FINAL REPORT

FHWA-WY-15/01F

State of Wyoming
Department of Transportation

U.S. Department of Transportation
Federal Highway Administration

INVESTIGATION OF APPROACH SLAB AND ITS SETTLEMENT FOR ROADS AND BRIDGES

By:

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December 2014

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FHWA-WY-15/01F</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Investigation of Approach Slab and its Settlement for Roads and Bridges</td><td colspan="2">5. Report Date
December 2014</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Kam Weng Ng, Seyed Yashar Yasrobi, Thomas V. Edgar</td><td colspan="2">8. Performing Organization Report No.
RS05213</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Department of Civil & Architectural Engineering
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1000 E. University Avenue, Dept. 3295
Laramie, Wyoming 82071</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
64737</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Organization Name and Address
Wyoming Department of Transportation
5300 Bishop Blvd, Bldg 6100
Cheyenne, WY 82009-3340</td><td colspan="2">13. Type of Report and Period Covered
Final Report – March 19, 2013 to December 31, 2014</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
WYDOT technical contact Michael E. Menghini, P.E. Assistant State Bridge Engineer</td></tr>
<tr><td colspan="4">16. Abstract
Approach slabs serve as a transitional system between an approach road and a bridge. Settlement of bridge approach slabs and their supporting backfill has been experienced by more than ten Departments of Transportation throughout the United States. According to current Wyoming Department of Transportation inspection reports, bridge approach slab settlements occurred not only on existing bridges but also on newly built bridges that were just opened to traffic. These settlements typically create voids ranging from 6-in to 12-in between the base of the approach slab and the geotextile reinforced backfill. This research presents factors causing bridge approach slab settlements and provides necessary design and construction recommendations. A comprehensive literature review pertaining to approach slabs was performed to examine outcomes of research conducted by 12 states. The current specifications and standards on bridge approach slabs of the corresponding states' Departments of Transportation were also evaluated. A nationwide survey was conducted to fill in the missing knowledge identified in the literature review. The results of the survey are categorized in three groups based on the percentage of bridges experiencing approach slab settlements in that state. Results of the survey show that 46 percent of the total 28 respondents are not satisfied with their current approach slab designs. The survey results revealed that the most common cause of approach slab settlement is poor construction practices. The most important finding of the survey is that performing in-situ tests to control backfill compaction reduces the amount of approach slab settlement. Using the lessons learned from the literature and the results of the survey, potential amendments to current Wyoming Department of Transportation design and construction manuals are recommended</td></tr>
<tr><td colspan="2">17. Key Words
Approach slab; Settlement; Bridge; Design; Construction; Wyoming</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classification (of this report)
Non-Classified</td><td>20. Security Classification (of this page)
Non-Classified</td><td>21. No. of Pages
169</td><td>22. Price</td></tr>
</table>

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Sponsored by
Wyoming Department of Transportation
(Grant No: 64737)

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CHAPTER 1 - INTRODUCTION

1.1 Introduction

An approach slab serves as a transitional system between an approach road and a bridge. The primary function of the approach slab is to diminish the amount of differential settlement between a filled embankment and a bridge abutment. If the approach slab functions properly, a driver will not feel a bump while driving across a bridge abutment.

The Wyoming Department of Transportation (WYDOT) has been using a geotextile reinforced backfill for concrete approach slabs for about 20 years. Original development of the approach slab system was based on a research project completed by Edgar et al. (1989) with the objectives of 1) reducing long-term maintenance costs as a result of excessive embankment settlement; and 2) alleviating lateral load acting on bridge abutment walls and lateral deformation causing expansion device closure.

For many years, settlements of the concrete approach slab and backfill have been observed by WYDOT engineers and site personnel both at new bridges just opened to traffic, as well as at older bridges. These settlements create typical voids ranging from 6-in to 12-in between the base of the approach slab and the backfill. WYDOT has observed that settlements occurred at the approach roadway end as well as at the bridge end. These voids reduce the bearing support from the backfill material to the approach slab, and in several cases, cause damage to abutment corbels. On the entrance ends, road bumps due to the settlement create a greater impact load to the bridge, increasing damage to joints and decks.

1.2 Background

Geotextiles have been used by the Wyoming Highway Department (WHD), now the WYDOT, since the 1980s to reduce approach slab settlement and lower maintenance costs (Price and Sherman, 1986). At that time, it was estimated that the WHD typically spent $1,600 annually per bridge in maintenance costs to address problems related to the approach slab settlement (Sherman, 1988). Undeniably, much higher repair costs would be expected today.

Beginning in the fall of 1984, the WHD sponsored a research project with the objective of improving the performance of the approach slab with a geotextile reinforced backfill system (Edgar et al., 1989). A series of laboratory tests were conducted to examine several backfilling methods for approach slabs behind bridge abutments. A field test program was subsequently conducted at the I-80 bridge over the Union Pacific railroad (Ozone Bridge Project) to validate the laboratory test methods. The field test results concluded that the approach slab with a geotextile reinforced backfill and a 2-inch to 4-inch cardboard to form a gap between the backfill and the abutment:

- Showed significantly less settlement.
- Reduced lateral load acting on the abutment.

After monitoring for about a year, a maximum vertical settlement of 1.06-in and lateral settlement of 0.5-inch were measured near the mid-width and behind the East Bound Lane-West bridge abutment. Further research to evaluate the long-term performance of the approach slab was suggested but not implemented.

Several issues have been encountered by WYDOT over the years, briefly described as follows:

- It is difficult to ensure the tightness or tension of woven geotextiles during installation.
- The polypropylene woven geotextile fabric may not effectively drain water.
- It is difficult to construct a 1.5 to 1 side slope of a filled embankment.
- It is difficult to compact previous backfill material although it complies with the graduation requirements specified in the WYDOT Standard Specifications for Road and Bridge Construction (2010), Subsection 803.14.
- It is difficult to ensure the cardboard is saturated and eventually forms a gap between the backfill and the bridge abutment.
- Challenges exist in detecting voids beneath approach slabs; consequently, many problematic approach slabs are yet to be discovered.
- No guidelines exist for retrofitting.

The above issues may have been caused by a number of potential factors, which will be confirmed by this research, such as:

- Suitability of current material specifications for backfill material and geotextile.
- Deficiencies in construction processes, such as compaction requirements and excavation preparation.
- Inadequate design of the reinforced approach slab system.

Since the 1989 WYDOT project, many other state agencies have conducted research on approach slab systems, and new technologies have been developed to improve them. These research outcomes will enhance our understanding of the problem and possibly provide solutions to similar approach slab settlement problems encountered in Wyoming. This previous research will also provide a basis for future research.

1.3 Research Objectives

Recognizing the urgent need to solve approach slab settlement problems and their associated maintenance costs, a research project is proposed. The project includes a thorough literature review of approach slab settlement problems and provides potential solutions. The objectives of this study are:

- Identify and narrow the focus on specific parameters causing the settlement problems.
- Develop rational approaches to retrofit approach slab systems.
- Revise and improve approach slab system design and construction procedures.
- Propose changes in current WYDOT design and construction manuals for approach slab systems.

1.4 Research Plan

The research plan was developed based on the aforementioned problem and research objectives. The research objectives were achieved by completing four major tasks which are described below.

Task A: Literature Review

This task focuses on conducting a comprehensive literature review pertinent to the reinforced approach slab. The review includes the following:

- Documentation and review of current states of knowledge and practice, including personal experiences, relating to bridge approach slab systems.
- Examination of approach slab problems experienced by WYDOT and other state DOTs along with their methods of remediation.
- A study of current approach slab system specifications and guidelines prepared by state and national agencies.
- Identification of potential applications and adaptations through the literature review.
- Identification of gaps in the body of knowledge necessary to develop a nationwide survey in Task B.

Task B: Nationwide Survey

Knowledge gaps were identified and formulated in a series of questions for a nationwide survey. The survey was sent to relevant state and local agencies (e.g., state DOTs) and the American Association of State Highway and Transportation Officials (AASHTO). Survey data was collected, analyzed, and used to fill in missing knowledge, so that comprehensive recommendations could be developed in Task C. To improve data collection and enhance security, the survey was developed and administered using the commercial online survey software, SurveyMonkey®.

Task C: Conclusions and Recommendations

Paramount factors causing approach slab settlement problems were identified in this task. Limitations of existing approach slab systems were highlighted. Recommendations were made to 1) provide rational methods to retrofit problematic approach slabs on existing roads and bridges; and 2) suggest improvements regarding the design and construction of approach slab systems.

Task D: Implementation

Integrating the outcomes obtained from previous tasks, changes to current WYDOT design and construction specifications for approach slab systems were proposed.

1.5 Report Outline

The report consists of five chapters, summarized as follows:

- ***Chapter 1 – Introduction*** introduces the problem and presents research scope, objectives, and research tasks.
- ***Chapter 2 – Literature Review*** reviews and analyzes the literature on approach slab settlement and presents specifications of approach slab design in various states.
- ***Chapter 3 – Survey*** presents the survey questions and results of the survey.
- ***Chapter 4 – Analysis of Results*** summarizes the lessons learned from the literature review and analyzes the survey results.
- ***Chapter 5 – Conclusions and Recommendations*** presents conclusions, suggests changes to current WYDOT design and construction specifications, and makes recommendations for future research.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

This chapter provides a detailed review and background information on approach slab research conducted by various states. Also, specifications for approach slab used in some states are briefly described.

2.2 Research on Approach Slab

In this section, research activities related to bridge approach slab are presented by state.

2.2.1 Wyoming

Edgar et al. (1989) evaluated different methods of constructing reinforced soil embankments behind bridge abutments. The type of reinforcement to the approach slab backfill was limited to polypropylene woven geotextile fabric in continuous sheets. After extensive laboratory studies, a field study was conducted to evaluate different construction methods at the Ozone Bridge on Interstate 80, located 25 miles west of Cheyenne, Wyoming. Four embankments were reconstructed using different techniques for reinforcing the embankments and supporting the soil at the abutment. The embankment construction schemes were:

- No geotextile reinforcement.
- Geotextile-reinforced soil backfill directly against the face of the abutment.
- Initial 2-inch void between the geotextile-reinforced soil backfill and abutment.
- Initial 6-inch void between the geotextile-reinforced soil backfill and abutment.

After instrumentation was installed, repeated initial measurements (i.e., vertical and horizontal deformations and earth pressure) were taken to establish the reference position of the embankments. They found that geotextile reinforcement appeared to be an effective technique to control short term deformations. The technique of constructing a 6-in void between the reinforced embankment and abutment with cardboard also appeared to be an easy and effective method of reducing lateral loads on the abutment. The findings of this research are summarized as follows:

- Embankments constructed with cardboard voids showed lower lateral earth pressures than those constructed directly against the abutment.
- The unreinforced embankment showed larger settlement compared to the reinforced embankments.
- Geotextile reinforcement and the creation of a void between the backfill and the abutment resulted in smaller lateral movements under the roadway surface than on the side slopes.
- It appeared that heavily reinforced concrete approach slabs were necessary to span the voids in the embankment caused by differential settlement.

Recommendations by Edgar at al. (1989) for constructing bridge embankments with geotextile fabrics are presented in table 1. These recommendations are based on issues encountered during the design and construction of the four embankments. Their scope is limited by these specific site observations. These recommendations represent guidelines to resolve the issues encountered in this study.

Table 1 Recommendations for constructing geotextile reinforced bridge embankments (Edgar et al. 1989)

Issue	Technical Concerns	Recommendations
Cardboard form	Appears that this technique works. Slightly larger loads measured in the cells mounted in the corbel may become significant in time.	Use the 2-in cardboard form to create a void between the reinforced embankment and the abutment.
Storing Cardboard	Moisture reduces the strength of the cardboard causing premature collapse.	Store in a room free of moisture.
Plywood form	Appears from the construction observations that reduced lateral pressure would develop on the abutment. Technique did not maintain the desired gap.	Redesign the plywood form and/or the embedment length of the fabric. A form with hinged spacers may be easier to remove. The wrap length of the fabric should be extended to prevent pullout of the wrap.
Wrapping the sides of the excavation	Deformation may become significant for high, steep embankments since lateral movements may be anticipated.	Use transverse sheet reinforcement and wrap the sides of the embankment similar to the technique used at the abutment.
Laying the fabric perpendicular to the abutment as opposed to parallel to the roadway	The fabric should be laid parallel to the center line of the road, to prevent deep failure. In order to provide support and reduce deformations at the abutment wall, the fabric should be laid at a skew with the center line of the roadway, perpendicular with the abutment.	For situations where soft foundations exist, laying the fabric parallel with the center line of the roadway may be preferred. If stable foundations are present, laying the fabric perpendicular with the center line of the roadway may be permitted.

2.2.2 Missouri

Petry et al. (2002) conducted research to identify, document, and prioritize geotechnical problems based on Missouri Department of Transportation (MoDOT) bridge design specifications revised in 1993. Their research identified bridge approach slab settlement as one of the major geotechnical problems. As part of this research, a survey was distributed to all district geologists, area engineers, resident engineers, operation engineers, and construction inspectors. The survey results indicated that the 10 surveyed districts in the State of Missouri all had bridge approach slab problems.

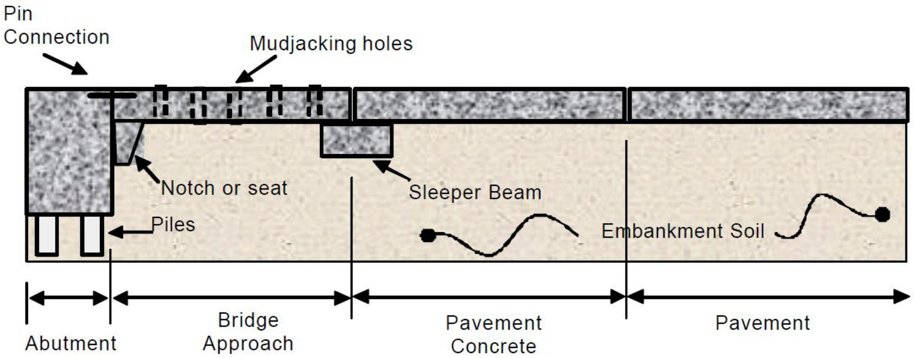


Figure 1 MoDOT Post-1993 bridge approach design (Lunda et al. 2004)

The 30-ft constructed bridge approach slabs were supported by the bridge abutment and the sleeper beam-on-grade. The bridge approach slab design as shown in figure 1 included a grid of mudjacking holes for the purpose of “pressure grouting”, which was used by MoDOT as the common retrofitting method for differentially settled bridge approach slabs. According to this research the five main causes of bridge approach slab settlement are due to:

- Poor selection of materials.
- Inappropriate types of foundation soils.
- Drainage problems.
- Embankment erosion.
- Inadequate compaction of fill.

However, it was concluded that the primary cause of bridge approach slab settlement was due to compression and consolidation of embankment soil. In some cases where expansive soil from borrow was used, soil heaving was noticed. Where the bridge approach slab was built on cut subgrade, rock cut, and/or with a small embankment fill, very little or no differential settlement was observed. On the other hand, thick embankment fill with no drainage led to settlement (figure 2).

Another concern related to bridge approach slab settlement is the movement of the sleeper slab foundation subjected to the same settlement of the underlying fill. This settlement caused the bump to move further away from the end of the bridge.

Following the research completed by Petry et al. (2002), Luna et al. (2004) evaluated the performance and design of bridge approach slabs. The research objective was to identify and quantify the failure mechanisms of those bridge approach slabs supported on approach abutments. The bridge approach slab movement mechanisms are summarized as follows:

- Settlement or creation of voids beneath the sleeper beam and approach slab was attributed to inferior embankment fill, such as having drainage problems or being composed of a poorly compacted material.
- Improper compaction practices or the use of soils subject to volume change led to consolidation, shrinkage, or heaving of embankment soils.

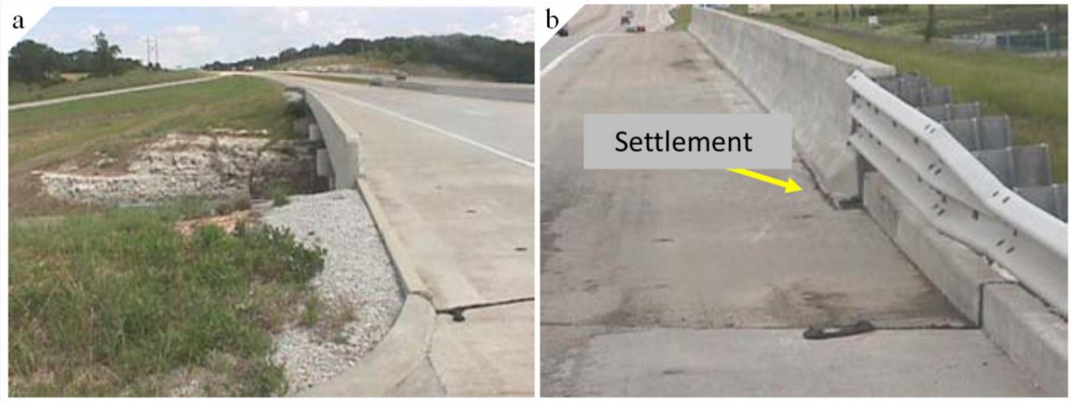


Figure 2(a) No settlement on bridge approach slab with unused mudjack holes shown, and (b) Differential settlement occurred on a bridge approach slab (Petry et al., 2002)

After studying 185 bridges statewide, Luna et al. (2004) concluded that Missouri’s bridge approach slabs were not performing at an acceptable level. Embankment and bridge approach slab were majorly affected by construction sequence. They suggested that delaying the construction of bridge approach slab would improve performance as the embankment becomes less compressible when stiffened.

Thiagarajan and Gopalarthnam (2010) performed research on bridge approach slabs with the objective of developing a cost-effective approach slab system. A nationwide survey was conducted to determine the geometric properties of the bridge approach slabs used by each state. The results of the survey, summarized in figure 3 to figure 5, reveal span lengths varying from 10-ft to 33-ft and thicknesses varying from 8-inch to 17-inch The design moment capacity of Wyoming bridge approach slabs was among the lowest.

Additionally, Thiagarajan and Gopalarthnam (2010) performed numerical analyses of bridge approach slabs. The analyses demonstrated that design moment varies considerably depending on initially assumed boundary conditions and lane loads. When compared with a simply supported bridge approach slab considered in the MoDOT design procedure, the recommended cast-in-place approach slab supported on elastic soil was found to cut construction costs by 22 percent. The cost reduction was attributed to the 50 percent moment distribution from slab to underlying soil.

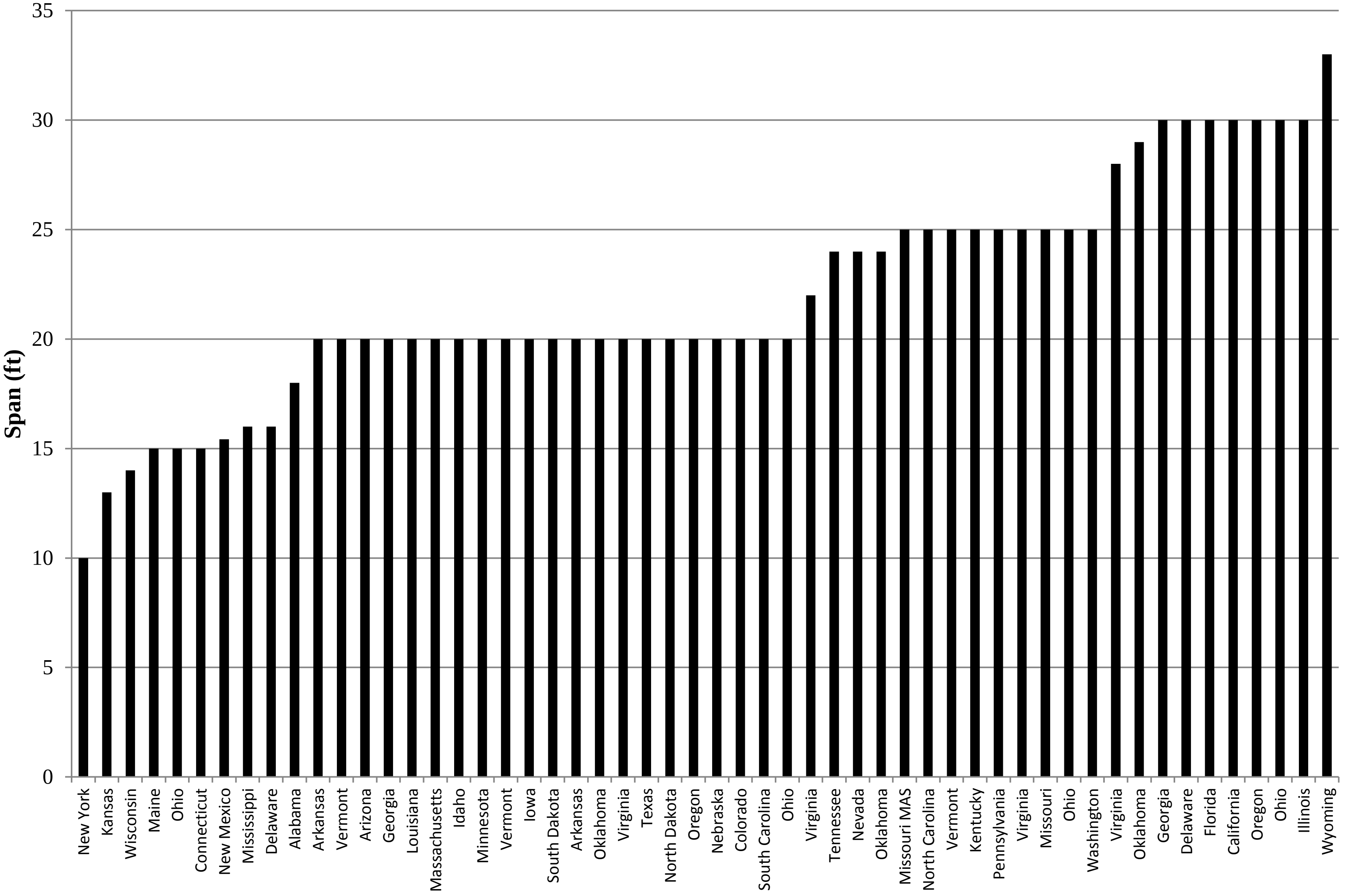


Figure 3 State data sorted by span of bridge approach slab (Thiagarajan and Gopalarthnam, 2010)

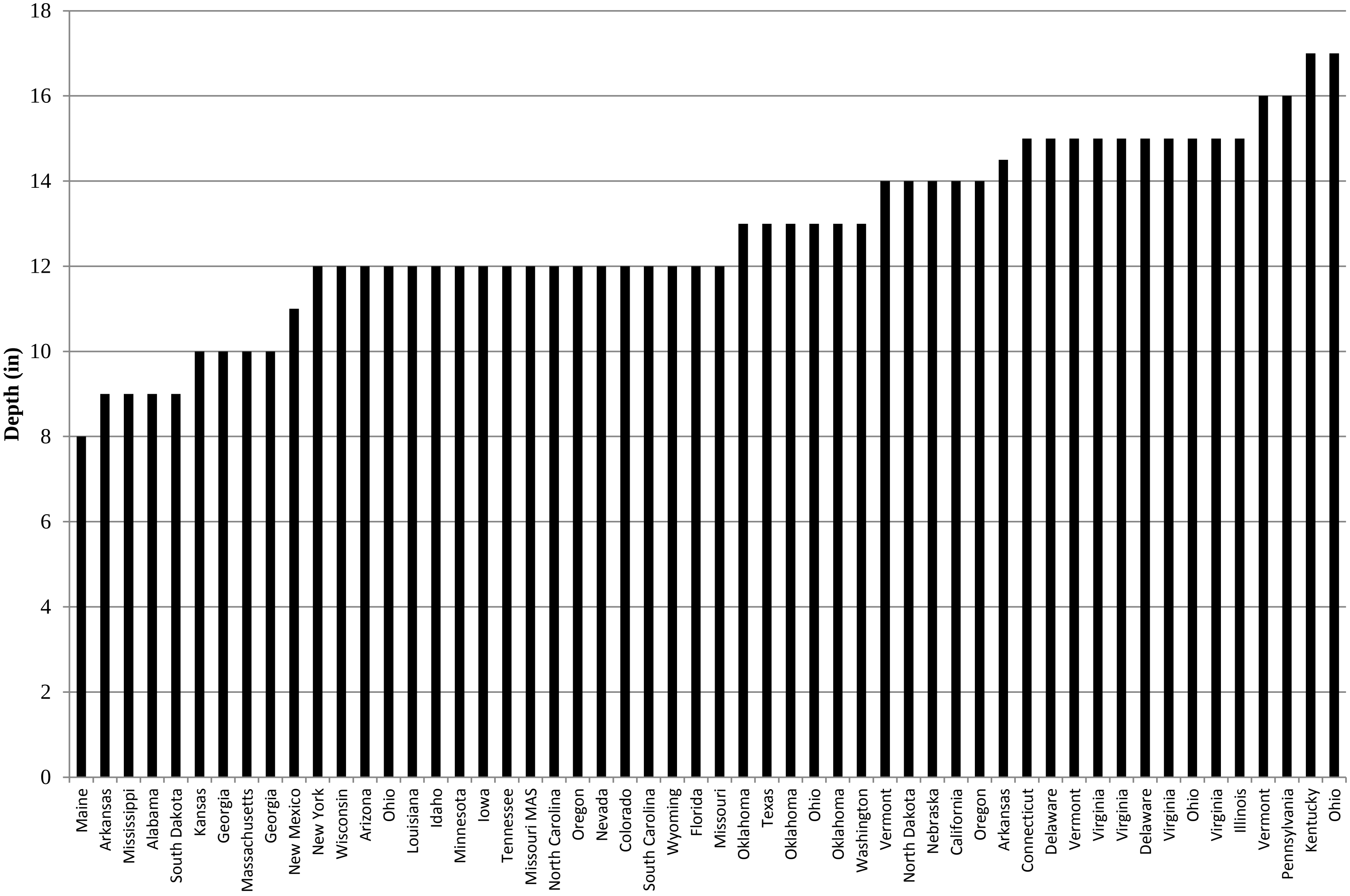


Figure 4 States data sorted by thickness of bridge approach slab (Thiagarajan and Gopalarthnam, 2010)

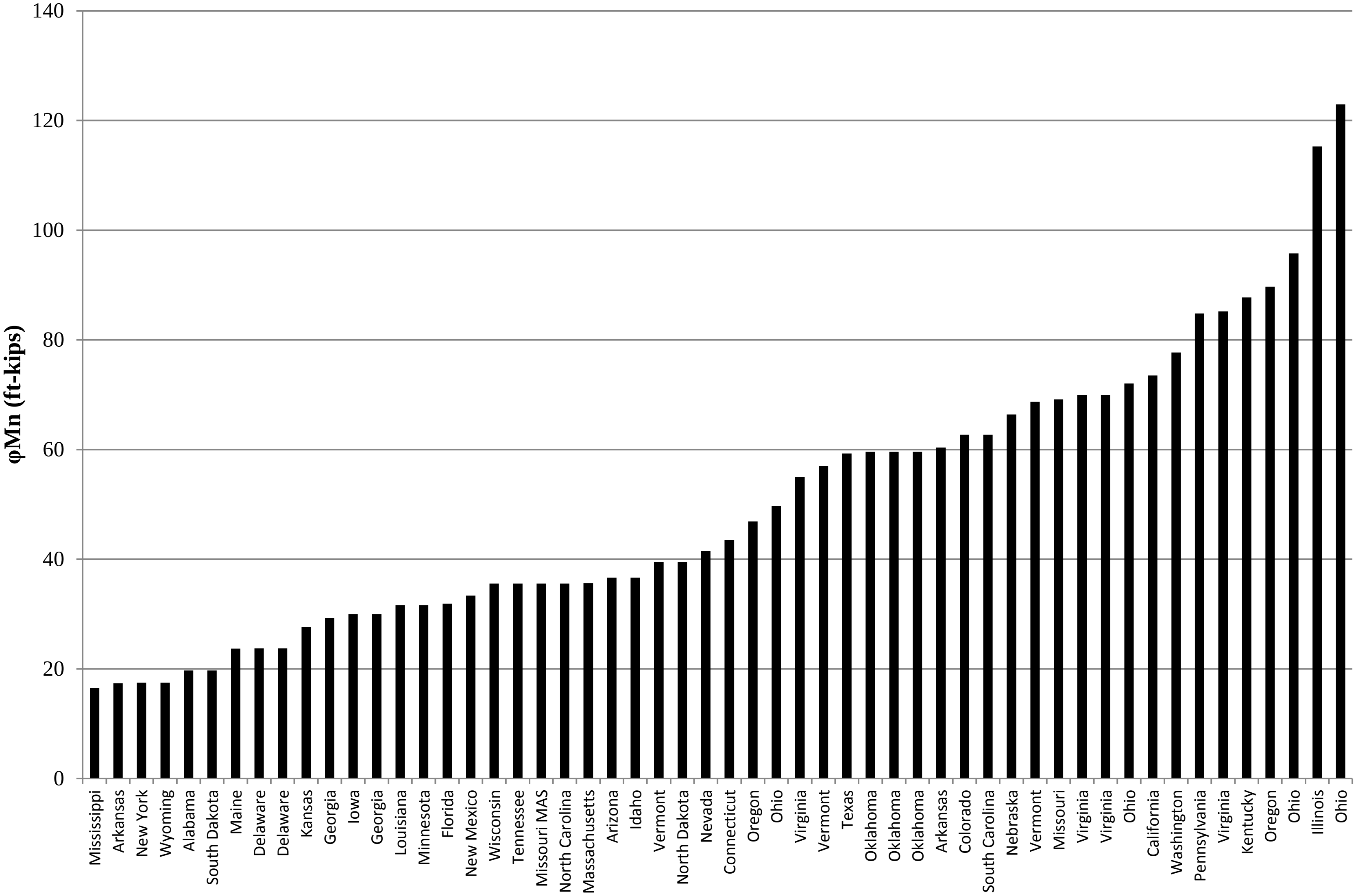


Figure 5 States data sorted by design moment capacity of bridge approach slab (Thiagarajan and Gopalarthnam, 2010)

This new recommended design retains the standard 12-in slab thickness but decreases the steel reinforcement in the approach slab. Thus, the original sleeper slab system was replaced in the design procedure by the newly recommended, continuously supported, cast-in-place slab system.

Furthermore, this research proposed a retrofitting solution for bridge approach slab replacement using a precast prestressed slab with transverse ties. Detailed cost analyses showed that it is cost effective for both newly constructed and existing bridge approach slabs.

2.2.3 Iowa

After identifying design, construction, and maintenance practices related to bridges in Iowa, White et al. (2005) conducted a study with the goal of reducing bridge approach slab settlements. Bridge abutment and approach slab details, such as backfill gradation, compaction rate, and drainage systems, were reviewed, and causes leading to the formation of the bump were identified. Backfill gradation requirements specified by various DOTs including Iowa's are presented in table 2.

Iowa DOT limits the height of compacted backfill layers to 8-inch. It is specified that the first layer from the bottom should be compacted to 90 percent of its maximum dry density and the following layers to 95 percent. Table 3 summarizes compaction requirements in different states. All states' DOTs require backfill to be compacted to at least 95 percent of its maximum dry density. Additionally, three drainage systems used in different states were categorized in this research:

- Porous backfill around a perforated drain pipe.

- Geotextile wrapped around porous backfill.
- A vertical geo-composite drainage system.

Schematic drawings of three different drainage systems used in Iowa, Wisconsin, and Missouri as examples are presented in figure 6 to figure 8. The drainage systems used in various states are summarized in table 4.

