ABSTRACT

Title of Thesis:	WHEN ROADS WANT TO BE DAMS: LOOKING TO DAM SAFETY TO REGULATE TRANSPORTATION EMBANKMENTS
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The potential for various failure processes impacting transportation embankments temporarily impounding water has not been a common consideration in the design and management of these structures. However, changes in water elevations due to land development and climate change has prompted concern about impoundment on seepage rates and overall stability of the constructed embankments. The goal of the research was to examine how different aspects of dam safety can be incorporated in transportation embankment management. Current U.S. Mid-Atlantic state policies were summarized, evolving issues pertaining to water impoundment were investigated, transportation and dam embankments were compared, and seepage and slope stability numerical modeling were conducted to understand how example transportation embankments behave under various water impoundment scenarios.

Performance assessment of granular materials commonly used in transportation embankments indicates their ability to withstand piping erosion but poor slope stability during rapid drawdown. Results demonstrate the need for infrastructure inventories and hydrologic research on this topic.

WHEN ROADS WANT TO BE DAMS: LOOKING TO DAM SAFETY TO REGULATE TRANSPORTATION EMBANKMENTS

by

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Chapter 1 : Introduction

Several different types of engineered embankments exist, including embankments for transportation infrastructure and earth dams. On the surface level, these embankments have similar geometries, materials, and construction methods (Briaud et al. 2016). However, their purposes are different, and thus their designs are unique. Transportation embankments provide an elevated, level surface for the roadway, which facilitates safety in the transportation system (Perry et al. 2003). On the other hand, dam embankments serve to impound water (FEMA 2004). Dam embankments range from small agricultural or stormwater ponds to large drinking water reservoirs.

Since transportation embankments are sometimes constructed in the flow path of a stream, there has been recent concern about the embankments temporarily impounding water during storm events. Research has indicated that this problem is likely to get worse with climate change (Butcher 2021; Johnston et al. 2021; Polemio and Lollino 2011).

Transportation embankments are regulated with the primary goal of ensuring the overlying roadway and pavement is safely traversable (Ariema and Butler 1990). Additionally, culverts through embankments serve to convey channel flow and prevent accumulation of water behind the embankment that could threaten safety or the roadway during a given design storm (e.g., MDOT SHA 2009). Although culvert design allows a small amount of temporarily impounded water, these water levels are not taken into consideration for the geotechnical design or management of the embankment (Polemio and Lollino 2011).

Several regulations informing design and management exist to prevent catastrophic failure of regulatorily-defined dams and other dam-type embankment structures. Management

includes dam break analysis, yearly inspections and maintenance based on hazard class, and development of an emergency action plan. Other, typically smaller, dam-type embankments are managed more leniently with stormwater management guidelines, or, in many U.S. states, the Natural Resources Conservation Service (NRCS) Code 378. As such, embankments managed under Code 378 do not require a dam break analysis and have less frequent inspection and maintenance requirements than regulatory dams (NRCS 2011). To guard against seepage and erosion, design of both regulatory dams and dam-type embankments requires specific materials, drainage structures within the embankment, and geometries (FEMA 2004; NRCS 2011). Additionally, water release control structures, including risers, principal spillway pipes (PSP), and emergency spillways are designed to prevent unsafe levels of water from accumulating behind the embankment (FEMA 2004; NRCS 2011).

Regulators have started to consider situations where transportation embankments begin to overlap with dams with the release of policy memoranda, but safe management of transportation embankments with the potential to impound water is not well developed or standardized. Several similarities and differences exist between transportation embankments and dam embankments, and the differences make it impractical to broadly apply dam safety regulations to transportation embankments. In 2017, the US Federal Highway Administration (FHWA) published a memorandum that advises state Departments of Transportation (DOTs) against allowing any impoundment of water against transportation embankments because impounded water creates a hazard (FHWA 2017). In 2019, 2020, and 2022, the Maryland Department of Environment (MDE) published and subsequently updated a memorandum that applies modified dam safety regulations from Maryland Code 378 to transportation embankments that are capable of

impounding large amounts of water (MDE 2022a). Therefore, Maryland is aiming to regulate some transportation embankments as low hazard dams through Code 378.

The goal of this research was to explore how and when aspects of dam safety could be applied to transportation embankments. The objectives were to identify current design of transportation embankments temporarily impounding water, explore how state agencies manage this scenario, determine the current scientific and engineering considerations related to the evolution of risks, evaluate similarities and differences between dam and transportation embankments, apply numerical modeling to explore how embankments behave under temporarily impounded water conditions, and provide recommendations for the improvement of embankment safety. The state of Maryland is a leader in developing regulations to address the overlap between dam safety and transportation embankment management (i.e., MDE 2022a; b; NRCS MD 2000). Therefore, the state policy aspect of the research focused on Maryland and geographically and climatically similar states, that is, states in the Mid-Atlantic region (Delaware, Maryland, New Jersey, New York, Pennsylvania, West Virginia, and Virginia). Current design guidance and policies in the Mid-Atlantic region concerning dam safety, embankment design, and stormwater management were collected, relevant Mid-Atlantic state agency representatives were interviewed, transportation embankment failures were analyzed, global scientific literature was reviewed, and seepage and slope stability analyses were conducted on example transportation embankments under a variety of water level conditions.

This chapter has provided a brief background and objectives of the report. Chapter 2 explains the methods for the policy review, literature review, and modeling. Chapter 3 synthesizes the policy review including Mid-Atlantic state guidelines and regulations and agency interviews. Chapter 4 examines scientific reasoning that could provide recommendations for

changes. Chapter 5 discusses the outcomes of the geotechnical modeling. Chapter 6 provides conclusions.

Chapter 2 : Methods

Mid-Atlantic State Policy Review

In the policy review, Mid-Atlantic states included Maryland, Delaware, Pennsylvania, West Virginia, Virginia, New Jersey, and New York. Mid-Atlantic states were of interest due to their geographic proximity lending to similarities in climate, climate change impacts, common natural hazards, topography, geologic characteristics, and water quality regulation interests. Guidance and regulatory documents pertaining to dam safety and transportation embankments (and related infrastructure) were collected from state websites. Table A-1 summarizes state agencies of interest, their websites, and related documents used.

After documents were collected and analyzed, state agencies responsible for dam safety and transportation in each state were contacted via email. Phone calls/video conferences were conducted with each agency (contact listed in Table A-1). The primary goal was to determine how the agency manages embankments impounding water, if there are specific safety standards, and if there are issues with transportation embankments impounding water. Notes from the interviews are included in the appendices.

Literature Review

Engineering, scientific, and policy databases (listed in Table A-2) were searched for peer-reviewed literature concerning design, maintenance, operation, inspection, incidents, and failures of transportation embankments, earthworks, roadfill, and small dams (Table 2-1). Federal design documents and state DOT research reports were also included in the analysis. Emphasis was placed on case studies and research concerning the Mid-Atlantic region, however, there was not a large amount of literature available on this specific topic.

Collected literature was synthesized (see Chapter 3) to determine the current understanding of several issues. The current and projected future impacts of flooding and precipitation events on transportation embankments were analyzed. Failure mechanisms, geotechnical and hydraulic design components, and inspection and maintenance of transportation embankments and small dams were compared and contrasted. Lastly, past failures of transportation embankments due to flooding were explored.

Table 2-1. *Summary of sources collected for literature review.*

Topic	Summary	Number
Case Studies	Related to embankment damages or failures globally	9
Climate Change	How climate change may impact transportation infrastructure, with an emphasis on flooding	10
Culverts	Culvert materials, culverts as a source of erosion, and trash racks	7
Dams	Relevant issues in dams including internal erosion and breaching	5
Embankments	Design and performance of general and/or transportation embankments including special considerations for embankments subject to river environments	34
Failure	Failure mechanisms and case studies of embankment failures	24
Maintenance	Assessments of inspection and maintenance programs	6
Data	Monitoring infrastructure with instruments and data collection	5
Materials	Experimental studies of materials commonly used in transportation and dam embankments	9
Modeling	Modeling of porewater pressures and stability within embankments	11
Roads	Issues specific to roadways on top of embankments	8
Spillway	Design of spillways	5
Water Quality	Use of transportation embankments in stormwater management	14
Water Quantity	Role of embankments in flood control	4

Embankment Modeling and Stability Analysis

The policy and literature review indicated gaps in the state of knowledge concerning transportation embankments temporarily impounding water. Therefore, a variety of example embankments were analyzed under recommended conditions provided in a 2016 Transportation Research Board (TRB) report on flooding risks to transportation embankments (Briaud et al. 2016) and an NRCS technical release (TR60) on earth dam embankments (NRCS 2019). The TRB report recommended analyzing overtopping erosion, seepage through the embankment, seepage through the foundation, wave erosion, softening by saturation, lateral sliding/spreading, culvert capacity, and rapid drawdown stability (Briaud et al. 2016). All the above areas were tested, excluding wave erosion, which is not applicable, and softening by saturation and culvert capacity, which are relevant to specific embankments and cannot be generalized for the model embankments tested. TR60 recommended downstream slope stability testing at normal and flood water levels (NRCS 2019). A combination of equations (provided in the TRB report) and numerical seepage and slope stability modeling (performed with GeoStudio SEEP/W and SLOPE/W, respectively) were used to analyze the recommended conditions and are discussed further in this chapter.

Representative embankment materials were selected from a prior Maryland DOT State Highway Administration (MDOT SHA) report (MDOT SHA 2020), a TRB study (NASEM 2010), and typical values used by other state DOTs (e.g. MnDOT 2007). All materials met MDOT SHA criteria for common borrow for embankments [i.e., unit weight greater than 15.7 kN/m^3 (100 pcf)]. Table 2-2 summarizes the materials; all materials listed were tested. Sandy silt was used for the foundation material in all cases.

Additionally, example embankment geometries were selected based on embankment cross sections in Maryland [including typical cross sections of MD-182 (MDOT SHA 2011) and I-495 (MDOT SHA 2016a)] and MDOT SHA highway geometry guidelines. Slopes tested were 2H:1V, 4H:1V, and 6H:1V; 2H:1V is the shallowest slope permitted in Maryland (MDOT SHA 2016b). Top widths tested were 9.14, 15.2, and 24.4 meters (30, 50, and 80 feet); highway lanes must be at least 3.66 meters (12 feet) wide, so these widths roughly correspond with 2, 3, and 5 lanes, respectively (MDOT SHA 2016b). Heights tested were 6.10, 9.14, and 15.2 meters (20, 30, and 50 feet). Smaller heights, although common, were not selected because testing impounded water was of interest for the study.

According to dam safety guidance, dams should be tested at a variety of water levels, including normal pool elevation, maximum recorded pool elevation, probable maximum flood (PMF) elevation, and brimful (USBR 2019). Therefore, water levels tested were 1.52 meters (5 feet), 3.05 meters (10 feet), 4.57 meters (15 feet), 6.10 meters (20 ft), and brimful to represent more common flood events and extreme flood events in accordance with the U.S. Bureau of Reclamation (USBR) guidance. Table 2-3 reports what geometries, materials, and water levels were used in each test and the minimum design factors of safety (FS). Figure 2-1 shows an example input to the GeoStudio model and locations of FS gathered from the model.

Table 2-2. *Embankment material properties tested with geotechnical modeling.*

Material	Class	VWC Function	K (m/hr, *ft/hr*)	SWC	RWC	β (1/kPa, *1/psf*)	γ (kN/m^3, *pcf*)	γ_{sat} (kN/m^3, *pcf*)	Cohesion' (kPa, *psf*)	ϕ'
Silty Sand	USCS SM	Sample function-sand[1]	0.18 *0.6*[3]	0.5[4]	0.05[4]	$1.4x10^{-7}$ *$3.0x10^{-6}$*[4]	18.9 *120*[5]	19.6 *125*[3]	12.0 *250*[6]	31[6]
Sandy Silt	USCS ML	Sample function-silt[1]	$9.87x10^{-4}$ *$3.24x10^{-3}$*[3]	0.45[4]	0.045[4]	$5.3x10^{-7}$ *$1.1x10^{-5}$*[4]	17.3 *110*[5]	18.9 *120*[3]	9.58 *200*[6]	28[6]
Silt Clay	AASHTO A-4	Fredlund & Xing- a = 1128 psf, n = 0.859, m = 0.881[2]	$8.23x10^{-5}$ *$2.70x10^{-4}$*[3]	0.45[2]	0.045[2]	$1.4x10^{-7}$ *$3.0x10^{-6}$*[4]	17.3 *110*[5]	18.1 *115*[3]	19.2 *400*[6]	32[6]
Fine Sand	AASHTO A-3	Fredlund & Xing- a = 1409 psf, n = 3.845, m = 0.923[2]	1.5 *5*[3]	0.45[2]	0.045[2]	$1.4x10^{-7}$ *$3.0x10^{-6}$*[4]	18.9 *120*[5]	20.4 *130*[3]	0	37[6]
Clay	AASHTO A-6/USCS CL	Fredlund & Xing- a = 672 psf, n = 0.700, m = 0.700[2]	$1.65x10^{-5}$ *$5.40x10^{-5}$*[3]	0.43[2]	0.043[2]	$5.3x10^{-7}$ *$1.1x10^{-5}$*[4]	16.5 *105*[5]	17.3 *110*[3]	19.2 *400*[6]	27[6]

Notes: [1] Geostudio, [2] (NASEM 2010), [3] (Coduto et al. 2010), [4] (MDOT SHA 2020), [5] (FHWA 2006), [6] (MnDOT 2007). USCS: Unified Soil Classification System, AASHTO: American Association of State Highway and Transportation Officials, VWC: volumetric water content, K: hydraulic conductivity, SWC: saturated water content, RWC: residual water content, β: compressibility, γ: unit weight, ϕ': angle of internal friction.

In steady-state analyses, the impounded water level was maintained until equilibrium was reached inside the embankment; this is consistent with how dams are tested and applied to transportation embankments to be conservative. In the first rapid drawdown analysis, the water level similarly reached equilibrium, then was removed instantly. Water levels behind transportation embankments would likely not be maintained long enough to reach equilibrium (Briaud et al. 2016); actual water levels and impoundment durations would vary based on the storm event, embankment geometry, culvert, and local topography. Therefore, the non-equilibrium rapid drawdown test explored how the FS against upstream slope failure ($FS_{upstream}$) would change if the water level did not reach equilibrium, and instead rose steadily over 24 hours and was removed instantly. Although this test does not represent an actual hydrologic

scenario, it provided insight into the impact of water impoundment duration on embankment stability.

Table 2-3. *Summary of embankment analyses and modeling parameters tested, data collected, and software used. All heights (6.10, 9.14, and 15.2 meters), top widths (9.14, 15.2, and 24.4 meters), and soil materials (clay, fine sand, sandy silt, silty clay, and silty sand) were analyzed.*

Embankment Test	Water Levels (m)	Side Slope	Data Collected	FS	Design FS	Software	Numerical Model
Overtopping Erosion	6.1, 9.1, 15	NA	v_{max}, v_c	NA	NA	NA	NA
Seepage Through Embankment	1.5, 3.1, 4.6, 6.1, 9.1, 15	2H:1V, 4H:1V, 6H:1V	i_{exit}	FS_{piping}	1.5[1]	SEEP/W	Steady State
Seepage Under Embankment	1.5, 3.1, 4.6, 6.1, 9.1, 15	2H:1V, 4H:1V, 6H:1V	i_{exit}	$FS_{foundation}$	1.5[1]	SEEP/W	Steady State
Lateral Sliding/Spreading	1.5, 3.1, 4.6, 6.1, 9.1, 15	2H:1V, 4H:1V, 6H:1V	P_{water}, $P_{resistance}$	$FS_{spreading}$	1.5[2]	NA	NA
Downstream Slope Stability	1.5, 3.1, 4.6, 6.1, 9.1, 15	2H:1V, 4H:1V, 6H:1V	$FS_{downstream}$	$FS_{downstream}$	1.4[1]	SEEP/W, SLOPE/W	Steady State
Rapid Drawdown	1.5, 3.1, 4.6, 6.1, 9.1, 15	2H:1V	$FS_{upstream}$	$FS_{upstream}$	1.2[1]	SEEP/W, SLOPE/W	Transient
Rapid Drawdown-non-equilibrium	6.1	2H:1V	$FS_{upstream}$	$FS_{upstream}$	1.2[1]	SEEP/W, SLOPE/W	Transient

Notes: [1] (NRCS 2019), [2] (Holtz et al. 1998). NA: Not Applicable.

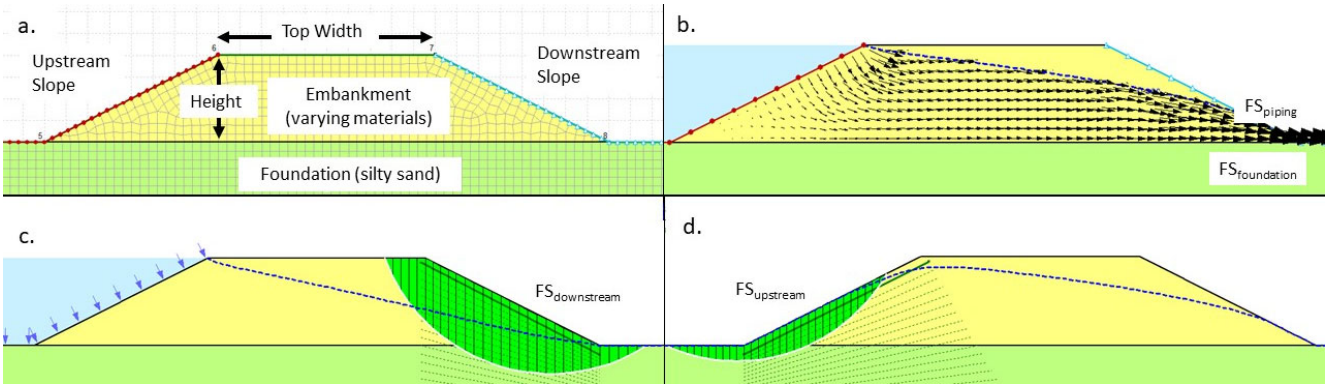

Figure 2-1. *GeoStudio inputs and outputs: a) embankment geometry features, (b) example seepage vectors and location of FS_{piping} and $FS_{foundation}$, (c) critical slip surface for $FS_{downstream}$, and (d) critical slip surface for $FS_{upstream}$.*

Additionally, the presence of a culvert would allow flow of water through the embankment and change water levels, thus altering the FS against piping through the embankment (FS_{piping}), FS against piping through the foundation ($FS_{foundation}$), FS against downstream slope failure ($FS_{downstream}$), and FS against upstream slope failure ($FS_{upstream}$). The culvert was omitted to be conservative, similar to past studies (e.g., MDOT SHA 2020). Also, omitting the culvert from the model represents the scenario where the culvert is blocked, which is a realistic outcome (Pedrozo-Acuña et al. 2017). Lastly, the impact of the culvert on the system would vary on a case-by-case basis and determining that impact would require a hydrologic analysis. The hydrologic analysis was outside the scope of this work due to the difficulty of generalizing local topographies and resultant flows to represent example embankment scenarios, lack of available culvert dimension inventories, and vast differences in storage volume behind embankments.

