, hydraulic, and hydrological conditions of a roadway largely govern its flood vulnerability. Such factors include its elevation, the thickness and condition of surface layer, water sensitivity of unbound layers, and drainage conditions largely govern its flood vulnerability. Two types of flooding vulnerability of a roadway section were considered in this study: (1) the vulnerability of a roadway section being flooded during a given storm, which largely depends on the location, topographic and hydrological conditions of the roadway, as well as the characteristics of floods (i.e., the size of a flood), which is denoted as vulnerability factor 1 (VF1); and (2) the vulnerability of a flooded roadway section in terms of the likelihood of deterioration of its structural loading capacity caused by the flooding, which is related to structural, drainage, subgrade, and surface layer conditions of the roadway; this vulnerability factor is denoted as vulnerability factor 2 (VF2). Under a given storm, whether a specific roadway section is either to be inundated or not, depends largely on its location, elevation, and proximity to water bodies. Consequently, VF1 is of binary nature and thus has a value of either 1 (being inundated) or 0 (not being inundated), under a given size of flood. VF2 is related to how water infiltrates into roadway, the deteriorating effect of moisture increase on the structural loading capacity of the roadway, and the process of recovery of the reduced strength and stiffness of the roadway after the flooding. Thus, it largely depends on the following factors: existing cracks of the pavement surface that govern the ease of water infiltrating into pavement structure, thickness of bonded pavement layers that reflects its structural loading capacity, subgrade conditions that determine whether a subgrade is sensitive to the increase of moisture content, and drainage conditions of base layer that govern how fast the infiltrated water can drain out of the flooded pavement and hence affects the strength recovery of the pavement after the flooding.

The overall vulnerability factor (VF) of a roadway section is the product of VF1 and VF2, while VF2 is the weighted sum of the above parameters, with the value for each of them ranging from 1 to 5.

$$VF = VF_1 \times VF_2 = \begin{cases} VF_2 = w_{EC}EC + w_{ST}ST + w_{SG}SG + w_D D, & VF_1 = 1 \\ 0, & VF_1 = 0 \end{cases} \tag{6}$$

where, VF is the overall vulnerability factor; VF_1 is the vulnerability factor of a roadway section related to whether the roadway is to be flooded or not during a given storm; VF_2 is the vulnerability factor quantifying the extent of deterioration effect of strength and modulus of a flooded roadway caused by flooding; EC is the parameter related to the existing cracks of the surface of the roadway that governs the rate at which water infiltrates into the roadway; w_{EC} is the weighting factor of existing crack; ST is the parameter related to the structural capacity of the roadway, whose value depends on the thickness of bound layer; w_{ST} is the weight factor of ST; SG is the parameter related to subgrade conditions of the roadway that reflects the sensitivity of subgrade layer's resilient modulus to the increase in moisture content due to flooding; w_{SG} is the weighting factor of SG; D is the parameter related to drainage conditions of the roadway, which is approximated by the hydraulic permeability of the base layer of the roadway; and w_D is the weighting factor of drainage parameter (D). Note that the sum of the above weighting factors is equal to one.

The numerical value of VF_1 can be determined with the aid of various flooding risk map, including FEMA flooding map provided by FEMA Flood Map Service Center (https://msc.fema.gov/portal/search?AddressQuery=baton%20rouge#searchresultsanchor), NOAA's Coastal Flood Hazard Composite Map Service (http://www.arcgis.com/home/webmap/viewer.html?url=https%3A%2F%2Fmaps.coast.noaa.gov%3A443%2Farcgis%2Frest%2Fservices%2FFloodExposureMapper%2FCFEM_CoastalFloodHazardComposite%2FMapServer&source=sd), and state or local resources such as LSU AgCenter Flood Maps (http://maps.lsuagcenter.com/floodmaps/). For a given size of flood, whether a particular roadway segment is inundated or not can readily be determined by referring to one of the above maps. The value of VF_1 is either 1 for the case of being inundated or 0 for the case of not being inundated. For instance, a section of Interstate I10 in East Baton Rouge Parish, as marked with a red rectangle in the flooding map of Figure 8, is expected to be flooded in the event of a 100-year storm.

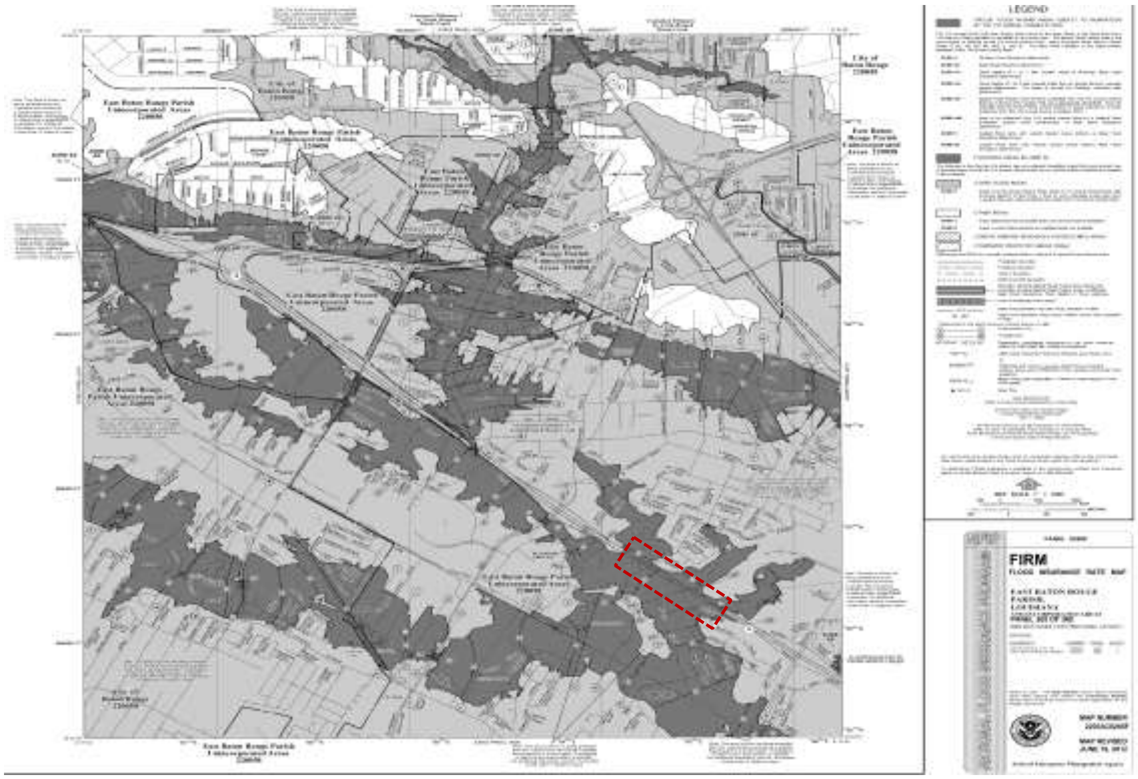

Figure 8

Flooding risk map of East Baton Rouge, LA, under a 100-year flood (downloaded from https://msc.fema.gov/portal/): the shaded areas indicate the places will be likely to be inundated in the event of 100-year storm