Table 2 Backfill gradation of different DOTs (White et al., 2005)

State	Percentage Passing				
	Max. Sieve size (mm)	4.75 mm (#4)		0.075 mm (#200)	
		min	max	min	max
Illinois	75	50	100	0	4
Indiana	50	20	70	0	8
Kansas	101	0	60	0	5
Michigan	25	-	-	0	7
Minnesota	50	0	50	0	4
Missouri	50	0	5	-	-
Montana	50	20	40	0	8
Nebraska	9.5	92	100	0	3
North Dakota	75	35	85	0	15
Ohio	75	-	-	0	20
South Dakota	37.5	0	20	-	-
Wisconsin	75	25	100	0	8
Virginia	75	16	30	4	14
Colorado	50	30	100	5	20
Washington	50	22	66	0	5
New York	101	0	70	0	15
Tennessee	50	35	55	4	15
South Carolina	50	30	50	0	12
Oklahoma	75	0	45	0	10
Kentucky	101	0	30	0	5
North Carolina	9.5	80	100	0	20
California	75	35	100	-	-
Idaho	75	55	100	0	5
Massachusetts	12.5	40	75	0	10
Louisiana	12.5	-	-	0	10
Nevada	75	35	100	0	12
Iowa	76.2	20	100	0	10

Table 3 Compaction requirements for various states (White et al., 2005)

State	Percent of maximum dry density	Test Method
Illinois	95	AASHTO T-99 C
Indiana	95	AASHTO T-99
Kansas	95	AASHTO T-99 C/D
Minnesota	95	AASHTO T-99
Missouri	95	AASHTO T-99 C
Nebraska	100	AASHTO T-99
North Dakota	95	AASHTO T-99
Ohio	100	AASHTO T-99
South Dakota	95	AASHTO T-99
Wisconsin	95	AASHTO T-99 C
Colorado	95	AASHTO T-180
Washington	95	AASHTO T-99
New York	95	Standard Proctor
Tennessee	95	AASHTO T-99 C
South Carolina	95	AASHTO T-99 A/C
North Carolina	95	AASHTO T-99
California	95	Standard Proctor
Idaho	95	AASHTO T-99 A/C
Massachusetts	95	AASHTO T-99 C

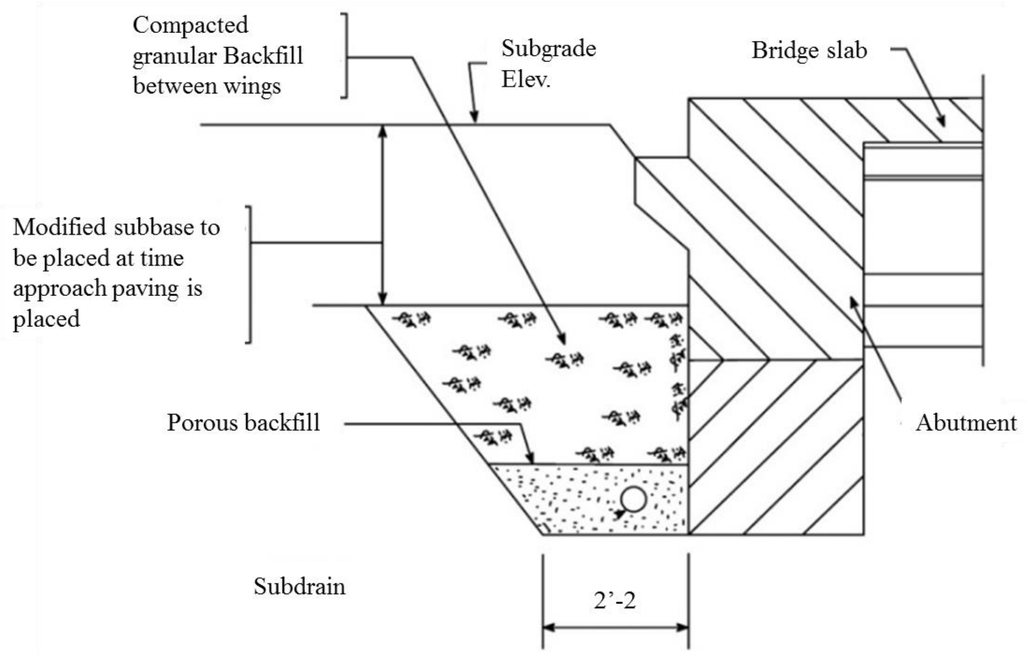


Figure 6 Porous fill surrounding subdrain used in Iowa (White et al., 2005)

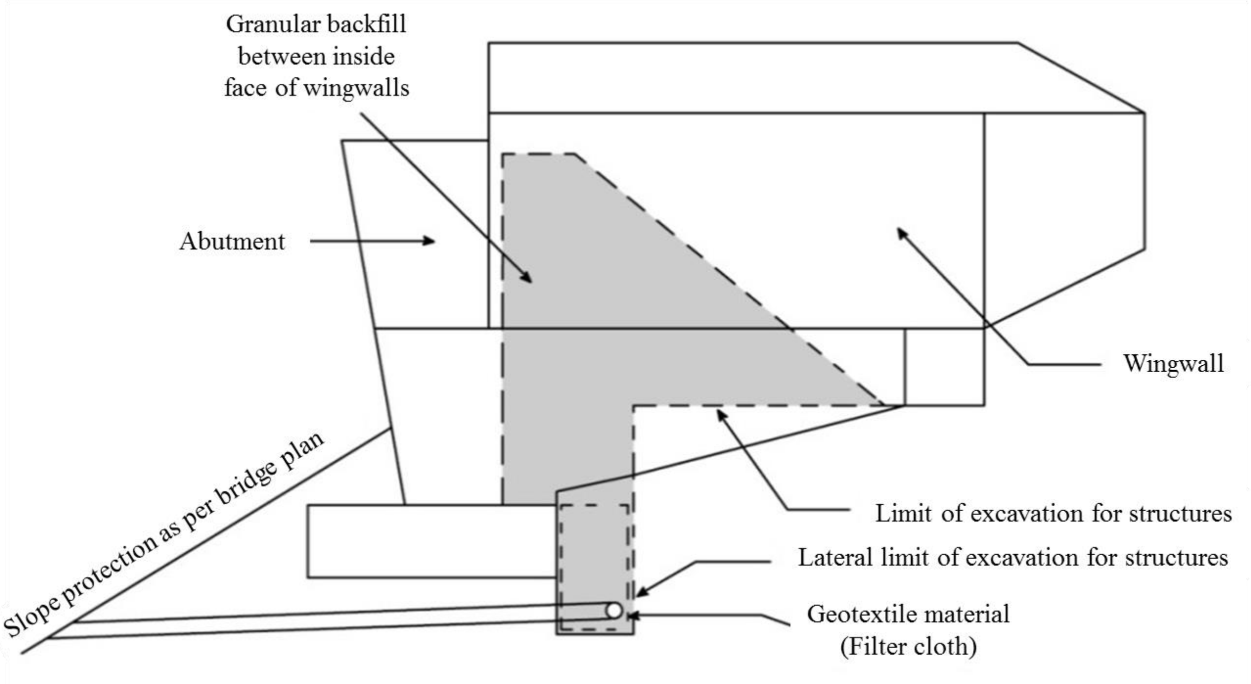


Figure 7 Granular backfill wrapped with geotextile filter material used in Wisconsin (White et al., 2005)

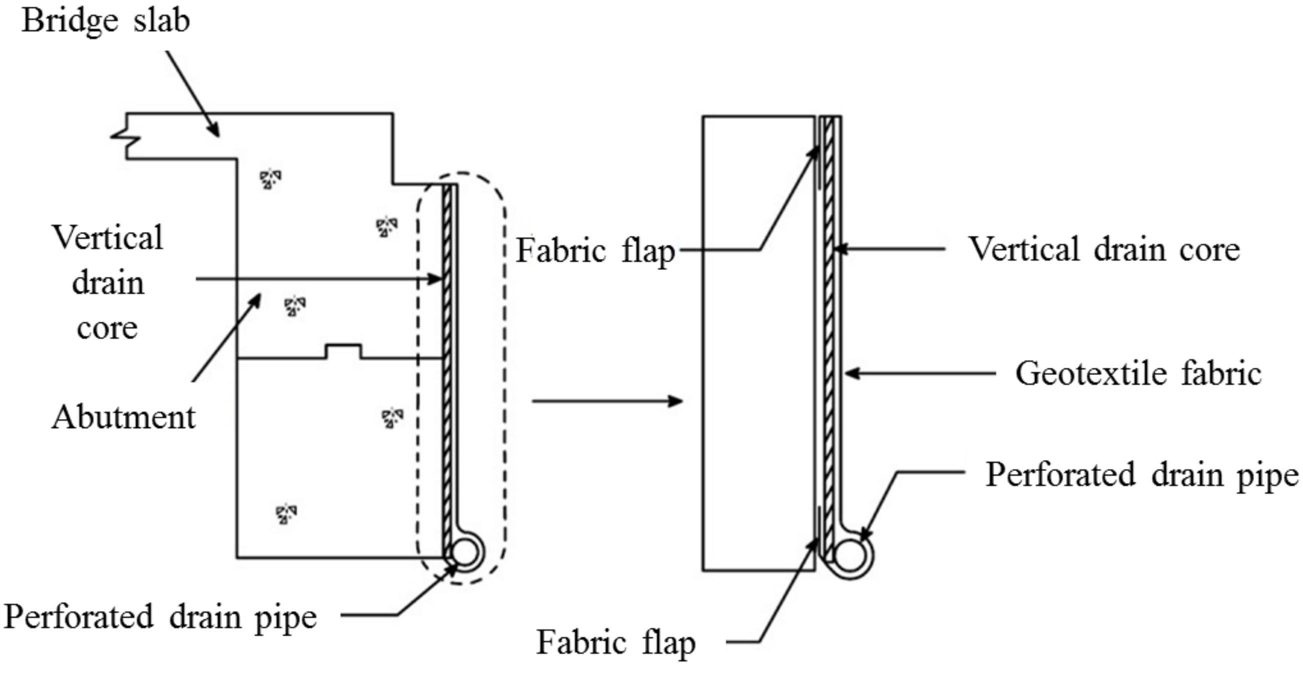


Figure 8 Geocomposite vertical drain wrapped with filter fabric used in Missouri (White et al., 2005)

Table 4 Drainage systems used in various states (White et al., 2005)

State	Porous fill	Geotextile	Geocomposite drainage system
Iowa	×	-	-
California	×	×	×
Colorado	-	×	×
Indiana	×	×	-
Louisiana	×	×	×
Missouri	-	×	×
Nebraska	-	×	×
New Jersey	×	×	-
New York	-	-	×
North Carolina	×	×	-
Oklahoma	×	×	-
Oregon	×	×	-
Tennessee	×	×	-
Texas	×	×	-
Washington	×	-	-
Wisconsin	×	×	-

After completing the literature review, White et al. (2005) conducted field investigations to identify frequent problems encountered in existing approach slabs in Iowa. These problems are summarized in figure 10 based on the bridge approach slab system typically used by Iowa DOT (shown in figure 9). Six findings obtained from the field investigations are presented as follows:

- Voids under the bridge approach that developed within one year after construction indicate inadequate backfill moisture control and compaction.
- Voids developed under the bridge are also caused by poor water management and erosion of backfill material. Backfill erosion also leads to faulting of the approach slab and slope protection failure, which exposes the steel H-pile foundation supporting the abutment.

- Materials such as flexible foam and tire joint fillers are not suitable for sealing the expansion joint.
- Grouting does not appear to significantly prevent further settlement or loss of backfill material due to erosion.
- Asphalts overlaid on the approach slab at several bridge sites show signs of distress and continuous approach slab settlement.
- Surveys of elevation profiles of several bridge approach slabs revealed that compression of the embankment material or foundation contributes to frequent problems.

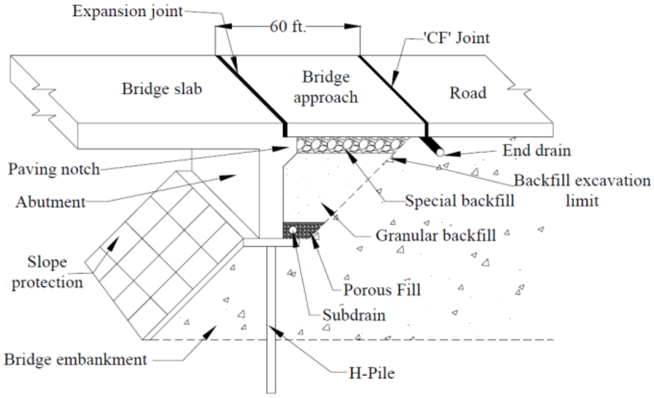


Figure 9 Schematic diagram of Iowa DOT bridge approach section (White et al., 2005)

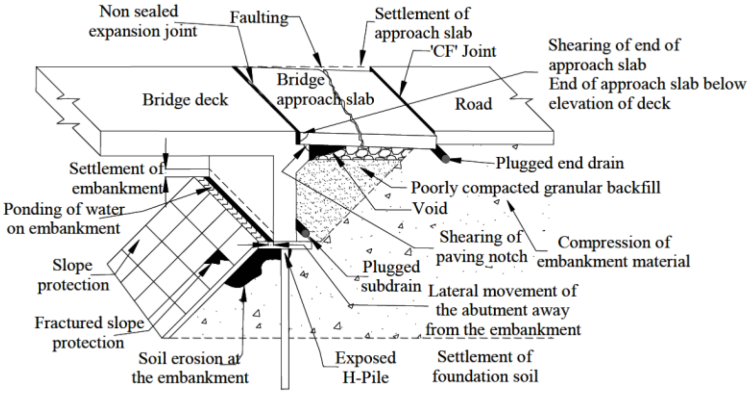


Figure 10 Schematic diagram summarizing frequent problems observed at several bridge sites (White et al., 2005)

Unlike the previous field study, eight new bridges that were under construction and did not follow the Iowa DOT's specifications were also inspected by White et al. (2005). Major problems observed and tests conducted on these new bridges are summarized in table 5. Although Iowa DOT specifications require 8-inch lift compaction, five bridges did not have compaction of the granular backfill and seven bridges did not have porous backfill around the subdrain.

Table 5 Summary of major problems and tests conducted at eight under-constructed bridges (White et al., 2005)

Bridge Location	District	Major Problems	Tests Conducted
35th St. over I-235	1	• No compaction of backfill • Backfill at bulking moisture content • Subdrain filled with soil	Grain size distribution, moisture content, and relative density
Polk blvd. Bridge	1	• No compaction of backfill • Backfill at bulking moisture content • No porous fill around subdrain • Subdrain filled with soil	Grain size distribution, moisture content, relative density, DCP, and nuclear gauge
19th St. over I-235	1	• None	Grain size distribution and relative density
Pennsylvania Ave bridge	1	• Subdrain filled with soil	None
E 12th St. bridge	1	• No compaction of backfill	Grain size distribution and relative density
Euclid Ave bridge	1	• No compaction of backfill • Subdrain filled with soil	None
Bridge over Union Pacific	3	• No compaction of backfill • Backfill at bulking moisture content • No porous fill around subdrain • Poor construction of paving notch	Grain size distribution and air permeability test
57.6R030	6	• Poorly constructed paving notch	Grain size distribution

Subsequently, Merrit et al. (2007) conducted research on Precast Prestressed Concrete Pavement (PPCP) bridge approach slab. The research summarized the construction of a PPCP demonstration project designed with an integral abutment on Highway 60 near Sheldon, Iowa. In order to improve the performance of the approach slab by keeping it in compression, the precast panels were post-tensioned in both directions. A post-tensioned panel gains the ability to act as a “slab bridge” and span voids that may form in backfill soil due to erosion or settlement. The benefits of using PPCP are:

- Rapid construction.
- Improved durability and performance.
- Reduced slab thickness.
- Extended construction season.
- Improved ability of the approach slab to span voids and weak backfill material.
- Increased distance between expansion joints and abutment by increasing the permissible slab length between joints.

Although this study was conducted on a new bridge, the findings can be utilized for reconstruction of existing damaged approach slab. This concept can be adapted to various approach slab lengths, widths, thicknesses, and skew angles. Also, PPCP can be used for full-width or partial-width (lane-by-lane) construction of approach slabs.

To reduce the bump at the end of the bridge, Iowa DOT was interested in using integrally connected approach slabs. In the following year, Greimann et al. (2008) conducted research to determine the effects of different approach slab systems on bridge performances and the design considerations of a range of forces acting on abutment bridges with integrally connected approach slabs. Results of a one-year monitoring of two integrally connected abutment bridges yielded the following observations:

- No longitudinal movements were observed in integrally connected approach slab bridges.
- Bridge abutment displacements and girder forces are affected by mechanically tying the approach slab to the bridge.
- Strains measured in the approach slab indicate force at the expansion joint which should be considered when designing both the approach slab and the bridge.
- Seasonal and short term cycles were evident in most data, probably caused by friction ratcheting.

2.2.4 Colorado

Monley and Wu (1993) evaluated the effectiveness of tensile reinforcement in reducing approach slab settlement using a finite element model. The results of the finite element model were verified by two large-scale bridge abutment tests. The researchers concluded that the following factors affected approach slab settlement:

- Poor compaction of the backfill;
- Difference in foundation strength, which causes differential settlement;
- Excessive external loads;
- Erosion of the abutment wall; and
- High shear stress development by soil-structure interaction.

In these two bridges, unreinforced and geogrid-reinforced backfills were compared. The results show that 6.7 to 7-inch of settlement occurred at the unreinforced bridge, while the bridge with reinforced backfill showed negligible settlement. The conclusions of this study are described as follows:

- Placing geosynthetic reinforcement and increasing the approach fill stiffness alone were not capable of reducing the settlement;
- Placing a collapsible inclusion between the reinforced approach fill and rigid abutment mobilized the geosynthetic reinforcement; and
- In cases where small movement of fill was allowed after construction to mobilize the tensile force of the geosynthetic reinforcement, small lateral movements were observed in backfill.

Yeh and Su (1995) tested three backfill types and evaluated their effectiveness in reducing the bump at the end of bridge. These three backfill types consisted of Expanded Polystyrene (EPS), flow fill, and select backfill. The EPS had shown excellent performance in alleviating settlement, and its properties are presented in table 6. The specified ingredients of the flow fill backfill are shown in table 7.

Table 6 Physical properties of expanded polysyrene (Yeh and Su 1995)

Properties	Value
Density	1.5 pcf
Compressive Strength (at 10% Deformation) (ASTM D1621)	15 psi
Flexural Strength (ASTM C203)	10 psi
Shear Strength (ASTM D732)	26 psi
Shear Modulus	450 psi
Modulus of Elasticity	320 psi
Water Absorption	Less than 2.5% of Volume
Coefficient of Thermal Expansion (ASTM D696)	3.5×10^{-5}

Table 7 Specified Ingredients for Flow Fill (Yeh and Su 1995)

Ingredients	lb./cu. yd.
Cement (0.45 sack)	42
Water (39 gallons)	325
Coarse Aggregate (Size No. 57)	1700
Sand (ASTM C-33)	1845

Conclusions drawn from true-scaled bridge tests are:

- Significant settlement of bridge approach slab was observed when granular subsurface material was used for backfill.
- Lesser immediate foundation settlement was observed when the super-light EPS was used as backfill.
- The most significant factor contributing to approach slab settlement was compression of the embankment and backfill.
- Lateral pressure and movement of the bridge abutment were significantly affected by temperature change.
- Among the three backfill types, flow fill material had the best performance.

Abu-Hejleh et al. (2000 and 2001) investigated the performance of the Founders/Meadow Bridge near Denver, which opened to traffic in July, 1999. Figure 11 displays the southeast view of the completed Founders/Meadows Bridge. Geosynthetic-reinforced segmental retaining wall was used in this bridge. Also, a thin layer of fill material was placed between the reinforced backfill and the bridge abutment to avoid the effect of thermally induced movements on the backfill. The construction and monitoring of this bridge took place in two phases. Phase I was dedicated to the southern half of the bridge, and the northern part constructed by extending the Phase I structure occurred in Phase II. The overall performance of this bridge under service load was considered satisfactory before opening to traffic. The instrumentation data revealed that the smallest vertical stresses occurred closer to the wall facing while the largest stresses occurred along the centerline of the bridge abutment.

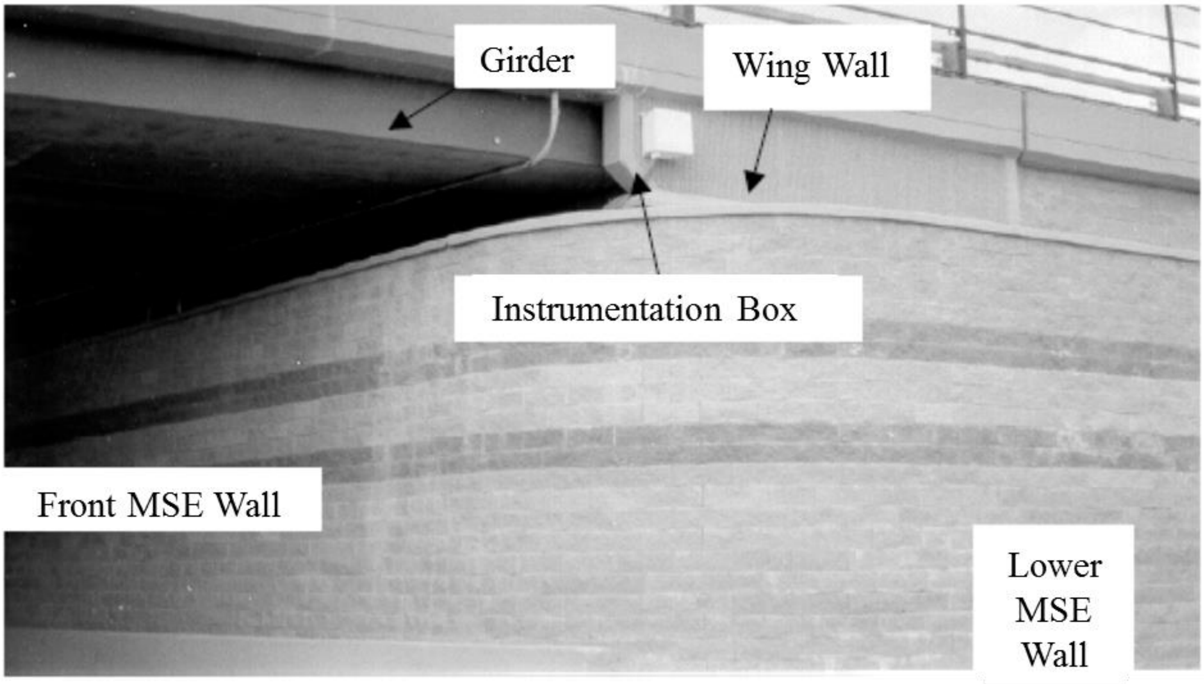


Figure 11 View of the south-east side of the completed Founders/Meadows Bridge (Abu-Hejleh et al. 2000)

Abu-Hejleh et al. (2001) concluded that the front Geosynthetic-Reinforced Soil (GRS) walls enabled excellent performance in the Founders/Meadows Bridge based on the following observations:

- The measured movements within the bridge superstructure were satisfactory as they were smaller than the expected values.
- The measured tensile loads of the geogrid were within 43percent to 57 percent of its design loads.
- Eccentricity of the measured forces acting inside the front GRS wall was negligible.

2.2.5 Louisiana

Cai et al. (2005) carried out a finite element analysis to relate the deformation and internal force of an approach slab to approach embankment settlement. The approach slab has one end supported by the abutment and other by a sleeper beam. This analysis demonstrated that differential settlement decreases the contact area between the approach slab and embankment soil. Consequently, the sleeper beam receives a larger portion of the load introduced to the approach slab, causing soil movement toward the sleeper beam. This movement increases stress in the contact region as well as internally in the sleeper beam. The approach slab loses its soil contact with further settlement, and thus, the soil beneath the approach slab will not affect the performance of the system. The research also showed that embankment soil settlement was not considered in the current design. The researchers proposed that the steel reinforcement within the approach slab should be increased to overcome backfill settlement; the currently recommended slab thickness of 12-inch for a 60-ft span approach slab was not satisfactory. For approach slabs longer than 60-ft, a ribbed slab system was suggested to increase structural stiffness.

Bakeer et al. (2005) evaluated a prototype semi-integral bridge abutment system constructed in 1989 by the Louisiana Department of Transportation and Development (LADOTD). The semi-integral system is a modified design of an integral system, in which joints are eliminated to protect conventional moveable bearings. However, a horizontal joint is required in the semi-integral bridge to separate the abutment from the superstructure. The end diaphragm in a semi-integral bridge does not integrate with the foundation but with the superstructure. In an integral abutment bridge, the thermally active superstructure of the bridge is connected to its thermally inactive substructure. This connection creates thermal forces to the backwall and additional stresses in the bridge substructure. Figure 12 shows the semi-integral prototype bridge used by LADOTD.

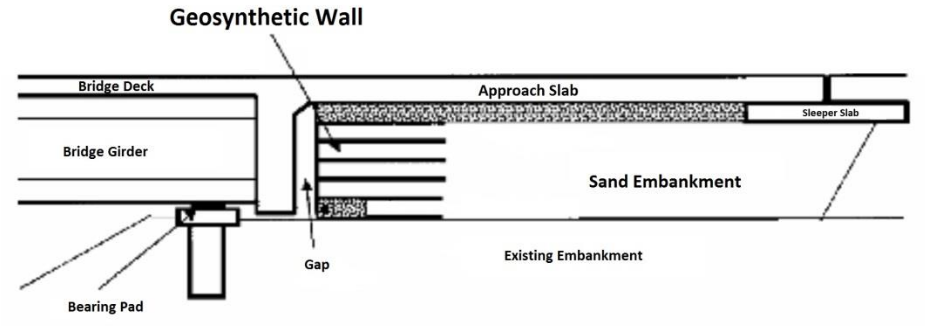


Figure 12 Semi-integral abutment configuration (Bakeer et al., 2005)

Bakeer et al. (2005) confirmed the performance of the semi-integral abutment and recommended ongoing use of this system in LADOTD's design. Semi-integral abutment is considered an innovative system which has been recommended by many researchers. Design recommendations for the semi-integral bridge system are described as follows:

- To allow the backwall to freely move in the longitudinal direction and overcome problems associated with annual thermal cycle effects, a 6-inch gap should be created behind the backwall.
- To avoid possible closure of the gap during construction, a larger space (6-inch) than required is specified.
- Contractors should be warned that the gap could be filled with falling debris during construction. An EPS geofoam block can be inserted to maintain the gap opening.
- It is recommended to keep the drainage behind the backwall well maintained.

Abu-Farsakh and Chen (2014) evaluated the performance of a new approach slab design proposed by LADOTD. This new design increases the approach slab’s flexural rigidity and uses a reinforced foundation beneath a sleeper slab as shown in figure 13. This new design was implemented in Bayou Courtableau Bridge on Louisiana Highway 103 in St. Landry Parish. The thickness of the approach slab was 16-inch. The sleeper slab using a strip footing had a width of 4-ft, and the reinforcement under the sleeper slab consisted of six layers of geogrid placed with 12-inch spacing. To evaluate performance, two static load tests were performed on both east and west approach slabs. Conclusions drawn from this research are described as follows:

- The approach slab showed no loss of contact with the embankment soil after the first load test. The second load test caused the most contact loss between the approach slab and the embankment soil.
- One and a half years after construction, the new approach slab has performed satisfactorily.

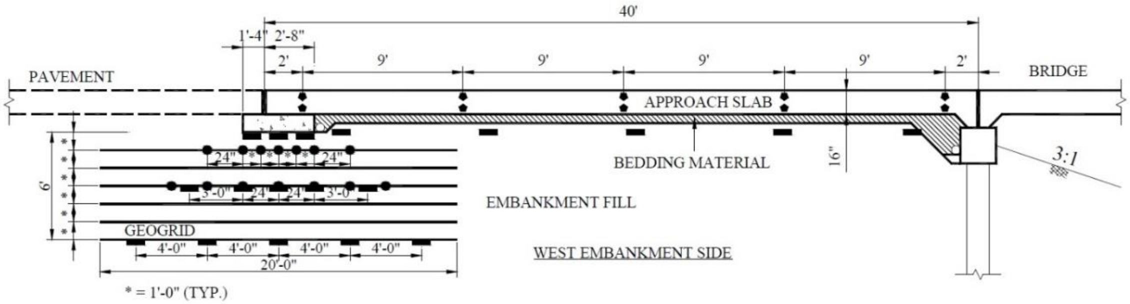


Figure 13 New approach slab design used by LADOTD (Abu-Farsakh and Chen 2014)

2.2.6 Texas

Ha et al. (2002) investigated approach slab settlement through a literature review, survey, site investigation, and numerical analysis program. The outcomes of the survey including literature review led to the following conclusions:

- Twenty five percent of the bridges in United States are affected by approach slab settlement problems.
- The total maintenance cost for settlement problems in the United States was estimated to be 100 million dollars.
- The dominant causes for creation of bumps at the ends of bridges were determined to be; weak natural soil, weak compression of the embankment fill, voids under the pavement due to erosion, abutment displacement due to pavement growth, slope instability, or temperature cycles.

The parameters affecting the severity of the bump are summarized in table 8.

Table 8 Parameters affecting the severity of the bump (Ha et al. 2002)

More Severity	Less Severity
• High embankment. • Abutment on pile. • High average daily traffic. • Soft natural soil. • Intense rain storms. • Extreme temperature cycles. • Steep approach gradients.	• Existence of approach slab. • Appropriate fill material. • Good compaction or stabilization. • Effective drainage. • Good construction practice and inspection. • Adequate waiting period between fill placement and paving.

Two bridge overpass sites on major highways in Houston, US290 over FM362 and SH249 at Grand road were chosen by Ha et al. (2002) for the site investigation. After examining current practices for approach slab planning, design, construction, maintenance, and rehabilitation, the following conclusions were drawn:

- The recommended maximum boring spacing for embankments higher than 15-ft is 200-ft. At least two borings are suggested for each abutment, and additional borings should be considered when their length exceeds 100-ft.

- The specified Plasticity Index (PI) of the soil within 150-ft of the abutment shall not exceed 15. Also, relative compaction should be over 95 percent in this area.
- Five types of abutment are in use: closed or high abutment, stub or perched abutment, pedestal or spill-through abutment, integral abutment, and mechanically stabilized abutment.
- For closed, spill-through, and integral abutments, the approach slab’s embankment must be built first. However, for perched abutments the approach slab’s embankment should be constructed after the abutment is built.
- Most bridges designed in Texas have stub or perched abutments with the approach slab and wide flange terminal joint.

Ha et al. (2002) performed a numerical analysis on current approach slab design to determine the maximum settlement of pavement as a function of slab length. The results are presented in table 9 and figure 14. Summary of results are as follows:

- The slope between the abutment wall and the support slab depicted in figure 15 is affected by the stiffness near the abutment. The slope increases by 20 percent as the stiffness of the backfill soil decreases to half.
- The presence of the abutment wall is one of the causes of differential settlement as it prevents adjoining soil from settling, but the soil further from the wall is not affected. This differential settlement causes a bump at the end of the bridge.
- As the lengths of the sleeper slab and support slab increase, settlement decreases. Optimum length has been determined to be 5-ft.

- The settlement in embankment with a height of 10-ft is 31 percent less than the embankment which is 21-ft high.