Overtopping Erosion

To determine if erosion occurs when the embankment is overtopped, the maximum velocity of water overtopping the embankment is compared to the critical velocity of the soil (Briaud et al. 2016). The maximum water velocity (v_{max}) was calculated conservatively based on conservation of energy in Equation 2-1, where g is acceleration due to gravity and h is embankment height (Briaud et al. 2016). A less conservative estimate would incorporate the effect of crest width, crest roughness, and nonzero tailwater, but these elements vary based on specific embankments and hydrologic scenarios. Therefore, for the example embankments, the conservative estimate below was selected.

$$v_{max} = \sqrt{2gh} \tag{2-1}$$

Critical velocity was calculated based on mean grain size of the material. Equation 2-2 was used for sands and Equations 2-3 and 2-4 were used for silts and clay as the lower and upper bounds, respectively; in these expressions, v_c is the critical velocity in m/s and D_{50} is the median grain size in mm (Briaud et al. 2016).

$$v_c = 0.35(D_{50})^{0.45} \quad (2\text{-}2)$$

$$v_c = 0.1(D_{50})^{-0.2} \quad (2\text{-}3)$$

$$v_c = 0.03(D_{50})^{-1} \quad (2\text{-}4)$$

Seepage

SEEP/W (Seequent 2021) was used to determine the seepage velocities and exit gradients within the embankment and foundation. Steady-state SEEP/W models were created according to the manufacturers manual (Geo-Slope International 2012) and exit gradient data was collected from the entire downstream slope and downstream foundation. The critical gradient (i.e., the gradient where the water begins to mobilize soil particles) was calculated for each material with Equation 2-5 where i_c is the dimensionless critical hydraulic gradient, γ_{sat} is the saturated unit weight, and γ_w is the unit weight of water (Briaud et al. 2016).

$$i_c = \frac{\gamma_{sat} - \gamma_w}{\gamma_w} \quad (2\text{-}5)$$

The maximum exit gradients in the embankment ($i_{\text{embankment exit}}$) and foundation ($i_{\text{foundation exit}}$) (Figure 2-2) were compared to the critical gradient for that material; FS_{piping} and $FS_{\text{foundation}}$ were calculated by Equations 2-6 and 2-7, respectively, where i_c is from Equation 2-5 and $i_{\text{embankment exit}}$ and $i_{\text{foundation exit}}$ were produced by the SEEP/W software.

$$FS_{piping} = \frac{i_c}{i_{embankment\ exit}} \tag{2-6}$$

$$FS_{foundation} = \frac{i_c}{i_{foundation\ exit}} \tag{2-7}$$

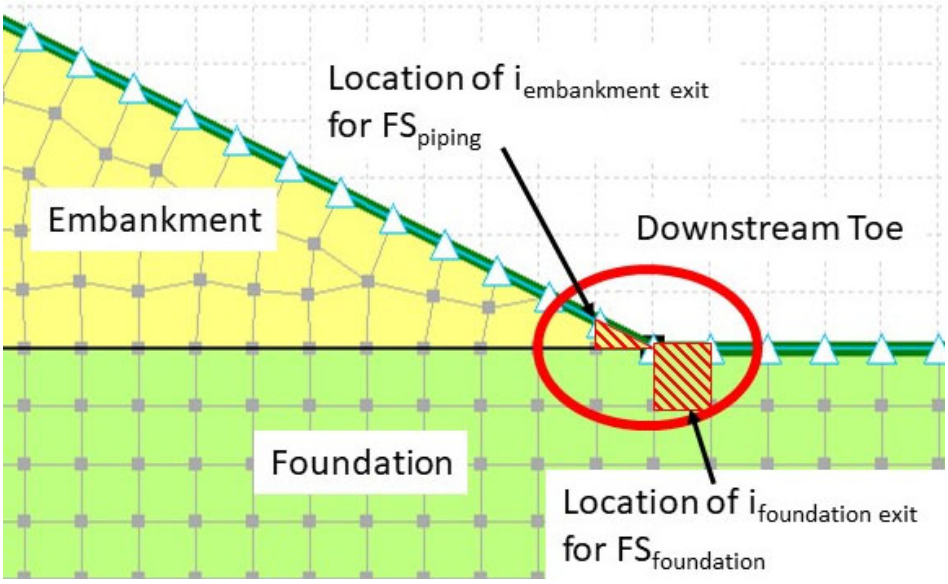

Figure 2-2. *Location of exit gradients for each seepage analysis.*

Lateral Sliding/Spreading

The horizontal force exerted by the water impounded behind the embankment was compared to the frictional resistance of the embankment to determine the FS against lateral sliding/spreading ($FS_{spreading}$). Equation 2-8 was used to calculate the lateral push of the water (P_{water}), where γ_w is the unit weight of water and h is the height of the embankment (Briaud et al. 2016). Equation 2-9 was used to calculate the frictional resistance ($P_{resistance}$), where γ is the unit weight of the embankment material, H is embankment height, b is the horizontal length from the downstream edge of the crest to the toe, and ϕ' is the internal friction angle of the fill. Equation 2-10 was used to calculate $FS_{spreading}$.

$$P_{water} = \frac{1}{2}\gamma_w h^2 \quad (2\text{-}8)$$

$$P_{resistance} = \frac{1}{2}\gamma H b \tan\varphi' \quad (2\text{-}9)$$

$$FS_{spreading} = \frac{P_{resistance}}{P_{water}} \quad (2\text{-}10)$$

Downstream Slope Stability and Rapid Drawdown

Upstream slope stability data due to rapid drawdown (transient) and downstream slope stability due to water impoundment behind the embankment (steady state) were evaluated using SLOPE/W (Seequent 2021). The SLOPE/W software uses the limit equilibrium method of slices and Morgenstern Price method to calculate the FS against instability for hundreds of slip surfaces (Geo-Slope International 2012). The lowest (most critical) FS was collected as $FS_{downstream}$ and $FS_{upstream}$ in the downstream slope stability and rapid drawdown tests, respectively.

Two rapid drawdown scenarios were evaluated: one where the impounded water reached equilibrium before rapid drawdown, and a second, non-equilibrium model where water levels increased for 24 hours, and then rapid drawdown occurred. Transient models were created and $FS_{upstream}$ values were recorded before drawdown, immediately after drawdown, and for five days following drawdown. $FS_{upsream}$ was used as an indicator of upstream slope stability.

Chapter 3 : Mid-Atlantic Policy Review

Dam Regulations

Each Mid-Atlantic State has its own regulatory definition for a dam as determined by its dam safety law (e.g., 4VAC50-20 1989). The definitions across the region are similar (Table 3-1); a dam is a structure that impounds a certain height and/or volume of water. Generally, transportation embankments are not intended to impound water and are thus designed and regulated differently. Throughout the Mid-Atlantic region, transportation embankments are not explicitly excluded from dam safety regulations, but the enforcing agency typically does not apply dam safety to transportation embankments (i.e., Delaware, Pennsylvania, West Virginia, Virginia, and New Jersey).

Table 3-1. *Regulatory definitions of dams in the Mid-Atlantic.*

State	Height (m)	Volume (m^3)	Drainage Area (ha)	Purpose	Other
MD	> 6.1	--	--	--	--
	--	--	> 260	--	--
	--	--	--	--	High or significant hazard
DE	> 7.6	--	--	--	Publicly owned and significant or high hazard
	--	> $6.2x10^4$	--	--	Publicly owned and significant or high hazard
PA	> 4.6	> $1.8x10^4$	0	Impounding water	--
	> 4.6	--	> 40	Impounding water	--
	--	> $6.2x10^4$	> 40	Impounding water	--
WV	> 7.6	> $1.8x10^4$	--	--	Roadfill generally excluded
	> 1.8	> $6.2x10^4$	--	--	Roadfill generally excluded
VA	> 7.6	> $1.8x10^4$	--	--	Does not include free flow structure (i.e., culvert)
	> 1.8	> $6.2x10^4$	--	--	Does not include free flow structure (i.e., culvert)
NJ	> 1.5	--	--	--	--
NY	> 4.6	> $4.6x10^3$	--	--	--
	> 1.8	> $1.3x10^4$	--	--	--

Additional guidance exists to regulate small dams. Notably, NRCS Code 378 is used in many states to regulate small and low hazard ponds which: do not result in loss of life or significant damage upon failure, have a storage (m^3) times effective height (m) < $1.1x10^6$, are hazard class "a" (ponds where failure may only damage non-inhabited buildings, farmland, or floodplains), and are < 10.7 meters (35 feet) tall (NRCS 2011). There are slight differences among states' adaptation of the code (e.g., it can only be used for agricultural ponds in Virginia), but they are very similar.

Culvert Design

New Jersey DOT (NJDOT) (2015), New York DOT (NYDOT) (2021), and Pennsylvania DOT (PennDOT) (2015) explain in their drainage/highway manuals that highway embankments can be barriers to flow and therefore may impound or detain water under some circumstances. Additionally, PennDOT requires that transportation embankments with deep ponding be investigated for catastrophic failures, because the breach in highway fill could be similar to dam failure (2015). Table 3-2 summarizes flood recurrence intervals used for design and testing of culverts and other design requirements, such as headwater over diameter ratio (H_W/D), requirements for allowable headwater (AH_W), and permitted water surface elevation (WSEL) changes.

Some states recommend or require structures to protect the upstream embankment from damage due to the AH_W. Virginia DOT (VDOT) and West Virginia DOT (WV DOT) require headwalls with cut-off walls for culverts greater than 1.2 meters (48 inches) and 0.91 meters (36 inches) diameter, respectively, to improve embankment stability, prevent erosion, and minimize piping and undermining along the culvert (VDOT 2021; WV DOT 2007). NJDOT and PennDOT recommend end structures to prevent erosion and keep embankment material in place; also,

PennDOT recommends using methods such as watertight joints, anti-seep or cutoff collars, or weep holes to reduce the velocity and quantity of seepage flow when upstream ponding is a part of the culvert design (NJDOT 2015; PennDOT 2015).

Table 3-2. *Culvert design regulations in the Mid-Atlantic states.*

State	Culvert classification method	Culvert design return period (years)	Culvert test storm	HW/D	Other requirements	Ponding?	Source
MD	AASHTO Classification	Expressways (100), Arterials (50), Collectors (25), Local Roads (10)	100-year	< 1.5	AH_W below shoulder, not increase 100-year floodplain	No	(MDOT SHA 2009)
DE	Functional Classification	Expressways, Arterials, and Urban Collectors (50), Rural collectors and local roads (25)	Design storm	NA	AH_W 0.15 m (6 in) below roadway, ideally 0.30 m (1 ft) below	No	(DelDOT 2008)
PA	Location	Urban (100), Suburban (50), Rural (25)	100-year	NA	Cannot increase WSEL > 0.30 m (1 ft) above pre-culvert conditions	Yes, follow dam safety	(PennDOT 2015)
WV	Roadway Type	Divided highways and principal arterials (50), highways > 400 ADT (25), highways < 400 ADT (10)	100-year or overtopping	< 1.5	Ensure WSEL is below subgrade and does not divert flow around the culvert	Yes, for flow detention	(WV DOT 2007)
VA	Roadway Type	Freeway and Urban Minor Arterial (50), Rural Minor Arterial and Major Collector (25), Minor Rural and Major Urban Collector and Local Street (10)	Design storm	$1< H_W/D < 1.5$	Impounded water 0.46 m (18 in) below shoulder	Yes, requires special design	(VDOT 2021)
NJ	Facility Description	Requires NJDEP permit for non-delineated stream (100), Freeway (50), land service highway (25)	Design storm	NA	Max WSEL is to top of culvert (new structures) or outside edge of road (existing)	Yes, if sufficient storage below AH_W	(NJDOT 2015)
NY	All	50	100-year		Avoid raise in headwater and WSEL reaching pavement sub-base	No	(NYDOT 2021)

Notes: ADT: Average Daily Traffic, NJDEP: New Jersey Department of Environmental Protection, DelDOT: Delaware DOT, NA: Not Applicable

Failures

A handful of transportation embankment failures due to excess water were discussed in the interviews. Both Delaware Natural Resources and Environmental Control (DNREC) and New Jersey Department of Environmental Protection (NJDEP) shared reports of dual-purpose road-dams that had been damaged during extreme rain events including severe rain in 2004, Hurricane Irene in 2011, and a rainstorm combined with tidal surges in 2016. Damages included overtopping, scour, partial road collapse, and upstream and downstream erosion (Figure 3-1) (DNREC 2016; Oman and Hatala 2011; Oman and Tamagno 2004). Virginia Department of Conservation and Recreation (VADCR) shared a report of an embankment failure on Virginia Route 54 where the spillway outlet pipe failed and caused washout of the crest and roadway (Killgore 2022; Pittman 2018). Because the height (5.5 meters) and storage volume ($7.0x10^4$ m^3) of the transportation embankment met dam regulations, the existing control structure will be replaced with open culverts to avoid designing the embankment as a dam (Pittman 2018). Lastly, a Maryland embankment (U.S. Rt. 50) experienced severe erosion of its slopes in 2011. The slopes were repaired with Geoweb, a vinyl web secured to the side slope and filled with soil (Figure 3-2) (Presto Geosystems 2016).

Figure 3-1. *Damage to upstream slope following overtopping of Pleasant Mills Dam, New Jersey (left, from Oman and Hatala 2011), and downstream damage to Chipman's Pond Dam, Delaware (right, from DNREC 2016). Arrows indicate the direction of flow.*

Figure 3-2. *Installation of Geoweb on eroding Rt. 50 slope, Maryland (from Presto Geosystems 2016).*

Solutions

A common theme among interviews was that state DOTs avoid designing transportation embankments that would otherwise meet the regulatory definition of a dam (i.e., Virginia, New York) and emphasize that culverts designed for a 50-year storm would result in rare and temporary water impoundment (i.e., Delaware, New York) (Hastings and Shute 2021; Matthews 2021; VanKampen 2021). Furthermore, West Virginia Department of Environmental Protection (WVDEP) has investigated about half a dozen transportation embankments with temporary water impoundment and found that water levels are "low" compared to the road level, or, in one case, analysis of the embankment under the PMF storm indicated that seepage failure would only cause half of one lane to fail, so WVDEP decided not to pursue dam regulations (Shriver 2021). Lastly, NYDOT inspects large culverts (> 1.5 meter diameter) on a two-year cycle to decrease risks of blockage (NYDOT 2021; VanKampen 2021).

Some states are working to account for increased future runoff due to predicted climate change. NYDOT applies multipliers (1.1x or 1.2x) to test storms based on culvert location (VanKampen 2021). PennDOT noted that it has seen many failures recently associated with large storm events; rain data indicate that climate change and weather pattern changes are to blame for

losing structures that were not originally thought to be susceptible to flood damage (such as low/small embankments) (Vivian 2021). PennDOT conducted an extreme weather vulnerability study to determine how to adapt infrastructure to climate change (PennDOT 2017); they are considering using 500-year test storms (Vivian 2021).

Maryland is the only Mid-Atlantic state to apply dam safety to transportation embankments. Two dam safety memoranda apply Maryland Code 378 to transportation embankments that impound a significant amount of water (MDE 2022a). First, MDE states that transportation embankments must be designed to not impound water by using sufficiently sized culverts, but if they do impound water, they must be regulated and operated as dams (MDE 2022a). If a transportation embankment with a height > 10.7 meters (35 feet) satisfies one of the following criteria, it must be designed as a dam:

- The difference in height between the headwater (upstream) and tailwater (downstream) is > 3 meters (10 feet) and the $H_W/D > 2$,
- A permanent pool with a depth > 0.9 meters (3 feet) is present,
- The culvert includes a water control structure (e.g., riser, weir), or
- Pipe capacity has been decreased to manage stormwater discharges (MDE 2022a).

Embankments that have < 3 meters (10 feet) of height (as measured from the downstream toe to the crest) can be exempt under specific criteria. Additionally, there are exceptions to the dam safety procedures if the transportation embankment is sufficiently wide relative to the volume and height of impounded water (Table 3-3) (MDE 2022b). A transportation embankment that meets both the criteria for a Maryland Code 378 dam and superwide embankment qualifies for exemptions: it is automatically low hazard, it does not require a breach analysis, and impervious

core and cutoff trench requirements can be waived. Superwide embankments must follow dam safety regulations, including: they must safely pass the 24-hour 100-year storm with 0.6 meters (2 feet) of freeboard, trees must be removed, utilities are discouraged, embankment materials must meet MDOT SHA guidelines, culverts must be reinforced concrete, and a filter diaphragm is required (MDE 2022b).

Table 3-3. *Minimum width of a transportation embankment defined as superwide according to MDE (2022b). Across the top, embankment heights in meters are 0-3 m, 3-4.6 m, 4.6-6.1 m, 6.1-9.1 m, 9.1-12.2 m, 12.2-15.2 m, 15.2-18.3 m, 18.3-21.3 m, 21.3-24.4 m, 24.4-27.4 m, and 27.4-30.5 m. The maximum storage volumes in cubic meters are $6.2x10^3$, $1.2x10^4$, $2.5x10^4$, $3.7x10^4$, $6.2x10^4$, $9.3x10^4$, $1.2x10^5$, $2.5x10^5$, $3.7x10^5$, $4.9x10^5$, $6.2x10^5$, and $1.2x10^6$ m^3. Widths in the table include 15 m (50 ft), 23 m (75 ft), 30 m (100 ft), 38 m (125 ft), 46 m (150 ft), 52 m (175 ft), 61 m (200 ft), 69 m (225 ft), 76 m (250 ft), 91 m (300 ft), and 107 m (350 ft).*

Maximum Storage Volume (Vw), acre-feet	Embankment Height (H), feet										
	0 to 10	10.01 to 15	15.01 to 20	20.01 to 30	30.01 to 40	40.01 to 50	50.01 to 60	60.01 to 70	70.01 to 80	80.01 to 90	90.01 to 100
5	50	50	50	50	50	50	50	50	50	50	50
10	75	50	50	50	50	50	50	50	50	50	50
20	125	75	50	50	50	50	50	50	50	50	50
30	175	100	50	50	50	50	50	50	50	50	50
50	250	150	100	50	50	50	50	50	50	50	50
75	350	200	150	75	50	50	50	50	50	50	50
100	Not Superwide	250	175	100	50	50	50	50	50	50	50
200		Not Superwide	300	175	100	50	50	50	50	50	50
300			Not Superwide	225	150	100	50	50	50	50	50
400				300	200	125	50	50	50	50	50
500				350	225	150	100	75	50	50	50
1000				Not Superwide	Not Superwide	300	225	175	125	75	50

The prevalence of rain-induced damages to and failures of transportation embankments in the Mid-Atlantic suggests that there are areas for improvement in design and management. The literature review (Chapter 4) examines scientific reasoning that could provide recommendations for changes. The geotechnical modeling (Chapter 5) uses seepage and slope stability analysis to further understand how transportation embankments behave when subjected to temporarily impounded water during large storms.

Chapter 4 : Synthesis of Literature

This literature review focuses on the current design and management of transportation embankments, including geometry, materials, drainage, culvert/spillway, inspection and maintenance, and failures. Additionally, these aspects of transportation embankments are compared with those of dam embankments. First, the flooding-related risks to transportation embankments are discussed (e.g., water impoundment and overtopping). Next, design of embankments is discussed, followed by management. Lastly, failures in experimental settings and case studies are discussed.

Typical Failure Modes of Embankments

Earth embankments are susceptible to hydraulic problems such as overtopping, seepage, and rapid drawdown due to their permeable and erodible construction materials (Adamo et al. 2020; Hou et al. 2021; Zhang et al. 2009). A recent TRB synthesis report asked state DOTs to rank failure modes of transportation embankments; the determined order, from most common to least common, was overtopping erosion (50%), soil softening by saturation (i.e., rapid drawdown) (31%), seepage/internal erosion (19%) (Briaud et al. 2016). These failure modes are described below in the context of transportation and dam embankments.

Overtopping. Overtopping occurs when the water level rises over the embankment crest; the resulting erosion can cause the embankment to breach and very frequently results in embankment dam failure (Powledge et al. 1989). Overtopping can result in structural damage to the culvert or embankment, such as pavement damage, scour/erosion, and culvert/structure collapse (FHWA 2016b). Embankments composed of granular materials are also susceptible to

breach during overtopping (Johnston et al. 2021). Figure 4-1 illustrates the process and damage of overtopping.

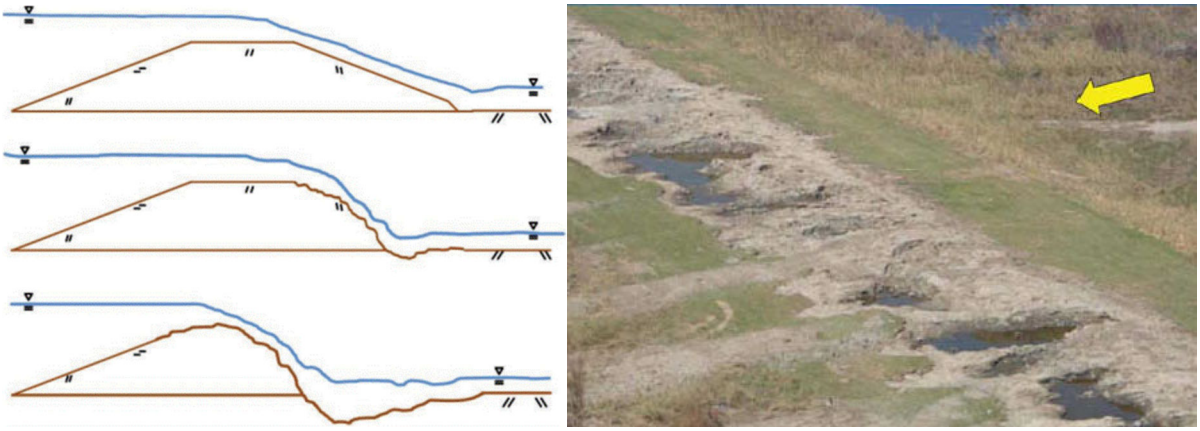

Figure 4-1. *Illustration of the progression of transportation embankment overtopping and erosion (left) and image of roadway washout due to embankment breach from overtopping during Hurricane Katrina in 2005 (right) (from Briaud et al. 2016).*

Rapid drawdown. Rapid drawdown occurs when the water level in the reservoir decreases quickly (Adamo et al. 2020). When the water declines, the newly exposed upstream slope has low strength and stiffness (effective strength parameters), but no longer has horizontal water pressure supporting it, which can result in a slope stability failure (Figure 4-2) (Hou et al. 2021). Unlike dams that are designed to permanently hold water, transportation embankments might not experience a storm where a water level is maintained long enough to result in soil saturation, and damage from rapid drawdown in highly dependent on the duration of high water levels (Briaud et al. 2016).