Although currently only the flooding map for 100-year flood is available from FEMA's flooding risk management map portal, similar flooding maps for floods with different recurrence intervals (e.g., 50-year, 25-year, and 10-year) can be generated by state agencies or local municipalities and referred to for determining the vulnerability of a roadway for flooding.

The value of EC depends on the severity of surface cracking, and ranges from 5 for the high severity of cracking, 3 for moderate level of cracking, to 1 for low level of cracking. A weighting factor of 0.2 is recommended for EC. The criterion for the severity of surface layer cracking can be based on the LTPP's (Long-Term Pavement Performance) definitions. For example, different severity levels for fatigue cracking are defined as below [*42*]:

- **Low:** An area of cracks with no or only a few connecting cracks; cracks are not spalled or sealed; pumping is not evident.

- **Moderate:** An area of interconnected cracks forming a complete pattern; cracks may be slightly spalled; cracks may be sealed; pumping is not evident.
- **High:** An area of moderately or severely spalled interconnected cracks forming a complete pattern; pieces may move when subjected to traffic; cracks may be sealed; pumping may be evident.

The value of ST depends on the thickness of bound layers, with a lower value for the roadway with thicker bonded layer. Specifically ST values of 5, 3, and 1 are recommended for the roadway with thin bound layer ($\leq$ 2 in.), moderate bound layer (4~6 in.), and thick bound layer ($\geq$ 6 in.), respectively. A weighting factor of 0.2 is recommended.

The value of SG depends on the extent of reduction in resilient modulus of subgrade layer as a result of increase in saturation increases due to flooding. Higher the reduction in the modulus, larger is the value of SG. Usually coarse-grained soils are relatively less sensitive to the increase in its moisture content and thus 1 is assigned to the value of SG for these soils while fine-grained soils are affected more significantly by the increase of moisture content in terms of its resilient modulus, as illustrated by Figure 9. For the fine-grained soils, its sensitive to the increase in moisture content can be approximated by the weighed plasticity index (wPI), which is the product of fine content (w, percentage of particles passing through No. 200 sieve) and plasticity index (PI), as proposed by MEPDG design guide. Accordingly, 3 and 5 are recommended for the values of SG for the soils with wPI of 0.1 and 50, respectively. In case where neither D_{60} nor wPI is available, a SWCC can be estimated from suggested D_{60} or wPI value for each of AASHTO soil classification (summarized in Table 4). The weighting factor of 0.2 is recommended for SG. When soil boring data are not available, a good resource to identify subgrade soil in the state of Louisiana is a web-based GIS map system: http://ladotd.maps.arcgis.com/apps/webappviewer/index.html?id=55c09f56253045e49c36f99c41409add%20, where comprehensive information about subgrade soil is compiled and freely downloadable, including soil classification, layer thickness, particle size distribution, Atterberg limits, saturated hydraulic conductivity, mechanical properties (e.g., CBR-California Bearing Capacity, resilient modulus), and soil-water characteristic curves.

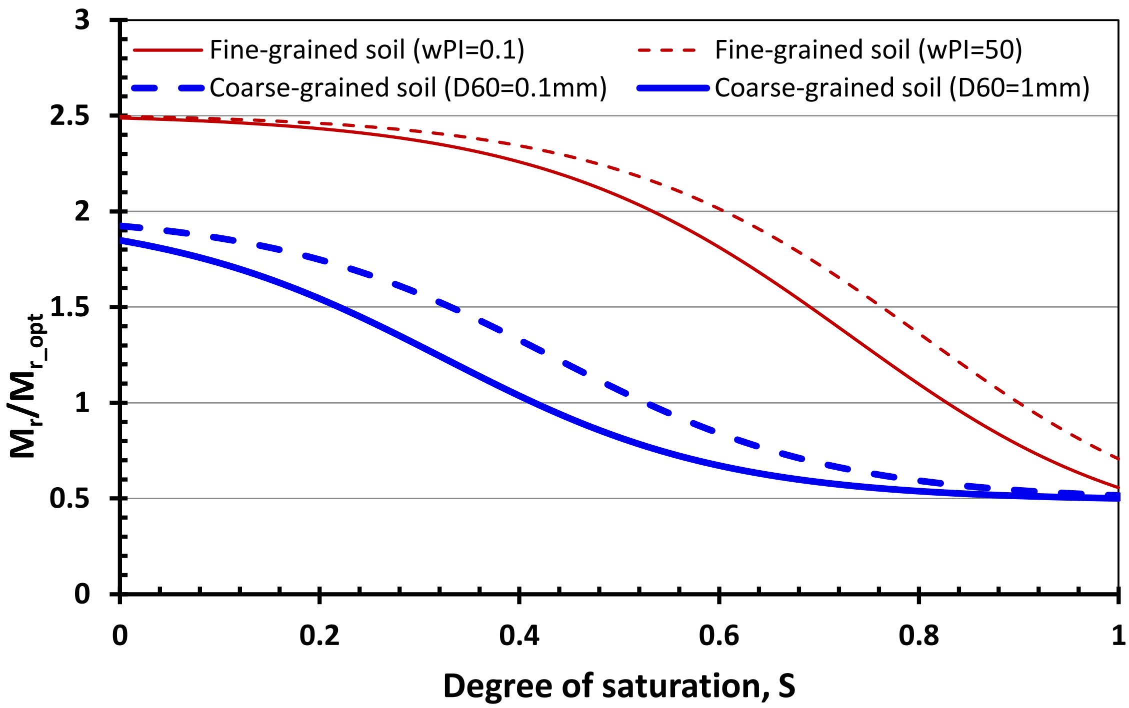

Figure 9

Relationship between normalized resilient modulus relative to resilient modulus at the optimal condition vs. degree of saturation for various soil types (derived from the regression equations suggested in MEPEG design guide) [*44*]