Table 9 Settlement as a function of the length of slab (Ha et al. 2002)

Length of Support Slab (m)	Max. Settlement (m) of the Pavement	Length of Sleeper Slab (m)	Max. Settlement (m) of the Pavement
0.00	0.0125	0.00	0.0113
0.20	0.0105	0.23	0.0098
0.60	0.0081	0.69	0.0083
1.00	0.0068	1.15	0.0077
3.12	0.0056	1.62	0.0074
-	-	2.08	0.0072
-	-	2.54	0.0069
-	-	3.00	0.0067

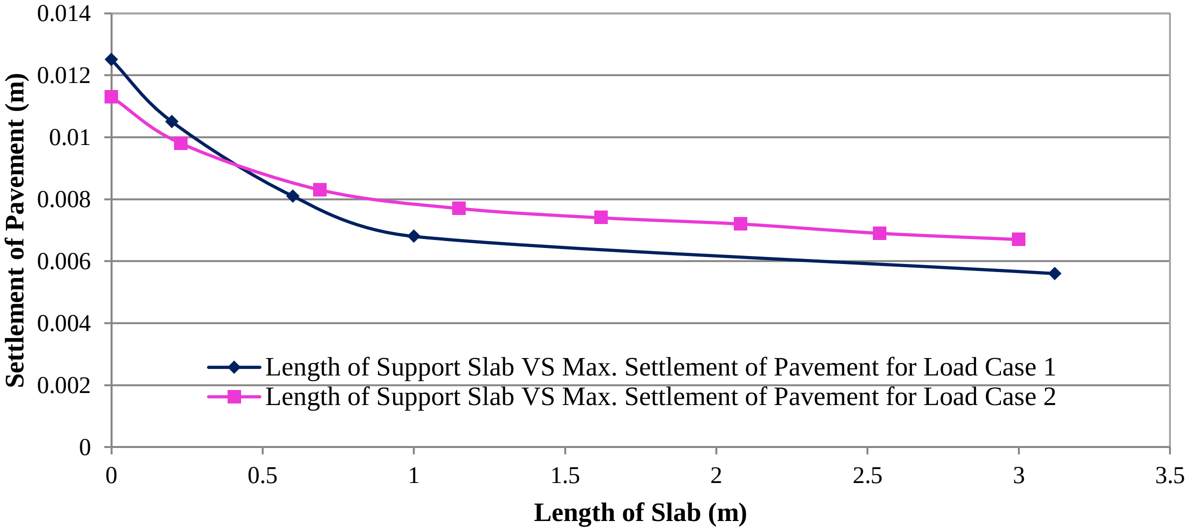


Figure 14 Settlement as a function of the length of slab (Ha et al. 2002)

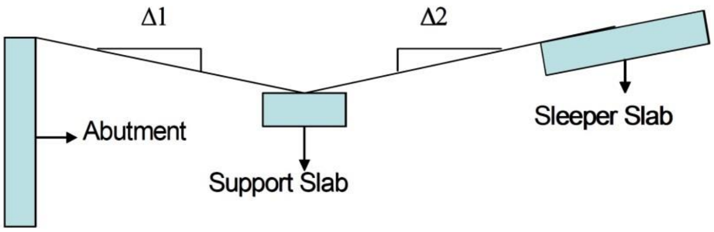


Figure 15 Gradient of slope (Ha et al. 2002)

Ha et al. (2002) proposed a new approach slab design by reviewing parameters which lead to settlement. The proposed approach slab is a one-span slab as illustrated in figure 16. The researchers built and tested a 1/20th scale model of the new design and drew the following conclusions:

1) The proposed bridge approach slab with a 20-ft span length resulted in a smaller bump than the current design.
2) Embankment soil with higher compaction developed a smaller bump than soil with lower compaction at the sleeper slab.

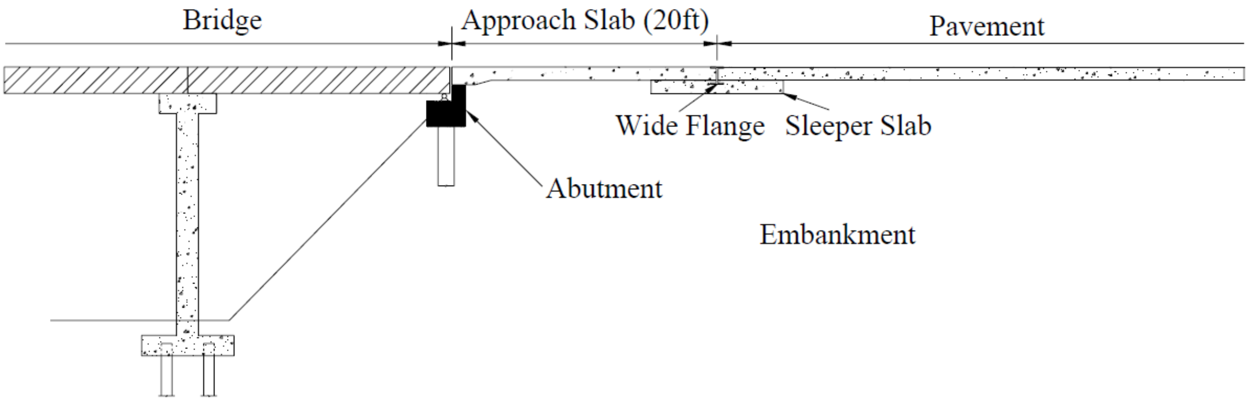


Figure 16 One-span approach slab (Ha et al. 2002)

Puppala et al. (2011) conducted research after Ha et al. (2002) with the title "Recommendations for design, construction and maintenance of bridge approach slabs." Their summaries of methods and techniques for ground improvement for cohesionless and cohesive soils are presented in table 10 and table 11.

Table 10 Summary of ground improvement methods based on soil type (Puppala et al. 2011)

Technique	Cohesionless	Cohesive soils
Excavation and Replacement	No	Yes
Preloading w or w/o Surcharge	Yes	Yes
Dynamic Compaction	Yes	Yes
Grouting	Yes	Yes
Wick Drains	No	Yes
Compaction Piles	Yes	No
Gravel Columns	Yes	No
Lime Treatment	No	Yes
Stone Columns	No	Yes
Soil Reinforcement	Yes	Yes
Geopier	Yes	Yes

Table 11 Summary of ground improvement techniques (Puppala et al. 2011)

Embankment on Soft Soil Improvement Techniques		
Mechanical	**Hydraulic**	**Reinforcement**
Excavation and Replacement Preloading and surcharge Dynamic compaction	Sand drains Prefabricated drains Surcharge loading	***Columns*** Stone and Lime Columns Geopiers Concrete Injected Columns Deep Soil Mixing Columns
		Deep foundations In-situ: Compacted piles CFA piles Driven piles: Timber and Concrete piles
		Geosynthetics Geotextiles / Geogrids Geocells

2.2.7 Oklahoma

Miller et al. (2011) studied causes of bridge approach slab settlement via literature review, field investigation, and laboratory investigations. Design and construction solutions were proposed as outcomes of this research. The three causes of approach slab settlement concluded from this research are settlement, erosion, and embankment height, described as follows:

1. Settlement

- Settlement of foundation soil: Immediate, primary, and secondary settlement occurs in foundation soil. Immediate settlement usually will not cause a problem for the approach slab, but the time dependent behavior of primary and secondary consolidation are considered significant factors in approach slab settlement.
- Wetting-induced collapse: Factors contributing to wetting-induced collapse are soil type, total overburden stress, pre-wetting moisture content, and dry unit weight. These factors will cause an increase in the moisture content of the backfill or embankment soil, which yields settlement.
- Nondurable material causing settlement: Nondurable rocks are considered to be prone to slake in the presence of water. If these types of rocks are used in the embankment soil, they will collapse under excessive compressive load, causing settlement of the bridge approach slab.
- Poor drainage causing settlement: Approach drainage involves either directing surface water away from the embankment or removing infiltrated water from behind the abutment. Improper drainage increases the moisture content of the embankment soil, causing collapse or excessive settlement and finally, a bump at the end of the bridge.

2. Erosion

- Piping: This phenomenon will create cavities which will cause collapse of the embankment soil structure. The cavities can have progressive behavior resulting in more severe damages; and
- Suffusion of Granular Soils: In this process fine aggregates are dislodged into coarse aggregate with the aid of water without disturbing the coarse aggregate's structure. This creates voids in the embankment soil, resulting in settlement of the approach slab.

3. Embankment Height

- Embankment height is related to the load transfer within the embankment. As the height of the embankment increases, its resistance for load transfer increases.

To overcome approach slab settlement, several design and construction solutions are suggested in table 12:

Table 12 Design and construction solutions to overcome approach slab settlement (Miller et al., 2011)

Component	Solution
Foundation Soil	Piles
	Deep soil mixing
	Controlled Modulus Columns (CMC)
Embankment Backfill	Geotextile and geogrid reinforcement
	Mechanically stabilized earth and lightweight Expanded Clay and Shale (ECS) as fill
Field Compaction	Intelligent compaction
	Dynamic compaction

2.2.8 New Hampshire

Boisvert (2010) investigated the performance of fiber-reinforced concrete approach slabs unrelated to settlement problems. The mat reinforcement in the approach slab is prone to corrosion due to the chlorides applied during road maintenance. This research studied the feasibility of replacing traditionally reinforced approach slab with fiber-reinforced concrete approach slab.

New Hampshire Department of Transportation (NHDOT) performed quality control tests on fresh, fiber-reinforced concrete, consisting of slump, air content, temperature, permeability, and compressive strength tests. According to NHDOT all the mixes met the required specifications. Also, freeze/thaw tests were performed on these specimens, and they showed minor physical deterioration.

In addition to laboratory tests, field tests were also performed on true scale approach slabs to confirm the quality of the fiber-reinforced concrete approach slab. Three and a half years after construction, both mat-reinforced and fiber-reinforced approach slabs showed the same performance. The long term ability of the fiber-reinforced concrete against steel corrosion is not expected to be evaluated for a few years. In applications where delaying the effects of steel corrosion is of interest, fiber-reinforced concrete is recommended.

2.2.9 North Dakota

Marquart (2004) investigated replacing the backfill beneath the approach slab with a better material because the conventional compacted granular material has been shown to be ineffective. This new design has the following features:

- A 20:1 slope is formed from the abutment to the end of approach slab that intersects with the pavement.
- A void is installed between the abutment and backfill, with a retaining wall built against the void.
- The backfill is geotextile-reinforced and compacted in 1-ft layers.
- A drainage system is also included.

This design reduced the rate of settlement but was unable to completely eliminate it. The research did not provide any conclusions on the amount of total settlement.

2.2.10 Virginia

Hoppe and Gomez (1996) evaluated the effects of secondary forces (thermal expansion) applied to the bridge superstructure by investigating the long term performance of an integral backwall bridge consisting of two-span, 321.5-ft long composite steel girders.

During the 2.5 years of study, no distress was observed in the superstructure, and the performance of the integral backwall bridge was considered acceptable. The following conclusions were made:

- The load behind the backwall was shown to be fully passive and was increasing after the end of construction. The maximum load behind the backwall was recorded in the 2nd summer after the end of construction.
- The soil behind the abutment exhibited at-rest behavior and did not show significant changes during the monitoring period.

- Ambient air temperature variation as a result of expansion and contraction in the superstructure caused changes in soil pressure.
- Cyclic movement of the backwall due to thermal expansion magnified soil settlement.

A survey was conducted by Hoppe (1999) to obtain feedback from DOTs regarding the use, design, and construction of approach slabs. The survey was distributed to 48 states, and 39 of them responded. The important survey results are presented as follows:

- Advantages of Using Approach Slabs: An approach slab provides a smooth ride to the bridge, enhances drainage, and reduces impact loads on the backwall.
- Disadvantages of Using Approach Slabs: An approach slab incurs high initial construction cost. Maintenance, settlement problems, and difficulties with staged construction are among other disadvantages.
- Special Inclusion/Exclusion Circumstances: Twenty four percent of the respondents were concerned about excessive settlement of the approach slab, and 30 percent of the respondents did not consider an approach slab in their designs.
- Typical Dimensions of Approach Slabs: The typical approach slab dimensions gathered from the survey are summarized in table 13.
- Fill Specifications: To reduce soil plasticity and enhance drainage, the most common limiting requirement for fill specification is the percentage of fine particles. The percentage passing through a No. 200 sieve is limited to between 4 percent and 20 percent by various states. The results are summarized in table 14.

Table 13 Typical approach slab dimensions (Hoppe, 1999)

State	Length, ft	Slab Thickness, in.	Miscellaneous
AL	20	9	n/a
AZ	15	n/a	n/a
CA	10-30	12	n/a
DE	18-30	n/a	n/a
FL	20	12	n/a
GA	20-30	10	n/a
ID	20	12	n/a
IL	30	15	n/a
IN	20.5	n/a	Length varies with skew angle
IA	20	10-12	n/a
KS	13	10	Length varies with skew angle
KY	25	n/a	Length varies with skew angle
LA	40	16	n/a
ME	15	8	n/a
MA	n/a	10	Length varies with skew angle
MN	20	12	T-beams
MS	20	n/a	n/a
MO	25	12	Timber header at sleeper slab
NV	24	12	n/a
NH	20	15	n/a
NJ	25	18	Used with transition slab 30-ft × 9 to 18-in.
NM	15	n/a	n/a
NY	10-25	12	Sleeper slab, length varies with abutment type
ND	20	14	n/a
OH	15-30	12-17	Length varies with embankment and slew angle
OK	30	13	n/a
OR	20-30	12-14	Length varies with fill height and skew angle
SC	20	n/a	n/a
SD	20	9	n/a
TX	20	10	n/a
VT	20	n/a	n/a
VA	20-28	15	Length varies with skew angle
WA	25	13	Length varies with skew angle
WI	20.5	12	n/a
WY	25	13	Sleeper slab 0.5-ft × 10-in.

n/a- not available.

Table 14 Embankment material specifications (Hoppe, 1999)

State	Same/Different from Regular Embankment	% Passing No. 200 Sieve (75 µm)	Miscellaneous
AL	Same	n/a	A-1 to A-7
AZ	Different	n/a	n/a
CA	n/a	<4	Compacted previous material
CT	Different	<5	Pervious material
DE	Different	n/a	Borrow type C
FL	Same	n/a	A-1, A-2-4 through A-2-7,A-4,A-5,A-6
GA	Same	n/a	GA Class I, II or III
ID	n/a	n/a	A yielding material
IL	Different	n/a	Porous, granular
IN	Different	<8	n/a
IA	Different	n/a	Granular, can use Geogrid
KS	n/a	n/a	Can use granular, flowable or light weight
KY	n/a	<10	Granular
LA	n/a		Granular
ME	Different	<20	Granular borrow
MA	Different	<10	Gravel Borrow type B, M1.03.0
MI	Different	<7	Only top 3-ft are different
MN	n/a	<10	Fairly clean granular
MS	Different	n/a	Sand or loamy, non-plastic
MO	n/a	n/a	Approved material
MT	Different	<4	Pervious
NE	n/a	n/a	Granular
NV	Different	n/a	Granular
NH	Same	<12	n/a
NJ	Different	<8	Porous fill (Soil Aggregate I-9)
NM	Same		n/a
NY	n/a	<15	<30% Magnesium Sulfate loss
ND	Different	n/a	Graded mix of gravel and sand
OH	Same	n/a	Can use granular material
OK	Different	n/a	Granular just next to backwall
OR	Different	n/a	Better materials
SC	Same	n/a	n/a
SD	Varies	n/a	Different for integral; same for conventional
TX	Same	n/a	n/a
VT	Same	n/a	Granular
VA	Same	n/a	Porous backfill
WA	n/a	n/a	Gravel borrow
WI	Different	<15	Granular
WY	Different	n/a	Fabric reinforced

n/a- not available.

Table 15 Lift thickness and percent compaction requirements (Hoppe, 1999)

State	Lift Thickness, in.	% Compaction	Miscellaneous
AL	8	95	n/a
AZ	8	100	n/a
CA	8	95*	* For top 2.5-ft
CT	6*	100	* Compacted lift indicated
DE	8	95	n/a
FL	8	100	n/a
GA		100	n/a
ID	8	95	n/a
IL	8	95*	* For top, remainder varies with embankment height
IN	8	95	n/a
IA	8	None	One roller pass per inch thickness
KS	8	90	n/a
KY	6*	95	* Compacted lift indicated; Moisture = +2% or -4% of optimum
LA	12	95	n/a
ME	8		At or near optimum moisture
MD	6	97*	* For top 1-ft, remainder is 92%
MA	6	95	n/a
MI	9	95	n/a
MN	8	95	n/a
MS	8	n/a	n/a
MO	8	95	n/a
MT	6	95	At or near optimum moisture
NE	n/a	95	n/a
NV	n/a	95	n/a
NH	12	98	n/a
NJ	12	95	n/a
NY	6*	95	* Compacted lift indicated
ND	6	n/a	n/a
OH	6	n/a	n/a
OK	6	95	n/a
OR	8	95*	* For top 3-ft, remainder is 90%
SC	8	95	n/a
SD	8-12*	97	* 8 in for embankments, 12-in. for bride end backfill
TX	12	None	n/a
VT	8	90	n/a
VA	8	95	+ or – 20% of optimum moisture
WA	4*	95	* Top 2-ft, remainder is 8-in.
WI	8	95*	* Top 6-ft and within 200-ft, remainder is 90%
WY	12	n/a	Use reinforced geotextile layers

n/a- not available.

- Construction Specifications: Table 15 shows that an 8-inch lift thickness of granular fill compacted to 95 percent of the Standard Proctor value is the most common compaction requirement for approach slabs.
- Drainage Provisions: Plastic drainpipes, weep holes in abutments, and use of granular material are the most common drainage methods used by DOTs. Also, 24 percent of the respondents reported using geosynthetic material fabrics and geocomposite drainage panels.
- Construction Problems: Achieving the specified soil compaction close to the abutment was the major problem reported by 50 percent of the respondents.
- Is Approach Slab Settlement a Problem? A majority of the respondents stated that approach slab settlement is a significant maintenance problem while only 16 percent of the respondents did not consider it a problem.

2.2.11 Wisconsin

Abu al-Eis and LaBarca (2007) performed research on two test sites to evaluate the URETEK pavement lifting method as an approach slab retrofitting method. The URETEK method uses high-density polyurethane foam to fill a void between a concrete pavement slab and backfill. This method helps to lift, realign, and under-seal concrete slab. Liquid high-density polyurethane is injected through small holes drilled through the concrete slab. Then the injected polyurethane foam expands to fill the void and lift the approach slab to the desired elevation. To re-support and realign the approach slab accurately, multi-pattern drilled injection locations were used. The researchers concluded that the URETEK method was successful in raising the approach slab to within ¼ to ½-inch of the intended elevation. One year after performing the retrofitting method, one of the test sites showed minor cracks on the approach slab. Moreover, this investigation showed that the amount of backfill material needed for the repair was significantly underestimated by a factor of 5. Therefore, this method is not recommended for the cases in which a large void is meant to be filled.

Helwany (2007) compared the applicability and efficiency of two mitigation methods used in four bridges in Wisconsin. The two methods were geosynthetic-reinforced fill and flowable fill. Flowable backfill was not suggested for small projects as it was not a cost effective mitigation method. Two bridges were constructed on incompressible granular soils while the other two bridges were constructed on a compressible soil foundation. The author concluded that the approach slab with the granular foundation yielded lesser settlement than that based on a compressible foundation. Moreover, side movement of the embankment caused by erosion incurred subsequent movement of backfill material.

Oliva and Rajek (2011) studied the effects of foundation and abutment settlement on approach slab rotation. Cracking, rotation, and other problems related to the approach slab were quantified based on the following parameters:

- Approach slab length.
- Slab material.
- Subgrade soil type.
- Abutment height.
- Possible settlement trenches that may develop under the slab near its abutment support.

The results and conclusions drawn from this study are:

- Abutment and Settlement Trench Geometry: The height of the abutment affected the influence of the trench on approach slab rotation. Trenches longer than 6-ft had noticeable effects on approach slab rotation.
- Abutment Height: Abutment height significantly affected approach slab performance. The strains within the approach slab and the recorded settlement were higher in high abutments. The 12-ft and 6-ft high abutments showed rotations of 0.00173 and 0.00125 radians, respectively.
- Approach Slab Length: No significant impact was observed as the length of the approach slab increased.
- Backfill Soil Stiffness: Loose soil had a huge impact on both cracking and rotation of the approach slab.
- Concrete Slab Stiffness: Higher concrete slab stiffness yielded less cracks in the approach slab. Precast concrete slab was preferred over cast-in-place concrete slab.
- End Rotation: The end rotation of the approach slab that occurred near the abutment was significant for the loose soil condition.

2.2.12 Ohio

Islam (2010) conducted research with the goal of reducing bumps at pavement-bridge interfaces. The research focused on identifying structural and geotechnical causes and determining long-term solutions to approach slab settlement. A 3-D finite element analysis using ALGOR found that a great deflection appeared in the approach slab when the soil beneath moved away from it, causing a decrease in the moment bearing capacity of the slab. As another important step of the research, Islam (2010) calculated the moment bearing capacity and the introduced moment to the slab. The results are shown in table 16. The author concluded that the current approach slab specifications of Ohio State should be improved.

Phares et al. (2011) completed research for the Ohio DOT (ODOT) to develop better pre- and post-construction strategies to avoid or minimize approach slab settlement. Reviewing current design specifications of various states' DOT, they also investigated the behavior and condition of some in-service bridges. The authors presented their conclusions in three main categories: General, Structural, and Geotechnical. General conclusions were not included here as they are not in line with the objectives of this study. Conclusions on the structural and geotechnical aspects are described as follows:

- **Structural:** Integral abutment has shown to be more reliable by many researchers while ODOT has different definitions and designs for integral and semi-integral abutments. Although complete connection of the abutment and superstructure is not allowed, the bridge superstructure and approach slab are connected. This design leads to 1) the movement translation of the superstructure to the approach slab, and 2) no rotation of the bridge abutment due to live loads.
- **Geotechnical:** One of the causes of backfill material collapse is the existence of bulking moisture content, which should be avoided in all cases. In this study the measured bulking moisture of the backfill material was about 6 percent.

Table 16 Approach slab designs in different state DOT's (Islam, 2010)

State	L_{min} (ft)	h (in.)	f'_c (ksi)	A_s (in^2/ft)	A'_s (in^2/ft)	ΦM_n (kip*ft/ft)	M_u (kip*ft/ft)
AZ	15	12	3	1.053	0.133	37.57	9.77
FL	30	12	4.5	1.053	0.310	31.05	80.03
IN	20	10	4	0.630	0.203	19.14	30.16
KY	25	17	3.5	1.580	0	90.10	61.72
MI	20	12	4.5	0.895	0.895	21.87	31.72
OH	30	17	4.5	2.345	0.207	129.81	90.40
PA	25	16	3.5	1.693	0.310	85.22	60.50

L_{min}-Minimum length; h-Thickness; f'_c-Compressive Strength of Concrete; A_s-Bottom Steel Reinforcement Area; A'_s-Top Steel Reinforcement Area; ΦM_n- Factored Nominal Moment Capacity; M_u- Ultimate Capacity

Table 17 summarizes the possible causes of approach slab settlement problems based on visual investigation and their respective suggested troubleshooting methods.

Table 17 Summary bump identification metrics and troubleshooting Phares et al. (2011)

Possible Cause of Bridge Bump Problem	Indication of problem Based on Visual Investigation	Troubleshooting Method
Soil Erosion of Embankment	• Loss of spill through slope soil. • Ditching of embankment slopes. • Virgin soil deposits at toe of slope. • Curbs and surface drains plugged with debris or crushed. • Elevation of surface drain is higher than pavement. • Gap forming between abutment and embankment under bridge. • Slope protection under bridge shows signs of more than 1-in. of settlement. • Concrete slope protection has large fractures or broken void areas. • Poor grass cover and growth.	• Fill ditches and eroded areas with compacted soil and reestablish seeding. • Place piles of rip-rap rock in locations of erosion and ditches to slow water; fabric can be placed under rock. • Build fabric underlayed rock chutes/channels down embankments and under bridge to control movement of water away from embankment. • Build concrete gutters down embankments and under bridge to control movement of water. • Place curb and gutters along pavement and approach slab to control path of water. • Place surface drains with subsurface piping in pavement shoulder and embankment to drain water on bridge.

Table 17 Summary bump identification metrics and troubleshooting Phares et al. (2011) (Continued)

Possible Cause of Bridge Bump Problem	Indication of problem Based on Visual Investigation	Troubleshooting Method
Soil Erosion Under Approach Slab	• Void seen under approach slab from shoulder near abutment. • Soil deposits at shoulder or on embankment coming from approach slab. • Loss or deteriorated expansion joint material at joint. • Curbs and surface drains plugged with debris or crushed. • Elevation of surface drain is higher than pavement.	• Place curb and gutter on approach slab to control water movement. • Clean and remove debris from plugged drains. • Place surface drains in pavement with subsurface piping to drain water away from bridge. • Clean joints and expansion joints. Replace compressible joint fill material and strip seals to prevent water from getting below slab. • Remove approach slab; place compacted fill up to grade; dig in drainage tile field under slab and shoulder that is connected to existing subsurface drains; replace approach slab: include shoulder with curb, gutter, and surface drain in approach slab. • Fill erosion void below slab with flowable grout. • Use geocomposite drainage systems between abutment/backwall and backfill.
Settlement/Compression of Embankment or Abutment	• Approach slab relative gradient is greater than 1/200 (0.005). • Settlement cradled is evident in pavement profile. • Determine if abutment has settled based on constructed elevations and existing elevations. • Dip or crown in any 30-ft segment of mainline pavement going away from the approach slab up to 300-ft having a relative gradient larger than 1/200.	• Place asphalt wedge overlay to bring pavement up to grade. • Grout or liquid polyurethane jacking of the slab and pavement. • Grind pavement and approach surface to create smooth transition. • Monitor Settlement; If settlement is complete remove slab and pavement; place compacted fill up to original grade; replace slab and pavement. • Monitor Settlement; If settlement is not complete remove slab and pavement; Stabilize embankment by use of geotechnical practices such as light weight back fill, rammed aggregate piers, or in situ densification techniques. • If possible jack or shim abutment to align with pavements.

Table 17 Summary bump identification metrics and troubleshooting Phares et al. (2011) (Continued)

Possible Cause of Bridge Bump Problem	Indication of problem Based on Visual Investigation	Troubleshooting Method
Differential Vertical Movements	• Dip or crown greater than 1-in seen in riding surface relative to curbs or barriers of the approach slab. • Approach slab relative gradient is greater than 1/200 (0.005). • Differential joint movement greater than ½ in. at approach slab to mainline pavement or bridge interface. • Broken paving notch seen from the shoulders or suspected due to differential movement. • Non-uniform vertical gap in bridge parapet at the approach slab.	• Grind pavement and approach surface to create smooth transition. • Grout or liquid polyurethane jacking of the slab and pavement. • Remove and replace approach slab with new cast-in-place or precast approach slab. • Remove approach slab; add sleeper slab at approach slab to pavement interface; replace slab. • Remove end of approach slab and cast-in-place a doweled type expansion joint at pavement interface. • Remove enough approach slab to repair or replace failed paving notch, replace approach slab ensuring adequate bearing, approach slab depth and connection to abutment. • Resurface mainline pavement creating a smooth transition. • Remove mainline pavement and poor base and subbase material; replace with good compacted fill material and new pavement.
Differential Horizontal Movements	• Approach slab has pushed into asphalt mainline pavement causing a vertical bulge of 1-in or more. • Approach slab has pulled away from asphalt mainline pavement causing a ½-in or greater gap at interfaces. • Approach slab and concrete mainline pavement have compressed pressure relief joint causing a vertical bulge of 1-in or greater. • Asphalt in pressure relief joint has rutted, or channelized. • Approach slab and concrete mainline pavement have contracted causing a ½-in gap at pressure relief joint interfaces. • Expansion joint material is present but filled with debris on faces of joint.	• Clean debris from joints and refill with compressible joint material or replace strip seal. • For concrete pavements remove pressure relief joint and cast in doweled type expansion joint. • For asphalt pavements remove portion of approach slab and pavement; place a sleeper slab; relay asphalt pavement and cast in a doweled type expansion joint. • Grind any crowns caused by horizontal movement. • Apply asphalt wedge at any dip locations. • Remove enough approach slab to repair or replace failed connection to paving notch/bridge abutment.

Table 17 Summary bump identification metrics and troubleshooting Phares et al. (2011) (Continued)

Possible Cause of Bridge Bump Problem	Indication of problem Based on Visual Investigation	Troubleshooting Method
Approach to Mainline Pavement Joint Area Deterioration	• Transverse cracking on the surface of the approach slab or pavement. • Spalling of approach slab or pavement near joint. • Loss of expansion joint material in joint. • Deteriorated strip seal at the expansion joint. • Asphalt overlay placed over expansion joint causing cracking or spalling. • Expansion joint filled with debris and fines. • Vegetation growing in the expansion joint. • Strip seal cut short allowing water and debris into joint and under slab.	• Clean debris from joints and refill with compressible joint material or replace strip seal. • Remove enough approach slab and pavement to place a sleeper slab; replace pavement; cast in a doweled type expansion joint into approach slab. • Saw cut out spalling and cracked approach slab and pavement locations and replace.
Water Improperly Drained	• Plugged or crushed perforated drainage tiles and outlets. • Drainage outlets are covered by soil at base of embankment. • Ponding of water on roadway surface or on or near the bridge embankment. • Embankment soil erosion as stated previously in table. • Erosion under approach slab as stated previously in table. • Approach slab shoulder shows signs of heavy water runoff. • No surface curbing or surface drains to direct water away from bridge, approach slab, and joints. • Surface drains blocked by debris.	• Unplug or dig out crushed drainage tile and replace with tile that has adequate strength. • Uncover outlets that have been silted over or covered by embankment material. • Excavate or fill embankment locations that have ponding water to allow water to drain away from embankment. • Overlay approach slab and/or pavement with enough transverse crown in road to prevent water from ponding. • Place curb and gutters to direct water away from approach slab and joints. • Clean and unplug existing surface drains. • Install surface drains to prevent erosion of the shoulder or embankment. • Remove approach slab and pavement and replace with proper subbase and drainage.

Table 17 Summary bump identification metrics and troubleshooting Phares et al. (2011) (Continued)

Possible Cause of Bridge Bump Problem	Indication of problem Based on Visual Investigation	Troubleshooting Method
Riding-Surface Defects	• Large quantities of transverse cracks in approach slab with gaps larger than 0.016-in. • Pot holing in concrete approach slab, asphalt overlays, mainline pavement, or bridge surface. • Rutting, shoving, and channelizing of asphalt pavements. • Heavy oil staining, generally dark black and located 10 to 15-ft ahead of bump on the surface.	• Saw cut out spalling, cracked, or potholed approach slab and pavement locations and replace. • Remove pavement areas with rutting, shoving, and channelized asphalt pavements; correct base and subbase then replace pavement. • Remove approach slab and replace with one that has adequate reinforcing, especially at the end bearing regions to prevent cracking.

2.3 Specifications

In this section, specifications on different components of a bridge approach slab developed by various states are described. These components include approach slab system, subgrade, backfill, backfill reinforcement, structural slab, spacer, construction procedure, performance, and retrofitting methods.

2.3.1 Wyoming

2.3.1.1 Approach Slab System

Two approach slab systems are suggested in the WYDOT Bridge Applications Manual Chapter 4, Section 4.14 (WYDOT, 2008) depending on the type of road surface. Concrete approach slab should be used when the approach roadway has a concrete surface and/or is constructed in conjunction with a sleeper slab. Approach slab with asphalt surface should be used when the approach roadway has an asphalt surface. It is recommended that the thickness of concrete slab be 10-inch. When using asphalt overlay, the depth of asphalt should match that shown on a road plan. Otherwise, it should be one lift of 2-inch. The depth of concrete slab plus the asphalt overlay shall not exceed the depth of a corbel (WYDOT, 2008).

The approach slab system is constructed using backfill material, geotextile, and an underdrain pipe as shown in figure 17. A void is created between the backfill and abutment backwall to reduce pressure on the backwall and aid in drainage (WYDOT, 2008).