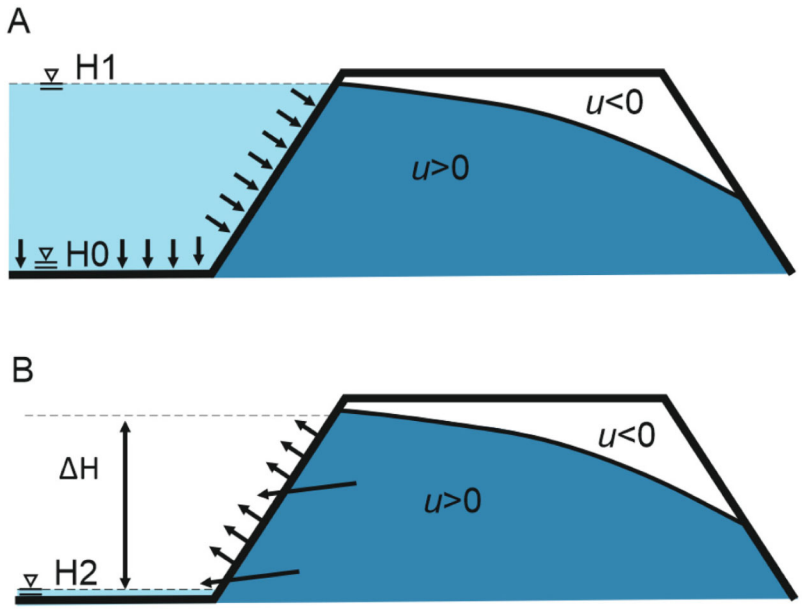

Figure 4-2. *Image A shows impounded water and the resultant phreatic line in the embankment. Image B shows the decrease in water level (rapid drawdown) and remaining saturation leading to slope instability (from Johnston et al. 2021). H0, H1, and H2 are the water heights at time 0, 1, and 2, respectively, ΔH is the change in height from time 1 to time 2, and u is the porewater pressure.*

Seepage/internal erosion. Internal erosion occurs when large hydraulic forces create water seepage through or under the embankment, mobilizing soil particles (Ali et al. 2021). Seepage will occur in any earth embankment that is impounding water; seepage only becomes an issue when it is uncontrolled, such as when large gradients occur during flood events (FERC 2006; Zhang et al. 2009). Internal erosion is one of the most common modes of embankment failure and 46% of damaged or failed embankment dams experienced internal erosion (Dallo et al. 2014). Although internal erosion is more commonly associated with dams and levees, it is a recorded cause of failure in transportation embankments (Figure 4-3) (Polemio and Lollino 2011). Similar to dam embankments, transportation embankments can experience backward erosion (Figure 4-4), concentrated leak erosion, and soil contact erosion (Briaud et al. 2016). Culverts in transportation embankments are a soil-structure interface that can serve as a location

for internal erosion to initiate (Kim et al. 2019), particularly causing sinkholes (Taher and Moore 2011).

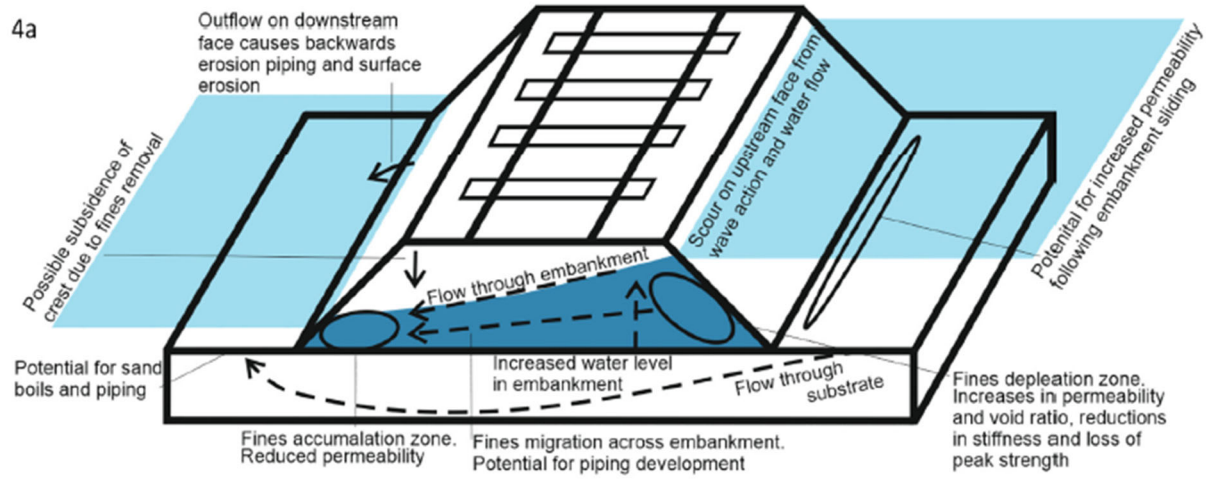

Figure 4-3. *Illustration of seepage and damage mechanisms to the embankment during an offset head flood (from Johnston et al. 2021).*

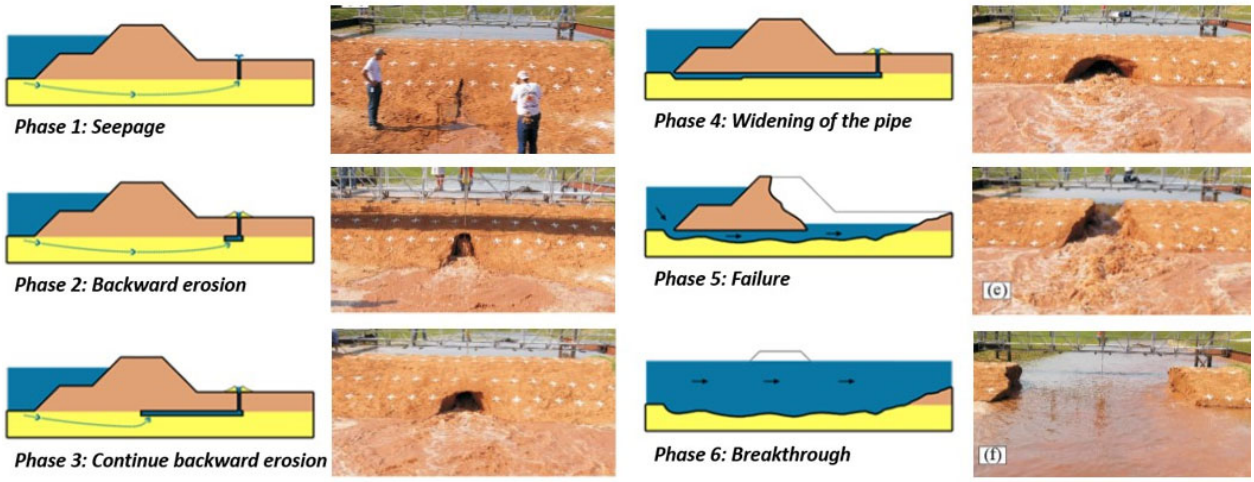

Figure 4-4. *Process of backwards erosion piping adapted from USBR (2019) and ASCE/EWRI (2011).*

FHWA maintains design guidance for addressing the above risks to transportation embankments (FHWA 2016b), such as:

- Focus on resiliency in the planning, design, and management of transportation embankments to prepare for increased precipitation
- Expect design storm exceedance during the structure's lifespan and understand the resultant risks and consequences
- Design embankments to be safely overtopped without causing breach risk or significant damage to the embankment

Flooding Impacts on Embankments

Transportation embankments are not designed with water impoundment as a major consideration, however, they constitute barriers to flow when intersecting streams, rivers, or drainage basins (Figure 4-5) (Johnson 2002). Additionally, many transportation embankments are subject to costal, surface, and river floods, with about 7.5% being vulnerable to the 100-year flood (Koks et al. 2019). Flooding and temporarily impounded water behind transportation embankments are management challenges in the U.S. (Briaud et al. 2016). In addition to immediate failures as described in the prior section, high water levels can reduce the lifetime performance of the embankment by increasing the frequency of landslides, road washouts, and road closures (Pedrozo-Acuña et al. 2017). It is estimated that damages to roadways and transportation embankments during years with extreme floods cost the U.S. $60 million annually (Richardson et al. 2001).

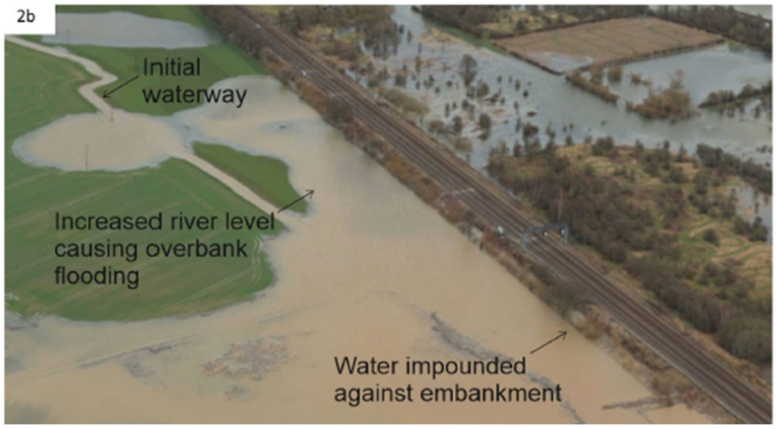

Figure 4-5. *Road embankment impounding water (from Johnston et al. 2021).*

Polemio and Lollino (2011) determined that temporary water impoundment occurs due to hydraulic inadequacy of the existing drainage structures; either the culvert is too small for the flood event or is obstructed by debris during the event. A 2005 flood event in Italy that damaged several transportation embankments (Figure 4-6) and killed six people was exacerbated by an undersized culvert (Polemio and Lollino 2011).

Figure 4-6. *Breached railway embankment during 2005 flood event in Italy (from Polemio and Lollino 2011).*

Many transportation embankments are currently hydraulically inadequate because they were designed for the 25-year storm event at the time of construction; land use change since design and increase in storm intensity have resulted in greater water arrival rate at the

embankments (Keller and Ketcheson 2011). The frequency of extreme hydrologic events has increased due to climate change, and associated flooding risks are greater (Tabrizi et al. 2017b). Precipitation has shown upward trends in the Eastern U.S., with average precipitation increasing 5% in the past 50 years (Peterson et al. 2013). Additionally, the intensity and frequency of extreme precipitation events is projected to increase throughout the U.S. (Butcher 2021). Therefore, most existing culverts do not have sufficient capacity to pass current and future storms safely and the resulting hydraulic inadequacy can result in water impoundment (Pedrozo-Acuña et al. 2017). Although water impoundment is an emerging issue, there is a lack of research on performance of transportation embankments during overtopping (Gao et al. 2020).

Embankment Design

Several elements are common to the design of all embankments, including materials, shape, and additional features (Figure 4-7). Each of these elements will be discussed in the context of flooding and impounded water.

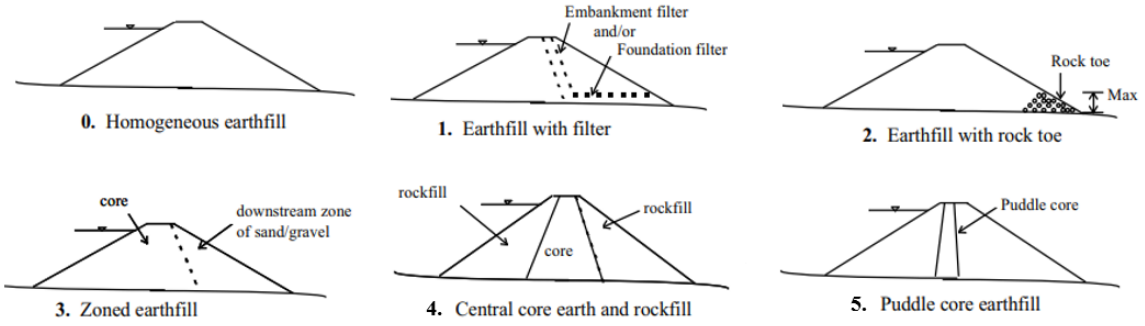

Figure 4-7. *Types of embankment dams (from ICOLD 2017).*

Materials

Transportation embankments are composed of native materials that meet compaction requirements, i.e., dry unit weight-water content requirements. These materials could theoretically include a wide range of particle sizes and properties compared to uniformly graded highway base materials (Figure 4-8). Table 4-1 lists differences in properties of materials generally used in embankments, which are discussed below.

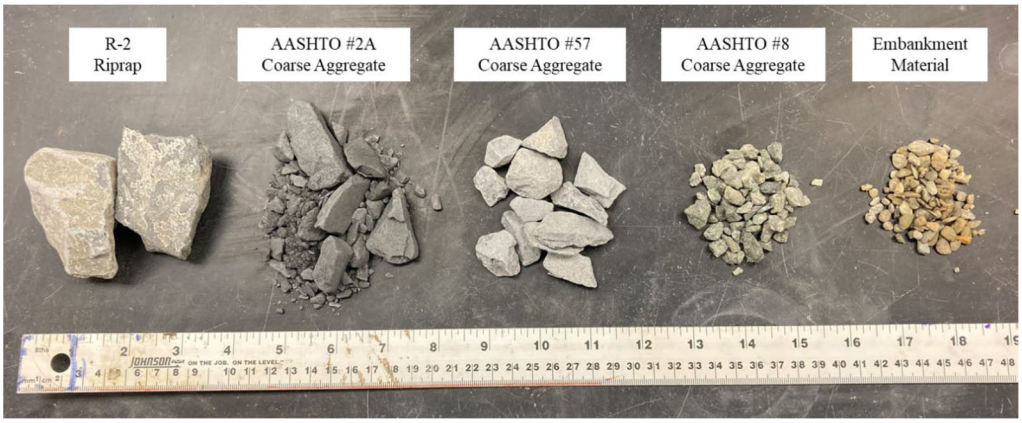

Figure 4-8. *Different grain sizes used in highway construction (from Gao et al. 2020).*

Unit weight is strongly influenced by compaction and moisture content (FHWA 2016a). As compaction increases, embankments are able to better withstand overtopping conditions (Tabrizi et al. 2017a). Additionally, Xie et al. (2019) found that compaction improved resistance of the soil to interfacial seepage. Both transportation and dam embankment regulations include specifications for compaction as percentages of maximum dry density (minimum void ratio that can be achieved in the laboratory). For example, MDOT SHA requires 92% of maximum dry density obtained using modified Proctor compaction effort (MDOT SHA 2021). Similarly, Maryland Code 378 requires 95% of maximum dry density per standard Proctor compaction effort (NRCS MD 2000).

D_{50} (median grain size) is one of the most important characteristics that controls embankment erodibility (Tabrizi et al. 2017a). Small coarse particles such as fine sand are most erodible during overtopping, but the finest particles (silt and clay) are controlled by electrostatic and electromagnetic forces, therefore, clays are generally the least erodible (Briaud et al. 2016).

Hydraulic conductivity controls the seepage rate through the embankment. Soils with hydraulic conductivity greater than 0.036 m/hour, such as clean sands, clean sand and gravel mixtures, and gravels, have good drainage (Gao et al. 2020). High conductivity allows water to move through the transportation embankment, decreasing the upstream and downstream head difference during storm events, which decreases water velocities, likelihood of overtopping, and piping potential (Gao et al. 2020). Clays are selected for dam embankments, on the other hand, due to their low hydraulic conductivity (Adamo et al. 2020).

Cohesion is a measure of attraction between soil particles (Yokoi 1968). Increasing cohesion increases slope stability (Mowafy et al. 2015). Internal friction angle represents how the individual soil grains interlock. Together with cohesion, it influences the soil shear strength, or the resistance of the soil to shear stress (Sidle 1985). Shear strength, while not reported in many of the experiments of Table 4-1, is an important indicator of the loads the soil is able to withstand (FHWA 2016a). Mixtures with sand tend to have higher shear strength (Vaughan et al. 2004).

Table 4-1. *Summary of geotechnical properties of materials used in construction of transportation embankments.*

Material Name	Class	Unit Weight (kN/m^3, *pcf*)	D_{50} (mm)	Cohesion, c (kPa, *psf*)	Hydraulic Conductivity, K (m/hr, *ft/hr*)	Internal friction angle, ϕ (°)	Source
Sand	NA	16.2 *103*	0.091	NA	NA	NA	Zhu et al 2011 experiment
Sand-Silt-Clay Mixture	NA	19-19.2 *121-122*	0.053-0.063	NA	NA	NA	Zhu et al 2011 experiment
Clay	CL [1], A-6 [2]	17.3 *110*	0.04	NA	6.7-18 x10^{-6} *2.2-5.8 x10^{-5}*	NA	Clopper and Chen 1988 experiment
Sand-Silt-Clay Mixture	SM-SC [1], A-4(0) [2]	19.1 *121.5*	0.045	NA	2.5 x10^{-6} *8.3 x10^{-6}*	NA	Clopper and Chen 1988 experiment
Clay silts	NA	13-14.6 *83-93*	0.01-0.02	19-51 *397-1065*	0.0034-0.013 *0.011-0.043*	30-32	Xie et al 2019 experiment
Clay	CL [1], A-6 [2]	14.8-18.7 *94-119* [3]	0.0005-0.001 [4]	9.6-19 *200-400* [5]	3.4 x10^{-9} – 3.4 x10^{-5} *1.1 x10^{-8} - 1.1 x10^{-4}* [6]	18-28 [5]	NA
Silt Clay	A-4 [2]	14.8-18.7 *94-119* [3]	0.002-0.005 [4]	9.6-19 *200-400* [5]	NA	18-32 [5]	NA
Sandy Silt	ML [1]	14.8-18.7 *94-119* [3]	0.006-0.01 [4]	9.6-19 *200-400* [5]	NA	25-32 [5]	NA
Silty Sand	SM [1]	17.1-19.6 *109-125* [3]	0.02-0.06 [4]	9.6-19 *200-400* [5]	0.034-0.34 *0.11-1.1* [6]	31-34 [5]	NA
Fine Sand	A-3 [2]	17.1-20.6 *109-131* [3]	0.02-0.06 [4]	0 [5]	0.034-3.4 *0.11-11* [6]	37-38 [5]	NA

Notes: [1] Per Unified Soil Classification System (USCS), [2] Per American Association of State Highway and Transportation Officials (AASHTO) Classification System, [3] FHWA (2017), [4] Krumbein (1934), [5] (MnDOT 2007), [6] Coduto et al. (2010). NA: Not Available.

Several researchers have tested homogenous embankments in laboratory-scale experiments to observe their susceptibility to different failure mechanisms related to erosion. Soil mixtures including fine materials are desirable in withstanding overtopping erosion longer; silty clayey sand outperforms clay (Clopper and Chen 1988), sandy mixtures outperform pure gravel (Kansoh et al. 2020), and sand-silt-clay outperforms sand (Zhu et al. 2011). In tests of internal erosion and piping, clay rich soils are more likely to withstand interfacial seepage and piping; lean (low plasticity) clay eroded internally more slowly than silty sand (Ali et al. 2021)

and critical hydraulic gradient increased with increasing clay content (21.8-29.8% clay) (Xie et al. 2019).

Shape

Shape descriptors includes top width (W), height (H), and side slopes. Transportation embankments are designed based on the roadway characteristics; multiple lane highways have large top widths to accommodate the wide road. Additionally, the height and side slopes are both influenced by the surrounding terrain. Side slopes are typically made as shallow as possible (2H:1V or flatter) to improve safety and recovery of vehicles that leave the road (MDOT SHA 2016b). Dam embankment shape is selected to maintain stability of the embankment during given design flows. Height is based on expected water elevation plus a freeboard. Top width and side slopes are based on a geotechnical analysis of embankment materials, or, for some low hazard dams, based on details in the Code 378 standard (NRCS 2011, 2019) .

Kansoh et al. (2020) conducted lab-scale breach studies where pure sand embankments impounded a brimful level of water. They found that increasing the top width increased the time to failure. The initial height did not influence the rate of embankment breach, but time to full breach and resulting peak flows were greater for the taller embankments because they have the capacity to impound more water. Additionally, shallower slopes result in decreased shear stress on the soil particles, increasing time to failure, as opposed to steep slopes.