Table 4
Typical soil property values vs. AASHTO soil classification [*44*]

AASHTO classification	wPI (Range)	D_{60} (mm) (Range)
A-1-a	0	3.0 (>2.0)
A-1-b	0	1.0 (0.5 - 2.0)
A-2-4	1.2 (0.2 - 3.5)	---
A-2-5	2 (0.2 - 3.5)	---
A-2-6	2.60 (0.55 - 5.25)	---
A-2-7	6 (0.75 - 15.75)	---
A-3	0	0.180 (0.074 - 0.450)
A-4	4.1 (1.44 - 10.00)	---
A-5	6.8 (1.44 - 10.00)	---
A-6	8.84 (3.96 - 15.00)	---
A-7-5	25.8 (10.8 - 45.0)	---
A-7-6	15.0 (5.4 - 29.0)	---

The value of D depends on the rate at which the infiltrated water drains out of the flooded roadway, which can be related to the hydraulic permeability of base or subbase layer of the roadway. The slower the water drains out, the larger is the value of D. To have a first-order approximation, the hydraulic permeability of the base layer can be estimated by its physical and index properties, such as D_{60} and , for coarse- and fine-grained soils, respectively, which is related to the hydraulic permeability as shown in equations (7) and (8) [*43*]. The weighting factor of drainage parameter (D) is recommended to be 0.4.

For coarse-grained soils:

$$k_{sat} = 118.11 * 10^{\left(-1.1275(logD_{60}+2)^2+7.2816(logD_{60}+2)-11.2891\right)} \quad (7)$$

For fine-grained soils:

$$k_{sat} = 118.11 * 10^{\left(0.0004*(wPI)^2-0.0929*wPI-6.56\right)} \quad (8)$$

where, k_{sat} is saturated hydraulic conductivity (ft/hr); D_{60} is grain size diameter at 60% passing (mm) in particle size distribution curve; and wPI is the weighed plasticity index that is equal to the multiplication of passing sieve No. 200 (w in decimal) and plasticity index (PI in percentage).

With their typical value ranges of 0.1 to 1 mm for D_{60} and 0.1 and 50 for wPI, respectively, the approximated hydraulic permeabilities for coarse- and fine-grained soils are summarized in Table 5. Based on the estimated hydraulic permeability, the values for the corresponding drainage factor D are recommended.

Table 5
First-order approximation of hydraulic permeability of coarse- and fine-grained soils and recommended values for Drainage factor

	D_{60} (mm)	wPI	K_s (ft/hr)	D
Coarse-grained soils	0.1	---	8.7E-04	1
	1	---	6.9E+00	1
Fine-grained soils	---	0.1	3.2E-05	3
	---	50	7.4E-09	5

A consequence factor (CF) is used to quantify the economic and social impacts of the damage to the structure caused by the hazard. The consequence of flood-induced damage to a roadway depends on the class of the roadway, traffic volume, and the costs associated with repairing and service restrictions. Consequence factor is approximated as the weighted sum of the parameters related to replacement/repair cost (RC) and the cost of service restriction to drivers (CD), with the value of the former related to the functional class of the roadway while the value of the latter related to the traffic volume of the roadway (i.e., AADT). Specific recommended values for these parameters are listed in Tables 6 and 7.

Table 6

Criteria and recommended values for quantifying replacement/repair cost (RC)

Functional class of roadways	replacement/repair cost
Interstates & Other Arterials	5
Collectors	3
Local roads	1

Table 7

Criteria and recommended values for quantifying cost of service restriction to drivers caused by flooding

Traffic volume (AADT)	cost of service restriction to drivers
>3,000	5
400-3,000	3
<400	1

As shown in Figure 10, the RF of a roadway section is plotted in a space of Criticality factor-Consequence factor in order to facilitate the determination of its risk to a given flooding event. The RF map can be divided into three zones: high risk zone with the risk factor ranging from 64 (corresponding to the case with all the parameters equal to 4) to 125 (corresponding to the case with all the parameters equal to the maximum value of 5); medium risk zone with the risk factor ranging from 27 (corresponding to the case with all the parameters equal to 3) to 64; and low risk zone where the RF is smaller than 27.

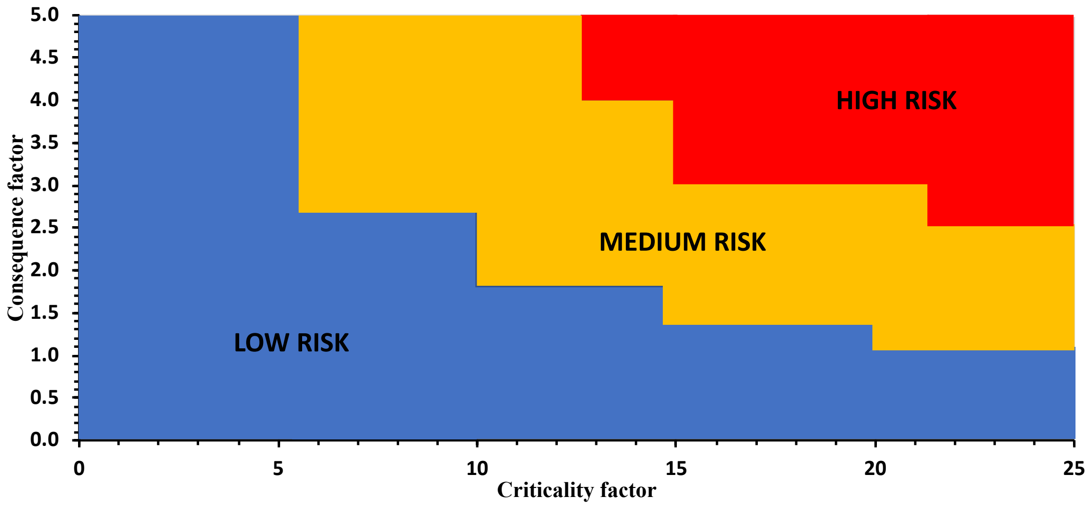

Figure 10

Risk factor map of a roadway section under a given size storm based on its risk factor in criticality factor-consequence factor space: high risk zone (64 ≤ Criticality factor x Consequence ≤ 125); medium risk zone (27 ≤ Criticality factor x Consequence ≤ 64); and low risk Zone (Criticality factor x Consequence ≤ 27)

Note that the recommended numerical values for the above parameters, the criteria of determining these numerical values, and the specific parameters for calculating hazard factor, vulnerability factor, and consequence factor, are yet to be finalized and the model variable may need further refinement; however, the proposed holistic evaluation framework can readily be revised or modified, based on the specific requirements of the end user, and available experience and performance data of flooded pavements.