The approach slab system generally depends on the depth of the abutment backwall. If the backwall is 5-ft or less below the top of the corbel, a shallow configuration is used (figure 18). If the backwall is more than 5-ft below the top of the corbel, a deep configuration is used (figure 19). The depth of the excavation and backfill shall be 2-ft minimum and 3-ft maximum, as measured from the bottom of the approach slab or sleeper slab to the back edge of the approach slab or sleeper slab (WYDOT, 2008).

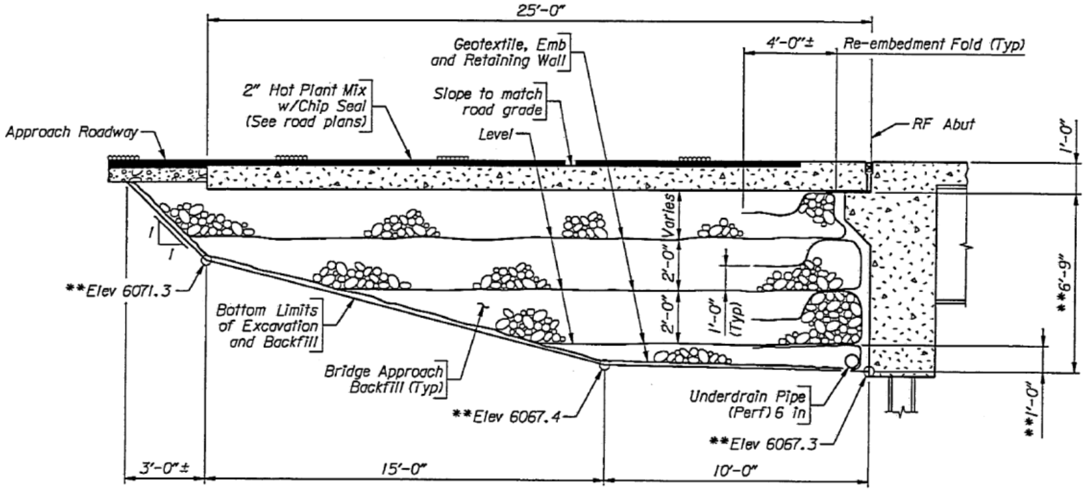


Figure 17 The approach slab system consisting of backfill material, geotextile, and an underdrain pipe (WYDOT, 2008)

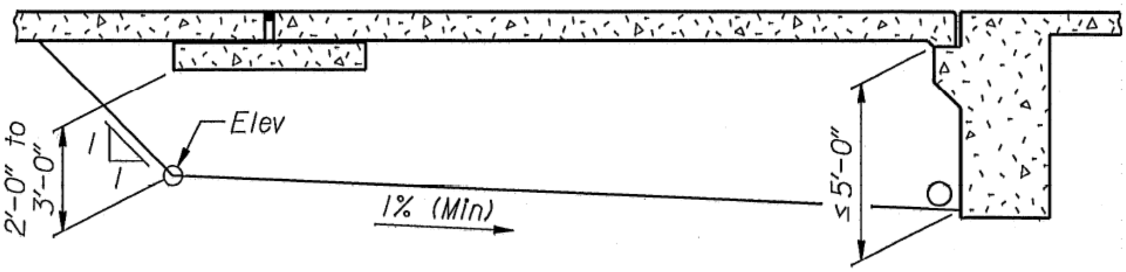


Figure 18 Shallow configuration (WYDOT, 2008)

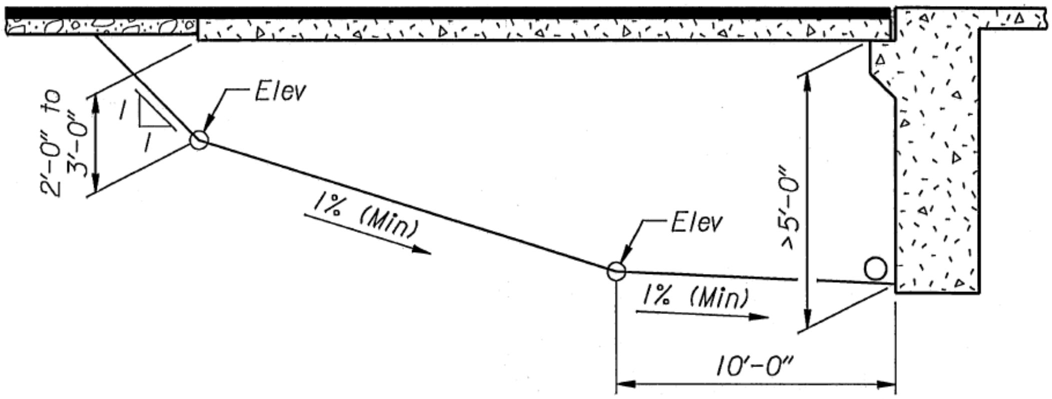


Figure 19 Deep configuration (WYDOT, 2008)

2.3.1.2 Backfill

WYDOT Bridge Applications Manual Chapter 4, Section 4.14 (WYDOT, 2008) specifies that pervious material should be used for approach slab backfill. The gradation requirement for pervious backfill is specified by the WYDOT Standard Specifications for Road and Bridge Construction Manual, Section 803 (WYDOT, 2010) is presented in table 18. The backfill material shall consist of nonplastic crushed gravel, crashed rock, manufactured sand, or combinations thereof. The liquid limit shall not exceed 30. Also, reinforced bridge approach fills should have an internal friction angle of at least 35°.

Table 18 Gradation requirement: pervious material (WYDOT, 2010)

Sieve	% Passing
2-in.	100
No. 4	0 to 50
No. 30	0 to 35
No. 100	0 to 10
No. 200	0 to 4

Neither the WYDOT Standard Specifications for Road and Bridge Construction Manual, Section 212 (WYDOT, 2010) nor the WYDOT Bridge Applications Manual Chapter 4, Section 4.14 (WYDOT, 2008) suggests a required compaction for backfill material. WYDOT Standard Specifications for Road and Bridge Construction Manual, Section 203 (WYDOT, 2010) specifies that the embankment material should be compacted to at least 90 percent of maximum density. Since this requirement is applied to embankment materials, a similar application to the approach slab backfill has yet to be confirmed. Also, the construction sequence is not mentioned in these documents.

2.3.1.3 Backfill Reinforcement

WYDOT Standard Specifications for Road and Bridge Construction Manual, Section 507 (WYDOT, 2010) specifies that geotextile reinforcement should be designed according to Section 217 of this manual. Moreover, it is suggested in this section to create a void of 2-inch to 4-inch between reinforced approach fill and the abutment backwall or wingwalls. The void should be created with stay-in-place honeycomb cardboard, a temporary slip form, or other approved method.

WYDOT Standard Specifications for Road and Bridge Construction Manual (WYDOT, 2010) Section 217 suggests using geotextiles as the reinforcing component of the backfill. Geotextiles are placed in order to reduce the settlement of the backfill. Placing and compacting materials above a geotextile, the following equipment loads should be met:

- A maximum wheel load of 9,945 pounds.
- A maximum contact pressure of 60-psi, as calculated from the applied wheel load in pounds and the resulting contact area in square inches.
- A lightening of equipment loads if ruts are produced greater than 3-inch deep.

While installing the geotextile the following considerations should be met:

- The geotextile should have at least 24-inch overlap at the ends and sides of adjoining sheets.
- Gravel or other specified materials should be placed on the geotextile so that it does not tear, puncture, or shift the geotextile.
- For repairing torn or punctured geotextile, a patch of the same type of geotextile should be placed over the ruptured area, overlapping at least 3-ft from the edge of any part of the rupture, or by patching with sewn seams that meet strength requirements in accordance with WYDOT Standard Specifications for Road and Bridge Construction (WYDOT, 2010), Subsection 805.2.
- Ruts exceeding 3-inch should be filled with additional cover materials.

The type of material used for the geotextile should have the following specifications as well as those summarized in table 19:

Table 19 Requirements for geotextile (WYDOT, 2010)

Fabric and Membrane Property	**Test Method**	**Drainage & Filtration**	**Erosion Control**	**Silt Fence**	**Separation & Stabilization (Non-Woven)**	**Embankment & Retaining Wall Reinforcement**	**Impermeable Plastic Membrane**	**Subgrade Reinforcement**
Performance Criteria During Service Life								
Equivalent or Apparent Opening Size, US Standard Sieve, in.	ASTM D 4751	40-100	40-100	20-50	40-100	30-60	-	30-50
Thickness, mils	ASTM D 5199	-	-	-	-	-	12	-
Permittivity, Sec-1	ASTM D 4491	1.0	1.0	0.05	1.0	0.02	10^{-7} cm/sec	0.25
Strength Requirements								
Wide Width Tensile Strength, Ultimate, lbs/ft	ASTM D 4595	-	-	-	-	-	-	2400
Wide Width Tensile Strength @ 2% strain, lbs/ft	ASTM D 4595	-	-	-	-	-	-	450
Grab Tensile Strength, lb	ASTM D 4632	100	180	100	160	300	150	250
Elongation at Failure, min., %	ASTM D 4632	50	50	15	50	15	15	10
Trap Tear Strength, lb	ASTM D 4533	45	70	50	60	110	50	110
Puncture Strength, lb	ASTM D 4833	60	90	50	85	110	60	120
Seam Efficiency, %	ASTM D 4632	90	90	90	90	90	-	90
Environmental Requirements								
Ultraviolet Resistance, % Strength Retention after 500 hours of exposure	ASTM D 4355	50	70	80	50	50	50	50

- The provided material for geotextile should be an impermeable plastic membrane consisting of a polypropylene, polyethylene, or polyester geotextile with a bonded polypropylene or polyethylene film.
- Avoid nylon thread for sewn seams. Use high-strength polyester, polypropylene, or Kevlar thread instead.

2.3.2 Colorado

2.3.2.1 Approach Slab System

A template drawing of the approach slab system with a sleeper beam used by the Colorado Department of Transportation (CDOT) is shown in figure 20. The typical length of the approach slab is 20-ft, and the thickness is 12-inch (CDOT, 2012).

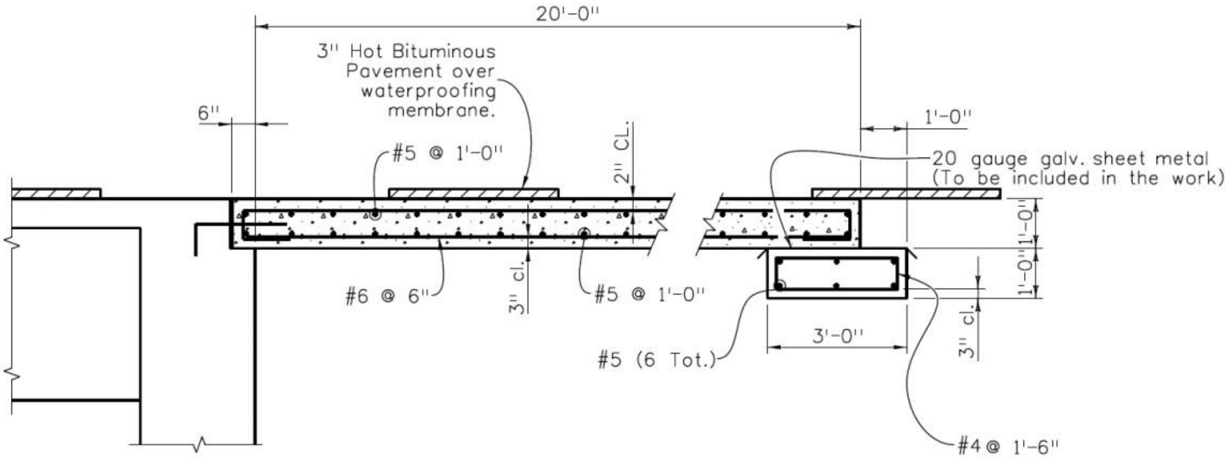


Figure 20 The approach slab system used in Colorado (CDOT, 2012)

2.3.2.2 Backfill

Table 20 shows the specification of selected backfill used by CDOT. This table indicates that all aggregates should pass the 3-inch sieve, and only a maximum of 5 percent should pass the No. 200 sieve. Thus, the backfill is classified as a coarse-grained material that would provide adequate gradation for water drainage. Furthermore, the backfill material should be compacted to 95 percent of maximum dry unit weight in accordance with AASHTO T-99 (CDOT, 2012).

Table 20 Backfill specification by CDOT (CDOT, 2012)

Sieve Size	Percent Passing by Weight
3 in.	100%
¾ in.	20 – 100%
No. 40	0 – 60%
No. 200	0 – 5%

2.3.3 Hawaii

2.3.3.1 Approach Slab System

Specifications on approach slab are not available.

2.3.3.2 Backfill

The specifications on selected backfill materials A and B specified by the Hawaii Department of Transportation (HIDOT) are presented in table 21. For both materials all aggregates must pass the 3-inch sieve. Passed percentage of material from the No. 200 sieve should be less than 15 percent for material A and zero for material B (HIDOT, 2005).

Table 21 Backfill specifications used by Hawaii DOT (HIDOT, 2005)

	Percent Passing by Weight	
Sieve Size	**Structure Backfill Material A**	**Structure Backfill Material B**
3 in.	100%	100%
No. 4	20 – 75%	20 – 100%
No. 200	0 – 15%	-

2.3.4 Iowa

2.3.4.1 Approach Slab System

Iowa Department of Transportation (IADOT) has two typical approach slab designs based on slab thicknesses of 10-inch and 12-inch as shown in figure 21 and figure 22, respectively. The length for both approach slab types is 40-ft. Also, integral and non-integral abutment designs are specified, and no sleeper slab is required in the approach slab design (IADOT, 2010).

2.3.4.2 Backfill

Specifications on backfill are not available.

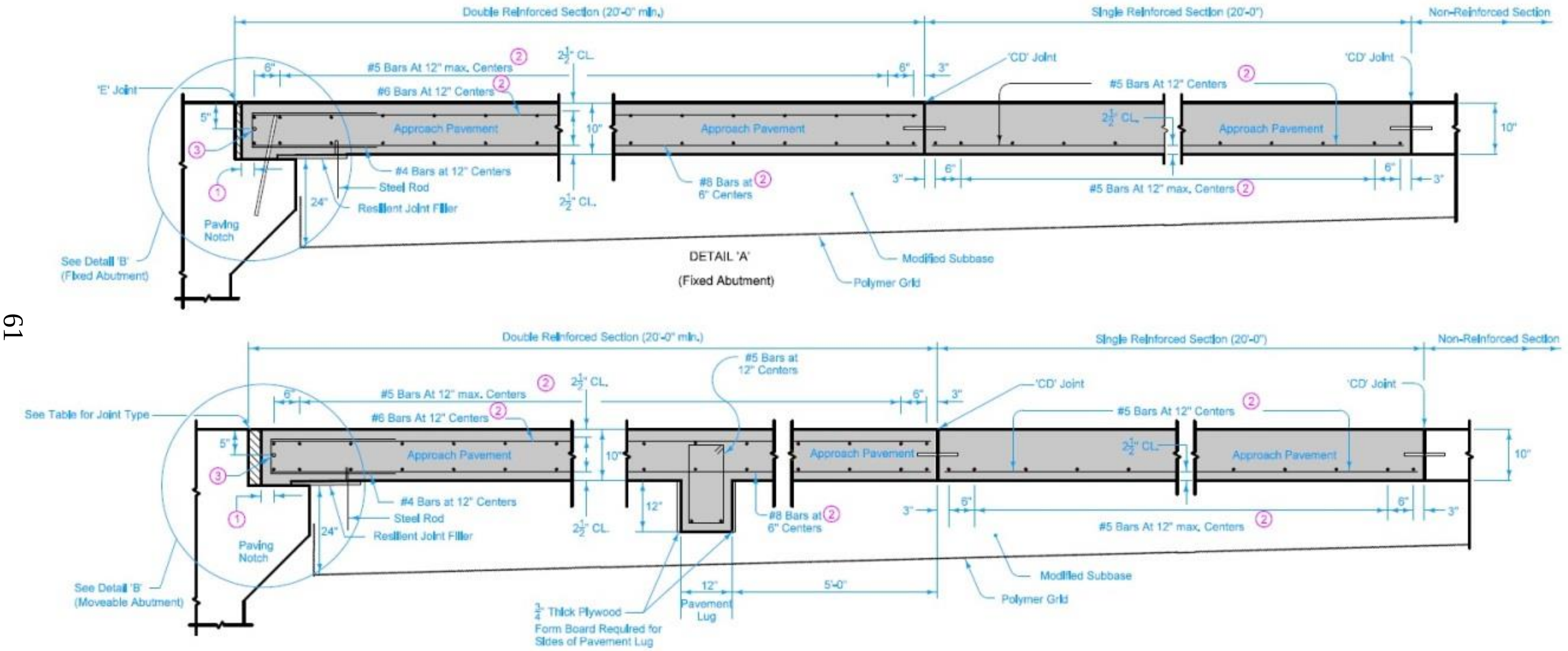


Figure 21 The 10-in thick approach slab system used in Iowa (IADOT, 2010)

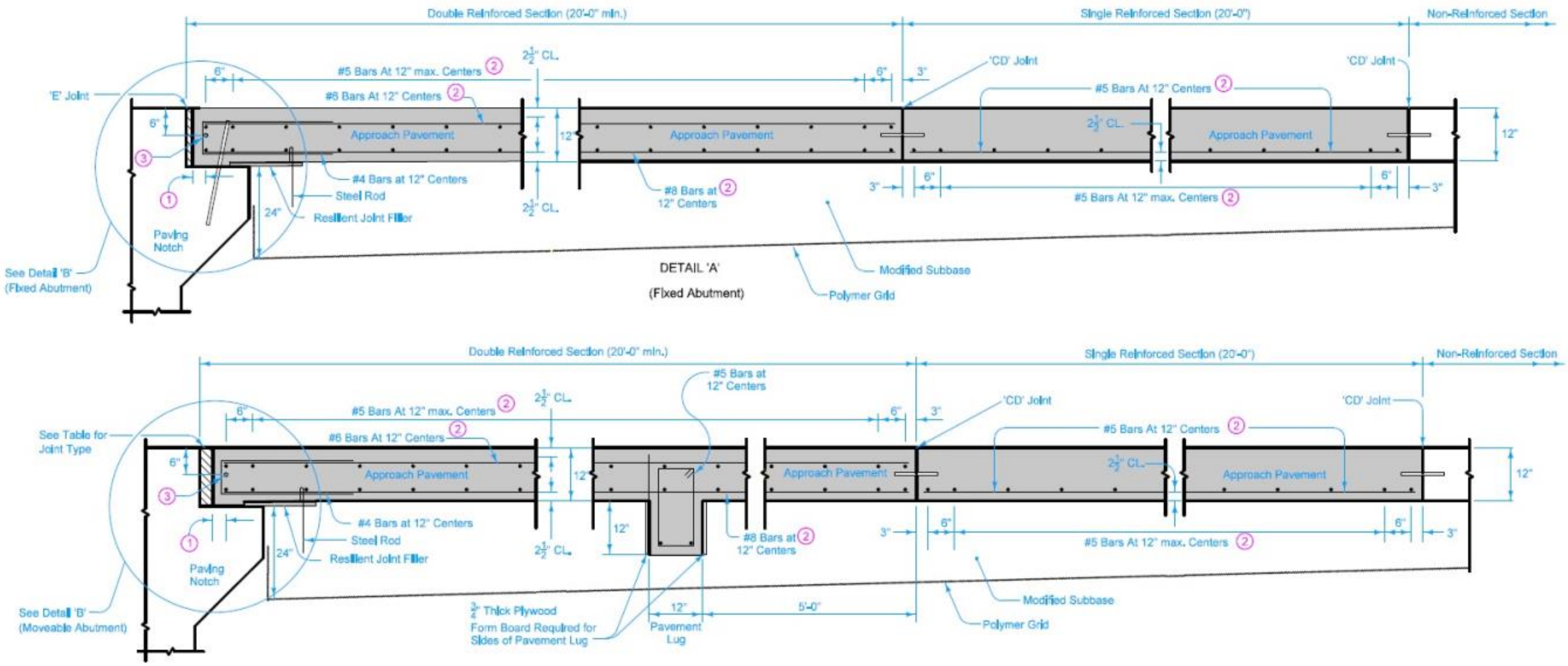


Figure 22 The 12-in thick approach slab system used in Iowa (IADOT, 2010)

2.3.5 Minnesota

2.3.5.1 Approach Slab System

Minnesota Department of Transportation (MNDOT) defines the length and the thickness of the approach slab to be 20-ft and 12-inch, respectively. Figure 24 and figure 23 show a typical plan and cross section view of the approach slab used by MNDOT. Note that a sleeper slab is used in the approach slab system. A contraction joint is specified at the bridge connector end of the approach slab, while an expansion joint is specified at the other end (MNDOT, 2014).

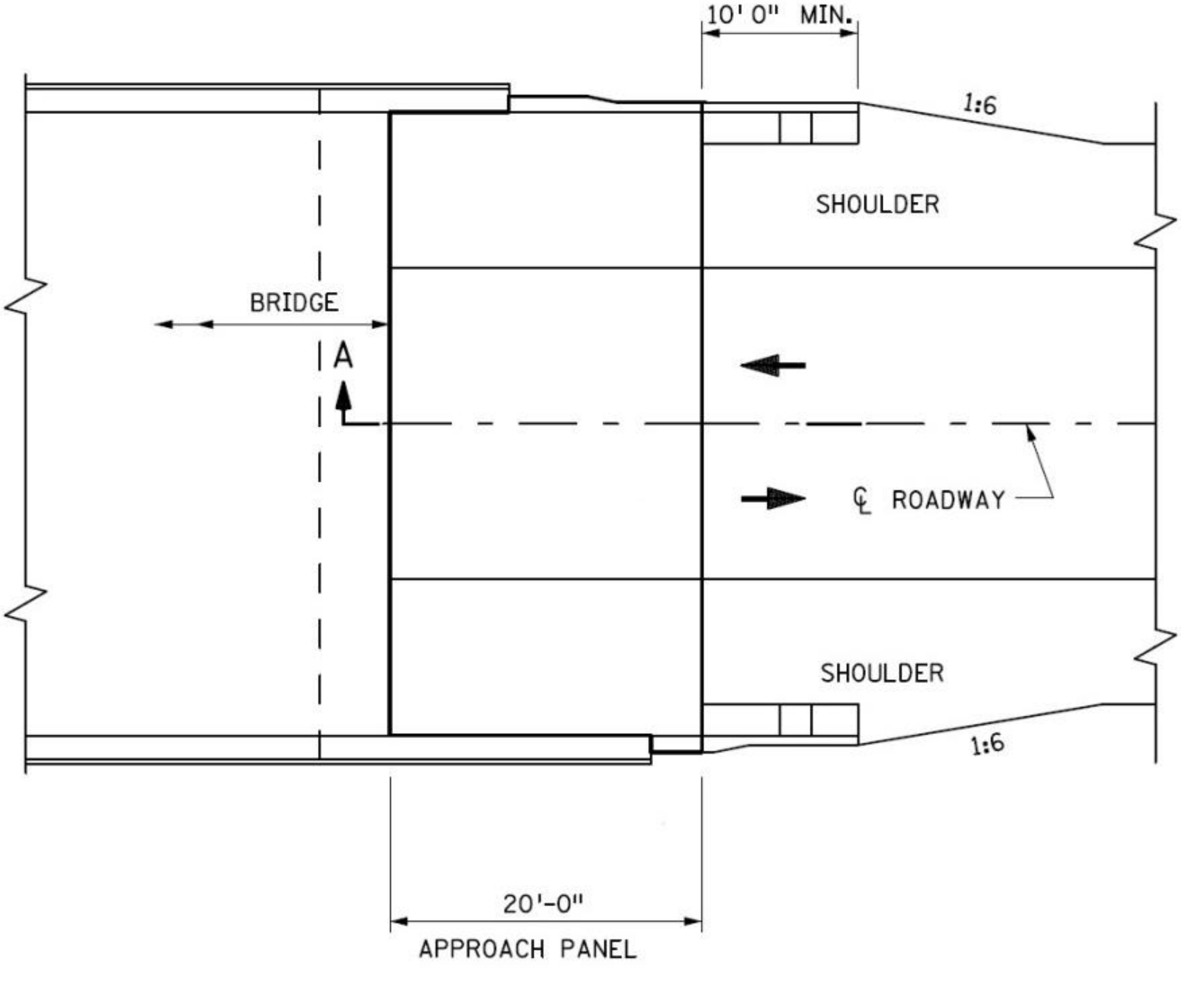


Figure 23 Plan view of the approach slab system used in Minnesota (MNDOT, 2014)

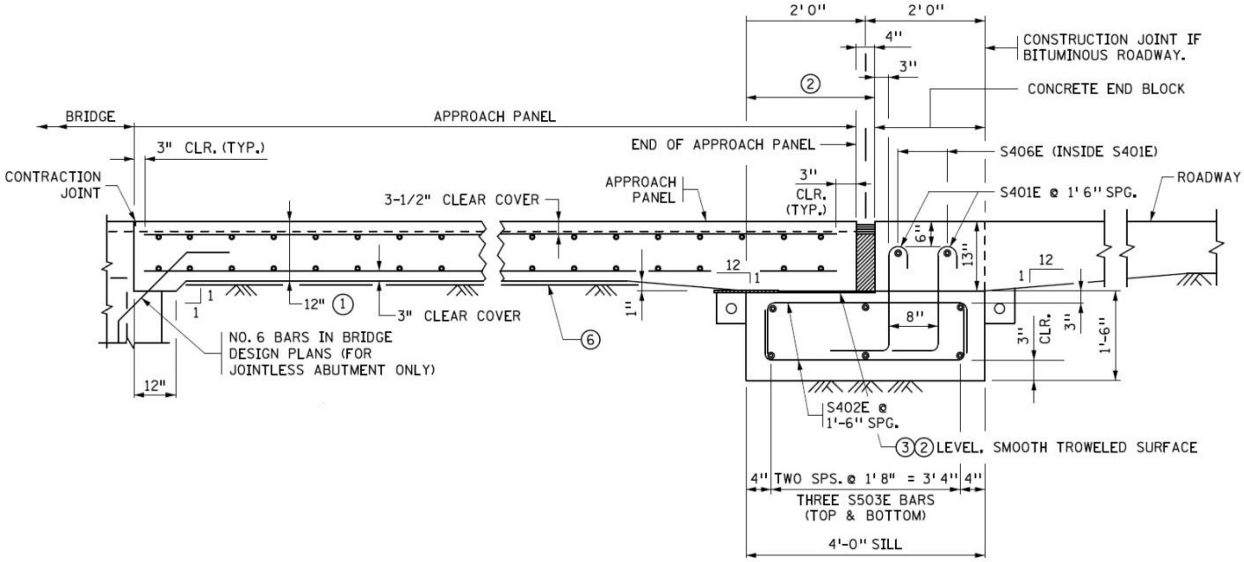


Figure 24 Cross section of the approach slab system used in Minnesota (MNDOT, 2014)

2.3.5.2 Backfill

Specifications on backfill are not available.

2.3.6 Missouri

2.3.6.1 Approach Slab System

Figure 25 and figure 26 depict the cross section and plan view of the approach slab system used by Missouri Department of Transportation (MODOT). The typical approach slab length is 25-ft, and the typical slab thickness is 12-inch. Figure 26 shows that a sleeper slab is used to support the approach slab, and a perforated drain pipe near the sleeper slab is used for drainage (MODOT, 2014).

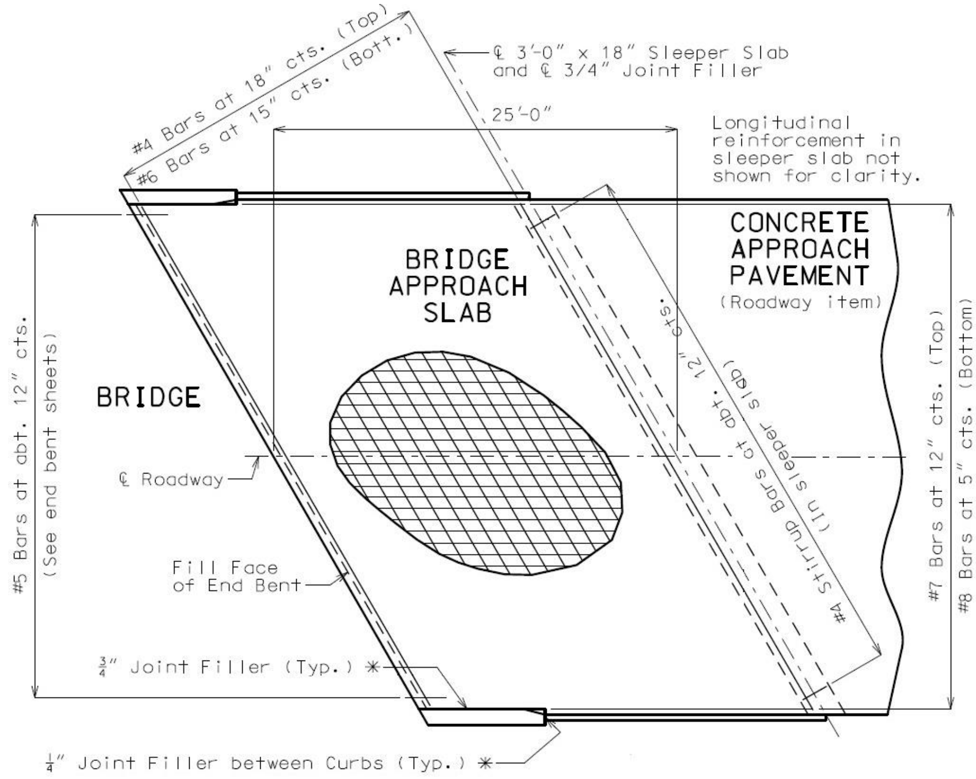


Figure 25 Plan view of the approach slab system used in Missouri (MODOT, 2014)

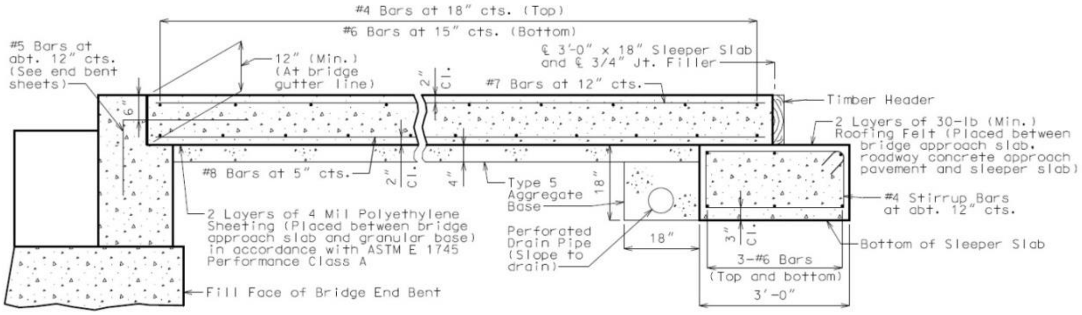


Figure 26 The approach slab system used in Missouri (Cross Section) (MODOT, 2014)

2.3.6.2 Backfill

Table 22 presents the specification on selected backfill material used by MODOT. Unlike the specifications by WYDOT and HIDOT, all aggregates should pass the 1-inch sieve, and no more than 15 percent should pass the No. 200 sieve. Based on this gradation, the backfill is classified as a coarse-grained material.

Table 22 Backfill specification for Missouri DOT (MODOT, 2014)

Sieve	Percent by Weight
Passing 1 in.	100%
Passing ½ in.	60 – 90%
Passing No. 4	35 – 60%
Passing No. 30	10 – 35%
Passing No. 200	0 – 15%

2.3.7 Nebraska

2.3.7.1 Approach Slab System

Specifications on the approach slab system used by the Nebraska DOT are not available.

2.3.7.2 Backfill

Specification on selected backfills used by the Nebraska Department of Roads (NDOR) is provided in table 23. All particles should pass the 3/8-inch sieve while no more than 3 percent of the particles should pass the No. 200 sieve (NDOR, 2007).