The American Society of Civil Engineers (ASCE) developed a summary report about predictor equations, based on case study failures and simulations, for breach parameters of embankments (time to breach, breach size and shape, peak outflows) in order to determine likelihood of total embankment failure (ASCE/EWRI 2011). Of the embankment shape

characteristics, the 21 equations presented utilized only height and downstream side slope. Wang et al. (2016) developed a physical model that directly uses the embankment height to predict peak breach flows, using a single empirically-derived coefficient that broadly covers several embankment characteristics, including geometry, material, embankment reinforcement, and construction methods. Developing these empirical models is difficult due to limited historical records (Kansoh et al. 2020). However, the development of these formulas shows that prediction is possible without knowing all the specific embankment parameters such as top width, side slope, and materials. The uncertainty in the predictor equations and the research by Kansoh et al. (2020) on the influence of embankment shape indicate that these unincorporated parameters may be important in predicting breach characteristics.

Other Features

Both dams and transportation embankments may include additional features to improve performance, for example, clay core, drainage, filters, flowable fill, geosynthetics, and vegetation. Table 4-2 summarizes these features.

Table 4-2. *Additional features included in embankments.*

Feature	Definition	Usage	Purpose	Notes
Clay core	Zone of impermeable/clay material (K < 3.6 x10^{-3} m/hr[1]) (Figure 10)[2]	Dams	• Reduce seepage and potential for piping[3] • Allow permeable fill (such as sand or gravel) to make up outside shell, giving the dam greater weight and stability[1]	• Can be a location for initiation of contact erosion[4] • High porewater pressures might need to be controlled with internal drainage[1]
Drain	Zone of coarse, permeable material[2]	Dams	• Lower phreatic line[2] • Controlled seepage removal[2] • Prevent internal erosion[2] • Improve downstream slope stability[2]	• Typically paired with a filter so that seepage water can move freely, but the embankment material is not eroded[5]
Filter	Layer of materials between the fill and the drain[5]	Dams	• Prevent removal of fines[5] • Prevent interfacial seepage flow[6]	• Effective in increasing the critical hydraulic gradient in silt-clay embankments[6]
Flowable Fill	Mixture of aggregate and cement with high water content[7]	TE	• High flowability and low strength material that can be poured around the culvert[7] • Reduce interfacial seepage[8]	• Does not rely on compacting the fill around the culvert[7]
Geosynthetics	Polymeric fabrics[9]	TE	• Subsurface drainage[9] • Erosion control[9]	• Geosynthetics wrapped around the core of the embankment help to increase strength when saturated, prevent erosion, improve stability, and possibly reduce piping[8]

Vegetation	Grasses and other vegetation planted on the side slopes of embankments	Both	• Reinforce slopes[10]
			• Improve wildlife habitat[10]
			• Provide visual and auditory buffers[10]
			• Overtopping protection on low hazard dams[11]
				• Deep rooted vegetation recommended on TE for overtopping erosion control[12]
				• Deep roots not acceptable on dams as
				  ○ Roots can initiate internal erosion[13]
				  ○ Water demand can deform the embankment[14]
				  ○ Can attract burrowing animals that dig seepage routes[15]

Notes: [1] FERC 2006, [2] Adamo et al. 2020, [3] Kansoh et al. 2020, [4] Briaud et al. 2016, [5] Dallo et al. 2014, [6] Xie et al. 2019, [7] Chittoori et al. 2014, [8] Gao et al. 2020, [9] Wu et al. 2020, [10] Glendinning et al. 2009, [11] Temple and Hanson 1998, [12] Keller and Ketcheson 2011, [13] Ali et al. 2021, [14] Briggs et al. 2017, [15] Calamak et al. 2021. TE: Transportation Embankment

Hydraulics

Culverts/Principal Spillways

The primary way that water flows through an embankment is through a culvert or principal spillway. Culverts are commonly used in transportation embankments and are typically sized for a particular design storm based on the roadway [e.g., MDOT SHA (2009)]. A PSP plus a riser are used in dams and are sized based on the storage of water (Figure 4-9). The two structures can be very similar, but because transportation embankments do not serve to impound water, culverts are often larger and do not include a riser structure.

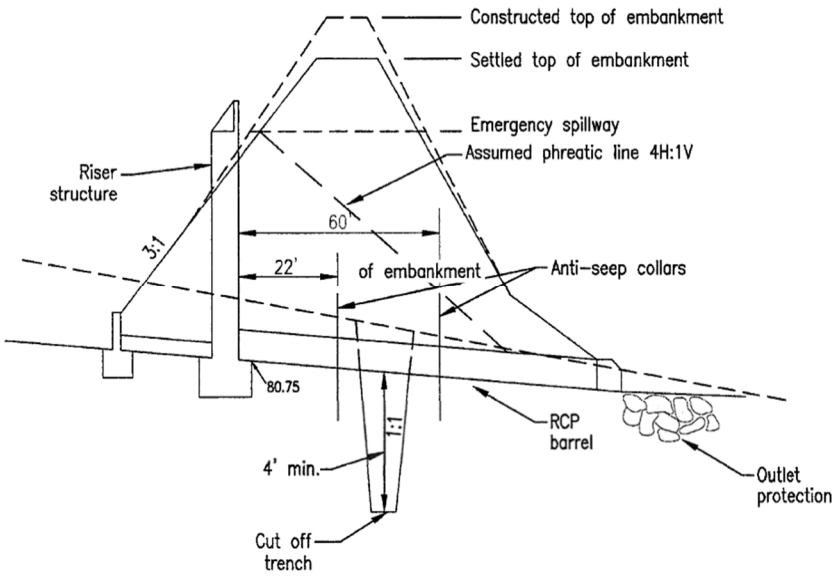

Figure 4-9. *Principal spillway pipe with riser in embankment dam (from VA DEQ 2011).*

A lack of capacity to convey storm flow can have several implications for the culvert and embankment arising from impounded water. The stream may leave its preferential flow path, causing upstream erosion of the streambed and embankment (Trueheart and Dewoolkar 2019). Buildup of hydraulic head could increase gradients and piping potential (Kim et al. 2019). Water could overtop the embankment, the culvert could be washed out, or at the end of the culvert's lifespan, the materials can become weak and collapse, forming an initial pipe for piping failure

(Hasan and Hossain 2019). Lastly, poorly designed culverts allow siltation to occur, which can fill the culvert with sediment and reduce outflows, or debris carried by storm events can cause jams at the culvert and significantly reduce capacity (Johnson 2002). A technique to avoid debris blockage of culverts is to implement trash racks (Keller and Ketcheson 2011).

Typically culverts are designed by determining the peak flow of a selected design storm and ensuring the culvert can pass that peak flow without causing damage to the roadway or loss in service (FHWA 2016b). Table 3-2 outlines common design storm return periods for culverts in the Mid-Atlantic. Designing culverts based on design storms may lead to hydraulic inadequacy under climate change and land use change (Richardson et al. 2001). A case study by Butcher (2021) illustrates that a culvert designed today for a 50-year event according to FHWA standards would result in a 16% risk of roadway overtopping during the 50-year event of 2055 and 30% risk of roadway overtopping during the 50-year event of 2085 (Figure 4-10). For reference, culverts should be designed to have the same service life as the roadway on the embankment, which can range from 50-100 years (i.e., MDOT SHA 2009) according to these standards (FHWA 2016b). Culverts are difficult to replace, and therefore, it is important to predict changes in flows so that the culvert retains appropriate capacity throughout its design life (Butcher 2021).

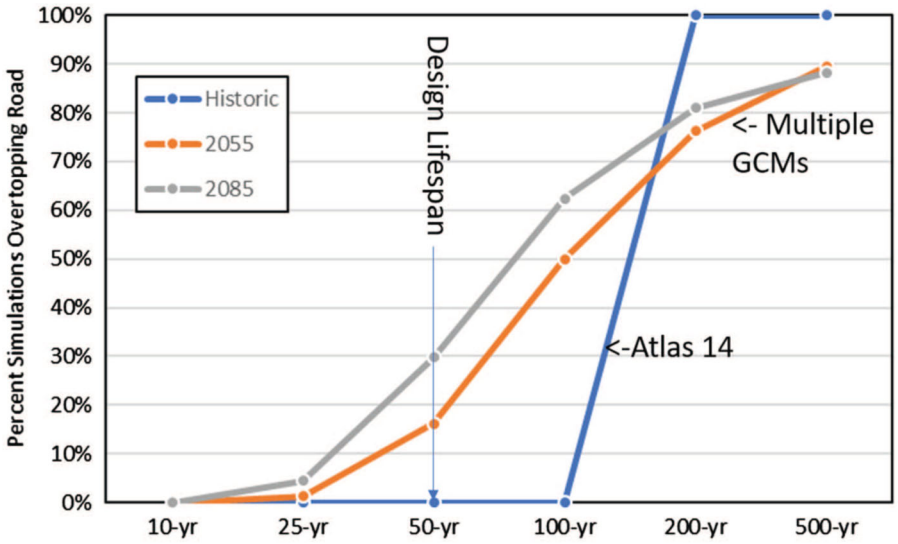

Figure 4-10. *Modeled risk of overtopping an example roadway with culvert in Maryland using different precipitation models (from Butcher 2021). "Atlas 14" refers to the National Oceanic and Atmospheric Administration Atlas 14 Intensity-Duration-Frequency (IDF) curves based on historical precipitation data, frequently used for infrastructure design* (NOAA 2017). *"Multiple GCMs" refers to an amalgamation of global climate models (GCM) that predict precipitation in 2055 and 2085.*

One concern with increasing the capacity of culverts to accommodate larger flows is that existing constricting culverts attenuate peak flows and may be relied upon to control downstream flooding (Trueheart and Dewoolkar 2019). However, Figure 4-11 shows the modeled culvert and overtopping flows in a case study conducted by Trueheart and Dewoolkar (2019) on transportation embankments with culverts during extreme (500-1000-year) flows; these results indicate that the flows from an overtopped (or breached) embankment would be far greater than those from an enlarged culvert. Because smaller culverts have greater risk of overtopping; enlarging some culverts would probably not significantly change the downstream flow regime. Keller and Ketcheson (2011) also recommend increasing the culvert capacity, specifically limiting the Hw/D ratio to 1.0-7.0. Additionally, an adequate culvert design accounts for debris and is positioned with the natural stream to reduce plugging capacity (Keller and Ketcheson 2011).

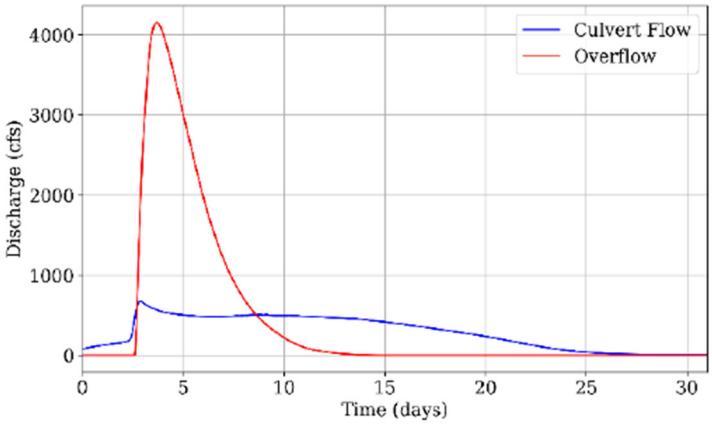

Figure 4-11. *Modeled flows through a transportation embankment including culvert flow and overtopping flow (from Trueheart and Dewoolkar 2019). The x-axis is time in days since the start of the storm event. The y-axis is discharge as 28.3 m^3/s (1000 ft^3/s), 56.6 m^3/s (2000 ft^3/s), 85.0 m^3/s (3000 ft^3/s), and 113 m^3/s (4000 ft^3/s).*

Emergency Spillway

Dams include emergency spillways to safely remove water when water levels surpass normal or design values. The emergency spillway in large dams usually passes the PMF so that the dam embankment remains intact under all foreseeable circumstances [e.g. VA DCR (2018)]. Transportation embankments do not include emergency spillways, but overtopping of the roadway can be considered as an emergency spillway (Trueheart and Dewoolkar 2019). Further, researchers and FHWA encourage overtopping as a design mechanism in both dam and transportation embankments (e.g. Abt et al. 2013, FHWA 2016). Because culverts in transportation embankments are sized for specific design storms, they are likely to become hydraulically inadequate within their lifetimes, potentially resulting in overtopping (FHWA 2016b). Therefore, safe overtopping of embankments should be considered, and is feasible if the embankment is adequately protected (Jin et al. 2022). Methods of preserving stability under overtopping include reinforced vegetation, flexible armoring, sacrificial embankment sections,

using coarse compacted embankment fill, culvert concrete headwalls, berms, soil cement, and riprap (Abt et al. 2013; Keller and Ketcheson 2011; Powledge et al. 1989).

Inspection and Maintenance

Historically, Perry et al. (2003) documented that transportation embankments are inspected and maintained in a reactive manner when damages disrupt the performance of the roadway; however, proactive maintenance should occur, especially as embankments age. A more recent study by Mamdouh and Tran (2020) found that the capacity for conducting routine inspections is hindered by funding and staff constraints and state agencies are in need of methods for prioritizing inspections. This lack of routine inspection and maintenance can result in blockage, clogging, and obstruction of culverts, leading to hydraulic inadequacy at critical points along the highway, as found by a case study by Pedrozo-Acuña et al. (2017) (Figure 4-12). The same study showed that these blockages put the highway at risk for being overtopped by 1.5 meters of water or more during the 100-year flooding scenario. Additionally, incorporating regular inspection and maintenance may be necessary to ensure that slopes remain stable and erosion is controlled following overtopping events (Keller and Ketcheson 2011).

Figure 4-12. *Obstructed culvert along highway 180D in Mexico (from Pedrozo-Acuña et al. 2017).*

Failure Case Studies

Bisantino et al. (2016) and Polemio and Lollino (2011) analyzed the failure of a railway culvert due to impounded water (Figure 4-6). The failure occurred in 2005 in Italy after a severe rainstorm that damaged 34 portions of culverts and embankments in the transportation system, resulting in six deaths. Based on modeling of the hydraulic gradients within the embankment during the storm event, it was determined that the embankment failed due to internal erosion, likely starting at the culvert-soil interface (Bisantino et al. 2016). The authors recommend that the water impoundment analyses performed in the post-failure analysis (determination of embankment material properties, seepage, and slope stability analysis) should be incorporated into the design of at-risk embankments (as determined by peak impoundment from extreme flood hydrographs) (Polemio and Lollino 2011).

Srivastava et al. (2010) conducted forensic evaluation of a road embankment that failed after a rainstorm in India (Figure 4-13). They found that the failure was due to high water levels from the rain that increased embankment saturation, steep slopes that decreased slope stability, and a heterogeneous mixture of gravel, sand, and silt in the embankment material that resulted in uneven strength and settling. They recommend that future embankments be constructed at 2H:1V slopes with well mixed and compacted native materials composed of approximately 31% gravel, 47% sand, and 22% clay/silt.

Figure 4-13. *Breached road embankment in India following heavy rainfall (from Srivastava et al. 2010).*

During major flooding of the Missouri River in spring 2019 in Iowa, portions of Interstates I-29 and I-680 were flooded (Figure 4-14) (Motz Enterprises, Inc. 2019). Parts of the embankment slope were damaged by erosion and repaired with Flexamat®, a grid tied concrete block mat that covered the embankment slopes, for emergency armoring (IowaDOT 2019).

Figure 4-14. *Overtopped highway embankment in Iowa due to Missouri River swelling in 2019 (from Motz Enterprises, Inc. 2019).*

Chapter 5 : Numerical Modeling of Impounded Water Failure of Transportation Embankments

A numerical study was conducted to analyze water and seepage induced stability of several transportation embankment scenarios. Table 2-3 summarizes the analyses included in this chapter and Table 2-2 summarizes the geotechnical properties of the soils utilized in the analyses. Two of the analyses, lateral sliding/spreading ($FS_{spreading}$) and seepage under the embankment ($FS_{foundation}$), produced FS above 1.5 for all geometries, materials, and water levels tested (Table 5-2). Therefore, these tests will not be discussed further. The sections below discuss the influence of embankment geometry, soil type and water height on seepage induced embankment soil loss (FS_{piping}), stability of the downstream side slopes ($FS_{downstream}$), and stability of the upstream slopes under equilibrium and non-equilibrium rapid drawdown conditions ($FS_{upstream}$).

Influence of Embankment Geometry

As side slopes become shallower, FS increases. For example, Figure 5-1 shows how FS_{piping} changes with side slope at 15.2 meters (50 feet) of impounded water. For silty sand, fine sand, sandy silt, and clay, FS_{piping} increases greatly as the side slope becomes shallower. Increasing stability with increasing side slope is supported in the research (Kansoh et al. 2020). Because most of the FS_{piping} are greater than 2.0 for 4H:1V slopes and all FS_{piping} are above 2.0 for 6H:1V slopes, the remaining analyses focus on the 2H:1V slope.

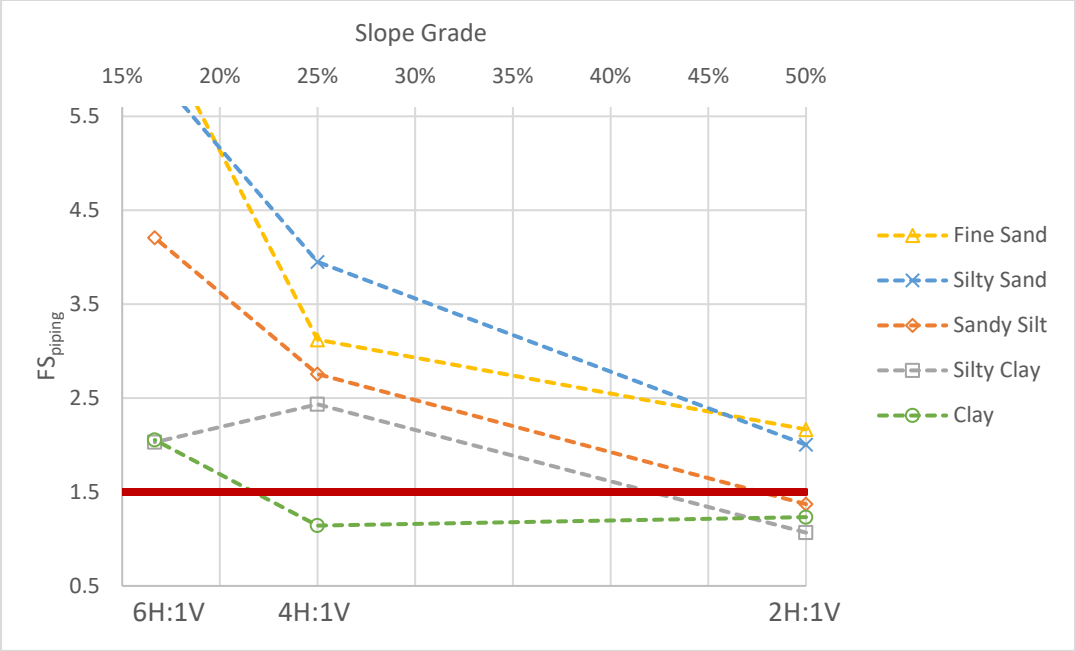

Figure 5-1. *FS_{piping} versus side slope for 15.2-meter (50-foot) height, 9.1-meter (30-foot) top width embankments of different materials impounding 15.2 meters (50 feet) of water. The line at FS_{piping} = 1.5 represents the design FS according to Table 3.*

Top width has a similar impact on FS; in general, increasing top width increases FS. FS_{piping} increased with increasing top width for sandy silt, silty clay, and clay, but did not change for fine sand and silty sand (Figure 5-2). $FS_{downstream}$ increases slightly with embankment top width for all materials. There is not a clear relationship between top width and $FS_{upstream}$.