For illustration, the composite indicator and the corresponding RF map detailed in this section were applied to some specific roadway sections which were flooded in the past. This is presented in the Results and Discussion section.

RESULTS AND DISCUSSION

Summary of Literature Review

Based on the comprehensive literature review conducted during this study, the researchers conclude that all types of inundated roadways suffer from the loss of the structural capacity at various extent during flooding, depending on pavement type, thickness and conditions of bound layer, thickness and characteristics of base layers, and characteristics of subgrade layer. During flooding, there are multiple, water-related, underlying processes that are responsible for the damage to and the reduction in the structural capacity of inundated roadways. Among them, the ingress of flooding water into the roadway underlying layers is one of the primary causes, which results in the increase in degree of saturation in unbound material layers, leading to the reduction in their strength and stiffness. On the other hand, the inundated roadways can regain the strength and stiffness partially or fully after the flooding water recedes, with the recovery rate largely depending on the hydraulic permeability of unbound base and subbase layers. Although roadway authorities are concerned with the flood-induced damage to inundated roadways, in most cases they do not conduct a thorough hydraulic or structural testing/evaluation of the pavements after flooding and rely solely on visual observations, or employ common in-situ pavement testing equipment, such as FWD, DCP, and GPR, to determine the post-flooding structural conditions of the roadways. Some more specific findings from the literature review are listed below:

- Flexible pavements are relatively more prone to flood-induced damages, especially those with thin AC layers, such as low volume and local roads under the jurisdiction of local municipalities.
- It is critically necessary to carry out regular monitoring of structural capacity of roadways that are deemed to be most vulnerable to flooding.
- Although vulnerability of roadways to flood-induced damage depends on many factors, base, subbase, and subgrade provide the bulk of the structural strength and thus the flood-induced reduction in the strength/stiffness of these layers is one of the primary causes of damage.
- The reduced quality of an asphalt pavement can be expected for a fairly long period of time for cases with aggregate base courses with very low hydraulic conductivity.
- The gradation of aggregate base plays a crucial role in governing the recovery of lost strength and stiffness of an inundated roadway during flooding and defining its resilience to flooding.

- The loss of roadway quality can be minimized by using appropriate base materials and/or by reducing the ingress of water into the base layer, through the use of a thicker AC layer.
- There is no guidance regarding which roadway section is more vulnerable to flood risk or what is appropriate evaluation procedure to determine flood-induced structural damage after a flooding.

Questionnaire Survey

Although the research team made the effort to identify the techniques used by local municipalities to assess structural damages of the roadways during flooding, it is time consuming and practically difficult to contact and reach many local municipalities for the questionnaire survey. As a result, only five local municipalities responded to the questionnaire survey, including Ascension parish Government, LA; City of Miden, LA; City of Shreveport, LA; City of Hartford, CT; and Town of Barnstable, MA. However, based on the limited survey responses of these above local municipalities, the used assessment techniques are not much different from those by state DOTs.

In addition, due to fewer received responses from state DOTs (19), the findings of the national questionnaire survey conducted for a FHWA sponsored research on flooded pavement were also incorporated here, in which the authors were PI and Co-PI of the WPI team. Only the responses relevant to the current study are summarized herein.

The responses to one of the main survey questions is shown in Figure 11: "**How do the engineers and/or policy makers in your agency decide whether or not significant damage occurred to the submerged roadway? "**

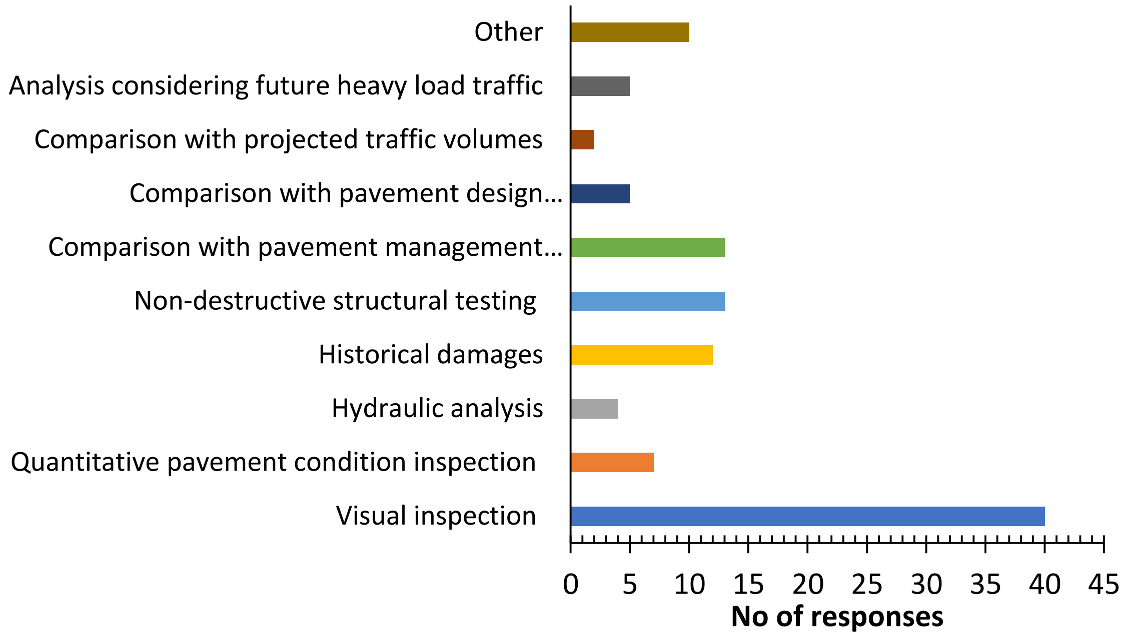

Figure 11

Summary of responses to questionnaire survey about the techniques used to evaluate flood-induced damage to roadway (with the total responses of 42) (revised from the questionnaire survey from [*4*])

Among the received responses from the current study and the FHWA sponsored research, visual inspection and use of photos or video recording is the most commonly technique employed to determine flood-caused damage to roadways, followed by various non-destructive structural testing techniques (e.g., FWD, GPR, etc.) and comparison with individual agency's pavement management database. Below is the list of the techniques used by state DOTs for assessing flood-induced damages to inundated roadways, with the ones used by most of the agencies at the top and the lest used ones at the bottom.