Table 23 Backfill specification by Nebraska DOT (NDOT, 2007)

Sieve Size	Percent Passing
3/8 in.	99 – 100%
No. 4	65 – 85%
No. 10	0 – 15%
No. 50	0 – 10%
No. 200	0 – 3%

2.3.8 New Hampshire

2.3.8.1 Approach Slab System

Specifications on the approach slab system used by the New Hampshire Department of Transportation (NHDOT) are not available.

2.3.8.2 Backfill

According to NHDOT, 100 percent of backfill material particles shall pass the 3-inch sieve, with 70 percent to 100 percent passing the No. 4 sieve (NHDOT, 2010).

2.3.9 New Mexico

2.3.9.1 Approach Slab System

The approach slab system defined by New Mexico Department of Transportation (NMDOT) is defined as follows (NMDOT, 2013):

- An approach slab with a sleeper beam is preferred on all new bridges, especially for bridges with integral and semi-integral abutments and concrete approach pavements.
- A minimum approach slab length of 14-ft should be used on all new bridges. For bridges built on a new alignment or in a high fill area, the approach slab length should be 20-ft.

2.3.9.2 Backfill

A-1-a material is specified as the backfill material (NMDOT, 2013); however, the gradation is not available.

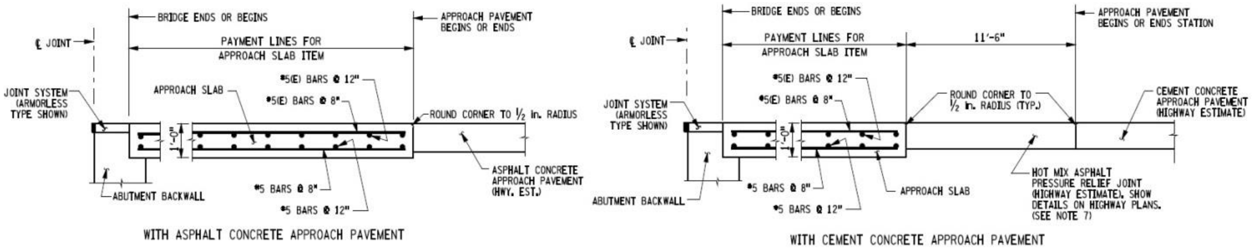
2.3.9.3 Spacer

If flowable backfill is used, a 3-inch extruded polystyrene spacer should be constructed between the abutment and backfill material. No spacer is required for the A-1-a backfill material (NMDOT, 2013).

2.3.10 New York

2.3.10.1 Approach Slab System

Figure 27 shows the details of approach slab systems used by the New York Department of Transportation (NYDOT) for both asphalt and cement concrete pavements. A typical approach slab length is not specified by NYDOT but the thickness is designated to be 12-inch. The approach slab system uses a sleeper slab as shown in figure 28 (NYDOT, 2014).



WITH ASPHALT CONCRETE APPROACH PAVEMENT

WITH CEMENT CONCRETE APPROACH PAVEMENT

Figure 27 The approach slab systems for asphalt and cement concrete pavements used by NYDOT (NYDOT, 2014)

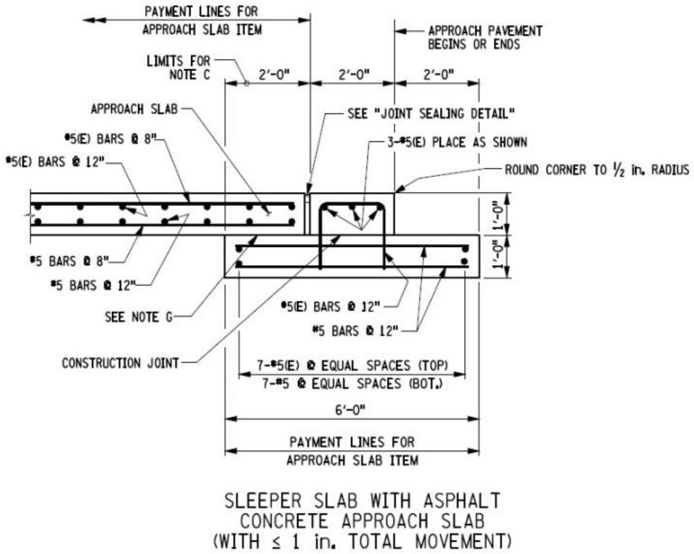


Figure 28 Detail of sleeper slab used by NYDOT (NYDOT, 2014)

2.3.10.2 Backfill

Specifications on backfill are not available.

2.3.11 Ohio

2.3.11.1 Approach Slab System

The typical cross section of an approach slab designed by Ohio Department of Transportation (OHDOT) is shown in figure 29. Four different lengths and thicknesses are specified by Ohio DOT for the approach slab design, as presented in table 24. No sleeper slab is integrated into the approach slab design (OHDOT, 2013).

Table 24 Length and thickness of approach slabs in Ohio (OHDOT, 2013)

Length (ft)	Thickness, T (in.)
15	12
20	13
25	15
30	17

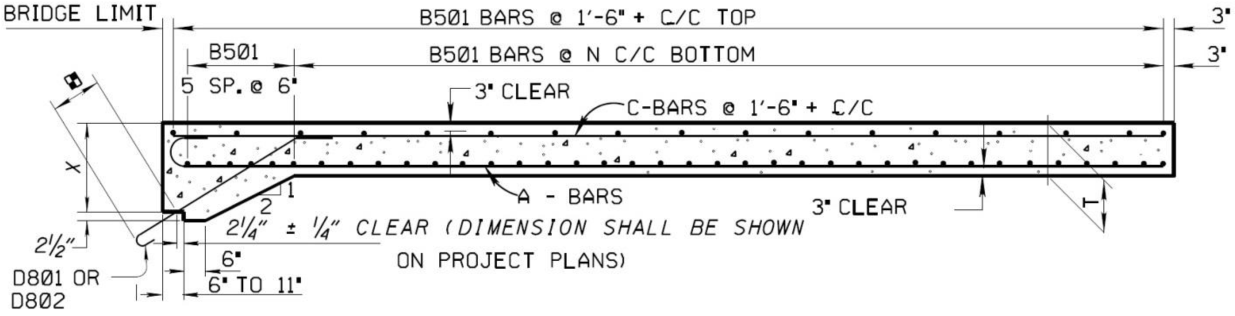


Figure 29 The approach slab system used in Ohio (OHDOT, 2013)

2.3.11.2 Backfill

The specification on backfill material beneath the approach slab used by OHDOT is presented in table 25. The material should have 100 percent passing the No. 30 sieve and less than 20 percent passing the No. 200 sieve (OHDOT, 2013).

Table 25 Backfill specification by Ohio DOT (OHDOT, 2013)

Sieve Size	Total Percent Passing
No. 30	100%
No. 50	95 – 100%
No. 200	0 – 20%

2.3.12 Oklahoma

2.3.12.1 Approach Slab System

Oklahoma Department of Transportation (OKDOT) uses the specification shown in figure 30 to construct an approach slab. The approach slab length and thickness are specified as 30-ft and 13-inch, respectively. No sleeper slab is defined in the specification (OKDOT, 2009).

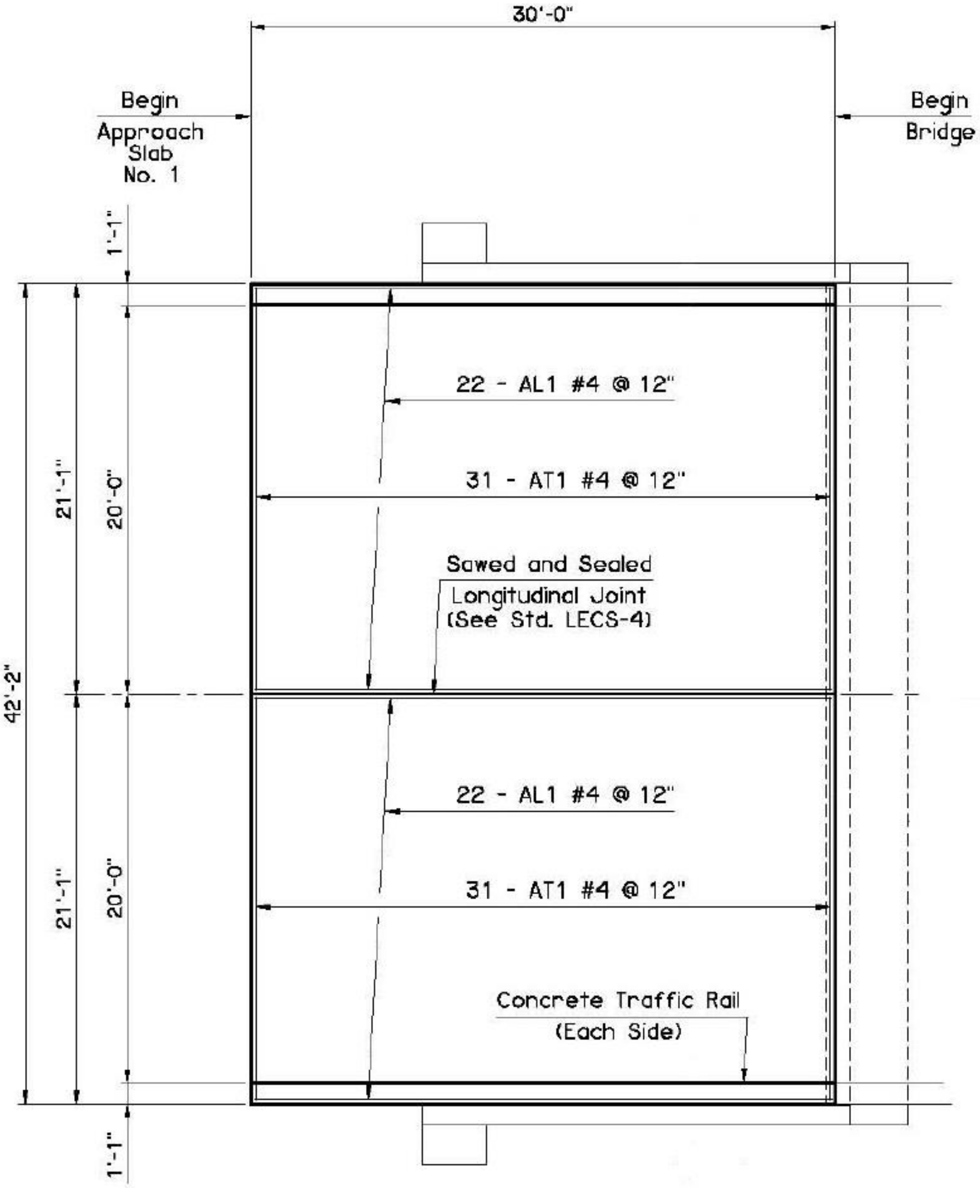


Figure 30 Plan view of the approach slab system used in Oklahoma (OKDOT, 2009)

2.3.12.2 Backfill

The backfill specification is presented in table 26. All aggregates must pass the 3-inch sieve, and the percent passing the No. 200 sieve must be less than 10 percent (OKDOT, 2009).

Table 26 Backfill specification for Oklahoma DOT (OKDOT, 2009)

Sieve Size	Percent Passing
3 in.	100%
1 in.	90 – 100%
No. 40	0 – 45%
No. 200	0 – 10%

2.3.13 Oregon

2.3.13.1 Approach Slab System

The approach slab cross section used by Oregon Department of Transportation (ORDOT) is shown in figure 31. The typical approach slab length defined by Oregon DOT is either 20.3-ft or 30.3-ft, with corresponding slab thicknesses of 12-inch and 14-inch, respectively. No sleeper slab is used beneath the approach slab (ORDOT, 2014).

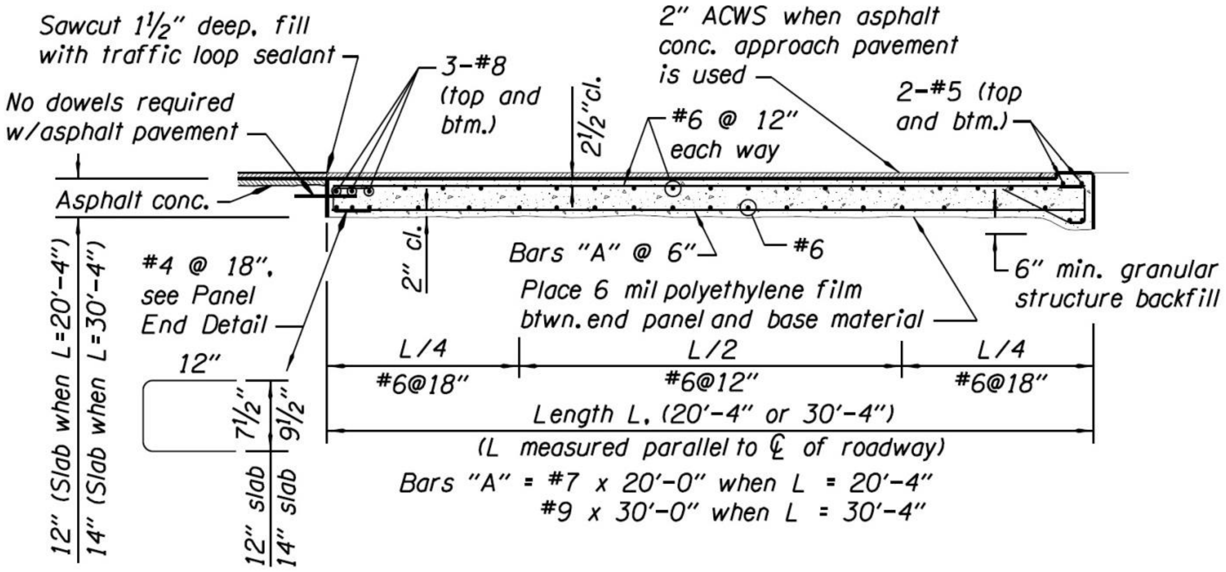


Figure 31 The approach slab system used in Oregon (ORDOT, 2014)

2.3.13.2 Backfill

Oregon DOT's backfill specification is shown in table 27. All backfill aggregates must pass the 3-inch sieve, and less than 6 percent must pass the No. 200 sieve (ORDOT, 2014).

Table 27 Backfill specification for Oregon DOT (ORDOT, 2014)

Sieve Size	Percent Passing (by Weight)
3 in.	100
3/8 in.	0 – 80%
No. 40	0 – 40%
No. 100	0 – 10%
No. 200	0 – 6%

2.3.14 Texas

2.3.14.1 Approach Slab System

Figure 32 and figure 33 depict the cross section and plan view of a typical approach slab used by Texas Department of Transportation (TXDOT). Typical approach slab length and thickness are 20-ft and 13-inch, respectively. A sleeper slab is not used in the approach slab system (TXDOT, 2004).

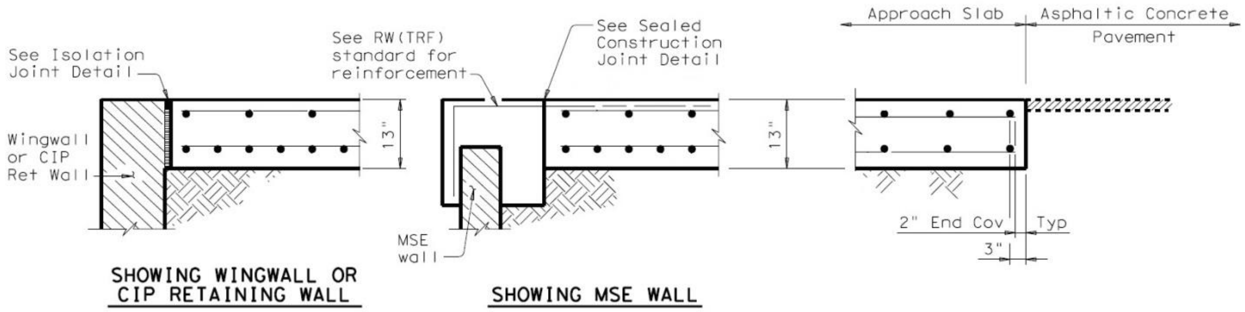


Figure 32 Cross section of the approach slab system used in Texas (TXDOT, 2004)

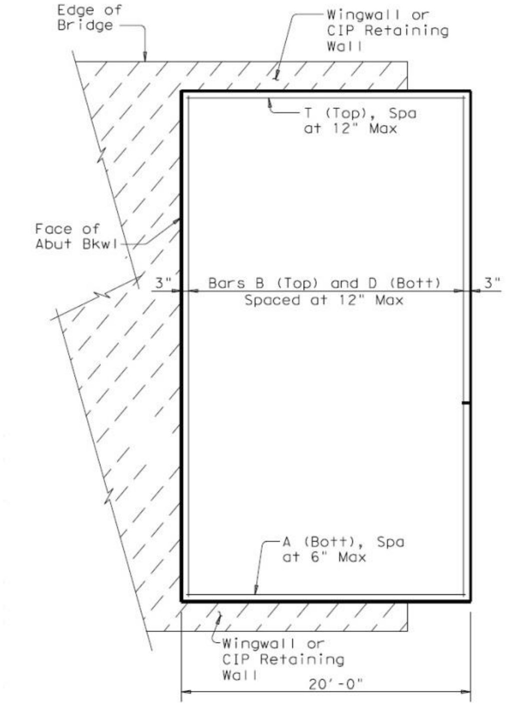


Figure 33 Plan view of the approach slab system used in Texas (TXDOT, 2004)

2.3.14.2 Backfill

Texas DOT specifies two types of backfill materials, A and B, as presented in table 28. For both types, all aggregates must pass the 3-inch sieve and almost all aggregates must retain on the No. 40 sieve for A and the 3/8-inch sieve for B (TXDOT, 2004).

Table 28 Backfill specification by Texas DOT (TXDOT, 2004)

Type	Sieve Size	Percent Retained
A	3 in	0
	½ in	50 – 100%
	No. 4	See Note
	No. 40	85 – 100%
B	3 in	0
	3/8 in	85 – 100%

Note: Use No. 4 sieve for determination of rock backfill as described in Sec 423.C, "Backfill".

2.3.15 Virginia

2.3.15.1 Approach Slab System

Specifications on the approach slab system are not available. The typical sleeper slab cross section used by Virginia Department of Transportation (VDOT) is shown in figure 34 (VDOT, 2007).

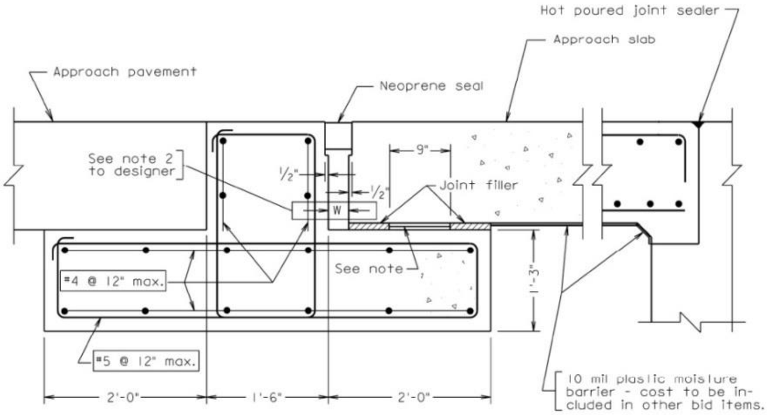


Figure 34 The sleeper slab detail used in Virginia (VDOT, 2007)

2.3.15.2 Backfill

Table 29 presents the required specification on selected backfill materials used in Virginia. The backfill material must completely pass the 3-inch sieve, and the percent passing the No. 200 sieve should be between 4 percent and 14 percent (VDOT, 2007).

Table 29 Backfill specification by Virginia DOT (VDOT, 2007)

Sieve Size	% by Weight of Material Passing Sieve
3 in.	100%
2 in.	95 – 100%
No. 10	25 – 55%
No. 40	16 – 30%
No. 200	4 – 14%

2.3.15 AASHTO

AASHTO LRFD Bridge Design Specifications (2012) were also reviewed to determine any specifications pertaining to approach slabs. AASHTO (2012) does not have any specific section on the approach slab system, but its structural slab can be designed accordingly.

CHAPTER 3 – SURVEY

3.1 Survey Development

The literature review in chapter 2 highlights a wide range of causes of approach slab settlement. Ranking the causes of settlement is difficult because of differences in approach slab systems, construction practices, and traffic and environmental conditions in various states. Furthermore, information about current DOTs' specifications on design and construction of approach slabs is not readily available online for review. To identify and fill in knowledge gaps among various states, a nationwide survey was conducted with a 22-item questionnaire (see appendix A). The survey was developed using the commercial online software, SurveyMonkey® and was distributed through AASHTO to all DOTs in the United States. Below is a list of the questions, which were purposely designed to gather information for subsequent analysis with the main objective of improving the current approach slab design and construction in the state of Wyoming:

a) **Question (2):** Has your state conducted research on approach slabs?

   Purpose: Some states have conducted research on approach slab; it would be beneficial to build a complete reference list of their works, in order to avoid redundancy and to facilitate a comprehensive literature review.

b) **Question (3):** What percentage of the bridges use an approach slab system?

   Purpose: Since not all constructed bridges are using an approach slab system, it is beneficial to determine the usage of approach slab in their bridges.

c) **Question (4):** What percentage of bridges with an approach slab system use an integral abutment?

Purpose: Integral and non-integral abutment design considerations were found to be one of the major differences in state DOTs' design specifications.

d) **Question (5):** Which approach slab systems are currently used in your state?

Purpose: It is important to identify the types of approach slab systems used in each state or specified in their respective design specifications.

e) **Question (6):** What percentage of bridges have approach slab settlements?

Purpose: To evaluate the significance of approach slab settlement, it is important to determine the percentage of approach slabs with settlement problems.

f) **Question (7):** What are the causes of approach slab settlement?

Purpose: One of the most ambiguous issues found in the literature was the causes of approach slab settlement. It is important to identify these causes with respect to their design/construction practices as well as local environmental and traffic conditions. Seismic effect was not taken into consideration because a newly constructed approach slab typically settles right after the opening of a new bridge, as experienced in Wyoming.

g) **Question (8):** What types of settlements have you experienced?

Purpose: Knowledge of the different types of settlement will help identify causes, potentially leading to better solutions for remediation and retrofitting.

h) **Question (9):** What types of approach slab backfill are currently used in your state?

Question (10): Is select backfill material used beneath the approach slab?

Question (11): What is the typical Geometry Specification (Average Depth) of your backfill?

Question (12): Is a drainage system used beneath the approach slab?

Question (13): Is a positive separation between subgrade and backfill provided?

Question (14): Is in-situ density test performed on compacted backfill?

Question (15): Are spacers being used between the backfill and the abutment wall to minimize the lateral load on abutment?

Purpose: A detailed understanding of backfill specifications will enable us to compare and contrast different approach slab systems used by other states with those recommended by WYDOT. Therefore, several of the survey questions are dedicated to this matter.

i) **Question (16):** What is the typical thickness of the structural approach slab?

Question (17): What is the typical span length of the approach slab?

Question (18): What retrofitting methods are used for approach slab settlement?

Question (19): What is the average cost per square-ft of each method mentioned in the previous question?

Purpose: We hope that these questions will shed light on structural slab specifications, retrofitting methods and their costs, and current design specifications used by each state.

j) **Question (20):** What is the current specification used for design and construction of approach slabs?

Question (21): Are you using typical drawings for the approach slabs?

Purpose: Because some state DOTs' current specifications and typical designs are not readily available online, these questions will allow us to obtain them for completing the literature review.

k) **Question (22):** Are you satisfied with your current design or are you planning on improving it?

Purpose: This question rates the satisfaction of the DOTs on the current performance of their approach slab systems.

3.2 Survey Results

A total of 34 responses from 31 states were gathered from this survey, and the results are presented in appendix B. These states are shown in figure 35. Several states presented multiple responses, among which the most logical response according to the respective state's specifications is chosen. These multiple answers are indicated in the appendix. Moreover, the states of Montana and Maryland mentioned that they are not using approach slabs in their bridge designs and constructions. After eliminating duplicate responses and responses from these two states, a total of 28 valid responses remained for analysis. Before presenting a complete analysis, a brief review of each response is presented alphabetically in table 30.

3.2.1 Overall Findings

A summary of the received responses and key points mentioned by each state is presented below.

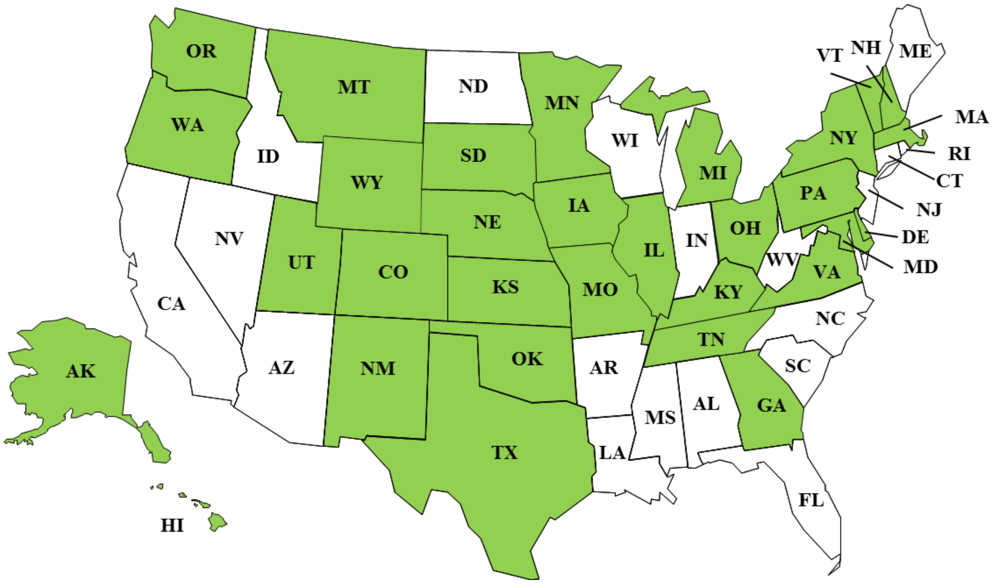


Figure 35 States responded to the survey

Table 30 Summary of the received responses and key points mentioned by each state

State	Total Bridges$^{(a)}$	Percent Use AS	Satisfaction of AS System	Comment
Alaska	1,196	75-100%	Yes	
Colorado	8,612	50-75%	No	Always room to improve.
Georgia	14,769	100%	Yes	
Hawaii	1,125	0-25%	Yes	
Iowa	24,398	75-100%	Yes	
Illinois	26,621	50-75%	Yes	Several cases are still under investigation
Kansas	25,171	100%	Yes	Recently improved the drainage under the approach slab.
Maryland	5,291	None	-	
Massachusetts	5,136	100%	Yes	
Michigan	11,022	75-100%	No	The aggregate base of the approach slab and sleeper slab is recently thickened in the design, and the drainage locations ae changed.
Minnesota	13,137	100%	Yes	

(a)-Total bridges obtained from http://www.fhwa.dot.gov/bridge/deficient.cfm; AS-Approach Slab, CIP-Cast In-Place Approach Slab.

Table 30 Summary of the received responses and key points mentioned by each state (Continued)

State	Total Bridges[(a)]	Percent Use AS	Satisfaction of AS System	Comment
Missouri	24,350	75-100%	No	The new findings of the research in 2014 are being implemented in the design. This research is based on lowering costs for construction and not reducing settlement issues.
Montana	5,126	None	-	
Nebraska	15,370	75-100%	No	Adding piles beneath the approach slab have eliminated the settlement problem, but cracks are being seen in this case.
New Hampshire	2,438	75-100%	Yes	
New Mexico	3,935	50-75%	Somewhat	New Mexico's natural foundation soil types vary greatly statewide. The challenge is determining which method of consolidation and foundation material will work best.
New York	17,442	75-100%	No	NYDOT is reviewing their jointless over the backwall detail where the approach slab is continuation of the deck slab and the bridge joint is at the end of the approach slab.
Ohio	27,015	100%	No	Bridges with integral/semi-integral expansion movements at the roadway end of the slab causes drainage and settlement issues. ODOT is considering the use of sleeper slab at the roadway end.
Oklahoma	22,912	75-100%	No	
Oregon	7,656	75-100%	Yes	
Pennsylvania	22,660	25-50%	No	Ohio DOT's design is under investigation to be implemented in the design of Pennsylvania.
South Dakota	5,875	50-75%	No	Inclusion of geotextiles within approach slab embankment to reduce differential settlement is under investigation.

(a)-Total bridges obtained from http://www.fhwa.dot.gov/bridge/deficient.cfm; AS-Approach Slab, CIP-Cast In-Place Approach Slab.

Table 30 Summary of the received responses and key points mentioned by each state (Continued)

State	Total Bridges$^{(a)}$	Percent Use AS	Satisfaction of AS System	Comment
Tennessee	20,058	75-100%	No	
Texas	52,561	25-50%	Yes	
Utah	2,974	100%	No	
Virginia	13,765	25-50%	Yes	Virginia DOT recently implemented the placement of a large mass of select backfill behind abutments and bumps at the end of bridge.
Vermont	2,731	100%	Yes	Very few problems with approach slabs including those for integral abutment bridges are observed. More and more precast approach slabs to support ABC projects are being made.
Washington	7,902	75-100%	Yes	
Wyoming	**3,099**	**75-100%**	**No**	

(a)-Total bridges obtained from http://www.fhwa.dot.gov/bridge/deficient.cfm; AS-Approach Slab, CIP-Cast In-Place Approach Slab.

3.2.2. Specific Findings

Figure 36 shows the percentages of bridges with approach slab systems used in each state. Two states, Montana and Maryland, do not use approach slab systems in their bridges while seven states use them in all bridges. Twelve states, including Wyoming, use approach slab in more than 75 percent of their bridges. Four states use approach slab for 50 to 75 percent of their bridges, and the same number of states use approach slab for 25 to 50 percent of their bridges. Only one state uses approach slab system in less than 25 percent of its bridges. The results conclude that most states use approach slab in their bridges.

Figure 37 summarizes the percentages of integral abutment bridges with approach slab in each state. The results show that all respondents use integral abutments in their bridges. Ten respondents reported that less than 25 percent of their integral abutment bridges have approach slab systems. Five respondents use approach slab in 25 to 50 percent of their integral abutment bridges. Six respondents, including Wyoming, use approach slab in 50 to 75 percent of their integral abutment bridges. Five respondents use approach slab in more than 75 percent of their integral abutment bridges while only two respondents, Pennsylvania and Massachusetts, use approach slab in all integral abutment bridges.