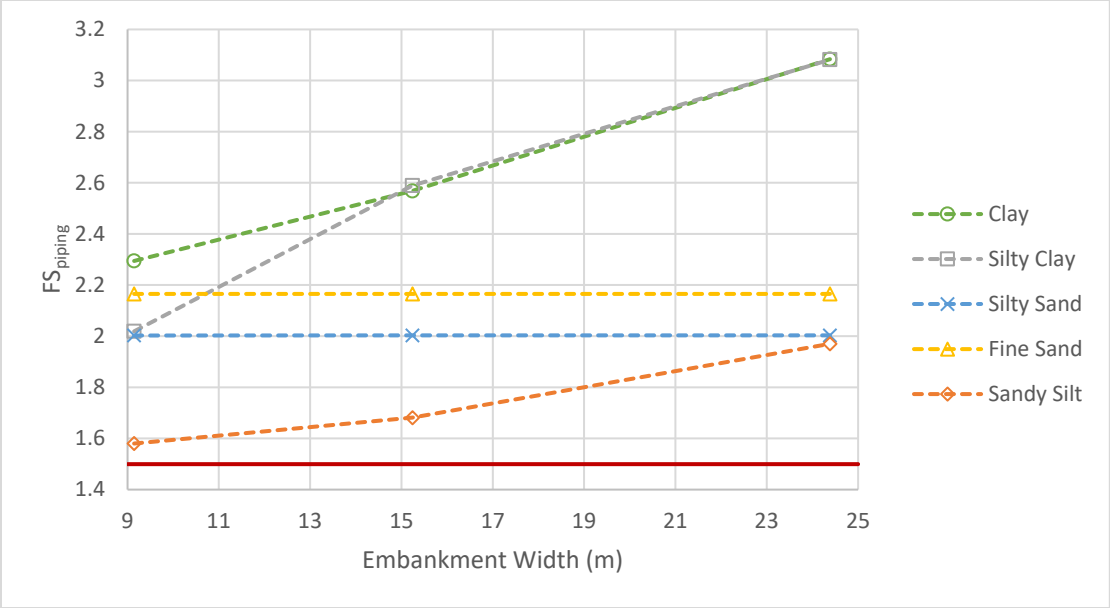

Figure 5-2. *FS_{piping} versus embankment top width for 6.1 meter (20 foot) tall, 2H:1V slope embankments of different materials impounding 6.1 meters (20 feet) of water. The line at FS_{piping} = 1.5 represents the design FS according to Table 3.*

Embankment height has a varying impact on FS. For overtopping erosion, greater embankment height translates to more energy and greater velocity of the water, increasing its erosive potential (Table 5-1). If the maximum velocity is greater than the critical velocity for a material (Table 5-1), erosion can occur. Only some fine silts and clays ($D_{50} \leq 0.002$ mm) would be able to withstand overtopping erosion for the 6.1-, 9.1- and 15.2-meter-tall embankments. The large difference between upper and lower bounds for these fine soils are due to difficulties in predicting the behavior of the electrostatic interactions without directly analyzing a soil sample (Briaud et al. 2016). Therefore, the most accurate assessment of overtopping erosion would require soil sampling.

The critical velocity results align with experimental results where sand-silt-clay mixtures withstand overtopping erosion better than sand embankments (Zhu et al. 2011). The extent of erosion is not determined by the velocity comparison analysis; therefore, additional analysis

would be needed to determine if the erosion could cause embankment failure during overtopping. Additionally, research suggests that this method may overestimate erosion risk because it assumes the soil is saturated; however, the downstream slope is typically unsaturated during the overtopping process (Mizutani et al. 2013). Moreover, if high quality vegetation is present on the embankment, the critical velocity can be increased to 0.76 – 2.1 m/s (2.5 - 6.8 ft/s) (Clopper and Chen 1988).

Table 5-1. *Critical velocity for overtopping erosion and critical gradient for piping erosion for a variety of materials and maximum velocity during overtopping of embankments of different heights.*

Material	D_{50} (mm)	v_c range (m/s, *ft/s*)	v_c Lower Bound Range (m/s, *ft/s*)	v_c Upper Bound Range (m/s, *ft/s*)	Saturated Unit Weight (kN/m^3, *pcf*)	Critical Gradient
Fine Sand	0.02 – 0.06	0.02 – 0.06 *0.07 – 0.20*	NA	NA	20.4 *130*	1.08
Silty Sand	0.02 – 0.06	0.18 – 1.5 *0.58 – 4.92*	NA	NA	19.6 *125*	1.00
Sandy Silt	0.006 – 0.01	NA	0.25-0.28 *0.82-0.91*	3.0-5.0 *9.84-16.4*	18.9 *120*	0.923
Silty Clay	0.002 – 0.005	NA	0.29-0.35 *0.95-1.14*	6.0-15.0 *19.7-49.2*	18.1 *115*	0.843
Clay	0.0005 – 0.001	NA	0.40-0.46 *1.31-1.50*	30.0-60.0 *98.4-197*	17.3 *110*	0.763

Embankment Height (ft)	Maximum overtopping velocity (m/s, *ft/s*)
20	10.9, *35.9*
30	13.4, *43.9*
50	17.3, *56.7*

As embankment height increases, FS_{piping} increases for silty clay, clay, and sandy silt, but remains the same for fine sand and silty sand (Figure 5-3). The change in FS_{piping} with height in the clayey soils is likely due to a change in phreatic line shape. On the other hand, $FS_{downstream}$ decreases with increasing embankment height for clay, silty clay, sandy silt, and silty sand (Figure 5-4). For fine sand, $FS_{downstream}$ increases with increasing embankment height. The impact

on $FS_{downstream}$ is not extreme enough to cause the value to fall below or exceed 1.4, respectively. There was not a clear relationship between height and $FS_{upstream}$.

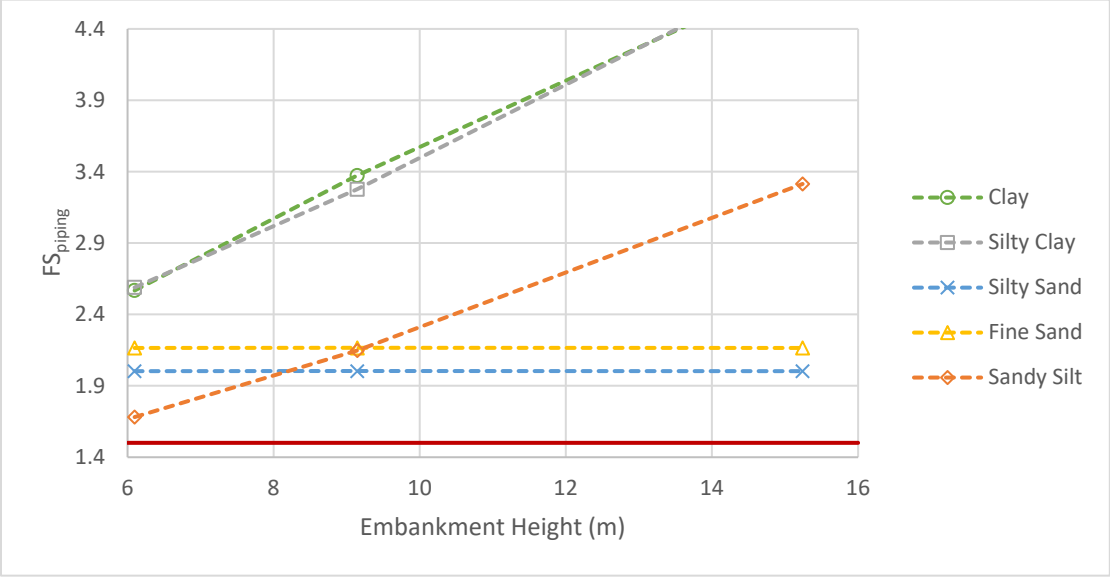

Figure 5-3. *FS_{piping} versus embankment height for 15.2-meter (50-foot) top width, 2H:1V slope embankments of different materials impounding 6.1 meters (20 feet) of water. The line at FS_{piping} = 1.5 represents the design FS according to Table 3.*

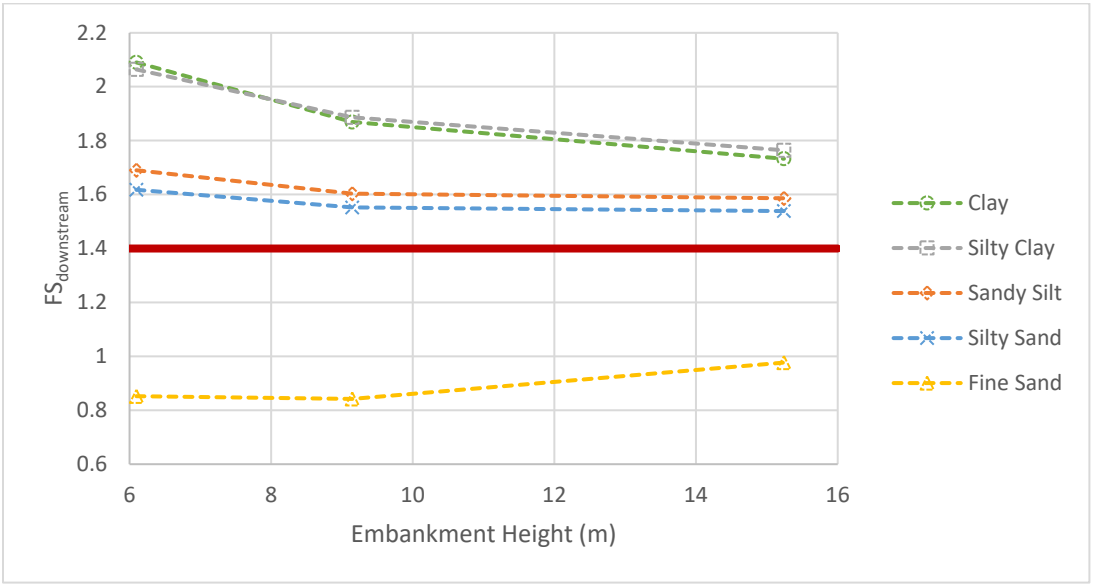

Figure 5-4. *$FS_{downstream}$ versus embankment height for 15.2-meter (50-foot) top width, 2H:1V slope embankments of different materials impounding 6.1 meters (20 feet) of water. The line at $FS_{downstream}$ = 1.4 represents the design FS according to Table 3.*

Influence of Soil Type

Each material has advantages and disadvantages based on the test scenario. As discussed above, the clay materials are most resistive to overtopping erosion. Silty sand and fine sand have higher seepage velocities due to higher hydraulic conductivity (Figure 5-5), but also have higher critical gradients due to higher unit weight (Table 5-1). Therefore, silty sand and fine sand have higher FS_{piping}, and all geometries and water levels tested have $FS_{piping} > 1.5$. Sandy silt, silty clay, and clay all have at least one geometry where $FS_{piping} < 1.5$ (Figure 5-6). Additionally, these materials have a hydraulic conductivity below sandy silt [$K < 9.8 \times 10^{-4}$ m/hr (3.2×10^{-3} ft/hr)] and consequently experience high levels of seepage through the foundation as opposed to the silty sand and fine sand embankments (Figure 5-6). However, $FS_{foundation}$ still remains above the design safety factor for all materials (Table 5-2).

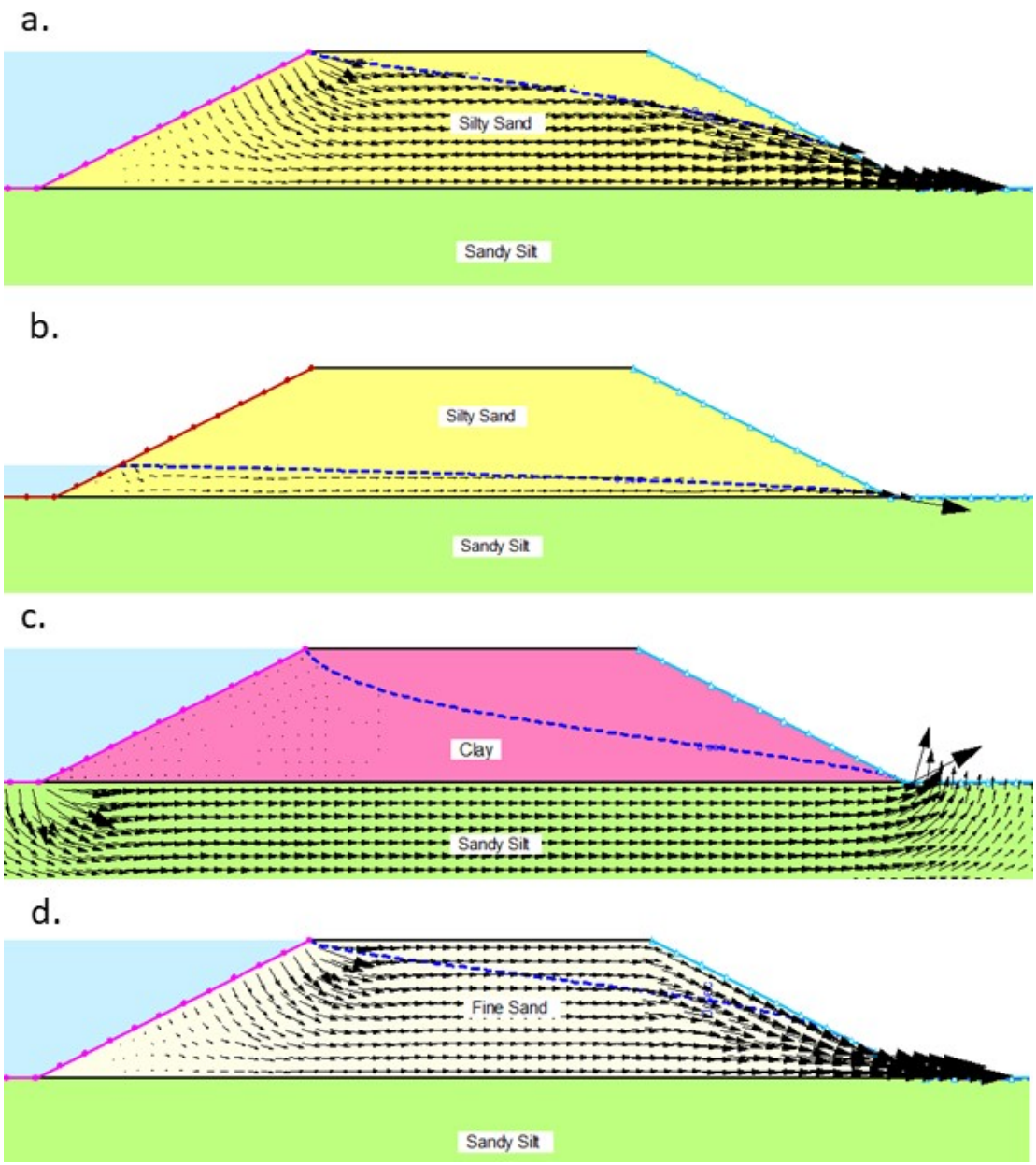

Figure 5-5. *Example output from SEEP/W model of equilibrium (steady) flow through a soil embankment. The dashed blue line represents the phreatic surface, and the black arrows represent seepage velocity vectors. The scenarios represented are (a) silty sand with 6.1 meters (20 feet) of impounded water, (b) silty sand with 1.5 meters (5 feet) of water, (c) clay with 6.1 meters (20 feet) of water, and (d) fine sand with 6.1 meters (20 feet) of water.*

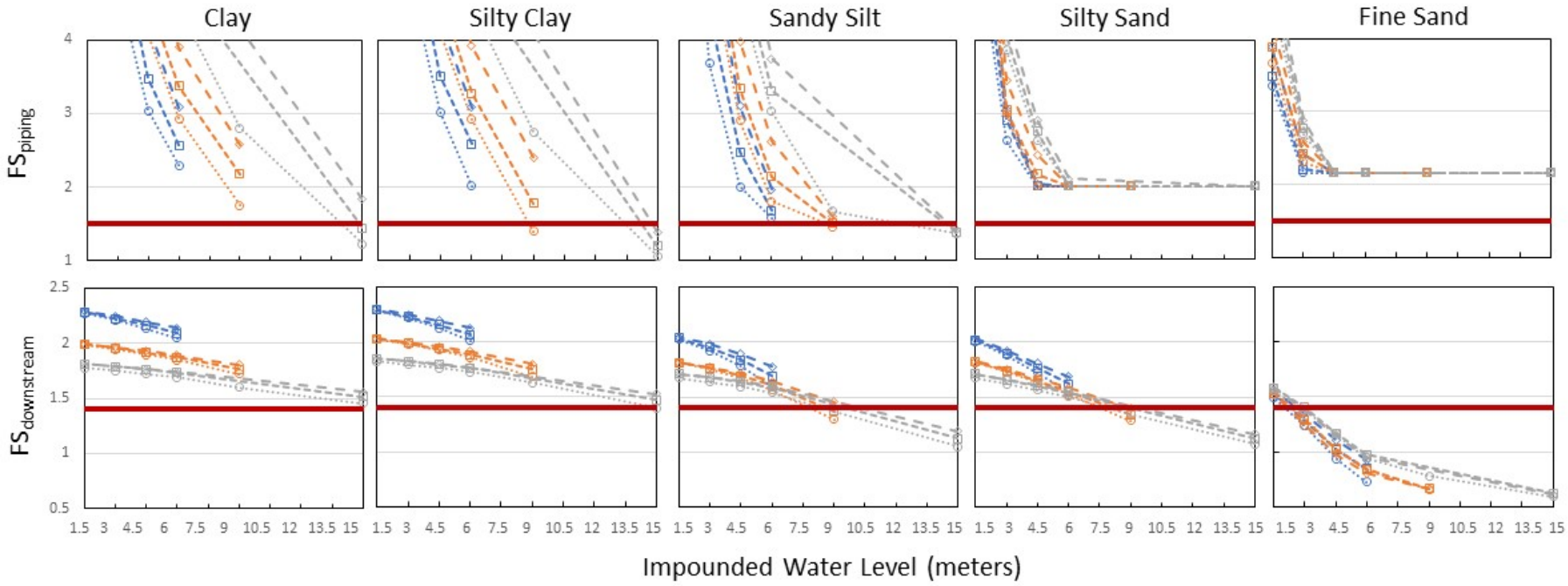

Figure 5-6. *FS_{piping} and $FS_{downstream}$ versus impounded water level for all embankments tested. Side slope is 2H:1V for all cases. The lines at FS_{piping} = 1.5 and $FS_{downstream}$ = 1.4 represent the design FS according to Table 3.*

In slope stability tests, $FS_{downstream}$ is highest in clay, with $FS_{downstream} > 1.4$ for all geometries. Silty clay, sandy silt, and silty sand also perform well, with most values of $FS_{downstream} > 1.4$. Fine sand has very low values of $FS_{downstream}$, with few scenarios performing with $FS_{downstream} > 1.4$ (Figure 5-6). The slope stability is influenced by the embankment saturation (controlled by hydraulic conductivity and water level) and material strength (controlled by geometry and soil strength). Fine sand has no cohesion, which results in its low values of $FS_{downstream}$.

Influence of Water Level

The water level determines the head differential and resultant forces on and within the embankment (i.e., velocity in overtopping erosion, pushing force in lateral spreading, maximum gradient in piping cases, and phreatic line which influences slope stability). Figure 21 (a) and (b) illustrate the differences in seepage vectors between an embankment impounding 6.1 meters (20 feet) of water and 1.5 meters (5 feet) of water. In almost all tests performed, FS decreases as the water level increases (e.g., Figure 5-6). However, FS_{piping} remains the same in fine sand and silty sand as the water level increases over 6.1 meters (20 feet). This result seems counterintuitive, because as hydraulic head (water level) increases, $i_{embankment\ exit}$ should increase and thus FS_{piping} should decrease. $i_{embankment\ exit}$ was plotted along the downstream slope for clay and fine sand to understand why FS_{piping} was staying constant for fine sand (Figure 5-6). Fine sand and clay have very different profiles of $i_{embankment\ exit}$ versus distance along the downstream slope, and this is due to differences in the location and shape of the phreatic line (Figure 5-5), which is controlled by hydraulic conductivity and the volumetric water content function (Table 2-2). Clay has a higher peak in $i_{embankment\ exit}$ and fine sand has higher values of $i_{embankment\ exit}$ along the downstream slope leading to the toe. As water level increases against the fine sand embankment, the phreatic

line intersects the downstream slope at a different location, illustrated by where $i_{embankment\ exit}$ approaches 0.5 in Figure 5-7.