- Visual inspection (use photos and video recording)
- Non-destructive and destructive pavement assessment testing procedures (e.g., FWD, DCP, GPR, etc.)
- Review of and comparison with STA pavement management database
- History of damage (DDIR and damage surveys)
- Performance of a quantitative pavement condition inspection
- Review of and comparison with pavement design standards
- Analysis considering future heavy load traffic
- Performance of a hydraulic analysis of paved or unpaved roads
- Review of and comparison with projected traffic volumes

It also appears that most of the agencies responding to the survey have employed some kind of annual or periodical inspections to document pavement conditions, ranging from visual inspection to automated pavement distress survey.

Illustrative Examples of Applying Composite Indicator for Flooding Risk Evaluation

Two roadway sections on LA 493, Sections 1A and 5, which were flooded during a storm in March 2016 and had the least and worst structural damage based on the change in their effective structural numbers due to the flooding, were analyzed by applying the composite risk factor detailed in Methodology section. The schematics of these two roadway sections are shown in Figure 12, and their subgrade layers are A-7(6) and A-7(5) for sections 1A and 5, respectively.

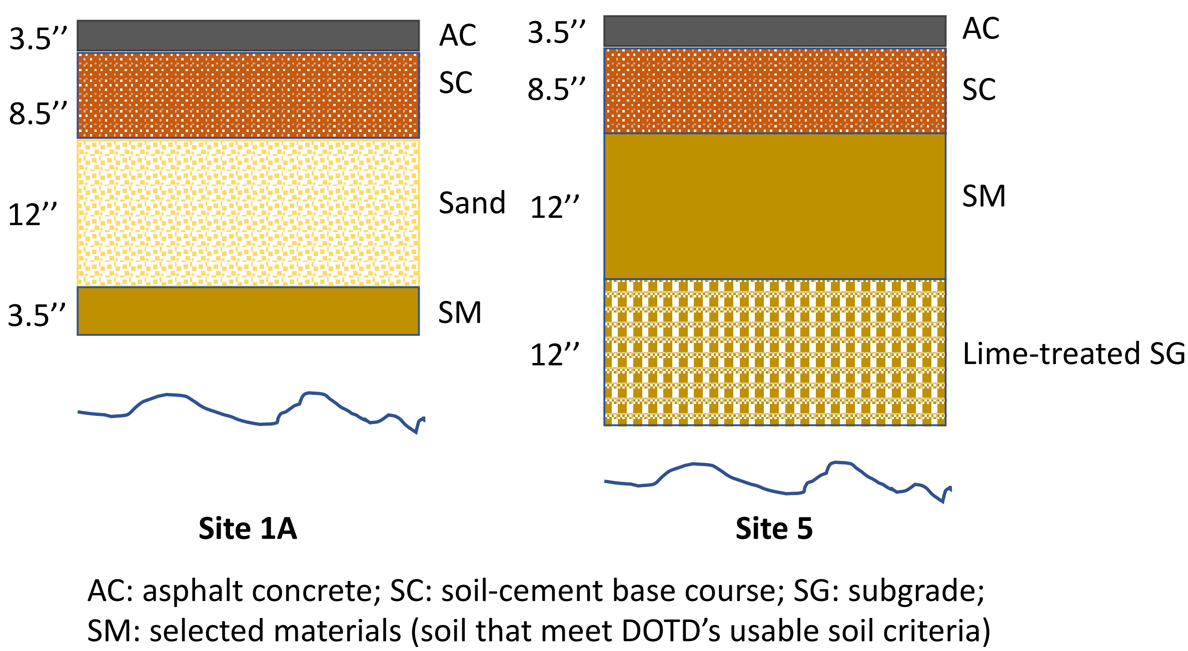

Figure 12
Schematics of two roadway sections in LA 493 that were flooded in March, 2016 storm [*45*]

Hazard Factor
Although no definite record of its peak discharge is available, the March 2016 storm can be viewed as 100-year storm, based on the extent of flooded areas, although no definite record

of its peak discharge is available. Consequently, a Hazard factor of 5 is assigned for the storm.

Vulnerability Factor

Since these roadway sections were flooded, their VF1 value is 1 (value of 0 is for the case of not being flooded). Based on their pavement configurations and subgrade layer, with the assumed moderate level of cracking in the surface layer, the VF2 for these two roadway sections are summarized in Table 8. Then VF values of 2.2 and 3.8 were calculated for sections 1A and 5, respectively, based on the criteria detailed previously in Methodology section.

Table 8

Summary of vulnerability factors for sections 1A and 5 in LA493 during March 2016 storm

Parameters	Section 1A	Section 5
Subgrade (w_{SG})	3 (0.2)	3 (0.2)
Drainage (w_D)	1 (0.4)	5 (0.4)
Structure thickness (w_{ST})	3 (0.2)	3 (0.2)
Existing Cracks (w_{EC})	3 (0.2)	3 (0.2)
VF1	1	1
VF2	2.2	3.8
VF=VF1*VF2	2.2	3.8

Note: The numbers in the parentheses are the respective weighting factors of the paramaters for calculating VFs.

Consequence Factor

With LA 493 being a rural highway of Louisiana and thus belonging to Other Arterials and its AADT of 330, its consequence factor is approximated as: $5 * 0.5 + 1 * 0.5 = 3.0$ [*44*].

Risk Factor

For sections 1A and 5, their risk factors are calculated as: $\underline{(5 * 2.2) * 3.0 = 11 * 3.0 = 33.0}$ and $\underline{(5 * 3.8) * 3.0 = 19 * 3.0 = 57.0}$, respectively.

To illustrate flooding risk of these two roadway sections during the March 2016 storm, their risk factors are plotted in the space of criticality factor-consequence factor, which is divided into three zones (see Figure 13): high risk zone with a risk factor ranging from 64 to 125; medium risk zone with a risk factor ranging from 27 to 64; and low risk zone with a risk factor smaller than 27. With their criticality factor and consequence factor values of (11, 3.0) and (19, 3.0), roadway Sections 1A and 5 both had medium risk to the storm; however, Section 5 falls to the boundary line between high and medium risk zones and had a much higher criticality factor, with the latter indicating that Section 5 is much more vulnerable to flood-induced damage.