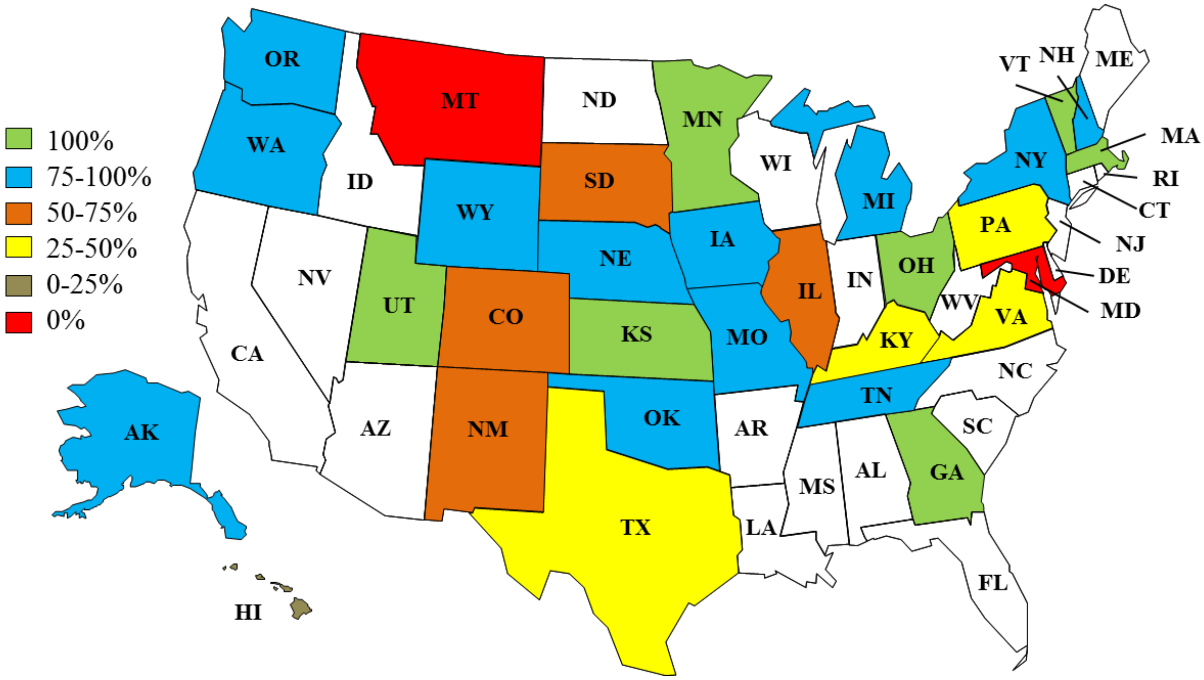


Figure 36 Percentages of bridges with approach slab system

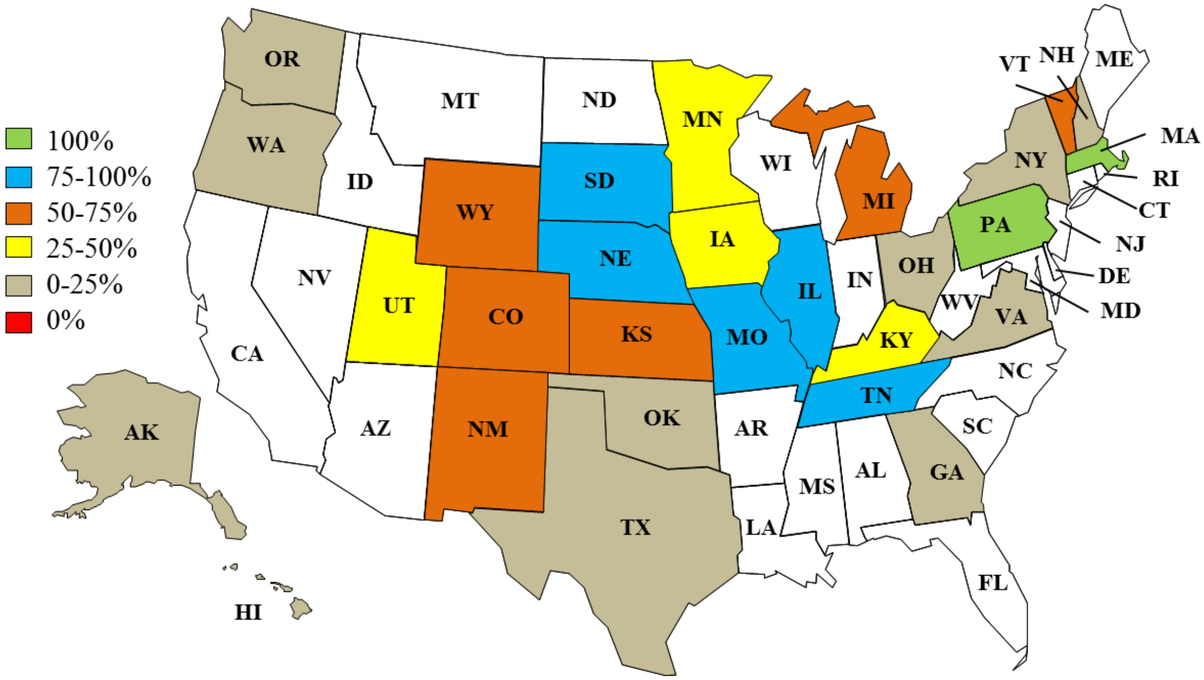


Figure 37 Percentages of integral abutment bridges with approach slab system

Figure 38 illustrates the different types of approach slab systems used throughout the United States. The results indicate that 21 respondents use the "cast-in-place" system, which is the most commonly used approach slab system. The sleeper slab approach slab system, used by 17 respondents, is the second most widely used. Precast is the least commonly used system with only 8 respondents. The results show that almost all respondents do not use other approach slab systems, and most states use both cast-in-place and sleeper slab systems. For example, Wyoming uses mostly the cast-in-place system with occasional sleeper slab.

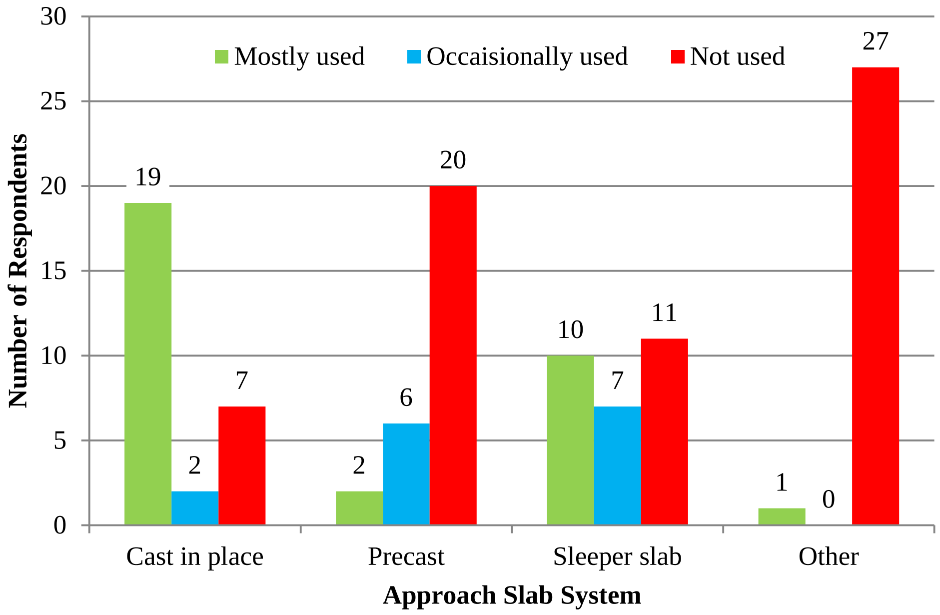


Figure 38 Approach slab systems currently used by states

Figure 39 depicts the percentages of bridges experiencing approach slab settlement. The results indicate that majority of the respondents, 17 out of 28 (including Wyoming), are experiencing settlement in less than 25 percent of their bridges. However, it is important to note that the actual number of bridges with approach slab settlement could be higher because not all bridge settlements are documented in the respective inventories as highlighted by the Wyoming DOT. No respondents reported approach slab settlement in all bridges. Five respondents reported approach slab settlement in 25 to 50 percent of their bridges, and four respondents reported approach slab settlement in 50 to 75 percent of their bridges. Only two respondents reported approach slab settlement in more than 75 percent of their bridges. It can be generally concluded that approach slab settlement does not occur at every bridge, and that every state experiences approach slab settlement in mostly less than 25 percent of their bridges.

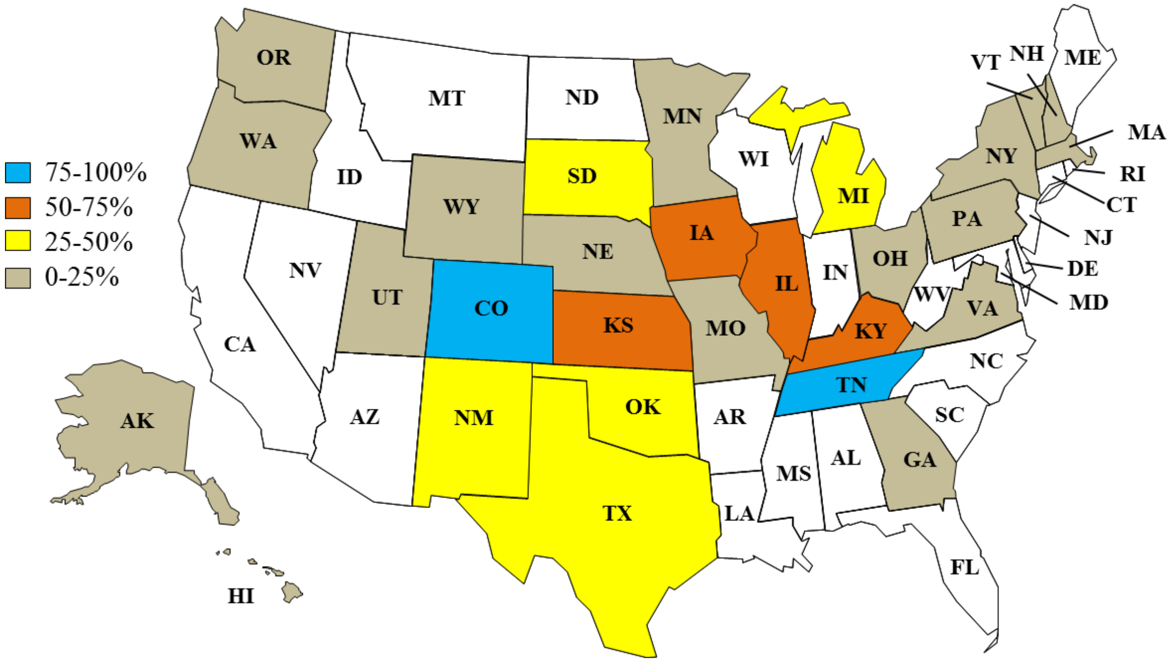


Figure 39 Percentages of bridges with approach slab settlement

Figure 40 illustrates 14 causes of approach slab settlement and their distributions. The most common causes are ranked as follows:

- Poor construction practices (14 respondents).
- High embankment fill (9 respondents).
- Secondary compression of backfill (9 respondents).
- Soft natural soil foundation (8 respondents).

The somewhat common causes of approach slab settlement are listed as follows:

- Inadequate design (13 respondents).
- Primary compression of backfill (11 respondents).
- Soil volume change (11 respondents).
- High average daily traffic (11 respondents).

- High embankment fill (10 respondents).
- Poor construction practices (10 respondents).
- Thermal effect (10 respondents).
- Soft natural soil foundation (9 respondents).
- Secondary compression of backfill (9 respondents).

In contrast, the least common causes of approach slab settlement are:

- Steep approach slab gradients (26 respondents);
- Broken corbels (23 respondents); and
- Steep side slope (21 respondents).

Combining the number of respondents selecting most and somewhat common causes, the following observations are described:

- Poor construction practice is considered the primary cause of approach slab settlement with 24 respondents including Wyoming.
- High embankment fill, secondary compression of backfill, and soft natural soil foundation are considered as the next most recognizable causes.
- The third most probable cause is a combination of 1) primary compression of backfill; 2) soil volume change; 3) thermal effect; 4) high average daily traffic; 5) inadequate design; and 6) weather effect.
- Steep approach slab gradients, broken corbels, and steep side slope appear to be the least probable causes of settlement.
- The low number of respondents selecting “other” as the common cause suggests that all possible causes have been included in this survey.

Wyoming's results are consistent with the overall results. Poor construction practice was recognized as the most common cause in Wyoming, while steep approach slab gradients and steep side slope were considered less common. Wyoming reported high embankment fill as the least common cause, while other states generally treated it as a common cause.

Figure 41 shows the results relating to types of approach slab settlement. Most respondents encountered uniform settlement, and 13 respondents mentioned that uniform settlement is the most common type. Six respondents including Wyoming reported differential settlement as the most common type of approach slab settlement. The results reveal that uniform settlement is about two times more common than differential settlement. According to WYDOT, uniform settlement could be caused by a broken corbel although it was noted as somewhat to least probable cause in figure 40. The amount of approach slab settlement reported by 18 states is presented in table 31.

Table 31 Amount of settlement

State	Settlement (in.)	State	Settlement (in.)
GA	3	OH	3-4
NH	2	OK	4<
IA	3	PA	<1
KY	12-18	SD	2-3
MI	1-2	TN	3
MO	2-3	TX	10
NE	2	UT	2
NM	4	VA	2-3
NY	4	WY	2-4

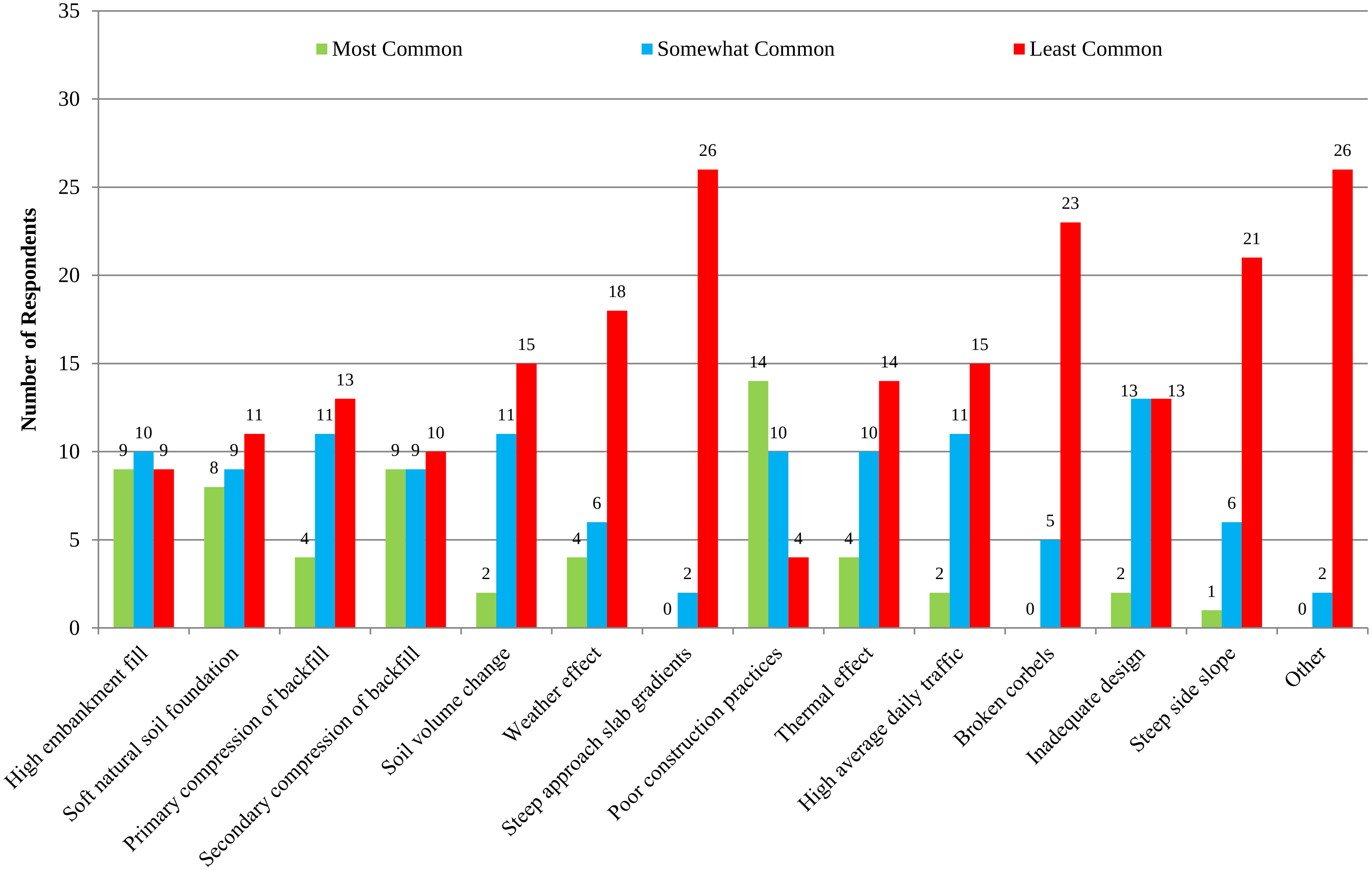


Figure 40 Causes of approach slab settlement

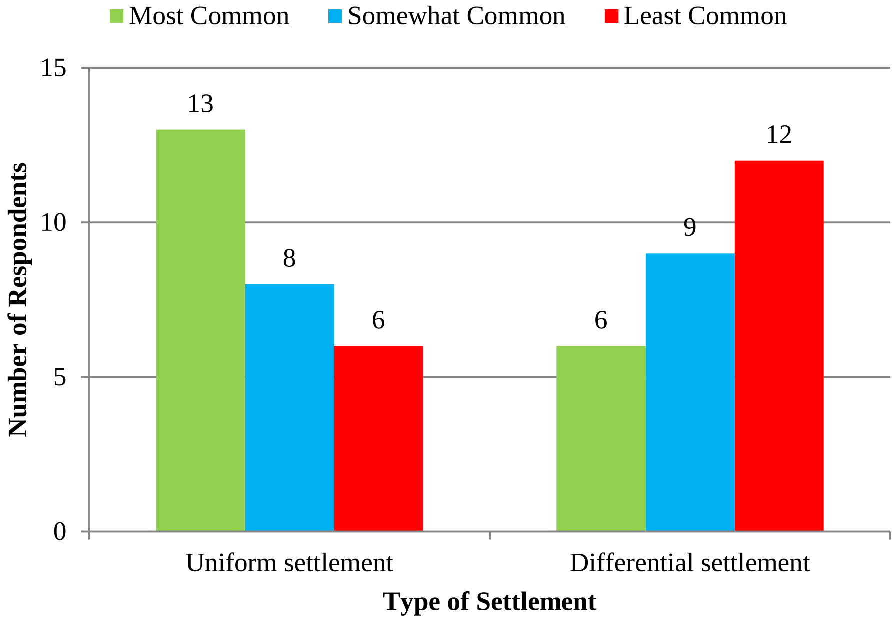


Figure 41 Types of settlements

Figure 42 illustrates the different types of approach slab backfill and their usage distributions. The conventional or non-reinforced compacted soil backfill system was found to be the most commonly used backfill system, indicated by 25 respondents. Most respondents considered the geotextile or fabric-reinforced backfill system as a somewhat or least common system, while only two respondents, Wyoming and Colorado, considered it the most common backfill. Most respondents considered light weight material and mechanical stabilized earth backfills as somewhat and least common systems, while none claimed them as the most common backfill. Results show that only two of 28 respondents use systems other than those referenced in this question. Most respondents did not consider other backfill systems, implying that backfill types were adequately covered by these four types.

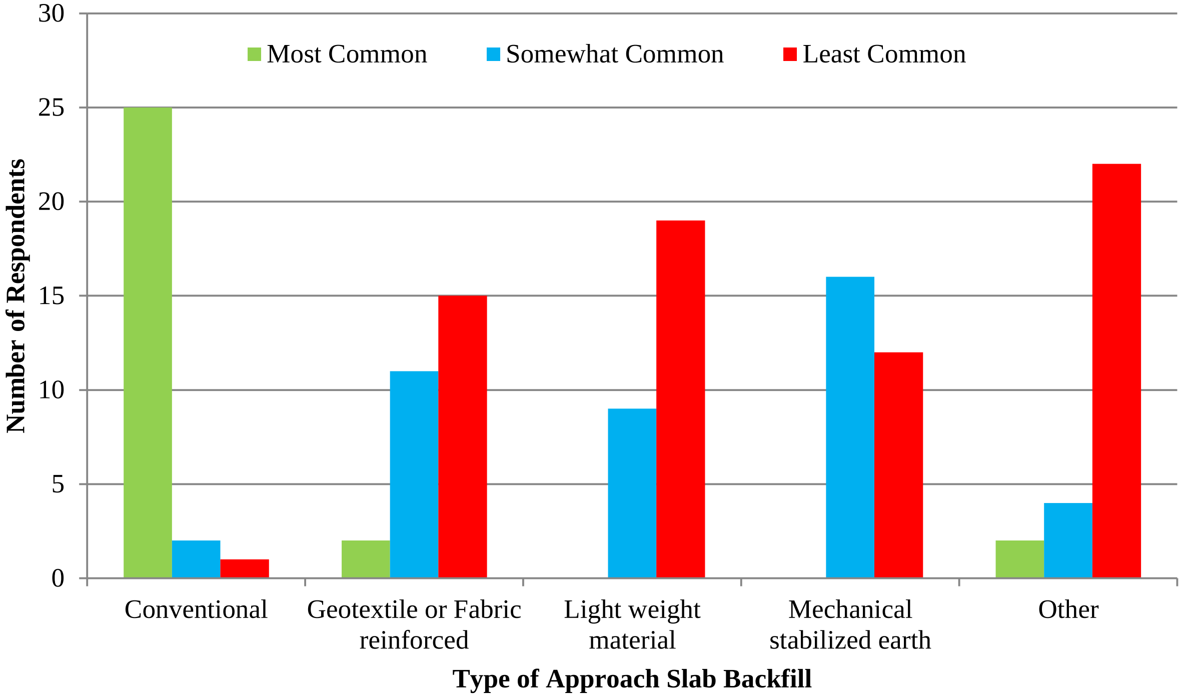


Figure 42 Types of approach slab backfill

Figure 43 shows that 22 of the 28 respondents including Wyoming use selected backfill material beneath the approach slab, indicating that this practice is overwhelmingly preferred.

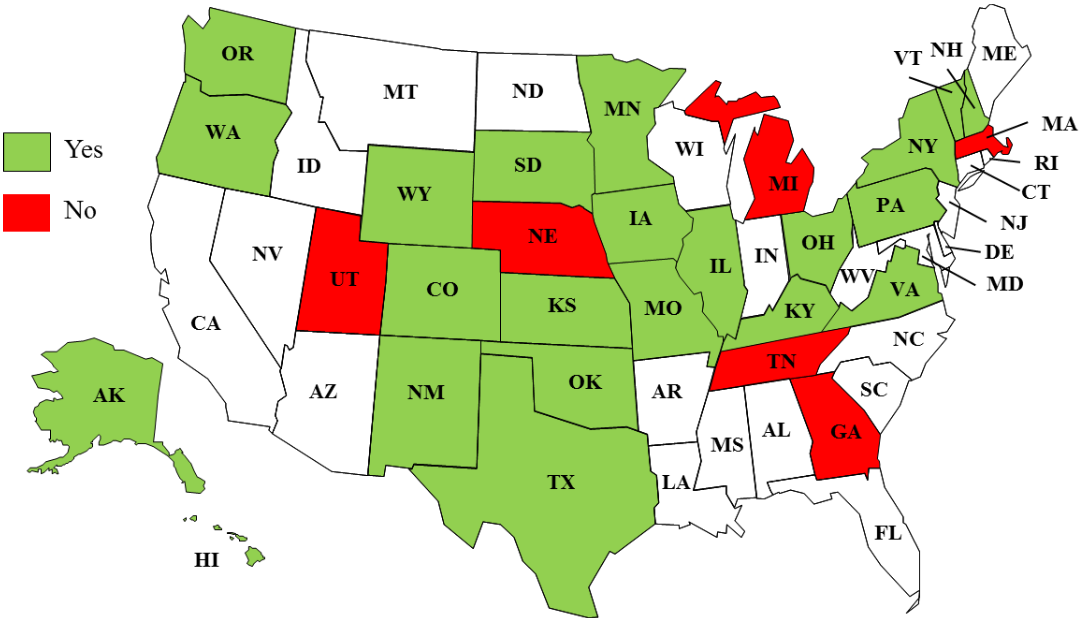


Figure 43 Usage of selected backfill material beneath the approach slab

Figure 44 shows that 17 respondents use deep configuration in their approach slab designs, while the remaining 11 respondents including Wyoming use shallow configuration. The result reveals that deep configuration is more commonly used in design.

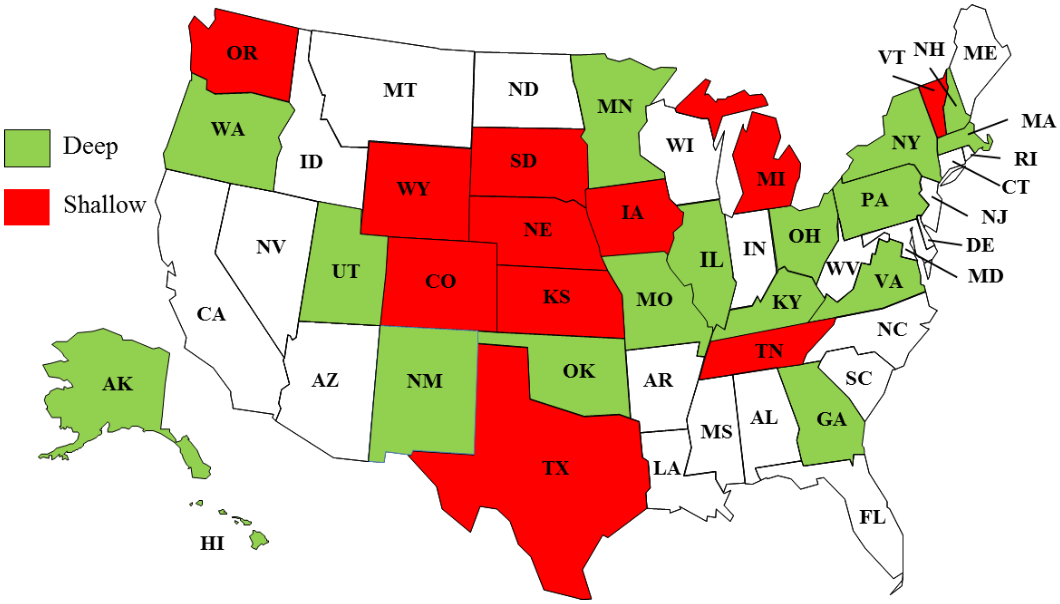


Figure 44 Typical geometry specification (average depth) of your backfill

The result shown in figure 45 reveals that half of the respondents including Wyoming use a drainage system beneath the approach slab while the other half does not.

The results presented in figure 46 indicate that most respondents do not provide a positive separation between subgrade and backfill materials. In contrast, eight respondents including Wyoming do provide a positive separation between the two.

Figure 47 reveals that most respondents perform in-situ density tests on compacted backfill, while the remaining eight respondents including Wyoming do not require these tests.

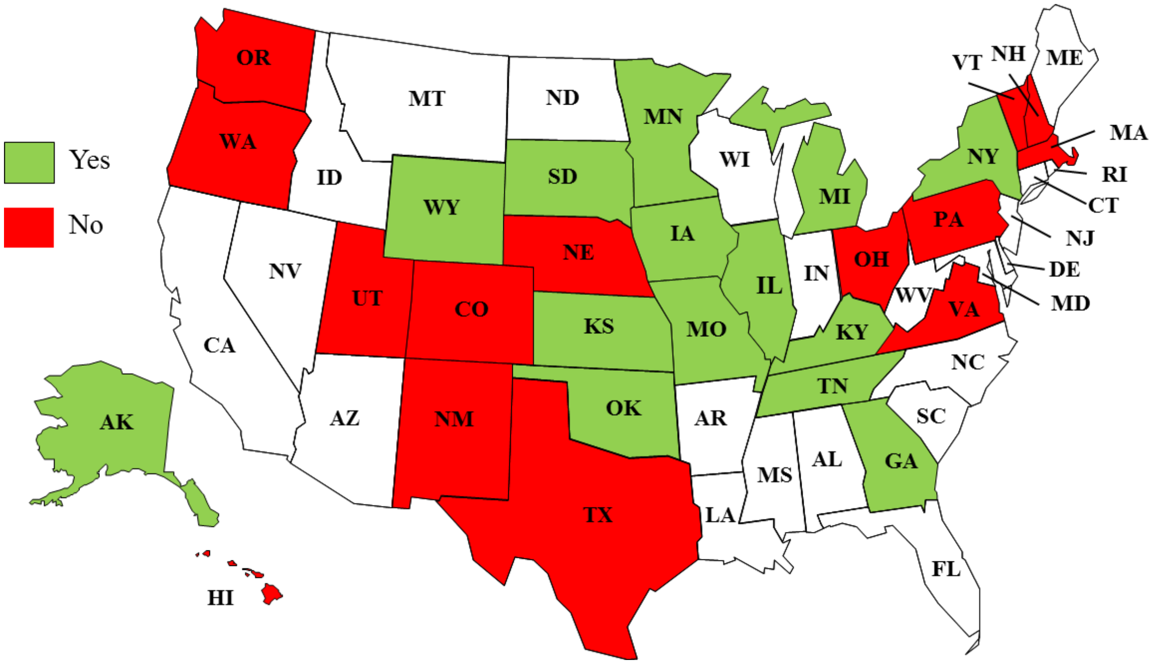


Figure 45 Usage of drainage system beneath the approach slab

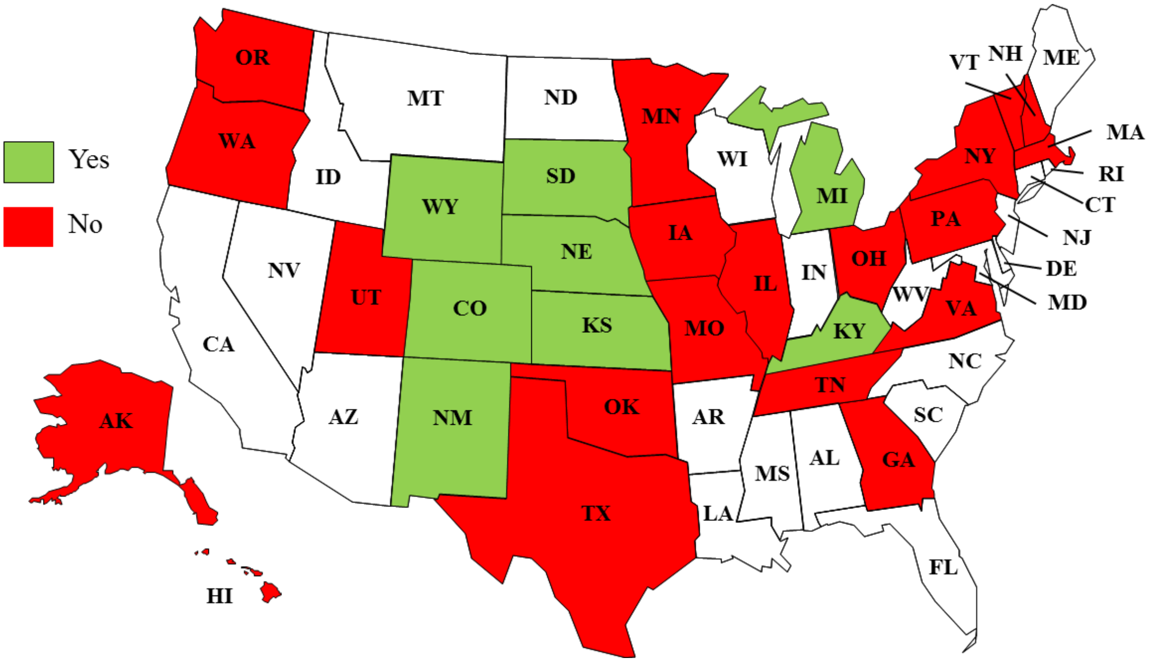


Figure 46 Usage of positive separation between subgrade and backfill

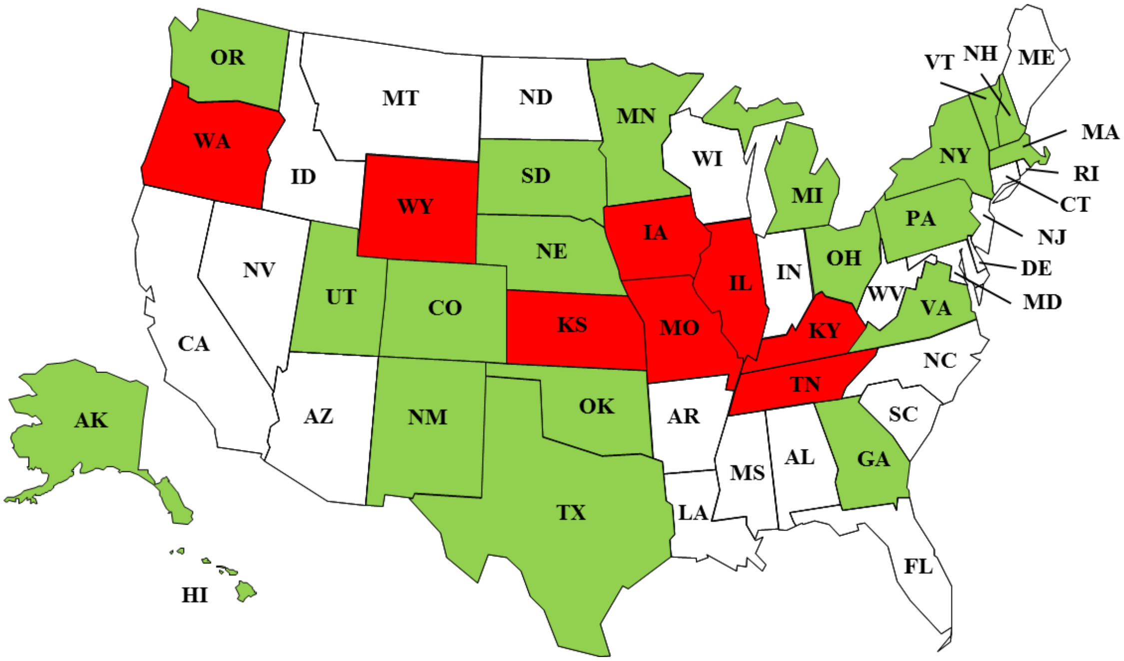


Figure 47 Usage of in-situ density test on compacted backfill

Figure 48 shows that most states do not require a spacer between the backfill and the abutment wall to reduce lateral load on the abutment. Seven respondents including Wyoming have incorporated spacers into their designs. For example, Wyoming specifies using 4-inch cardboard to create a space between the backfill and the abutment wall (WYDOT, 2010).