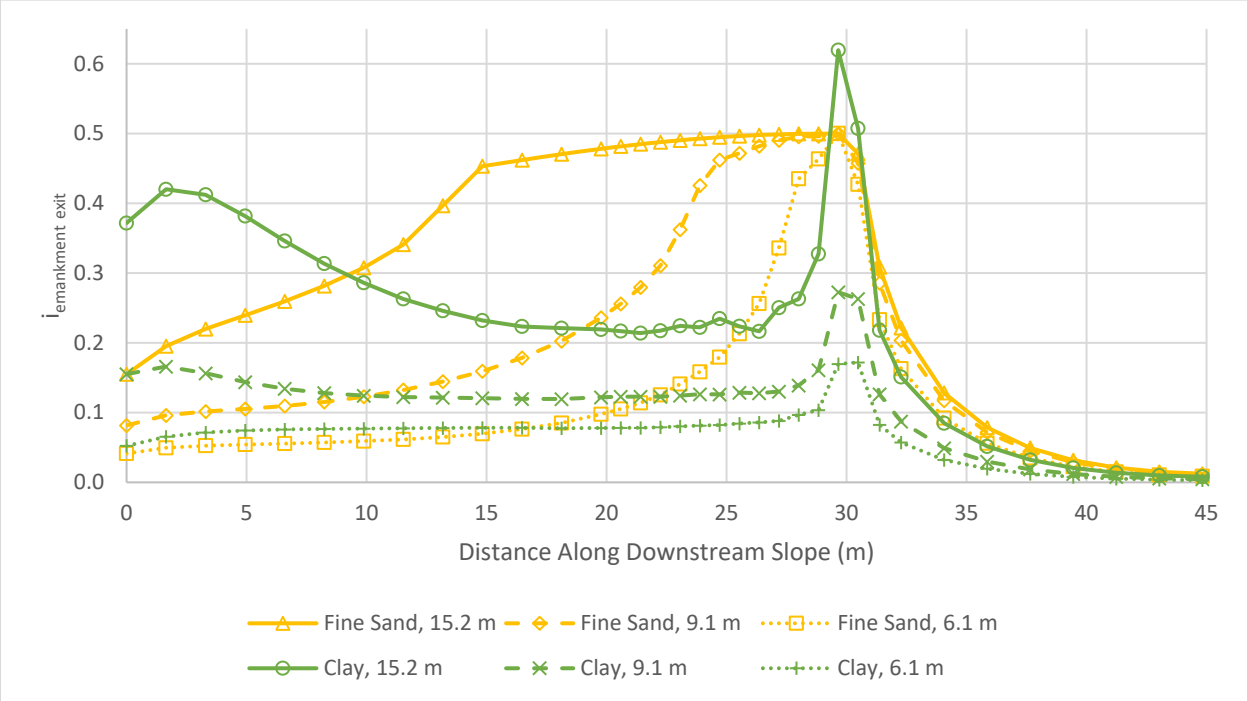

Figure 5-7. *Exit gradient along downstream side slope for 2H:1V, 15.2-meter (50-foot) tall, 9.1-meter (30-foot) wide, 2H:1V embankments made of fine sand and clay impounding 6.1, 9.1 and 15.2 meters of water. X = 0 m corresponds to the downstream edge of the embankment crest, X = 30.5 m (100 ft) is the embankment toe, and X = 45.7 m (150 ft) is the end of the modeled foundation.*

The impact of water level is most evident in the rapid drawdown tests. In the equilibrium rapid drawdown test, impounded water reached equilibrium (representative of a permanent water pool) and was removed instantaneously. All embankments tested can withstand rapid drawdown of 1.5 meters (5 feet) of water with $FS_{upstream} > 1.2$, but none of the embankments can withstand rapid drawdown of 3.0 meters (10 feet) of water (Figure 5-8). However, the non-equilibrium rapid drawdown testing aimed to further explore the impact of water level by not allowing the water level to reach equilibrium and instead allowing the water to build for 24 hours and then

removing it instantly, which is more representative of actual transportation embankment scenarios than the equilibrium case.

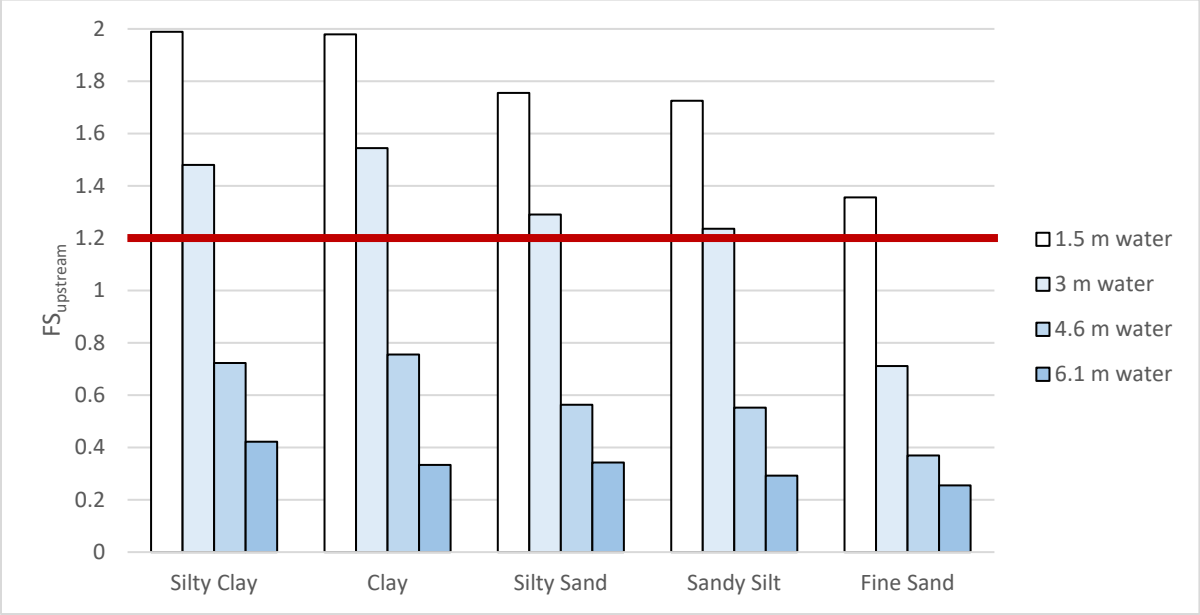

Figure 5-8. *Upstream slope stability $FS_{upstream}$ during rapid drawdown on 6.1-meter (20-foot) tall, 15.2-meter (50-foot) wide, 2:1 slope embankments of different materials impounding different water levels. The line at $FS_{upstream}$ = 1.2 represents the design FS according to Table 3.*

Alternatively, in the non-equilibrium test, $FS_{upstream}$ increased across all materials (Figure 5-9) as time increased. Figure 5-10 illustrates the difference in phreatic line and seepage vectors between both rapid drawdown tests. Additionally, clay, silty clay, and sandy silt were able to withstand rapid drawdown of 6.1 meters (20 feet) of water with $FS_{upstream} > 1.2$.

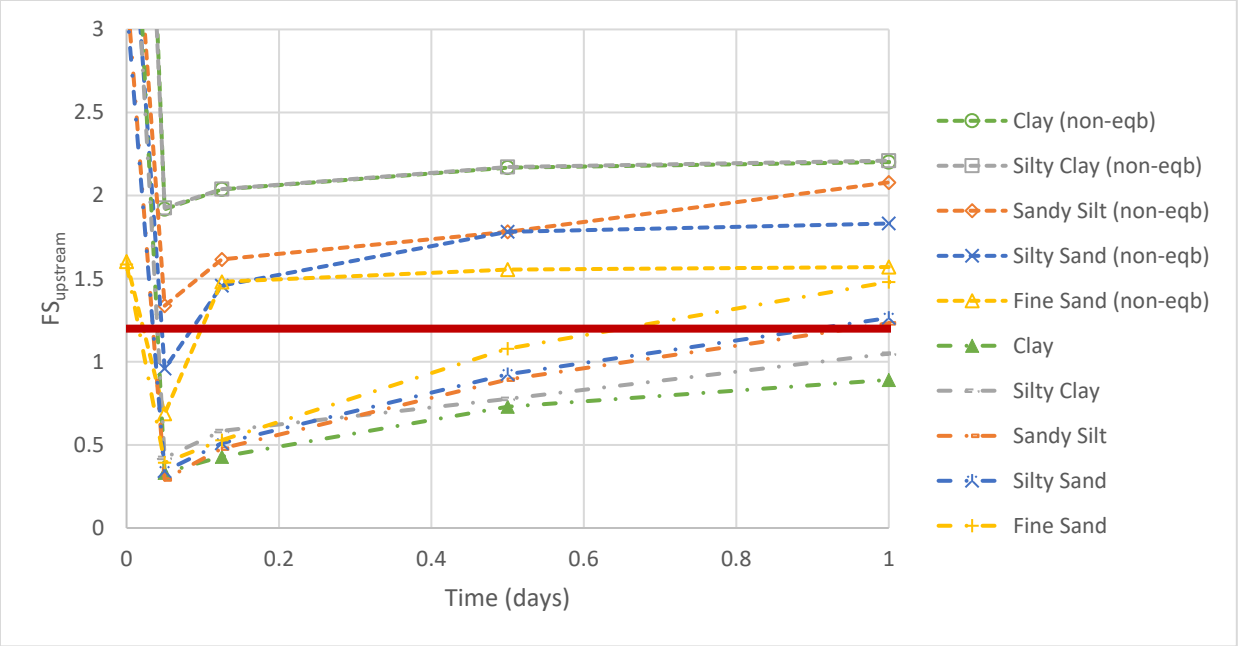

Figure 5-9. *$FS_{upstream}$ over time for both rapid drawdown tests: non-equilibrium (dashed) and equilibrium (dash-dot) on a 6.1-meter (20-foot) tall, 15.2-meter (50-foot) wide, 2H:1V side slope embankment of different materials impounding 6.1 meters (20 feet) of water. At time = 0 days, 6.1 meters of water is impounded and at time = 0.05 days, the water is removed instantaneously. The line at $FS_{upstream}$ = 1.2 represents the design FS according to Table 3.*

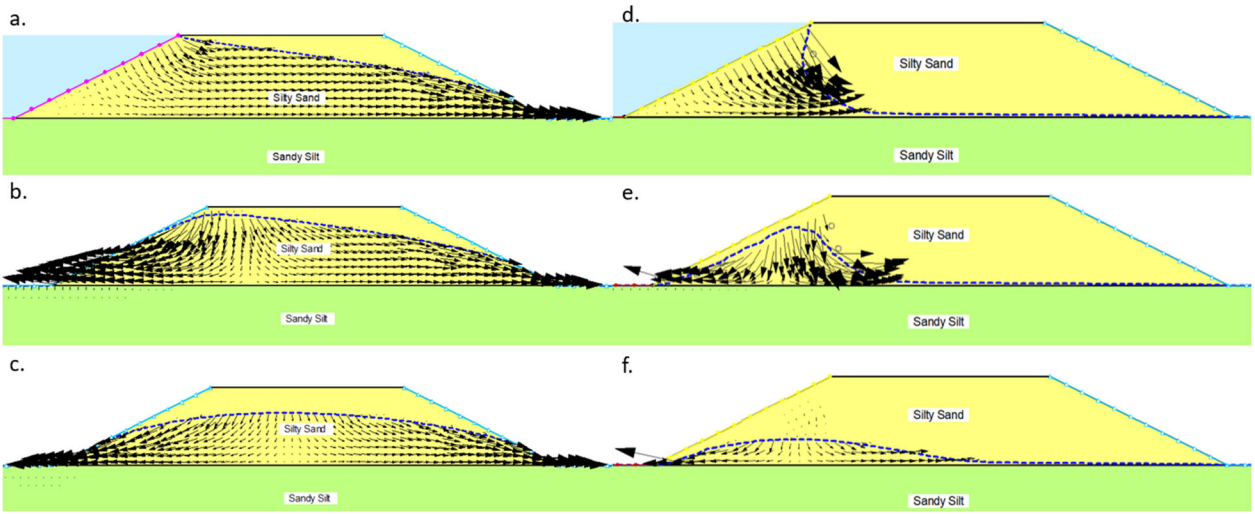

Figure 5-10. *Rapid drawdown (a-c) versus non-equilibrium rapid drawdown (d-f) in SEEP/W. Scenarios include t = 0, 6.1 meters (20 feet) of impounded water (a, d), t = 0.05 days, water removed (b, e), and t = 1 day, post rapid drawdown (c, f).*

These results indicate that performance of the transportation embankment is highly dependent on both the height of water impounded and the duration of water impoundment. It takes time for the impounded water to saturate the upstream slope and consequently make the embankment vulnerable to rapid drawdown induced upstream slope failure. The transportation embankments are not expected to constantly impound water, allowing equilibrium to be reached. In addition to impacting the rapid drawdown tests, the temporary nature of impounded water behind transportation embankments is expected to increase FS_{piping} and $FS_{downstream}$ due to decreased saturation of the embankment. Therefore, it is important to understand what water levels and durations may arise from hydrologic events to better design transportation embankments.

Summary

Table 5-2 includes the results from all analyses. According to the design FS in the seepage through embankment, seepage under embankment, lateral sliding, and slope stability analyses:

- Clay meets design guidelines for up to 9.1 meters (30 feet) of impounded water, with FS_{piping} under 15.2-meter (50-foot) water levels being insufficient.
- Fine sand meets design guidelines for up to 1.5 meters (5 feet) of impounded water, with $FS_{downstream}$ under 3+ meter (10+ foot) water levels being insufficient.
- Sandy silt meets design guidelines for up to 6.1 meters (20 feet) of impounded water, with FS_{piping} under 15.2-meter (50-foot) water levels and $FS_{downstream}$ under 9.1+ meter (30+ foot) water levels being insufficient.
- Silty clay meets design guidelines for up to 6.1 meters (20 feet) of impounded water, with FS_{piping} under 9.1+ meter (30+) foot water levels and $FS_{downstream}$ under 15.2-meter (50-foot) water levels being insufficient.

- Silty sand meets design guidelines for up to 6.1 meters (20 feet) of impounded water, with $FS_{downstream}$ under 9.1+ meter (30+ foot) water levels being insufficient.

Table 5-2. *Summary of FS values collected for each test. Minimum and maximum FS values are shown (all 2H:1V slopes). FS values below the design FS as specified in the above sections are bolded. ND indicates the value was not determined.*

Seepage Through Embankment (FS_{piping})						
Water Level	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1 m (20 ft)	9.1 m (30 ft)	15.2 m (50 ft)
Clay	9.42 – 21.7	4.76 – 10.4	3.04 – 7.15	2.29 – 5.32	1.75 – 2.80	**1.23** – 1.83
Fine Sand	3.35 – 5.11	2.16 – 2.89	2.16 – 2.17	2.16 – 2.17	2.17	2.17
Sandy Silt	8.98 – 21.9	3.69 – 9.58	2.01 – 5.66	1.58 – 3.75	1.46 – 1.67	**1.37** – 1.42
Silty Clay	10.1 – 23.2	4.84 – 11.2	5.66 – 7.43	2.02 – 5.43	**1.40** – 2.75	**1.07 – 1.39**
Silty Sand	5.53 – 11.6	2.62 – 4.34	2.00 – 2.91	2.00 – 2.11	2.00	2.00
Seepage Under Embankment ($FS_{foundation}$)						
Water Level	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1 m (20 ft)	9.1 m (30 ft)	15.2 m (50 ft)
Clay	20.1 – 44.4	9.91 – 22.1	6.53 – 14.6	4.84 – 10.9	4.12 – 6.05	3.50 – 4.14
Fine Sand	9.18 – 13.9	5.73 – 7.57	4.51 – 5.68	3.97 – 4.80	3.67 – 3.86	3.47 – 3.51
Sandy Silt	19.2 – 45.5	8.14 – 20.1	4.99 – 12.0	3.73 – 8.07	3.22 -4.14	2.89 – 3.03
Silty Clay	21.3 – 47.9	10.2 – 23.4	6.49 – 15.2	4.69 – 11.1	3.89 – 5.81	3.20 – 3.81
Silty Sand	12.5 – 25.8	6.18 – 9.89	4.41 – 6.59	3.72 – 5.14	3.42 – 3.78	3.23 – 3.27
Lateral Sliding/Spreading ($FS_{spreading}$)						
Water Level	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1 m (20 ft)	9.1 m (30 ft)	15.2 m (50 ft)
Clay	27.4 - 171	6.86 - 42.9	3.05 - 19.0	1.71 - 10.7	1.71	1.71
Fine Sand	46.4 - 290	11.6 - 72.4	5.15 - 32.2	2.90 - 18.1	2.90	2.90
Sandy Silt	30.0 - 187	7.49 - 46.8	3.33 - 20.8	1.87 - 11.7	1.87	1.87
Silty Clay	35.2 - 220	8.81 - 55.1	3.91 - 24.5	2.20 - 13.8	2.20	2.20
Silty Sand	37.0 - 231	9.24 - 57.8	4.11 - 25.7	2.31 - 14.4	2.31	2.31
Slope Stability ($FS_{downstream}$)						
Water Level	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1 m (20 ft)	9.1 m (30 ft)	15.2 m (50 ft)
Clay	1.78 - 2.29	1.75 - 2.24	1.72 - 2.19	1.69 - 2.14	1.60 - 1.81	1.46 - 1.56
Fine Sand	1.49 - 1.59	**1.24** - 1.41	**0.94 - 1.17**	**0.73 - 0.98**	**0.66 - 0.78**	**0.60 - 0.63**
Sandy Silt	1.67 - 2.04	1.64 - 1.98	1.59 - 1.89	1.54 - 1.78	**1.30** - 1.46	**1.05 - 1.19**
Silty Clay	1.82 - 2.30	1.79 - 2.25	1.76 - 2.19	1.73 - 2.12	1.63 - 1.80	**1.40** - 1.53
Silty Sand	1.68 - 2.03	1.62 - 1.92	1.57 - 1.81	1.50 - 1.69	**1.29 - 1.40**	**1.07 - 1.17**
Rapid Drawdown ($FS_{upstream}$)						
Water Level	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1 m (20 ft)	9.1 m (30 ft)	15.2 m (50 ft)
Clay	1.98	1.54	**0.76**	**0.33**	**0.134**	**0.202**
Fine Sand	1.23 - 1.38	**0.71**	**0.37**	**0.29 - 0.39**	**0.31 - 0.45**	**0.21 - 0.39**
Sandy Silt	1.73	1.24	**0.55**	**0.29**	**0.206**	**0.183**
Silty Clay	1.70 - 1.99	1.48	**0.72**	**0.36 - 0.42**	**0.309**	**0.19**
Silty Sand	1.57 - 1.76	1.28 - 1.30	**0.56**	**0.27 - 0.44**	**0.35 - 0.43**	**0.38 - 0.40**
Non-equilibrium Rapid Drawdown ($FS_{upstream}$)						
Water Level	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1 m (20 ft)	9.1 m (30 ft)	15.2 m (50 ft)
Clay	2.22	2.16	2.11	1.92	ND	ND
Fine Sand	1.54 – 1.57	1.57	1.56	0.69	ND	ND
Sandy Silt	1.95	1.81	1.65	1.34	ND	ND
Silty Clay	1.82 – 2.24	2.17	2.12	1.93	ND	ND
Silty Sand	1.69 – 1.98	1.72 – 1.84	1.68	0.96	ND	ND

Chapter 6 : Discussion and Conclusions

Summary of Research

Mid-Atlantic states are considering the implications of temporarily impounded water on transportation embankments, but do not see a straightforward solution. Concerns of state transportation and dam safety agencies in the region include:

- Differences in purposes and designs between the transportation and dam embankments
- Loss of peak flood attenuation if culvert sizes are increased
- Inability to prepare for all storms—in particular, Pennsylvania has noted losing infrastructure that they never considered to be vulnerable
- Lack of asset inventory
- Cost of inspection, maintenance, and retrofitting

Some Mid-Atlantic states have started to act on the issue. New York recently updated its drainage manual to size all culverts for the 50-year storm and inspect all culverts with diameters greater than 1.5 meters (5 feet) every two years. The reasoning for this strategy is to prevent impounded water under "normal circumstances." Pennsylvania conducted an extreme weather vulnerability study to determine how climate change would impact flooding of roadways and bridges. One aspect of the study's recommended climate resiliency planning is increasing the test flood for culverts to the 500-year storm. This will help planners understand how infrastructure would behave during an extreme rainstorm and consider if mitigation is necessary. Maryland is using Policy Memoranda to apply dam safety to transportation embankments. No other Mid-Atlantic state currently has published policies specifically related to transportation embankments temporarily impounding water.

Based on the literature review, dam and transportation embankments share many failure modes: seepage/internal erosion, overtopping, and rapid drawdown induced instability. These failure modes are documented much more extensively in dams but are still known to occur in transportation embankments. Transportation embankments are at risk of damage and failure due to extreme storm events, with hazardous recurrence intervals being as low as the 100-year flood. Under-designed, clogged, and aging culverts further exacerbate this risk. Additionally, climate change is increasing precipitation depth and intensity and the frequency of extreme precipitation events in the Mid-Atlantic region.

The materials used in the different embankments have distinct advantages and disadvantages with respect to withstanding failures and damage due to impounded water.