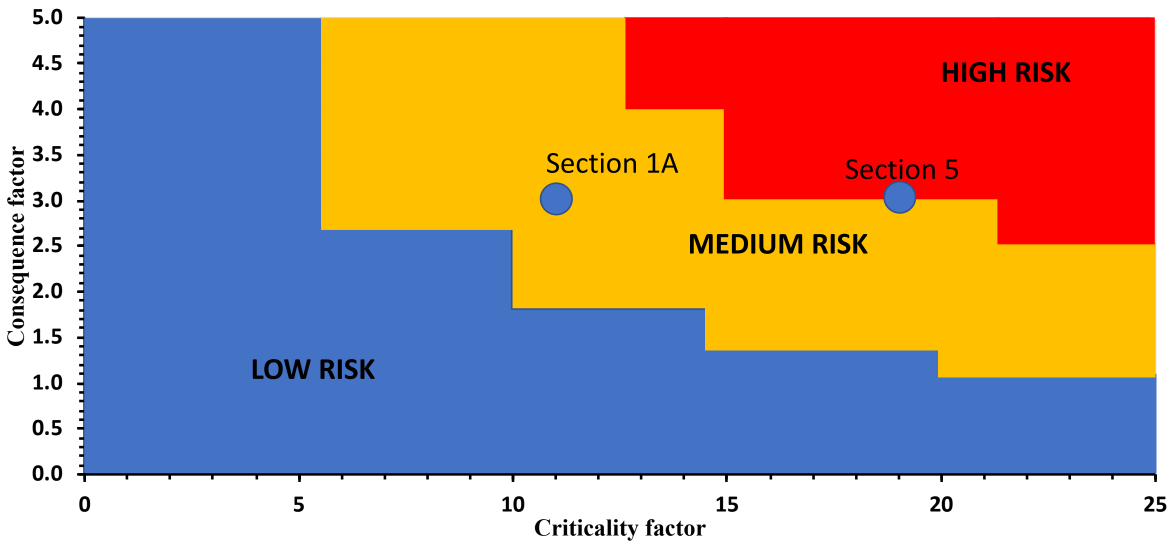

Figure 13
Flooding risk of roadway sections 1A (11, 3.0) and 5 (19, 3.0) in LA 493 during March 2016 storm in the space of criticality factor-consequence factor

Based on the composite evaluation indicator (i.e., Risk Factor) and the resulting risk factor map explained above, the following three levels of engineering evaluation are proposed to assess flood-induced damage to roadways. Level 1 is the most extensive engineering assessment for roadways with the highest Risk Factor while Level 3 is the simplest engineering evaluation for roadways with the lowest Risk Factor. Level 2 is recommended for roadways with an intermediate Risk Factor.

- Level 1: Hydraulic and pavement performance analyses (see the flow chart illustrated in Figure 14) + Nondestructive testing + Field Reconnaissance (visual inspection-data recording-checking) (the most robust engineering evaluation of flood-induced damage) (for the roadways with High Risk); Nondestructive testing procedures to be considered for assessing flood-induced damage to roadways include the following commonly used in-situ testing procedures: FWD, GPR, and DCP. Field reconnaissance will consist of visual inspection, taking picture and recording videos, and recording data to document any structural damage (e.g., pavement damage due to erosion or flooding water, breach of roadway embankment, erosion of pavement shoulder) and distresses (e.g., cracking, rutting, raveling).

- Level 2: Nondestructive testing + Field Reconnaissance (visual inspection-data recording-checking) (for the roadways with Medium Risk)
- Level 3: Field Reconnaissance (visual inspection-data recording-checking) or inferring damage based upon previous engineering studies (for the roadways with Low Risk)

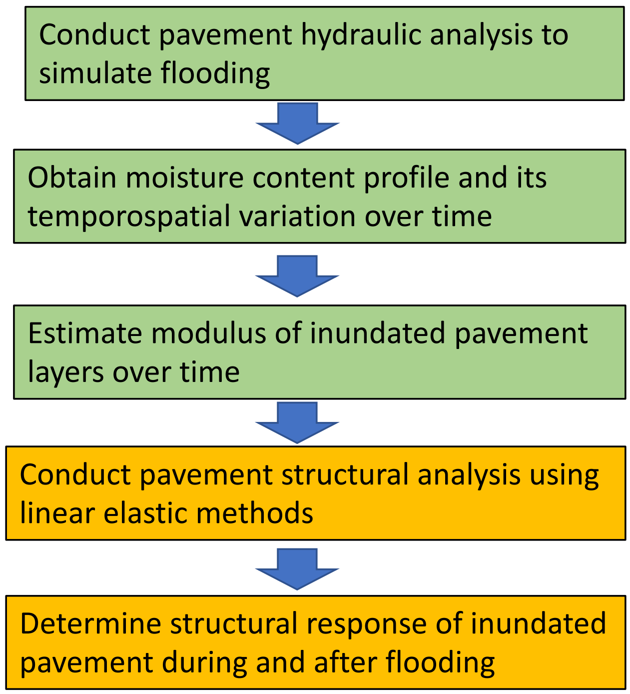

Figure 14

Flow chart of using combined hydraulic analysis and structural analysis to evaluate **structural damage to inundated roadways sections during and after flooding [40]**

CONCLUSIONS

It has been confirmed and well documented that floods can cause damages of different extent, primarily through a loss of structural strength. Based on a comprehensive literature review, the researchers conclude that flexible pavement, especially those with thin AC layers have been identified as more prone to flood-induced damage, compared to rigid pavement and composite pavements. Therefore, local and low-volume roads are most vulnerability to flood-induced damages, even though oftentimes these roadways appear to be intact after the flood.

Although flooding can cause deterioration in bound layers of roadways, such as asphalt concrete and Portland cement concrete, the water that infiltrates the unbound layers (e.g., base, subbase, and subgrade) causes most damage to the structural loading capacity of flooded roads. Therefore, physical, mechanical, and hydraulic properties of these unbound layers play important roles in terms of the vulnerability of roadways to flood risks. The gradations of aggregate base or subbase layers plays a crucial role in defining the resilience of a roadway to flooding by dictating how much time the infiltrated water takes to drain from the flooded roadway. Thus the structural loading capacity of a roadway with a base layer with low hydraulic permeability can be expected to remain at a reduced level of structural capacity for a significant period of time after flooding.

FWD, DCP, and GPR are commonly used in-situ tools to assessing structural damage caused by flooding, with the first sensor deflection, effective structural number, and subgrade resilient modulus as the quantitative indicators.