Figure 49 shows that the most common approach slab thicknesses range from 12-inch to 16-inch. The second most common thicknesses range from 10-inch to 12-inch, which is the common thickness used in Wyoming. The third most common thicknesses are between 8-inch and 10-inch and over 16-inch. None of the respondents uses approach slabs less than 8-inch thick.

Figure 50 reveals that the most common typical span length of approach slabs is 20-ft to 30-ft. This span length is also commonly used in Wyoming. The next most common span length ranges from 15-ft to 20-ft. Span lengths between 10-ft and 15-ft and those over 30-ft were rarely used. None of the respondents uses approach slab span lengths less than 10-ft.

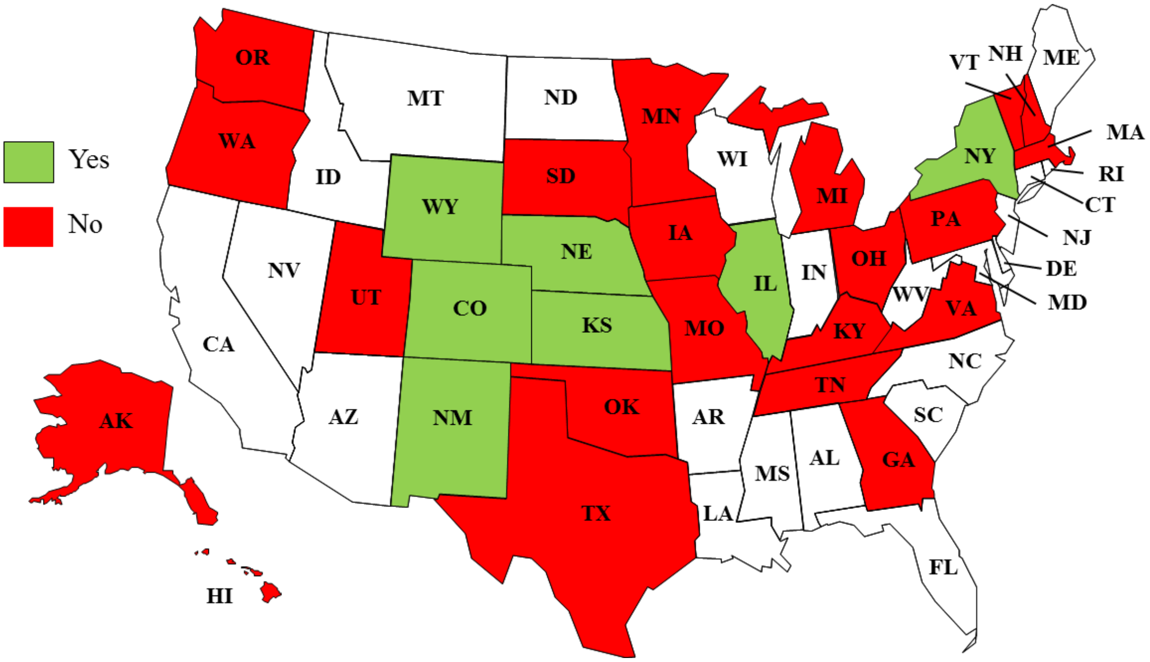


Figure 48 Usage of spacers between the backfill and the abutment wall

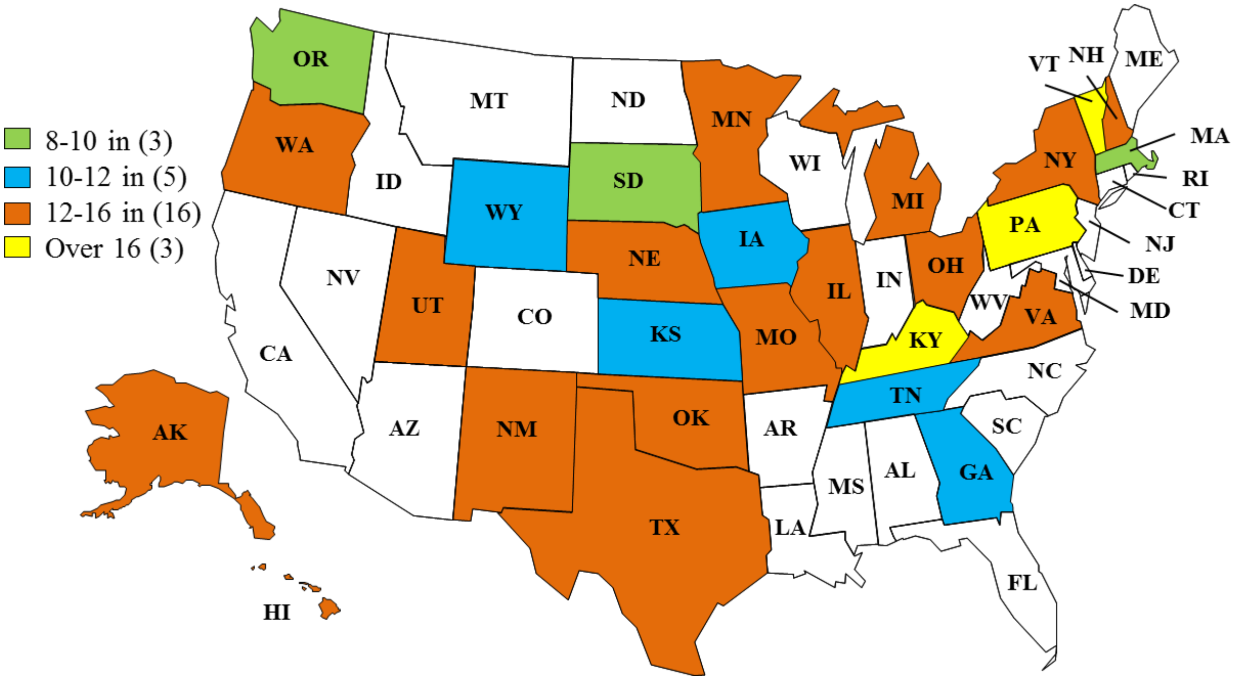


Figure 49 Typical thickness of the structural approach slab

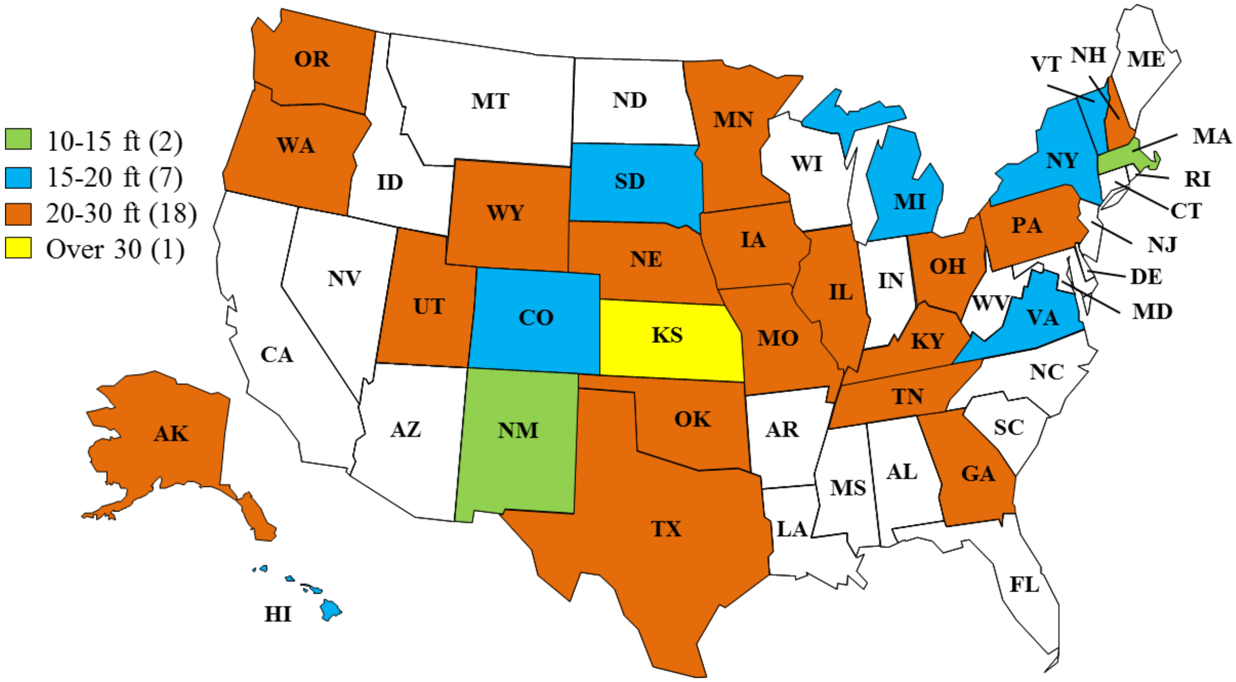


Figure 50 Typical span length of the approach slab

Figure 51 shows that overlaying is the most commonly used method for retrofitting approach slab settlement. Combining the number of respondents selecting mostly used and somewhat used methods, replacement is considered the next preferred retrofitting method, followed by the lifting and realigning method. With almost all respondents not using other retrofitting methods, these three methods have been regularly used for retrofitting in current practices. Wyoming most commonly uses replacement, while the other two retrofitting methods are occasionally used.

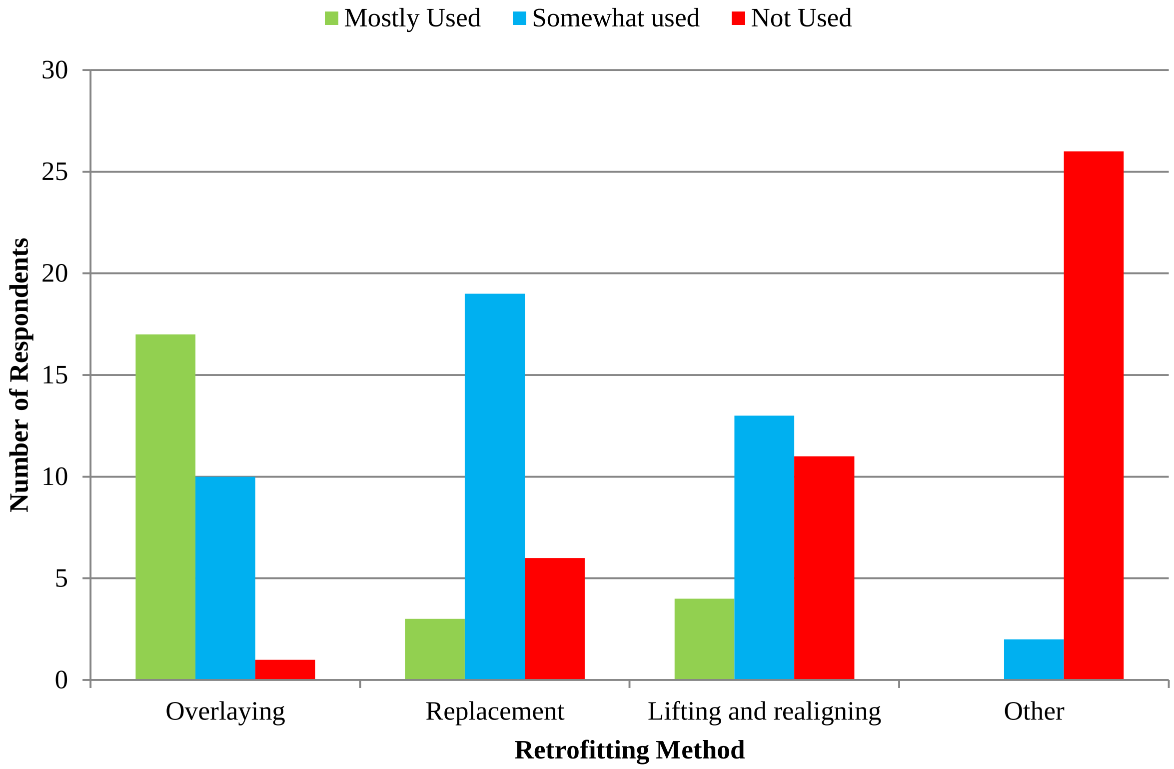


Figure 51 Retrofitting methods used for approach slab settlement

Figure 52 compares average costs of the three retrofitting methods by state. The overlaying method was considered the most cost effective with average costs ranging from \$3 to \$50 per ft^2. Costs for the most expensive retrofitting method, replacement, range from \$20 to \$260 per ft^2, while costs for lifting range from \$2 to \$139 per ft^2.

The result summarized in figure 53 shows that 23 states including Wyoming rely on typical template drawings for approach slab design while the remaining five states do not.

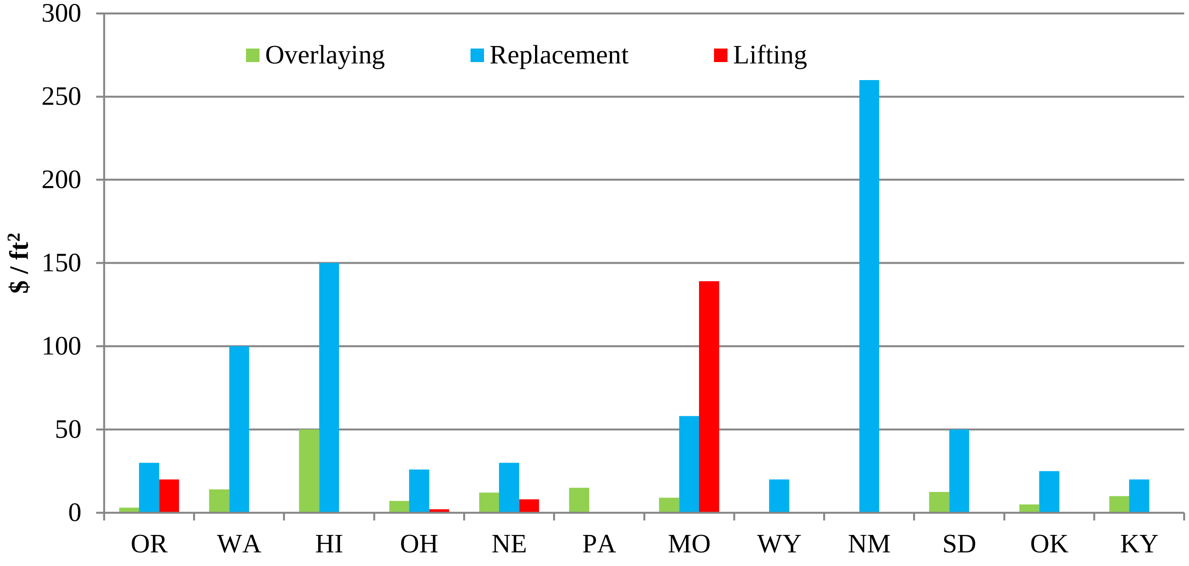


Figure 52 Average costs of three retrofitting methods

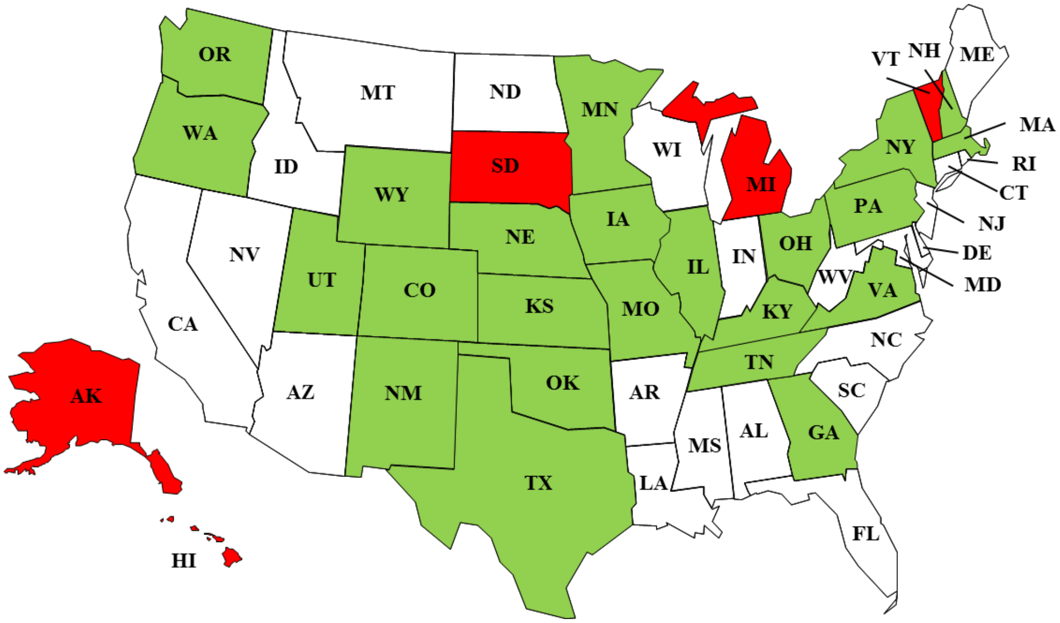


Figure 53 Usage of the typical template drawing for approach slab design

Although approach slab settlement is experienced in every state that responded to the survey as illustrated in figure 39, only 15 respondents are satisfied with their current designs (figure 54). The other 13 states including Wyoming are dissatisfied with their current approach slab designs. Therefore, improvement to current specifications in these states appears to be needed.

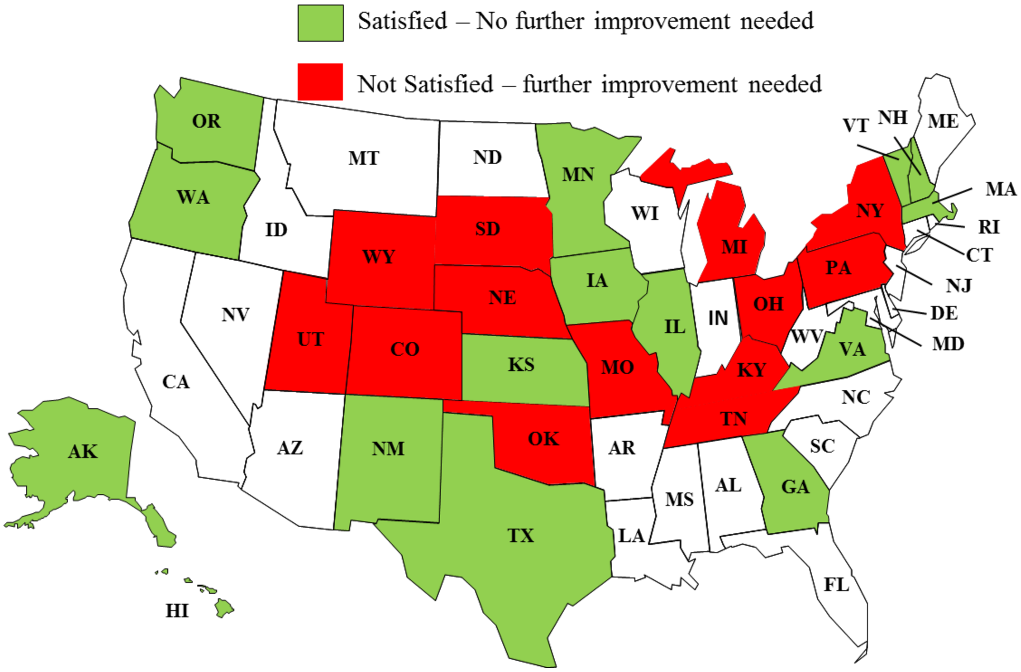


Figure 54 Satisfaction rate of states with their design

3.3 Survey Result Verification

In this section, the results of the survey are compared with specifications provided by the respective states' DOTs. The following discrepancies were observed between the survey results and specifications:

- **Iowa**

  The length of the approach slab specified in the specification is 40-ft, while the survey shows that the typical length is between 20-ft and 30-ft.

- **New York**

  The NYDOT specification specifies that sleeper slab should be integrated as part of the approach slab design, while the survey result indicates that cast-in-place slab is the mostly commonly used approach slab system in New York.

- **Oregon**

  Approach slab thickness specified in the Oregon DOT's Specification (ORDOT, 2014) for bridge designs is between 12-inch and 14-inch, whereas the survey result indicates that the most common approach slab thickness is about 8-inch to 10-inch.

- **Texas**

  The survey result indicates that the sleeper slab and cast-in-place systems are most commonly used in Texas. However, the TxDOT’s Specification (TXDOT, 2004) does not specify any sleeper slabs in the design.

CHAPTER 4 - ANALYSIS OF RESULTS

4.1 Introduction

In this chapter, critical information and results obtained from the literature review and survey are analyzed. The survey results are thoroughly evaluated, and these analyses are further supported by design specifications and past research findings reported in each respective state. This research outcome will provide the basis for developing recommendations for improving the approach slab system for the Wyoming DOT in Chapter 5.

4.2 Lessons Learned from Literature

To better understand the approach slab settlement problem, an extensive review of 23 technical reports covering 12 states and 15 state DOTs' design/construction specifications was completed in Chapter 2. Lessons learned from the literature review are summarized below, based on the different components of an approach slab.

4.2.1 Backfill

Past research studies concluded that the most significant factor contributing to approach slab settlement is compression of the embankment and backfill. Other factors are inadequate backfill compaction and large fill height. Using granular subsurface material or poorly graded material as backfill may also result in significant settlement. The most common limiting requirement for a backfill specification is the percentage of fine particles. Most states limit the percentage passing through a No. 200 sieve to between 4 percent and 20 percent. Plasticity of the backfill soil should be reduced to enhance drainage. Furthermore, bulking moisture content in granular backfill should be avoided in all cases to prevent collapse of the backfill. Bulking moisture content is referred as a moisture content typically ranging from 4 percent to 8 percent that causes an increase in volume while the weight of granular backfill remains constant.

Geotextile reinforcement reduces the short-term deformation of an approach slab; however, reinforcing the backfill alone cannot completely eliminate the approach slab settlement problem. A combination of geosynthetic-reinforced backfill and spacer between the abutment and backfill yields good performance under a service load. Geotextile reinforcement increases the stiffness of the backfill material and decreases approach slab settlement. To effectively mobilize the geotextile's strength, it is believed that it should be tightly pulled and installed. However, this construction practice was not mentioned in literature. Specifically, reinforced backfill beneath a sleeper beam improves slab performance. Alternatively, expanded polystyrene or flowable fill can be used as backfill to further lessen immediate settlement. However, flowable backfill is not recommended for small projects as it is not cost effective.

Compaction affects the stiffness of backfill material. A higher backfill compaction rate yields better approach slab performance. Movement of soil away from the approach slab yields a greater deflection and reduces the bearing support from the backfill soil. An 8-inch lift thickness of granular fill compacted to 95 percent of the Standard Proctor value is the most common compaction requirement for approach slab.

Embankment height influences traffic load distribution within an embankment. A higher embankment reduces the stress being transferred to the embankment foundation. On the other hand, several researchers concluded that a high embankment increases the severity of approach slab settlement and significantly affects performance.

4.2.2 Foundation

Inappropriate or soft foundation soils as well as inadequate subgrade compaction also contribute to approach slab settlement problems. It was concluded that an approach slab with a granular foundation yields lesser settlement than one based on a compressible foundation. Differential approach slab settlement could result from having different foundation soil strengths.

4.2.3 Drainage

Drainage is a common factor causing approach slab settlement. Poor drainage could cause undermining of a sleeper beam. Plastic drainpipes, weep holes in the abutments, and use of granular backfill material are the most common drainage methods used by DOTs. Also, it is recommended to maintain the drainage behind a backwall.

4.2.4 Spacer

A spacer between a backfill and an abutment reduces lateral loads on the abutment and helps mobilize the resistance of backfill geosynthetic reinforcement. The spacer also overcomes problems associated with annual thermal cycle effects.

4.2.5 Structural slab

Structural slab stiffness plays an important role in approach slab settlement. A heavily reinforced approach slab with high flexural rigidity enables the spanning of voids caused by settlement. Moreover, Precast Prestressed Concrete Pavement (PPCP) improves the ability of the approach slab to span voids in backfill material. Higher concrete slab stiffness also results in fewer cracks in the approach slab.

Integral abutments help to reduce approach slab settlement. Although an integral abutment is more sensitive to temperature cycles, this problem can be overcome with a spacer.

An approach slab system using a sleeper slab is prone to settlement; as in the case of a backfill settlement, the sleeper slab receives a larger portion of the total load. As a result, stress in the contact region increases as the soil moves toward the sleeper slab. This problem can be overcome by providing reinforcement to the soil beneath the sleeper slab. Also, increasing sleeper slab width will reduce settlement. Pre-cambering the precast or cast-in-place approach slab could partially avoid differential settlement.

A sleeper slab approach slab system can span a void created by backfill settlement. However, load transferred to the sleeper slab at one end of the approach slab concentrates stress at the soil foundation beneath the sleeper slab. If the soil foundation does not have adequate bearing capacity, excessive settlement, especially differential settlement, will occur. In contrast, an approach slab without a sleeper slab is supported completely on backfill material, in which less stress is experienced and lesser settlement may occur.

4.2.6 Approach Slab Geometry

Steep approach gradients could affect the severity of approach slab settlement. A 20:1 slope from the back of an abutment to the pavement was suggested. Approach slab length shows no significant impact on settlement.

4.2.7 Expansion Joint

Little or no research was conducted to investigate the effect of expansion joints on approach slab settlement. Materials such as flexible foam and tire joint fillers, however, were found to be unsuitable for sealing an expansion joint.

4.2.8 Erosion Protection

Erosion of the embankment has been identified as one of the main causes of approach slab settlement. Backfill erosion leads to approach slab faulting, slope protection failure, and exposure of the bridge foundation supporting the abutment. Grouting does not appear to significantly prevent further settlement or loss of backfill material due to erosion. For example, in Wyoming, curbs are placed on approach slabs to prevent erosion occurring at abutments.

4.2.9 Construction

Construction sequence has been shown to significantly affect approach slab settlement. For instance, an adequate waiting period between backfill placement and road paving lessens the severity of approach slab settlement. As suggested by Texas DOT, an approach slab’s embankment must be built first for a closed spill-through and integral abutment. However, for a perched abutment the approach slab should be constructed after the abutment is built. Achieving a specified soil compaction closer to an abutment is a major construction challenge.

4.2.10 Retrofitting

The URETEK method, a lifting method proposed by Abu al-Eis and LaBarca (2007), has shown promising results in retrofitting slabs experiencing small settlements. This method utilizes multi-pattern drilled injection locations to realign the approach slab. This method is explained in Section 2.2.11. Comprehensive retrofitting and trouble-shooting methods have been developed for the Ohio DOT to overcome soil erosion, compression of embankment soils, differential vertical and horizontal settlements, pavement joint deterioration, and improper drainage. Also, Texas DOT suggests several mitigation methods, such as excavation and replacement, preloading and surcharge, and dynamic compaction.

4.3 Survey Data Analysis

Based on the responses to survey question No. 6 regarding percentage of bridges with approach slab settlement, the 38 state respondents are categorized into three groups: Excellent Performance Group, Good Performance Group, and Fair Performance Group. These three groups are described as follows:

1) Excellent Performance Group (EPG): States with 0-25 percent of their bridges experiencing approach slab settlement. This group consists of 17 states, which are Alaska, Georgia, Hawaii, Massachusetts, Minnesota, Missouri, Nebraska, New

Hampshire, New York, Ohio, Oregon, Pennsylvania, Utah, Virginia, Vermont, Washington, and Wyoming.

2) Good Performance Group (GPG): States with 25-50 percent of their bridges experiencing approach slab settlement. This group consists of 5 states: New Mexico, Texas, Mississippi, South Dakota, and Oklahoma.
3) Fair Performance Group (FPG): States with 50-100 percent of their bridges experiencing approach slab settlement. This group consists of 6 states, which are Kansas, Kentucky, Illinois, Iowa, Tennessee, and Colorado.

Based on this grouping method, a summary of the survey results for these three performance groups is presented in table 32 through table 34.

Table 32 Summary of survey results for Excellent Performance Group

Settlement		0-25%																
States		OR	WA	HI	GA	VT	MN	AK	MA	NH	VA	OH	NY	NE	PA	MO	**WY**	UT
Integral Abutment		0-25	0-25	25-50	0-25	50-75	25-50	0-25	100	0-25	0-25	0-25	0-25	75-100	100	75-100	**50-75**	25-50
Slab System		CIP	CIP	CIP	CIP	CIP - Precast	Sleeper	CIP	CIP	CIP	CIP	CIP	CIP	Sleeper	Sleeper	Sleeper	**CIP**	CIP - Sleeper
Causes	Most Common	B D E	A F	A H	A D		H	B	H	B	C H	B	H J	B C H	A D H	A B D I	**H**	D H
	Somewhat Common	A C F G H I J L M	B E I J K L	D E J L		H		H	B L	F L	A B D E I							
Type of Settlement	Most Common	Diff		Uni	Uni		Uni		Uni	Uni				Uni	Uni	Diff	**Diff**	Uni
	Somewhat Common	Uni									Uni Diff	Uni	Diff	Diff				
Backfill Type		Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	Convent.	**Geotext.**	Convent.

Table 32 Summary of survey results for Excellent Performance Group (Continued)

Select Backfill		Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	**Yes**	No
Backfill Depth		Shallow	Deep	Deep	Deep	Shallow	Deep	Deep	Deep	Deep	Deep	Deep	Deep	Shallow	Deep	Deep	**Shallow**	Deep
Drainage		No	No	No	Yes	No	Yes	Yes	No	No	No	No	Yes	No	No	Yes	**Yes**	No
Separation		No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	**Yes**	No
In-situ Test		Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	**No**	Yes
Spacer		No	No	No	No	No	No	No	No	No	No	No	Yes	Yes	No	No	**Yes**	No
Thickness (in)		8-10	12-16	12-16	10-12	Over 16	12-16	12-16	8-10	12-16	12-16	12-16	12-16	12-16	Over 16	12-16	**10-12**	12-16
Length (ft)		20-30	20-30	15-20	20-30	15-20	20-30	20-30	10-15	20-30	15-20	20-30	15-20	20-30	20-30	20-30	**20-30**	20-30
Retrofitting Methods	Mostly Used	Ov.	Ov.	Ov.	Ov.				Ov.	Ov.	Ov.			Lf.	Ov.	Lf.	**Rp.**	Ov.
	Somewhat Used	Rp. Lf.	Rp.	Rp.	Rp.	Ov.	Ov. Rp. Lf.		Rp.		Rp.	Ov. Rp. Lf.	Ov. Lf.	Ov.	Rp.	Ov. Rp.	**Ov. Lf.**	Rp.