- Fine sand and large silts are the most susceptible to overtopping erosion, with erosion being possible for granular materials (D_{50} > 0.002 mm) without vegetation cover. Mixtures containing sand and gravel, or sand, silt, and clay perform better than pure sand during overtopping.
- Materials with low hydraulic conductivity [K < $9x10^{-4}$ m/hour ($3x10^{-3}$ ft/hour)], including sandy silt, clay, and silty clay have low FS_{piping} (< 1.5) when impounding 15.2 meters (50 feet) of water. Conversely, fine sand and large silts do not experience as high gradients during seepage due to their higher hydraulic conductivity [K > $9x10^{-4}$ m/hour ($3x10^{-3}$ ft/hour)], which improves resistance against piping failure (FS_{piping} > 1.8).
- Silty clay and clay perform the best in downstream slope stability with $FS_{downstream}$ > 1.4 for all water levels and geometries tested. Silty sand and sandy silt can impound up to 6.1 meters (20 feet) of water before $FS_{downstream}$ falls below 1.4. Fine sand can only impound 1.5 meters (5 feet) of water according to the design FS of 1.4.

The materials characteristics that make up transportation embankments in the Mid-Atlantic are generally unknown, but it can be assumed that the materials are more granular than the clays used in homogenous dams or clay cores in zoned dams. Currently, other than dry unit weight, Maryland does not have specifications for content or gradation of transportation embankment material (Table A-3). A well-graded mixture of sand, silt, and clay could provide the advantages of each material while minimizing the failure modes associated with each.

Geometry also plays a role in embankment performance. Larger top widths and shallower side slopes improve an embankment's resistance to overtopping failure and increase both the FS_{piping} and $FS_{downstream}$. Embankment width is not currently a factor in dam breach prediction equations. Additionally, dam breach prediction equations are typically developed empirically from dam failure data. Due to the differences in shape and material, it may not be appropriate to extrapolate dam breach equations to transportation embankments.

Some impounded water scenarios tested in this work resulted in high or low FS across the board regardless of geometry or shape. $FS_{foundation}$ and $FS_{spreading}$ indicated no potential failure with the values being greater than 2.8 and greater than 1.6, respectively, for all materials and geometries tested. Rapid drawdown of 4.6+ meters (15+ feet) of water, on the other hand, resulted in very low $FS_{upstream}$ (< 0.8) for all geometries and materials tested. Additionally, overtopping velocities may exceed critical velocities of many materials, potentially resulting in overtopping erosion. Although more specific hydrologic analyses would be required to fully assess susceptibility to overtopping erosion, this result stresses the importance of overtopping protection such as well-maintained vegetation.

Several aspects of dam design and safety were investigated to understand their potential application to transportation embankments:

- Drainage structures in dams allow water to be dissipated safely in low hydraulic conductivity, clayey materials. If the embankment material already has high hydraulic conductivity, supplemental drainage structures may not be necessary.
- Grasses and deep-rooted vegetation on transportation embankments can slightly increase the resistance to overtopping erosion. However, deep rooted vegetation or burrows caused by animals attracted by the vegetation can provide dangerous initiation points for piping if the embankment impounds water. The frequency of events (overtopping versus water impounded long enough to have the phreatic line reach the downstream slope) would have to be weighed to determine which vegetation scheme is more favorable.
- Lab-scale studies have indicated that compaction increases the length of time an embankment can resist overtopping due to an increase in dry unit weight, and compaction requirements are similar between both embankment types.
- Culverts are designed and tested for much less severe storms than dam embankments, spillways, and emergency spillways. Data exists to test culverts for the PMF. This information could be used to assess if culvert size needs to be increased. It is important to design culverts with adequate flow capacity as they last for 50-75 years, and the climate and land use may continue to change in that time.
- Culverts are inspected and maintained far less frequently than dams. A lack of inspection increases risk of culvert clogging, which drastically decreases the culvert capacity. Regular inspection and maintenance can decrease risk of clogged or blocked culverts.

Future Research Works

In order to better understand the behavior of transportation embankments temporarily impounding water in the Mid-Atlantic region, embankment failures and damages should be

documented and forensically investigated. Embankment materials, geometry, culvert size, and utilities should be documented and inventoried to improve modeling and better understand potential failure modes. Additionally, measurement of seepage rates in transportation embankments during a variety of storm events would provide a baseline of safe seepage rates for comparison with numerical modeling outcomes. Furthermore, hydrologic/hydraulic investigation is necessary to understand what water levels and water impoundment durations occur under specific weather events and what drawdown scenarios are realistic. This data collection would aid in the development of breach equations specific to transportation embankments and better modeling.

To improve the management of transportation embankments in the Mid-Atlantic region, guidelines for a new borrow category that applies to transportation embankments that could impound water, including more specific criteria for hydraulic conductivity and cohesion, should be developed. Another major development in both roadway and dam research is allowance for safe overtopping to increase resiliency to flood events. Flowable fill is a tool that can reduce the risk of seepage at the culvert interface and interfacial piping failure. Additionally, geosynthetics can provide added stability to the embankment core during water impoundment and overtopping. A recent research study in Pennsylvania showed promising results but further research is needed to evaluate how geosynthetics could be feasibly implemented (Gao et al. 2021). These tools should be further investigated for use in transportation embankments temporarily impounding water and incorporated into state guidance documents.

Recommendations for Existing Embankments

Major modifications to existing transportation embankments are likely to be costly and it may not be feasible to alter existing culverts or conduct dam-break analyses on the thousands of

existing culvert locations in the Mid-Atlantic region. Therefore, transportation embankments need to be prioritized for analysis and modification. Looking to dam safety hazard classification, transportation embankments could be prioritized based on several conditions:

- Proximity of downstream development, particularly frequently occupied structures such as residences and businesses
- Embankment height (i.e., taller embankments have the theoretical potential to create greater head differentials), where embankments greater than 9.1 meters (30 feet) tall may be of greatest concern based on the modeling outcomes of this study
- Embankment width (i.e., wider embankments require water to be impounded longer to become fully saturated), where all widths evaluated [9.1 – 24.4 meters (30 – 50 feet)] are not expected to become fully saturated during a 24-hour storm event. However, greater hydrologic analysis determining possible impounded water durations would be necessary to determine specific widths that may be considered lower risk
- Significant upstream development since construction of the embankment that may increase flows delivered to the culvert
- ADT of the roadway and/or criticality of roadway to evacuation and emergency routes

High priority embankments should have soil samples analyzed for cohesion, hydraulic conductivity, and unit weight. If the material is below the threshold in any of these categories, further analysis (like the modeling performed in this study and dam break analysis) should be conducted to determine appropriateness of retrofit and potential modifications to design. Based on this study, the potential thresholds for soil characteristics are cohesion > 19.2 kPa (400 psf), hydraulic conductivity > 9.8×10^{-4} m/hour (3.2×10^{-3} ft/hour), and unit weight > 17.3 kN/m^3 (110 pcf).

Chapter 7 Appendices

Table A-1. *Pertinent Mid-Atlantic state agencies, websites, documents collected, and employee contact information.*

State	Agency	Website	Documents	Contact	Email
Maryland	DOT	mdot.maryland.gov	Highway Drainage Manual		
Maryland	Dept. of the Environ.	mde.maryland.gov	Stormwater Design Manual, Dam Safety Policy Memoranda	John Roche and Scott Bass	john.roche @maryland.gov, scott.bass @maryland.gov
Delaware	DOT	deldot.gov	Road Design Manual	Jason Hastings	Jason.Hastings@delaware.gov
Delaware	Dept. of Natural Resources and Environmental Control	dnrec.alpha. delaware.gov	Dam Safety Code	Janice Shute	Janice.Shute @delaware.gov
Pennsylvania	DOT	www.penndot.pa.gov	Drainage Manual	Nicholas Vivian	nvivian@pa.gov
Pennsylvania	Dept. of Environ. Protection	www.dep.pa.gov	Dam Safety and Waterway Management Code	Richard Reisinger	ricreising@pa.gov
West Virginia	DOT	transportation.wv.gov	Drainage Manual	N/A	N/A
West Virginia	Dept. of Environ. Protection	dep.wv.gov	Dam Safety Rule	Delbert Shriver	delbert.g.shriver @wv.gov
Virginia	Dept. of Conservation and Recreation	dcr.virginia.gov	Impounding Structure Regulations	Mark Killgore	mark.killgore @dcr.virginia.gov
Virginia	Dept. of Environ. Quality	deq.virginia.gov	Stormwater Design Specifications	N/A	BMPClearinghouse @deq.virginia.gov
Virginia	DOT	virginiadot.org	Drainage Manual	John Matthews	John.Matthews @VDOT.Virginia.gov
New Jersey	DOT	state.nj.us/ transportation	Roadway Design Manual	Sandra Blick	sandra.blick @dot.nj.gov
New Jersey	Dept. of Environ. Protection	nj.gov/dep	Dam Safety Standards, Flood Hazard Area Control Act Rules	Richard Tamagno	Richard.Tamagno @dep.nj.gov
New York	DOT	www.dot.ny.gov	Highway Design Manual	Peter VanKampen	Peter.VanKampen @dot.ny.gov
New York	Dept. of Environ. Conservation	www.dec.ny.gov	Dam Safety Regulations	N/A	DOWinformation @dec.ny.gov

Table A-2. *Databases used for literature review.*

Name	Database Type	Website
ASCE Library	Peer-reviewed engineering literature	ascelibrary.org
Clarivate Web of Science	Compilation of science and engineering databases	www.webofknowledge.com
Transportation Research Board Transport Research International Documentation	Transportation research	trid.trb.org
United States Society on Dams Resource Center	White pages on large dams	ussdams.org/resource-center/publications/white-papers/
University of Maryland Library	Compilation of multidisciplinary databases	umaryland.on.worldcat.org/

Table A-3. *Embankment soil gradation requirements in different states (after Gao et al. 2020).*

Table 4.1 State DOT Embankment Gradations							
Size (mm)	76.2	25.4	4.75	2.36	0.15	0.075	D_{50} (mm)
Sieve	3-in.	1-in.	No.4	No.8	No.100	No.200	
IOWA DOT (2005)	100	---	---	20-100	---	0 - 10	0.34 ~ 9.0
Wisconsin DOT Type A (2021)	100	---	100	0-75	0-15	0 - 8	0.75 ~ 3.2
Michigan DOT Class II (2021)	100	60-100	50-100	---	0-35	0 - 7	0.31 ~ 5.0
New York DOT (2015)	---	100	0-70	---	---	0 - 15	1.2 ~ 12
Minnesota DOT (2018)	100	100	0-50	---	---	0 - 4	4.9 ~ 12
Missouri DOT (2018)	---	100	0-10	---	---	0 - 5	10 ~ 11
Ohio DOT (2008)	---	100	---	---	---	0 - 20	0.7 ~ 1.3
Colorado DOT (2019)	100	100	30-100	---	---	5 - 20	0.36 ~ 7.9
Kansas DOT (2007)	100	100	0-60	---	---	0 - 5	2.1 ~ 11
Illinois DOT (2016)	100	100	50-100	---	---	0 - 4	0.45 ~ 4.8
Oklahoma DOT (2009)	100	100	0-45	---	---	0 - 10	0.55 ~ 4.8
Tennessee DOT (2015)	100	100	35-55	---	---	4 - 15	3.0 ~ 7.0
Indiana DOT (2012)	100	90-100	20-70	---	---	0 - 8	1.2 ~ 10
Virginia DOT (1999)	100	100	15-30	---	---	0 - 14	7.7 ~ 9.3
South Carolina DOT (2006)	100	100	30-50	---	---	0 - 12	4.9 ~ 7.8
Louisiana DOT (2016)	100	100	---	---	---	0 - 10	1.0 ~ 1.5
Kentucky DOT (2012)	100	100	0-30	---	---	0 - 5	8.0 ~ 10.8
Montana DOT (2014)	100	100	20-40	---	---	0 - 8	6.1 ~ 9.0
PennDOT #8 (2020)	100	100	10 – 30	0 – 10	---	0 – 2	5.2~7.0
PennDOT #57 (2020)	100	95–100	0 – 10	0 – 5	---	0 – 2	11 ~ 18

Interview Responses

Note: All state agencies listed in Table A-1 were contacted, but not all agencies responded. Below are the notes taken during each interview.

Delaware

Jason Hastings (DelDOT) and Janice Shute (DNREC), 10/15/21

Background from Shute: The Delaware Department of Transportation (DelDOT) and Delaware Department of Natural Resources and Environmental Control (DNREC) co-own several dams—especially millponds where the embankment serves as the dam. Some embankments have a culvert and others have principal spillway pipe (PSP) risers. These ponds are permanent fish and wildlife ponds. DNREC only regulates publicly owned high and significant hazard dams (which is different from many states)—not private or low hazard. In the partnership, DelDOT tends to do the construction projects and DNREC tends to manage smaller more frequent things with ponds like maintenance.

1. I see the Dam Safety Program says that transportation embankments might be considered to be dams under special circumstances and if it is high or significant hazard class. Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam?

Under dam safety regulations—if it impounds water, it can be considered a dam—the dam needs to be publicly owned and high or significant hazard to be regulated. A few years ago, DNREC did a dam inventory with a Geographical Information System (GIS) study (therefore they only looked at active bodies of water, so this wouldn't include dry stormwater management (SWM) ponds) and did a quick dam break analysis. Temporarily impounded water generally does not fall into regulation (and is probably not even in the inventory). New construction would probably be regulated if DNREC saw it. Transportation embankments (TE) are not specifically exempt.

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

Some dams have roads on top—about 41 regulated dams and all but 2 or 3 have roads across them. Sometimes the road being on top influences hazard class, especially if it is an evacuation route. Most dams were built way before regulations existed (so they don't have a clay core).

3. How would you describe a transportation embankment that it is temporarily impounding water?

DNREC and DelDOT have no specific description. When constructing a new TE, water conveyances (culverts) are designed to not back up (i.e., designed for 50-year storm). SWM ponds still have to go through SWM regulations, and design of wet pond might have some soil regulations but not really any regulations concerning embankment construction.

When a culvert is > 1.9 m^2 (20 ft^2), it is considered a bridge, so it needs to be designed to bridge requirements which require greater conveyance and 0.3 meters (1 foot) of freeboard.

New TE would likely use 50-year design storm and temporary impoundment would be very rare.

4. Do you have any transportation embankments that intentionally temporarily impound water?

Probably yes. Tax ditches were used for drainage on shore, and many of these had oversized culverts (DelDOT found this when retrofitting the tax ditches). The whole state is very flat (like the eastern shore of Maryland) and also has tidal influence. If there are undersized culverts, there is no program to address it unless it is creating some other issue (like roadway maintenance, or sometimes flooding into private property can prompt retrofit).

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

If it falls as a regulated dam, yes, it follows dam safety regulations. If it is low hazard, it is not regulated

6. Do you have specific standards for super wide embankments? When an embankment impounds 7.6+ meters (25+ feet) of water, but is several lanes wide, does it still require a clay core?

The state does not have any superwide roads that are 7.6+ meters (25+ feet) tall. The state is very flat and does not tend to have TE that tall.

7. How are you designing culverts to not cause issues with water impoundment?

Culverts designed for the 50-year storm should not cause long-term water impoundment.

8. How do you manage undersized culverts? What is your retrofit process?

Culverts are addressed if they are causing other issues. See question 4.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

For example, Trussums pond dam had a design spillway that was too small and the road started to erode away. Shute supplied the incident report.

There have been several corrugated metal pipe failures due to holes forming in pipes and then washing out the fill.

Pennsylvania

Nicholas Vivian (PennDOT), 12/21/21

1. Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam?

The Pennsylvania Department of Environmental Protection (PADEP) has Chapter 105 [Pennsylvania Code Title 25, Chapter 105, Dam Safety and Waterway Management] which includes specific criteria: one being a minimum of a 4.6-meter (15 foot) impoundment and a minimum storage volume. The Pennsylvania Department of Transportation (PennDOT) has a lot of deep culverts in valleys, mountains, etc. When you can't put a bridge there's a culvert. The culvert could be 9.1 meters (30 feet) below the roadway which means that you could get 9.1 meters (30 feet) of head behind it, but most of these have a small drainage area so they're not classified as a dam. On page 13 of Chapter 105 there is a definition of a dam [including minimum storage volume and drainage area requirements]. From an objective point of view should PennDOT be treating these deep culverts as dams? No because dams fall under more stringent regulation than standard stormwater control measures. There are only one or two stormwater control measures that qualify as dams. Stormwater measures are getting inspected more and have more maintenance than dams. They also get a condition assessment every 10 years. This setup is better than trying to fit the stormwater measure into a dam regulation which doesn't really fit.

PennDOT revamped the maintenance program based on U.S. Environmental Protection Agency (EPA) requirements to do a better job with stormwater control measures. The stormwater facilities need a visual inspection every three years and intensive inspections every 10 years. This is a rather aggressive maintenance process and there are over 3000 storm water controls. The initial maintenance schedule required by the EPA was unattainable. It required that you checked each facility after the two-year storm. So PennDOT worked with the EPA to create very stringent documentation for the inspections. They also need to fill out the M80 form. Through this process all stormwater control measures were looked at including ponds. All of them were designed to not be considered dams.

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

Another related code is the Dam Safety and Encroachments Act. So, to define an encroachment you look at the 100-year flood plain boundary around the stream. Anything that crosses this boundary is considered an encroachment. Therefore 99% of culverts and bridges are considered encroachments. PennDOT admits about 100 to 150 permits for encroachments each year. PennDOT has a lot of infrastructure to maintain.

The only time dam safety regulations would apply to a culvert is if it was greater than 4.6 meters (15 feet) deep and had over 61,700 m^3 (50-acre-feet) of storage. And no, PennDOT does not have that.

3. How would you describe a transportation embankment that it is temporarily impounding water?

See discussion of encroachments in question 2.

4. Do you have any transportation embankments that intentionally temporarily impound water?

See discussion of deep culverts in question 1.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

PennDOT uses a program called Bridge Watch to draw drainage areas for each bridge in the state. The intensity-duration-frequency (IDF) curve is loaded in the system. In years past they would look at the 24-hour storm and they would be reactive and wait for a bridge or street to flood before they closed it. However, this new system is proactive and they can shut down roads and bridges before they flood.

6. Do you have specific standards for super wide embankments? When an embankment impounds 7.6+ meters (25+ feet) of water, but is several lanes wide, does it still require a clay core?

No.

7. How are you designing culverts to not cause issues with water impoundment?

See discussion of encroachments in question 2.

8. How do you manage undersized culverts? What is your retrofit process?

See discussion of encroachments in question 2.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

PennDOT has seen a lot of failures, but the reason for failures is because of climate change and weather changes. Between October 2020 and October 2021, they had 1265 alerts in the bridge watch system. 15 of these alerts were 500-year events 54 of the alerts were 200-year events and 205 alerts were 100-year events. They are seeing more and more microbursts which is a super large amount of rain in a short period of time. They also saw only 18 one-year events. Climate change is here now, and we need to figure out what happens to the infrastructure.

Hurricane Ida overtopped Willmore dam and they had to evacuate the areas of Willmore, Summerhill, and South Fork because they thought the event could be like the one in 1889. The climate has changed, and we are getting a lot of super short and large events and seeing lots of structural damage from them. He showed a picture of a short embankment that had failed in a large storm. He said it does not really matter how much water is impounded. We are losing things that we never thought we would lose. Therefore, PennDOT is focusing more on resiliency

of design. They also started mapping more flood prone areas. They have seen lots of road washouts. The problem is the change in the weather. Not necessarily which regulation that the infrastructure falls under.

Another example is Lehigh Valley Hospital. There is a highway with a dry pond basin. The 500-year event exceeded the detention basin and the water started flooding the roadway. They had to shut down I-78. This was hurricane Isaiah.

PennDOT is also working with Lehigh University on research for using Geo materials to help prevent scour around bridges.

PennDOT has never designed for the 500-year event before. The current weather output is exceeding the design parameters. Bridges usually have a 500-year check storm, but something like a stormwater control is not going to have that large of a design.

Richard Reisinger (PADEP), 12/16/21

1. I see the Dam Safety includes TE. Drainage manual also says, "the possibility of catastrophic failure should be investigated because a breach in the highway fill could be quite similar to a dam failure." Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam?

The Dam Safety Act and accompanying regulation chapter 105 cover highway and rail and other embankments in two categories. It can be a possible dam, or it can be a water obstruction/encroachment. The Dam Safety office of PADEP looks at intent; something can behave as a dam but not intend to, like an undersized culvert, so then it would be subject to the encroachment guidelines. This is Subsection B of Chapter 105. An example is that culverts needed to be sized to the 100-year storm event and the designer would need to look at how the embankment affects the water surface elevation and not change the water surface elevation substantially. There are some scenarios when the encroachment could become a dam when the owner intended for impounding water either permanently or temporarily. If the owner reduced the capacity of a pipe the Dam Safety Office would tell the owner that it is now a dam and make them follow the dam safety regulations.