A holistic framework for evaluating flooding risk of roadways was proposed, which considers degree of hazard (i.e., flooding), vulnerabilities, and consequence. A quantitative, composite indicator, risk factor, as a product of hazard factor, vulnerability factor, and consequence factor, can be estimated with storm characteristics (i.e., recurrence interval), pavement characteristics (including, severity level of surface cracking, moisture sensitivity of subgrade, thickness of bound layers, and drainage condition of base/subbase layer), and functional class of pavement & traffic volume (i.e., AADT). A flooding risk map is developed based on the risk fact in a space of criticality factor-consequence factor, which is divided into three different risk zones: high risk zone with a risk factor between 64 and 125; medium risk zone with a risk factor between 27 and 64; and low risk zone with a risk factor smaller than 27.

A risk factor based hierarchical engineering evaluation procedure is recommended as follows:

- Level 1: Hydraulic and pavement performance analyses + Nondestructive testing + Field Reconnaissance (visual inspection-data recording-checking) (for the roadways with high risk)
- Level 2: Nondestructive testing + Field Reconnaissance (visual inspection-data recording-checking) (for the roadways with medium risk)

Level 3: Field Reconnaissance (visual inspection-data recording-checking) or inferring damage based upon previous engineering studies (for the roadways with low risk)

RECOMMENDATIONS

In the context of more extreme weather events, it is highly recommended that state DOTDs and local municipalities regularly monitor and document structural conditions of roadways, especially those with thin AC layers that are deemed to be more vulnerability to flooding risk, such as local and low-volume roads. Specifically, the data related to structural loading capacity of roadways, including the first sensor deflection (D_1), effective structural number (SN_{eff}), subgrade resilient modulus (M_r), should be determined during annual or biennial pavement condition survey and documented in pavement management system. Such data are indispensable for providing a benchmark for the before-and-after flooding analysis to quantify flood-induced structural damage to roadways and to apply for funds from FEMA federal emergency programs. Common in-situ testing tools used by various highway agencies, including FWD, DCP, and GPR, are recommended for such a purpose.

The composite risk indicator (Risk Factor) and the flood risk map developed in this study can aid pavement engineers and decision makers in identifying roadway sections with different level of risk to a given size storm, which can be readily added to GIS-based roadway network maps of existing pavement management system. The holistic evaluation framework developed in this study can enable pavement practitioners to make informed decisions in: (1) selecting appropriate engineering methods to evaluate flood-induced damage for immediate post-flood response; (2) deciding when a flooded roadway can be reopened to what type of vehicles; and (3) allocating funds and resources to reduce flood risk of roadways falling in high risk zones in advance for long-term planning.

Although the proposed evaluation framework and the composite risk indicator are versatile for evaluating flood-related risk and resilience of roadways, it is still at an early developmental stage and therefore should be considered theoretical and not ready for adoption by any agency. Data should be collected from actual inundation events. That data should then be used to further refine the risk factor approach prior to be adopted by any agency.

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APPENDIX A

Questionnaire survey questions

***<u>Survey</u>* on "Best Practices for Assessing Roadway Damages Caused by Flooding"**
If you have any questions about this survey, please contact Dr. Mingjiang Tao at taomj@wpi.edu or 1- 508-831-6487.

You may return the completed survey by email, (taomj@wpi.edu), or fax (1-508-831-5808) or mail Department of Civil & Environmental Engineering, Kaven Hall 107, Worcester Polytechnic Institute, Attention: Dr. Mingjiang Tao, 100 Institute Rd, Worcester, MA 01609

Please return the survey by Thursday, July 20, 2018.

The Louisiana Transportation Research Center greatly appreciates the time you have taken to complete this survey!

This questionnaire survey is one part of the effort ongoing in the Louisiana Transportation Research Center's (LTRC) Project No. 18-3P and is intended to gather information on how the Federal Highway Administration (FHWA), Federal Emergency Management Agency (FEMA), state departments of transportation agencies (STA), local public agencies (LPA) and/or Department of Public Works engineers typically conduct inspections on pavements that are damaged as a result of a flooding event. The data from this survey will be used to (1) advance the current knowledge and state of the art in the understanding of flood related damage to pavements and its assessment for both short and long terms; and (2) prepare rational and practical guidelines that will provide the knowledge and tools for assessing the short and long term impacts of flooded pavements, all of which will be documented in a research report that will be assessable to the public via LTRC's website (http://www.ltrc.lsu.edu/pubs_final_reports.html).

Please provide your contact information below:

Name	
Title	
Agency	
Street Address	

City, State, Zip	
Email Address	
Phone Number	

Q1. Are you aware of any study(s) that has been conducted on submerged roads for estimation of structural strength and/or distresses?

☐ Yes, please proceed to the next 2 questions:

1a Please provide the source from which the project report or memo on the study(s) can be obtained.

1b Please provide the contact information (name, telephone number, email) of the person(s) who conducted the study. If more than one study was conducted, please provide contact information for each.

☐ No

Q2. Are you aware of any project(s) in your state where Federal Emergency Management Agency (FEMA) or any other organizations paid the state, local or county agencies funds to compensate for damage due to submergence of the road caused by flooding?

☐ Yes, please proceed to the next 2 questions:

2a Please provide the source from which the project report or memo on the study(s) can be obtained.

2b Please provide the contact information (name, telephone number, email) of the person who conducted the study. If more than one study was conducted, please provide contact information for each.

☐ No

Q3. How do the engineers and/or policy makers in your agency decide whether or not significant damage occurred to the submerged roadway? Check all that apply!

☐ Visual inspection and use of photos or video recording
☐ Pavement surface evaluation and rating (PASERS)
☐ Performance of a quantitative pavement condition inspection following STA, ASTM, FHWA, or other approach (ARAN, etc.)
☐ Performance of a hydraulic analysis of paved or unpaved roads

☐ History of damage [FHWA Detailed Damage Inspection Report (DDIR) and/or any sort of damage survey]from past emergency events on these roads

☐ Use of non-destructive structural testing (e.g., ground-penetrating radar (GPR), step frequency GPR, spectral analysis surface wave, falling weight deflectometer (FWD), or other NDT equipment)

☐ Review of and comparison with your agencies pavement management database

☐ Review of and comparison with your agencies current pavement design standards

☐ Review of and comparison with your agencies projection of design-year traffic volumes

☐ Analysis considering future heavy load traffic volumes (emergency vehicles, construction vehicles, husbandry vehicles) on these roads, in anticipation of future events

☐ Other <please describe>

Q4. How do the engineers and/or policy makers in your agency track the condition of your pavements and roadway embankments on a routine basis prior to a flooding event?

Please specify method(s) below:

Q5. Does your agency classify a priority system of routes for any of the following?

☐ Clearance of trees and other blocking debris for access back to affected area?

☐ Access by emergency vehicles after an event?

☐ Access by recovery vehicles (utilities, emergency vehicles etc.)

☐ Access for returning evacuees after an event?

☐ Primary and secondary haul routes for debris removal?

☐ Restoration of commerce and other routine functions?

☐ Other: Please describe below:

Q6. Were any geotechnical or remaining structural service life analyses on the roadways conducted by the STA or LPAs in any of your flooding events?

☐ Yes Please provide the contact information (name, telephone number, email) of the person who conducted the study. If more than one study was conducted, please provide contact information for each.

☐ No

☐ Other <please describe>

Q7. If "Yes" on Question 8, can you please share any of the following information with our research team based on the last two submergence events?

- ☐ If measurements were taken on the subgrade or base course saturation, prior to or after the submergence event, please provide them to us.
- ☐ If measurements were taken on the ground water table (GWT) depth, prior to or after the submergence event, please provide them to us.
- ☐ Any information on the type of analyses or tools used for hydraulic analyses (e.g., simulations under saturated or unsaturated conditions).
- ☐ Any information on the type of analyses or tools used for geotechnical or pavement analyses.
- ☐ Any information on special circumstances or surrounding conditions that enhanced or reduced drainage.

Q8. Were engineering tools used to assess the technical and economic aspects of restoring the submerged road to its pre-submergence status?

- ☐ Yes: Please provide the contact information (name, telephone number, email) of the person who conducted the study. If more than one study was conducted, please provide contact information for each.

- ☐ No

Q9. Who made the repair decision(s) on the submerged roadways?
Check all that apply.

- ☐ STA maintenance (in central or district office)
- ☐ STA research bureau
- ☐ STA pavements office (in central or district office)
- ☐ STA materials office (in central or district office)
- ☐ STA construction office (in central office or district office)
- ☐ STA design office (in central office or district office)
- ☐ STA safety office
- ☐ LPA public works or engineering office
- ☐ Consultants to the STA or LPA
- ☐ FHWA Division Office (Area, Pavement, or Material engineers)
- ☐ FHWA Federal Lands Division
- ☐ Uncertain
- ☐ Other <please describe>

<u>End of Survey</u>

The research team greatly appreciates the time you have taken to complete this survey!

APPENDIX B

Summary of the received response to the questionnaire survey

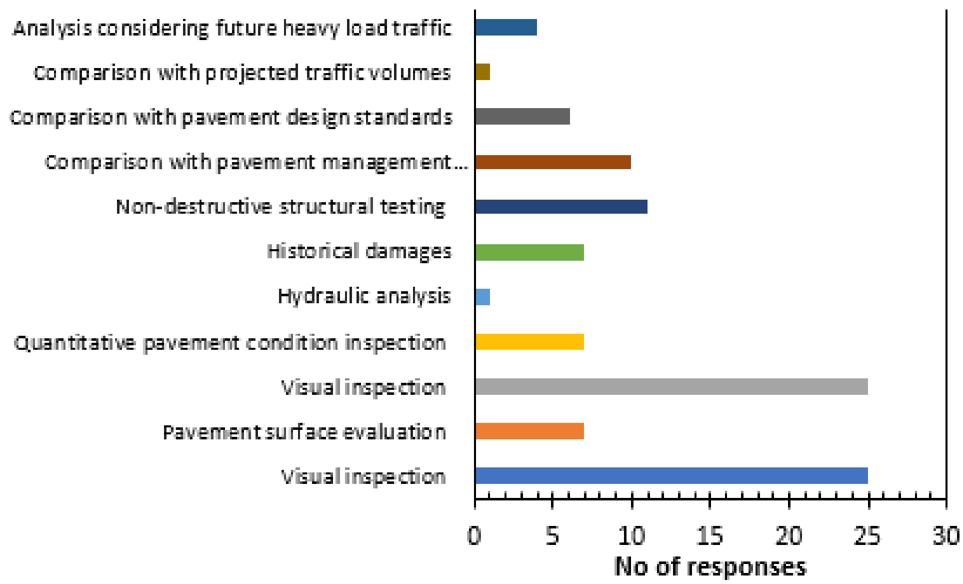
Q1. Are you aware of any study(s) that has been conducted on submerged roads for estimation of structural strength and/or distresses?

Answer choice	Responses
Yes	5
No	20

Q2. Are you aware of any project(s) in your state where Federal Emergency Management Agency (FEMA) or any other organizations paid the state, local or county agencies funds to compensate for damage due to submergence of the road caused by flooding?

Answer choice	Responses
Yes	7
No	18

Q3. How do the engineers and/or policy makers in your agency decide whether or not significant damage occurred to the submerged roadway? Check all that apply!



Q4. How do the engineers and/or policy makers in your agency track the condition of your pavements and roadway embankments on a routine basis prior to a flooding event?

Please specify method(s) below:

Responses: Among 25 received responses, 17 agencies use regular pavement survey, such as ARAN, FWD, GPR, to document roadway conditions, one use visual inspection and another one use maintenance repair records.

Q5. Does your agency classify a priority system of routes for any of the following?

Answer choice	Response
Clearance of trees and other blocking debris for access back to affected area?	5
Access by emergency vehicles after an event?	7
Access by recovery vehicles (utilities, emergency vehicles etc.)	4
Access for returning evacuees after an event?	2
Primary and secondary haul routes for debris removal?	5
Restoration of commerce and other routine functions?	3
Other: Please describe below:	3

Q6. Were any geotechnical or remaining structural service life analyses on the roadways conducted by the STA or LPAs in any of your flooding events?

Answer choice	Responses
Yes	2
No	21

Q7. If "Yes" on Question 6, can you please share any of the following information with our research team based on the last two submergence events?
Not enough responses.

Q8. Were engineering tools used to assess the technical and economic aspects of restoring the submerged road to its pre-submergence status?
Response: Three of the agencies use FWD while other two mentioned "project by project basis assessment" without specifying the techniques used.

Q9. Who made the repair decision(s) on the submerged roadways?
Check all that apply.

Answer choice	Response
STA maintenance (in central or district office)	14
STA research bureau	0
STA pavements office (in central or district office)	7
STA materials office (in central or district office)	5
STA construction office (in central office or district office)	3
STA design office (in central office or district office)	5
STA safety office	0
LPA public works or engineering office	3
FHWA Division Office	5

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