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

The design components of a dam versus a highway are different especially the pervious versus impervious fill. PennDOT does own and operate some stormwater control dams. These are typically small and an environmental feature and normally a separate structure from the transportation embankment. If the dam safety office becomes involved because the highway is being designed as a dam this study would have to conform to dam safety standards. The Dam Safety Office uses U.S. Army Corps of Engineers, Bureau of Reclamation, and U.S. Federal Emergency Management Agency (FEMA) documents, depending on the facility.

3. How would you describe a transportation embankment that it is temporarily impounding water?

See discussion of encroachments in question 1.

4. Do you have any transportation embankments that intentionally temporarily impound water?

Yes, Pennsylvania has some dual-purpose road-dams and transportation embankments. In general, the dam existed, and it was a perfect place to put a road. There are lots of cases of small roads and municipality roads where this has happened. They are generally old but there are a lot of rehabilitation projects going on lately. Generally, it is a clay embankment with road fill on top and then the pavement on top of that road fill.

Even when a road is on these facilities, the road owner is typically only responsible for the roadway and there is a separate dam owner who is responsible for the overall dam. This can place a large financial burden on the dam owner. Another component is the placing of utility lines through the dams with roads on top which is something that the Dam Safety Office does not like to see because it can provide additional seepage and piping paths. When these rehabilitation projects are done the standard detail includes roadway grade and asphalt not higher than the crest of the dam. The upstream and downstream sides have normal earthfill and the roadway is cut into the dam. This way there is no direct seepage path, and the road does not increase the height of the embankment. The Dam Safety Office does not want the road to increase in height because this can increase the amount of water impounded by the dam which has implications for the hydrologic design.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

See discussion of dual-purpose road dams in question 4.

6. Do you have specific standards for super wide embankments? When an embankment impounds 25+ feet of water, but is several lanes wide, does it still require a clay core?

There would be no difference. Most likely we would default to saying that the intention is for the embankment to be a highway with the culvert crossing and therefore would work with PennDOT to have it not be designed (and defined) as a dam.

Another aside is when they do breach analysis of dams, they have to look at the roadway downstream of the dam to see the impacts. When a 6 to 8 lane highway is downstream, they assume that the highway will be able to temporarily impound water and mitigate further downstream impacts.

Another consideration within the embankment that is temporarily impounding water for one to two days is that, unless it overtops, normally a wide structure would not develop enough internal phreatic loading to cause an issue. The issue might occur if there was overtopping on more erodible material.

7. How are you designing culverts to not cause issues with water impoundment?

There have been issues with culverts and roadways passing streams. Piping and seepage can occur and especially on older dams without modern design. Corrugated metal pipes deteriorate over time and can cause loss of material. This is especially a concern for deep pipes or high embankment fill because it is more difficult to replace.

8. How do you manage undersized culverts? What is your retrofit process?

See discussion of dual-purpose road dam retrofits in question 4.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

No.

West Virginia

Delbert Shriver (WV DEP), 10/27/21

1. I see the Department of Environmental Protection does not consider transportation embankments to be dams unless they "become a hazard to human life or property through the frequent or continuous impoundment of water." Can you elaborate on how this hazard would be evaluated? For example, would an embankment with undersized culverts be considered a dam? What frequency of impoundment is considered for classifying as a dam?

The West Virginia Department of Environmental Protection (WVDEP) does not usually get involved with West Virginia Division of Highways (WVDOH) culverts. WVDEP is mainly involved with driveways or streets with a corrugated metal pipe (CMP) that collapses. If the culvert is designed correctly (as they are in the highways designed by WVDOH), it is not a dam.

There is no set scale for frequency of impounded water. If it is impounding water enough to saturate embankment (or impounding water under normal conditions), it is investigated by the Office of Dam Safety. It would also be investigated r if it had a riser on it and is specifically impounding water.

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

There are about half a dozen WVDOH embankments that have small amounts of temporary water impoundment, but the water levels are really low compared to road level. There is an example of a 4-lane road that cut across two edges of an oxbow stream and had a higher culvert that caused some impoundment. This was a part of the design to try to reconnect the stream. The Office of Dam Safety tried to take some action to call these culvert locations dams, but it would be more fight that what it was worth. The Office of Dam Safety looked at the probably maximum precipitation (PMP) storm and the resultant flows would not even overtop the road.

3. How would you describe a transportation embankment that is temporarily impounding water?

Shriver would call it roadfill. Examples that WVDEP have been involved with (half dozen at most), most have been driveway or internal streets with CMP that was old and collapsed or blocked (i.e., not discharging water as designed). In the last 2-3 years there were 4-5 of these scenarios that WVDEP was involved with. To handle these, WVDEP issues an order to the owner to fix the culvert or says that they need to file to register it as a dam. The owner usually fixes the culvert and there is no problem. They had a scenario in 2008 where they took control of a road and made it into a dam because the owner did not have funding to fix the culvert. This was a 10.4-meter (34-foot) tall embankment that impounded enough water to be considered a big dam and the culvert had collapsed, which caused water to seep through.

4. Do you have any transportation embankments that intentionally temporarily impound water?

See discussion of WVDOH culverts in question 2.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

No, see discussion of oxbow stream in question 2.

6. Do you have specific standards for super wide embankments? When an embankment impounds 25+ feet of water, but is several lanes wide, does it still require a clay core?

Daughtry County 4-lane highway with median in between (referenced in question 2) is an example of a super wide embankment. WVDEP conducted a seepage analysis and found that seepage failure would only cause half of one lane to fail, and therefore it was not that big of an issue. Shriver sent more documentation related to this case.

7. How are culverts designed to not cause issues with water impoundment?

WVDOH has all standards for culvert design, head, etc. WVDOH uses the number of vehicles on that road to determine culvert design. WVDOH standards are considered sufficient for Dam Safety Office.

8. How do you manage undersized culverts? What is your retrofit process?

WVDOH inspects culverts themselves (unless culverts become an issue). 9 times out of 10, upstream person complains about flooding and that is how WVDEP finds out about the issue. Or WVDEP personnel see flooding while driving around.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

Shriver sent documentation of inspections.

Virginia

Mark Killgore (VA DCR), 1/28/22

1. Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam? Also, what is the difference between an impounding structure and a dam?

Impounding structures and dams are the same. The difference between TE and dams is tied in the way that the legislature defines the Virginia Department of Transportation (VDOT)versus the Virginia Department of Conservation and Recreation (VADCR). VDOT uses expected traffic loads to determine design event and VADCR uses the hazard class of the dam. For VADCR designs, 50-year storm would be the absolute minimum and generally the 100-year storm is used. Property damage and significant traffic is what triggers the hazard class to increase to significant or high. In the case of an undersized culvert the onus would be on VDOT to modernize the culvert and VADCR would not get involved. VADCR would be involved if a new roadway was being built on a dam or if a new roadway was going to touch a dam. There is an interesting scenario where a new roadway piling was going to touch a dam and VADCR required that the developers do an impact review of the road on the dam.

2. VDOT has some guidelines for designing transportation embankments as dams. In what cases would a transportation embankment be designed as a dam?

What VADCR sees most often is that dams get lowered in height to not have to comply with state regulations. So VDOT will make the impounded volume 60,000 m^3 (49 acre-feet) or decrease the height of the dam. If the embankment is not under state regulations, it becomes a county permitting issue. According to the state regulations, a dual-purpose road dam would not be allowed to use an incremental dam break. It would need to use the 1/2 probable maximum flood (PMF). VADCR is not seeing proposals for new roads on new dams. However, when they do see them, the onus is on the developer to prove that no other feasible alternatives for placement of the road are available.

As an example, a developer of a new development wanted to use a dam as a place for the egress route to meet fire evacuation standards and VADCR required that they conduct an alternatives analysis to see if there was a better place to put the road. If the analysis turns out that the dam is the best place for the route the developer would need to make the dam fully compliant with the state standards. This would likely involve a spillway upgrade or an overtopping armoring. It is quite often that roads will get shut down during floods. The worst-case scenario is if a lifeline road or an evacuation route gets shut down. VADCR is ultra-sensitive to these roads and also sensitive to dams surrounding these roads.

3. How would you describe a transportation embankment that it is temporarily impounding water?

This would be called a dry pond. They are regulated if they exceed the size in the regulations and they are regulated the same as any other dam although they are dry most of the time.

4. Do you have any transportation embankments that intentionally temporarily impound water?

See discussion of dual-purpose road-dams in question 2.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

See discussion of dual-purpose road-dams in question 2.

6. Do you have specific standards for super wide embankments? When an embankment impounds 15+ feet of water, but is several lanes wide, does it still require a clay core?

Super wide embankments are usually safer. The biggest issue that VADCR sees with inspections is trees on dams. Engineers have made the argument that super wide dams can have downstream trees within the 7.6-meter (25-foot) radius because of their width. The department understands that super wide embankments do have unique attributes, but it is not yet reflected in policy.

7. How are you designing culverts to not cause issues with water impoundment?

See discussion of sizing roadways to avoid dam regulations in question 2.

8. How do you manage undersized culverts? What is your retrofit process?

This is the responsibility of VDOT (see question 1).

9. Do you have an inventory of transportation embankment/road-dam failure? Information about inspection, maintenance, and performance of specific embankments?

Killgore sent a highway 40 case study.

There is an example of a dam failure on route 54 in Ashland, Virginia. This is a case study. A failure wiped out half of the highway and the developer built a separate dam upstream of the highway. This separate dam was a small dam and was not required to be regulated under state regulations. VDOT likes to avoid dams. If they have regulatory dams, they'll turn it over to a county or local homeowners association (HOA) as a private road so it doesn't have to be in their inventory. VDOT does however have a handful of dams. In Virginia any impoundment meeting regulations is considered regulatory size. Regulated dams need to have a control structure. There are many categories of exemptions from the dam act. For example, culverts with intended free flow are not considered dams. VDOT does not like roads on dams because of overtopping and eroding incidents.

John Matthews (VDOT), 10/8/21

1. I see that your Appendix 14C-1 General Instructions and Criteria Pertaining to Use of Highway Embankment as Dams says that transportation embankments can be used as dams given special design considerations. Can you elaborate on how dams versus transportation

embankments are defined? Would an embankment with undersized culverts be considered a dam?

No, embankments with undersized culverts are not considered a dam. We only consider embankments s as dams if they are designed as such. VDOT tries not to own any dams and they do not use transportation embankments as SWM facilities

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

See question 1 for discussion of VDOT not wanting dams.

3. How would you describe a transportation embankment that it is temporarily impounding water?

Not discussed.

4. Do you have any transportation embankments that intentionally temporarily impound water?

VDOT does not have anything that is intentionally designed to impound water.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

Do not have any specific standards beyond the headwater (Hw) ratio not to be exceeded in the other portions of the design manual.

6. Do you have specific standards for super wide embankments? When an embankment impounds 15+ feet of water, but is several lanes wide, does it still require a clay core?

There are no special considerations for long culverts (under superwide embankments), which also occur in the mountains. However, there are pipe strength considerations for culverts under deep fill

7. How are you designing culverts to not cause issues with water impoundment?

See discussion of undersized culverts in question 8.

8. How do you manage undersized culverts? What is your retrofit process?

Matthews is not aware of any undersized culverts, maybe 1 or 2 that were designed in the 1950s or 1960s. It is not a practice by VDOT to allow undersized culvert/designing the transportation embankment as a dam. Also, other parties are not allowed to use VDOTs embankments as SWM dams or levees.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

Matthews does not think there is an inventory. There is a permit database, but not something he has access to. He does not think that there have been any transportation embankment failures that have been in the mode of dam failure (like piping). Embankments do fail from overtopping, but this is a typical roadway failure.

There is an implied liability when a roadway also acts as a dam, and dam safety actions that VDOT would have to be responsible for. VDOT manages primary and secondary roadways, so this would be too much work to take up those additional responsibilities. Additionally, in the last 5-10 years, VADCR lowered the criteria to 1.8 meters (6 feet) and/or 31,000 m^3 (25 ac-ft) for dam qualification, and VDOT did not have any dams under this new regulation classification.

New Jersey

Sandra Blick (NJDOT), 12/8/21

1. Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam?

Embankments with culverts are not considered dams in New Jersey.

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

NJDOT has had conversations about this. NJDOT designs roads as a roadway, but if it becomes a dam, they design as a dam. 50-100 years ago, there were roads designed as roads, and now the department is going back to update them, and they have turned into dams as well—now they need a permit from the Office of Dam Safety. There are more conditions where road has weir of dam under it. There are no new dual-purpose road dams, but some might need retrofitting. With road-dams, the structure needs to address dam safety criteria, which means doing a dam overtopping analysis to determine if the embankment will scour. Additionally, trees need to be kept out of dam structure. Currently, NJDOT does not design any roadways as dams.

3. How would you describe a transportation embankment that it is temporarily impounding water?

Other states might call it a dam, but in NJ culverts are just culverts. Rarely culverts will be designed for all storm events, especially culverts that were designed 50-100 years ago. When a culvert size is increased and opened up, it is important to look at downstream impacts.

4. Do you have any transportation embankments that intentionally temporarily impound water?

Yes, see discussion of dual-purpose road-dams in question 2.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

Blick is not aware of any clay cores within the dual-purpose road dams. Also, she is not aware of clay linings being used.

6. Do you have specific standards for super wide embankments? When an embankment impounds 7.6+ meters (25+ feet) of water, but is several lanes wide, does it still require a clay core?

No.

7. How does are culverts designed to not cause significant water impoundment?

Blick is not aware of piping being a concern, but scour is taken into account with culverts. There are criteria for new dams to prevent piping, but this is not applied to roads. NJDOT has had issues with CMP, and they currently do not allow CMPs and remove them when they find them

8. How do you manage undersized culverts? What is your retrofit process?

See discussion of dual-purpose road-dams in question 2.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

NJDOT is in process of inventorying and bridge rating.

Richard Tamagno (NJDEP), 10/29/21

1. Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam?

In the early-mid 1980s NJDEP was creating the dam safety laws and there were public comments on culverts acting as dams—regulations back then said dams are designed for purpose of impounding water. The dam safety office decided that culverts do not count as dams because their purpose is not to impound water.

Also an issue: when someone removes a dam, they cannot increase the flood damage downstream, but they also cannot leave anything in the dam breach area that still counts as a dam (what is left over from a dam breach still might be able to impound 1.5+ meters (5+ feet) of water, so they need to ensure that this is removed after breach).

There are a lot of issues with jointly owned dams that meet my research interests. There have been court cases to get owner to acknowledge a TE is a dam.

2. Are there any cases where a transportation embankment would be designed as a dam (e.g. stormwater facility against roadway)? Do you have any transportation embankments that intentionally temporarily impound water?

Yes. There are some embankments where NJDEP does not know when they were constructed (sometimes a spillway on a bridge opening). Some of these embankments are clearly both a TE and a dam. They would fall under regulatory authority, but NJDEP does not always have details about construction. Tamagno does not think there are any that intentionally impound water and are not dams—the undersized culvert seems like a weird way to achieve flood attenuation.

3. How would you describe a transportation embankment that it is temporarily impounding water?

The name might have been inadequate culvert, back from the public comments on dam regulation creation.

4. Do you have any transportation embankments that intentionally temporarily impound water?

No, see question 2.

5. Are there specific safety standards for transportation embankments that impound water, even if they are not considered as dams?

There are no specific standards in dam safety regulations. This issue goes back to the definition of a dam, and it if is designed for the purpose of impounding water. Although it says impounding water on a permanent or temporary basis, this is considering things like a detention basin, and the purpose of the TE is not to impound water (it might be an unintended purpose).

6. Do you have specific standards for super wide embankments? When an embankment impounds 7.6+ meters (25+ feet) of water, but is several lanes wide, does it still require a clay core?

Yes, NJDEP has multiple lane dams. NJDEP handles them with hazard class. Our typical guidance is that county or state highway has to be at least a class II. A big highway could be high hazard. We could have some that meet this scenario (superwide, impounding water).

Every dam is completely different and not every dam will have its own seepage analysis, depends on owner. The phreatic surface is usually used in slope stability analysis. Doing a failure analysis depends on hazard class of dam—some require dam breach analysis, and in this case the width of the embankment does not matter.

7. How are you designing culverts to not cause issues with water impoundment?

The dam safety office does not do design, it just reviews permits, and reviews design of culverts. When NJDOT wants to rehabilitate a roadway that is also a dam, they still have to submit permit to NJDEP. When NJDEP looks at the permit, they typically are looking for foundation design materials, but not typically getting into structural features. NJDEP looks at hydraulic design ensuring passing of the design storm.

8. How do you manage undersized culverts? What is your retrofit process?

The dam safety office does not do culvert review and retrofit. The flood engineering group in NJDEP deals with flood mitigation and desnagging, so this might come up there.

9. Do you have an inventory of transportation embankment failure or incidents (overtopping, sinkholes, piping)? Information about inspection, maintenance, and performance of transportation embankments that are also dams?

NJDEP does not keep track of temporarily impounded water. Tamagno can think of 20+ dams/TE that overtopped and the downstream slope eroded. Tamagno sent NJDEP inspections of NJDOT TE and incident reports.

New York

Peter VanKampen (NYDOT), 10/20/21

1. I see the Highway Design Manual calls TE a "detention feature". Can you elaborate on how dams versus transportation embankments are defined? For example, would an embankment with undersized culverts be considered a dam?

The New York Department of Transportation (NYDOT) does not design TE as dams. TE are not lined with clay, they use native materials. Generally, TE design tries not to pond water. Culverts < 1.5 meters (5 feet) have an allowable headwater—designed based on 50-year storm, so the water impoundment is a very temporary moment. Depending on velocity, the upstream culvert will have headwalls or armored banks. NYDOT does not have detention facilities up against TE. TE are not impounding water like a dam; lateral flow is more of an issue (swales with check dams alongside highway). VanKampen remembers an issue in Iowa with overtopping and holding back water when a river was overflowing (AASHTO conference). The road was acting as a levee and needed to be reinforced.

According to drainage manual, culverts will only back up in 100-year flow, the new 50-year design is part of the recent Resiliency Act. Sometimes culverts get clogged and there is unintentional flooding

2. Are there any cases where a transportation embankment would be designed as a dam? Are transportation embankments specifically exempt from dam regulation?

TE does not equal a dam, unless it is a dam with a roadway on top.

3. How would you describe a transportation embankment that it is temporarily impounding water?

VanKampen does not think there is another way to describe this scenario. Part of the consideration is what happens downstream; bigger culvert increases flow downstream and this needs to be balanced with the potential damage to structures downstream.

4. Do you have any transportation embankments that intentionally temporarily impound water? Are there any TE in NJDEC Dam inventory?

TEs would not be in the dam inventory.

5. Are there specific safety standards for transportation embankments that impound water? When do they need a clay core? Emergency spillway?

NYDOT checks the 100-year storm as well for adverse impacts in surrounding areas, so this has them mostly covered. They used StreamStats program to determine how runoff might change in the future. A multiplier is added based on location in the state to account for this future runoff (1.2x in eastern part, 1.1x elsewhere). VanKampen personally has not seen any cases of water impoundment. Most failures are around culverts that clog. Additionally, the culvert is already a hole in the embankment, so the culvert is the weakest link.

6. Do you have specific standards for super wide embankments? When an embankment impounds 7.6+ meters (25+ feet) of water, but is several lanes wide, does it still require a clay core?

VanKampen does not recall anything different for superwide.

7. How are you designing culverts to not cause issues with water impoundment?

See discussion of culvert design storms in questions 1 and 5.

8. How do you manage undersized culverts? What is your retrofit process?

NYDOT has a maintenance viewer where they are tracking locations with problems in the past (repetitive sites). They have federal funding to approach retrofitting these problem areas with different fixes from the past hopefully to prevent the problem from occurring again. Larger culverts are inspected on a 2 year cycle. Smaller culverts are inspected less often because there are so many of them. They are also working on a database that has culverts for fish passage purposes. When inspections take place, they look at scour, condition around the culvert from beginning to end, and surface of roadway for problems.

9. Do you have an inventory of transportation embankment failure? Information about inspection, maintenance, and performance of specific embankments?

The agency is working on developing a share point site and putting more of this information out to the public. They have information about maintenance, inspections, and prior problems already inventoried, but is not yet open to public.

10. Based on the "defining allowable headwater elevation" section of the drainage manual, do you have any examples of "stability of roadway embankment above culvert"? How do you do this analysis?

The analysis depends on the materials, in general they want to avoid having water levels reach poor soils, but new TE should not be built with poor soils (and old poor soils should be

replaced). They use a 100-year check storm to ensure water is not getting up to the pavement subbase, which is permeable. This high-water level is applicable mainly to smaller culverts. In general, a raise in headwater is avoided. NYDOT is not currently using a seepage software. NYDOT gets soil borings to determine soils present in the TE. They also collect soil borings for pipe relining work because they need to know what soil pressure is (this is done by contractors who come back to NYDOT for approval).

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