A-High Embankment Fill; B-Soft Natural Soil; C-Primary Compression; D-Secondary Compression; E-Soil Volume Change; F-Weather Effect; G-Steep Approach Slab Gradient; H-Poor Construction; I-Thermal Effect; J-High Average Daily Traffic; K-Broken Corbels; L-Inadequate Design; M-Steep Side Slope; Uni-Uniform Settlement; Diff-Differential Settlement; CIP−Cast-in-place; Convent.−Conventional backfill; Geotext.−Geotextile reinforced backfill; Ov.-Overlaying; Rp.-Replacement; and Lf.-Lifting and realigning the approach slab by filling and sealing the void under the approach slab.

Table 33 Summary of survey results for Good Performance Group

Settlement		25-50%				
States		NM	TX	MI	SD	OK
Integral Abutment		50-75	0-25	50-75	75-100	0-25
Slab System		Sleeper	CIP - Sleeper	Sleeper	Sleeper	CIP
Causes	Most Common	A B	F H	C D H J	H M	A C
	Somewhat Common	C D E H M	A B C J L			
Type of Settlement	Most Common	Uni	Diff			Diff
	Somewhat Common		Uni	Uni Diff	Uni Diff	
Backfill Type		Convent.	Convent.	Convent.	Convent.	Convent.
Select Backfill		Yes	Yes	No	Yes	Yes
Backfill Depth		Deep	Shallow	Shallow	Shallow	Deep
Drainage		No	No	Yes	Yes	Yes
Separation		Yes	No	Yes	Yes	No
In-situ Test		Yes	Yes	Yes	Yes	Yes
Spacer		Yes	No	No	No	No
Thickness (in)		12-16	12-16	12-16	8-10	12-16
Length (ft)		10-15	20-30	15-20	15-20	20-30
Retrofitting Methods	Mostly Used	Lf.	Ov.		Ov. Rp.	Ov. Lf.
	Somewhat Used	Ov. Rp.	Rp. Lf.	Ov. Rp.	Lf.	Rp.

A-High Embankment Fill; B-Soft Natural Soil; C-Primary Compression; D-Secondary Compression; E-Soil Volume Change; F-Weather Effect; G-Steep Approach Slab Gradient; H-Poor Construction; I-Thermal Effect; J-High Average Daily Traffic; K-Broken Corbels; L-Inadequate Design; M-Steep Side Slope; Uni-Uniform Settlement; Diff-Differential Settlement; CIP−Cast-in-place; Convent.−Conventional backfill; Geotext.−Geotextile reinforced backfill; Ov.-Overlaying; Rp.-Replacement; and Lf.-Lifting and realigning the approach slab by filling and sealing the void under the approach slab.

Table 34 Summary of survey results for Fair Performance Group

Settlement		50-75%				75-100%	
States		KS	IL	IA	KY	TN	CO
Integral Abutment		50-75	75-100	25-50	25-50	75-100	50-75
Slab System		Sleeper	CIP - Precast	CIP	CIP	CIP	Sleeper
Causes	Most Common	A B D F H I L	D H	E F L	A H I	I	D
	Somewhat Common	C E G J		A H J K			
Type of Settlement	Most Common	Uni	Uni	Uni	Uni		Diff
	Somewhat Common	Diff			Diff	Uni	Uni
Backfill Type		Convent.	Convent.	Convent.	Convent.	Convent.	Geotext.
Select Backfill		Yes	Yes	Yes	Yes	No	Yes
Backfill Depth		Shallow	Deep	Shallow	Deep	Shallow	Shallow
Drainage		Yes	Yes	Yes	Yes	Yes	No
Separation		Yes	No	No	Yes	No	Yes
In-situ Test		No	No	No	No	No	Yes
Spacer		Yes	Yes	No	No	No	Yes
Thickness		10-12	12-16	10-12	Over 16	10-12	--
Length		Over 30	20-30	20-30	20-30	20-30	15-20
Retrofitting Methods	Mostly Used	Rp.	Ov.	Ov.	Ov.	Ov.	Ov.
	Somewhat Used	Ov. Lf.	Lf.	Rp. Lf.	Rp. Lf.	Rp. Lf.	Rp. Lf.

A-High Embankment Fill; B-Soft Natural Soil; C-Primary Compression; D-Secondary Compression; E-Soil Volume Change; F-Weather Effect; G-Steep Approach Slab Gradient; H-Poor Construction; I-Thermal Effect; J-High Average Daily Traffic; K-Broken Corbels; L-Inadequate Design; M-Steep Side Slope; Uni-Uniform Settlement; Diff-Differential Settlement; CIP−Cast-in-place; Convent.−Conventional backfill; Geotext.−Geotextile reinforced backfill; Ov.-Overlaying; Rp.-Replacement; and Lf.-Lifting and realigning the approach slab by filling and sealing the void under the approach slab.

4.3.1 Causes of approach slab settlement

Table 35 summarizes the most and somewhat common causes of approach slab settlement for the three performance groups described earlier in this section. Responses from the EPG indicate that poor construction is the most common cause of approach slab settlement, followed by high embankment fill, soft natural soil, and secondary compression. The results also show that inadequate approach slab design is a somewhat common cause of approach slab settlement. Therefore, settlement is mostly due to poor construction practices and the region's natural geology, and partially due to inadequate design. This conclusion is further validated by the relatively high 82 percent performing in-situ density tests as indicated in table 37.

Similarly to the EPG, the GPG also cited poor construction practices as the most common cause of approach slab settlement, followed by high embankment fill and primary backfill compression. It is strongly believed that the construction practice of improper compaction contributes to primary compression of backfill. On the other hand, table 37 indicates that 100 percent of the GPG perform in-situ tests during construction. This conflicting result may suggest that the approach slab design might be inadequate. Therefore, approach slab design should still be considered, even though only one respondent identifies it as a somewhat common cause.

For the FPG, table 35 shows that poor construction, secondary backfill compression, and thermal effects are the main causes of approach slab settlement, followed by weather effects and inadequate design. The relatively high percentage (83 percent) not performing in-situ test on backfill as a quality control during construction as indicated in table 37 aligns well with the fair approach slab performance in this group. This finding reveals that approach slab performance improves, or percentage of bridges with settlement decreases, when the in-situ test is performed during construction.

Furthermore, table 35 shows that soil volume change, steep approach slab gradient, broken corbels, and steep side slope are less likely to be causes of approach slab settlement.

Table 35 Causes of approach slab settlement

Performance Group	**Excellent**		**Good**		**Fair**	
Causes	**Most Common**	**Somewhat Common**	**Most Common**	**Somewhat Common**	**Most Common**	**Somewhat Common**
High Embankment Fill	**5**	2	**2**	1	2	1
Soft Natural Soil	**6**	**3**	1	1	1	0
Primary Compression	2	1	**2**	**2**	0	1
Secondary Compression	**5**	2	1	1	**3**	0
Soil Volume Change	1	**3**	0	1	1	1
Weather Effect	1	2	1	0	**2**	0
Steep Approach Slab Gradients	0	1	0	0	0	1
Poor Construction	**9**	**3**	**3**	1	**3**	1
Thermal Effect	1	**3**	0	0	**3**	0
High Average Daily Traffic	1	**3**	1	1	0	**2**
Broken Corbels	0	1	0	0	0	1
Inadequate Design	0	**5**	0	1	**2**	0
Steep Side Slope	0	1	1	1	0	0

4.3.2 Type of approach slab settlement

Table 36 depicts the types of settlement occurring in the three performance groups. Uniform settlement occurs when the stress beneath the approach slab is distributed evenly. Uneven distribution of stress introduced to the backfill may occur with inappropriate design or construction of the backfill and with inadequate approach slab design. Retrofitting can be more easily executed on uniformly settled approach slabs than on differentially settled approach slabs.

Table 36 shows that 65 percent to 73 percent of the EPG is more likely to experience uniform settlement while both settlement types are about equally experienced by the GPG. Inadequate design of supports, approach slab, and backfill lead to uneven stress distribution below the approach slab; hence, differential settlement occurs. Similar to the EPG, 67 percent to 80 percent of the FPG is more likely to experience uniform settlement.

The average settlement increases from 2.56-inch for the EPG to 8-inch for the FPG. This finding reveals approach slab settlement problems increase in severity from the EPG to the FPG. More than 50 percent of bridges in the FPG experienced a relatively high average settlement of 8-inch while the EPG reported that less than 25 percent of their bridges experienced average settlement of 2.56-inch. Certainly, this is a serious problem for the FPG. This high settlement is attributed to the combined effects of poor construction, inadequate design, and environmental factors as highlighted in table 35. Undeniably, this is also a concern for the GPG, 25 percent to 50 percent of whose bridges experienced both settlement types at an average of 4.6-inch. As indicated in table 35, this settlement is attributed to the combined effects of poor construction and high embankment fill leading to backfill compression.

4.3.3 Backfill design and construction practices

Table 37 presents design and construction practices of the backfill used by the three performance groups. The survey gathers information on the design and construction practices in terms of select backfill, backfill depth, drainage system, positive separation between subgrade and backfill, in-situ density test, and spacer between backfill and abutment wall.

Table 36 Summary of settlement types

Groups	**Type of Settlement**	**Most Common**		**Somewhat Common**		**Total %**	**Average Settlement (in.)**
		Quantity	%	Quantity	%		
Excellent	Uniform Settlement	**8**	**73%**	3	50%	**65%**	2.56
	Differential Settlement	3	27%	3	50%	35%	
Good	Uniform Settlement	1	33%	**3**	**60%**	50%	4.6
	Differential Settlement	**2**	**67%**	2	40%	50%	
Fair	Uniform Settlement	**4**	**80%**	2	50%	**67%**	8
	Differential Settlement	1	20%	2	50%	33%	

Table 37 Design and construction practices of backfill

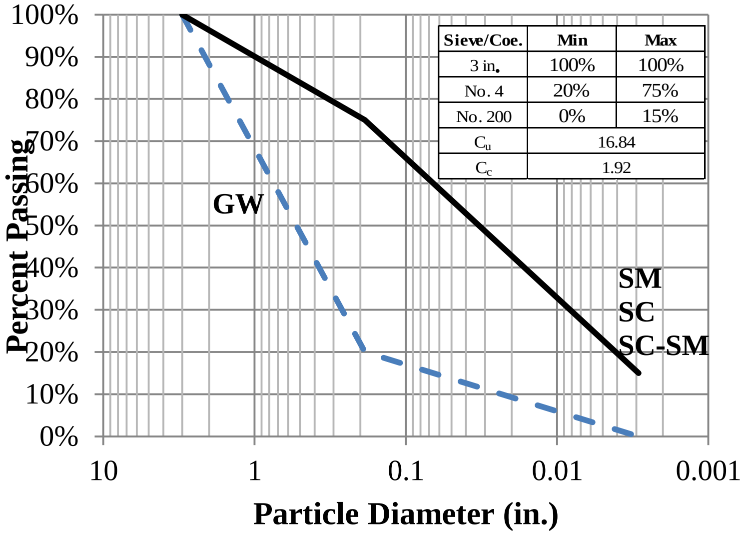
Group	**Practice**	**Answer**	**Quantity**	**%**	**Answer**	**Quantity**	**%**
Excellent	Select Backfill	**Yes**	**13**	**77%**	No	4	23%
	Backfill Depth	Shallow	4	23%	**Deep**	**13**	**77%**
	Drainage	Yes	6	35%	**No**	**11**	**65%**
	Separation	Yes	2	12%	**No**	**15**	**88%**
	In-situ Test	**Yes**	**14**	**82%**	No	3	18%
	Spacer	Yes	3	18%	**No**	**14**	**82%**
	Backfill Type	**Convent.**	**16**	**94%**	Geotext.	1	6%
Good	Select Backfill	**Yes**	**4**	**80%**	No	1	20%
	Backfill Depth	**Shallow**	**3**	**60%**	Deep	2	40%
	Drainage	**Yes**	**3**	**60%**	No	2	40%
	Separation	**Yes**	**3**	**60%**	No	2	40%
	In-situ Test	**Yes**	**5**	**100%**	No	0	0%
	Spacer	Yes	1	20%	**No**	**4**	**80%**
	Backfill Type	**Convent.**	**5**	**100%**	Geotext.	0	0%
Fair	Select Backfill	**Yes**	**5**	**83%**	No	1	17%
	Backfill Depth	**Shallow**	**4**	**67%**	Deep	2	33%
	Drainage	**Yes**	**5**	**83%**	No	1	17%
	Separation	Yes	3	50%	No	3	50%
	In-situ Test	Yes	1	17%	**No**	**5**	**83%**
	Spacer	Yes	3	50%	No	3	50%
	Backfill Type	**Convent.**	**5**	**83%**	Geotext.	1	17%

Convent.-Conventional backfill; Geotext.-Geotextile reinforced backfill.

Table 37 indicates that select backfill is mostly used by all three groups, ranging from 77 percent for the EPG to 83 percent for the FPG. Although select backfill is an important requirement as highlighted in Section 4.2.1, it may not be the main factor causing approach slab settlement, as 83 percent of the FPG uses select backfill. The gradations of select backfill for 6 states in the EPG are illustrated in figure 55 to figure 60. Both well-graded (non-uniform) and poorly-graded (uniform) backfill materials are specified in these states. The respective soil symbol is classified in accordance with the Unified Soil Classification System (USCS). According to the literature review, the percent passing a No. 200 sieve is an important factor. Nebraska limits this percentage to as low as 3 percent, Ohio limits it to 20 percent, with a median of 15 percent. The percentage of fines is limited, and coarser material is used to provide proper drainage and reduce compressibility of the backfill material. Figure 62 and figure 63 show the backfill gradations of Oklahoma (GPG) and Colorado (FPG), respectively. The backfills range from poorly-graded gravel (GP) to poorly-graded sand with silt or clay (SP-SM or SP-SC). The percent passing a No. 200 sieve or percentage of fines is limited to 5 percent and 10 percent for Colorado and Oklahoma, respectively, which are similarly specified as of EPG. Since similar select backfills are used among three performance groups, it is not a governing factor affecting approach slab settlement.

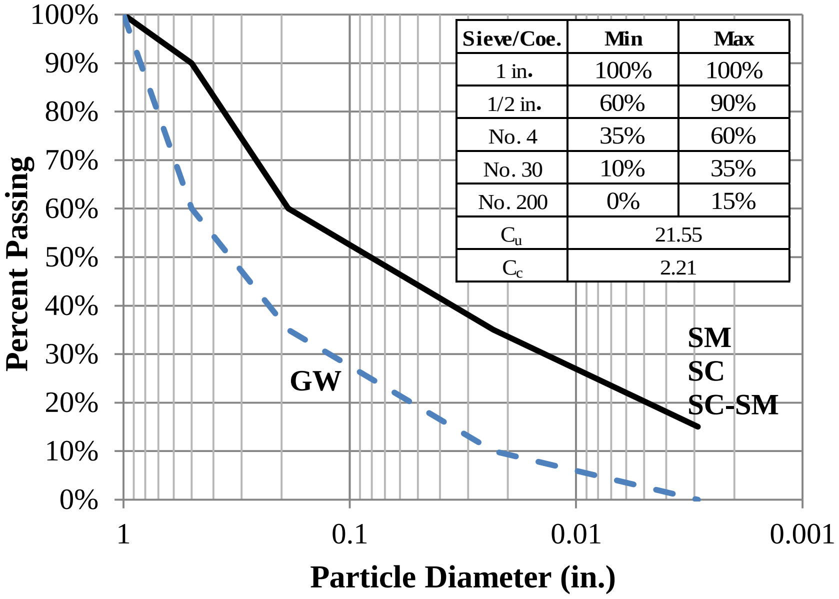
Table 38 presents the range of backfill materials based on minimum and maximum material gradations. Backfill materials range from well or poorly graded gravels to different sand materials, while poorly graded backfills are the most commonly specified. Specifically, poorly graded sand with clay or silt specified in both the GPG and the FPG may increase the probability of approach slab settlement. However, more data is needed to justify this claim.

A drainage system beneath an approach slab system is not specified by 65 percent of the states in the EPG. On the other hand, despite the fact that a drainage system is specified by most states in the GPG and the FPG, a higher percentage of bridges experience approach slab settlement in these groups.



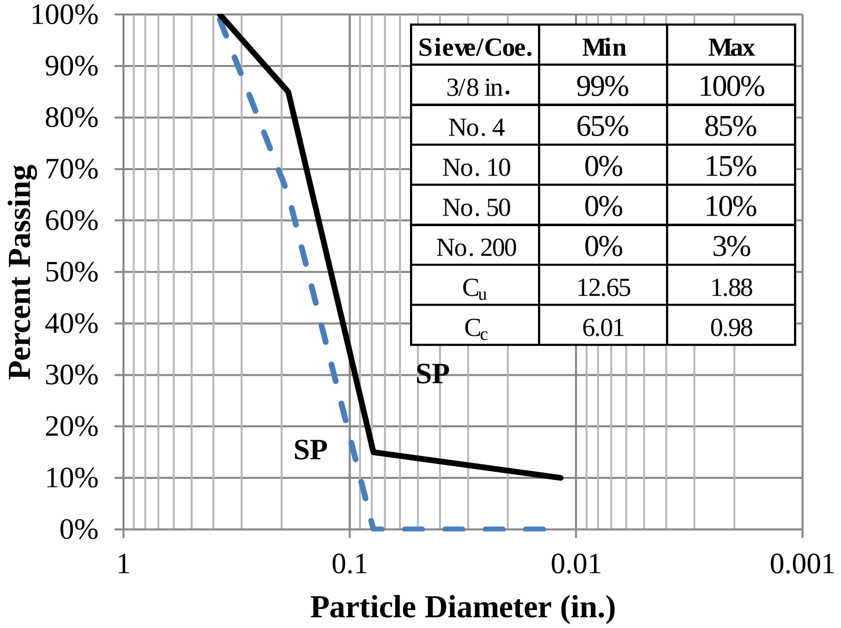
Sieve/Coe.	Min	Max
3 in.	100%	100%
No. 4	20%	75%
No. 200	0%	15%
C_u	16.84	
C_c	1.92	

Figure 55 Gradation of well-graded backfill material in Hawaii



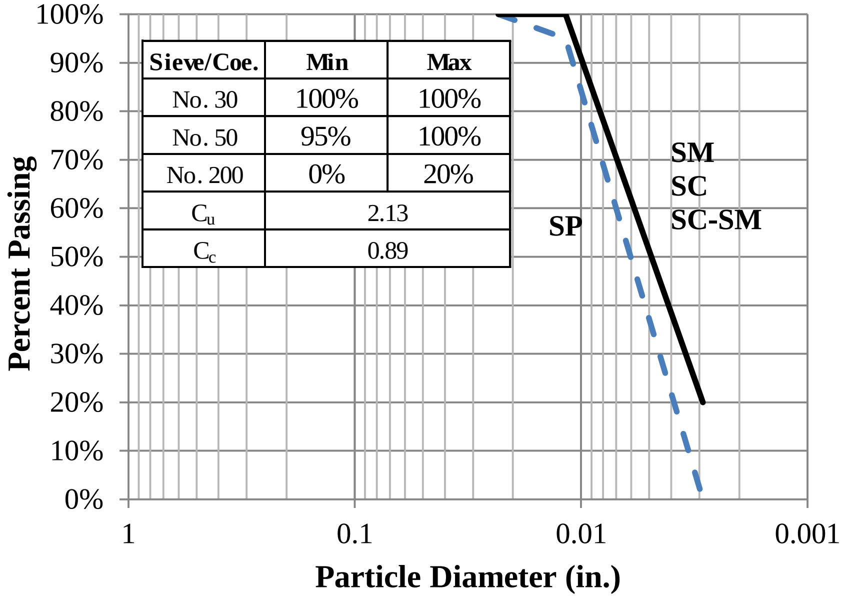
Sieve/Coe.	Min	Max
1 in.	100%	100%
1/2 in.	60%	90%
No. 4	35%	60%
No. 30	10%	35%
No. 200	0%	15%
C_u	21.55	
C_c	2.21	

Figure 56 Gradation of well-graded backfill material in Missouri



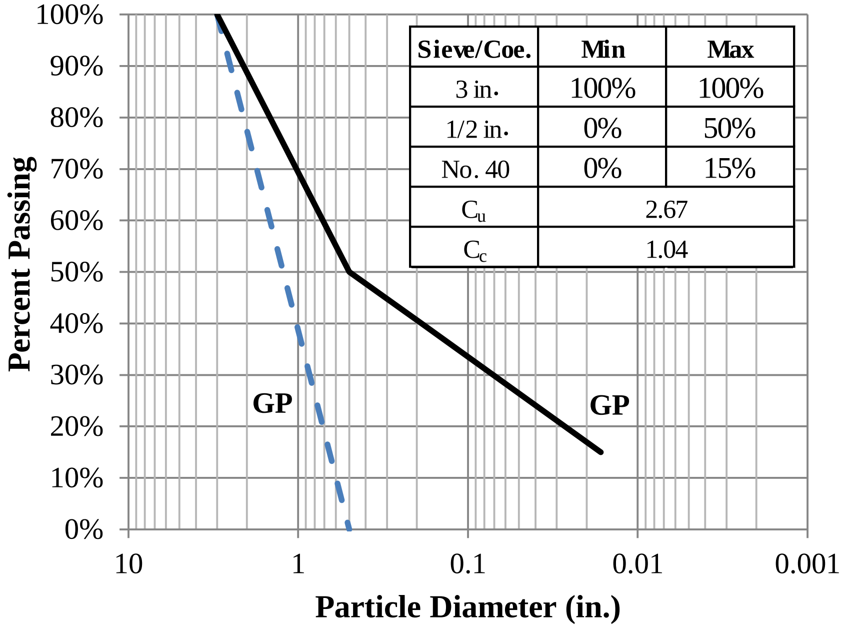
Sieve/Coe.	Min	Max
3/8 in.	99%	100%
No. 4	65%	85%
No. 10	0%	15%
No. 50	0%	10%
No. 200	0%	3%
C_u	12.65	1.88
C_c	6.01	0.98

Figure 57 Gradation of poorly and well-graded backfill material in Nebraska



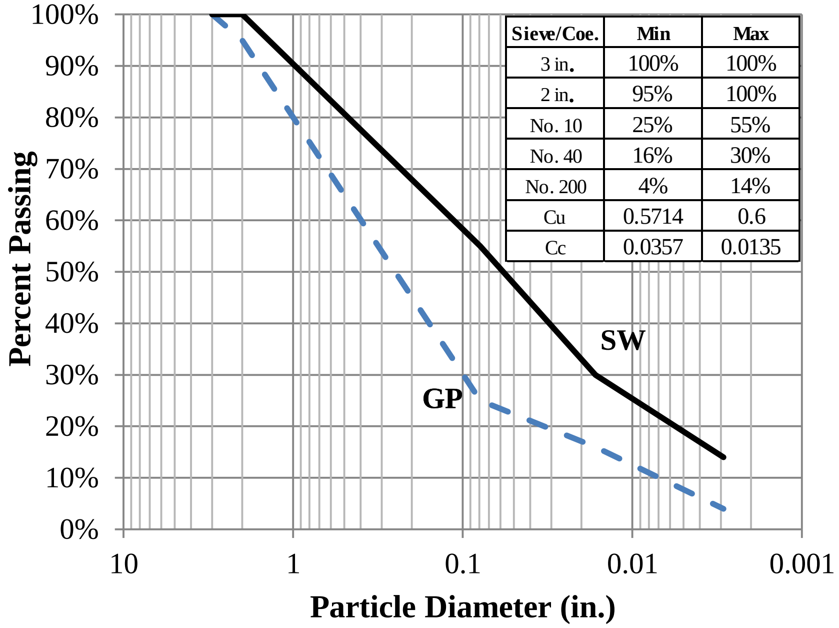
Sieve/Coe.	Min	Max
No. 30	100%	100%
No. 50	95%	100%
No. 200	0%	20%
C_u	2.13	
C_c	0.89	

Figure 58 Gradation of poorly-graded backfill material in Ohio



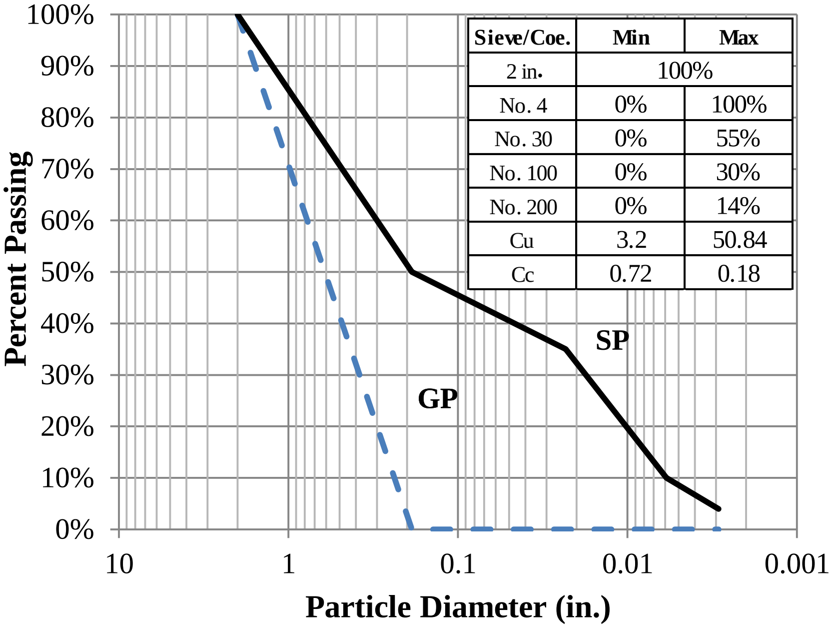
Sieve/Coe.	Min	Max
3 in.	100%	100%
1/2 in.	0%	50%
No. 40	0%	15%
C_u	2.67	
C_c	1.04	

Figure 59 Gradation of poorly-graded backfill material in Oregon



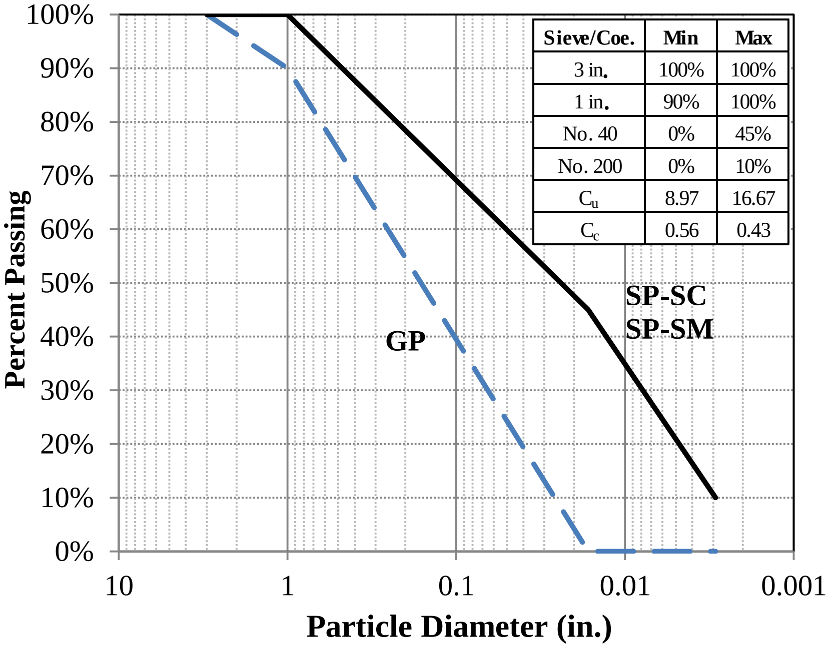
Sieve/Coe.	Min	Max
3 in.	100%	100%
2 in.	95%	100%
No. 10	25%	55%
No. 40	16%	30%
No. 200	4%	14%
Cu	0.5714	0.6
Cc	0.0357	0.0135

Figure 60 Backfill material gradation in Virginia



Sieve/Coe.	Min	Max
2 in.	100%	
No. 4	0%	100%
No. 30	0%	55%
No. 100	0%	30%
No. 200	0%	14%
Cu	3.2	50.84
Cc	0.72	0.18

Figure 61 Backfill material gradation in Wyoming



Sieve/Coe.	Min	Max
3 in.	100%	100%
1 in.	90%	100%
No. 40	0%	45%
No. 200	0%	10%
C_u	8.97	16.67
C_c	0.56	0.43

Figure 62 Poorly-graded backfill material gradation in Oklahoma (GPG)

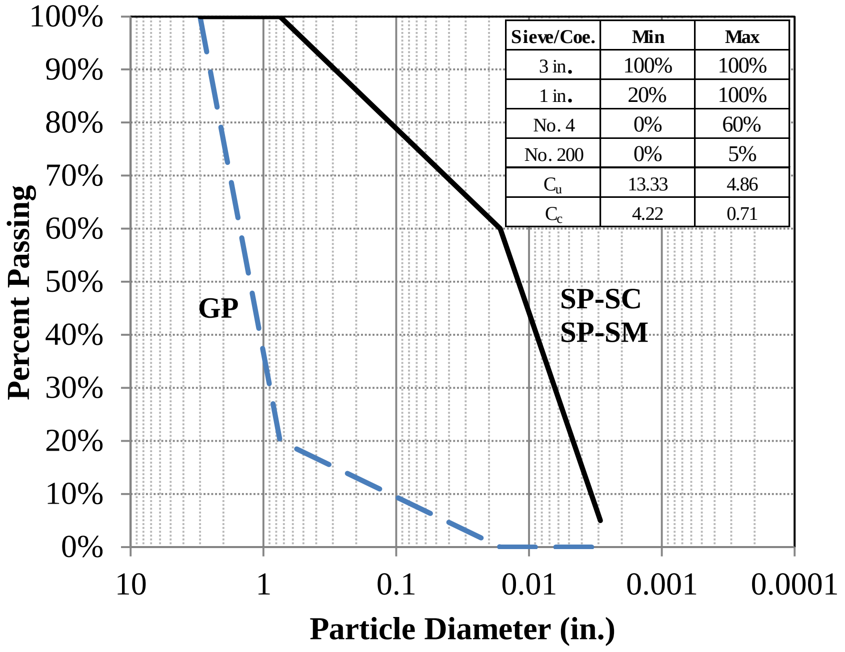


Figure 63 Poorly-graded backfill material gradation in Colorado (FPG)

Table 38 Range of backfill materials based on minimum and maximum gradations

Group	**State**	**Backfill**	
		Min	**Max**
EPG	HI	GW	SM, SC, SC-SM
	MO	GW	SM, SC, SC-SM
	NE	SP	SP
	OH	SP	SM, SC, SC-SM
	OR	GP	GP
	VA	GP	SW
	WY	GP	SP
GPG	OK	GP	SP-SC, SP-SM
FPG	CO	GP	SP-SC, SP-SM

Backfill depth in either shallow or deep configuration is reported as a typical backfill height behind an abutment. Although this parameter is affected by regional geology, the configuration type can be selected during design when the bridge is built on gentle topography. The survey results indicate that 77 percent of the states in the EPG use deep backfill configuration while shallow backfill configuration is mostly used by the GPG and the FPG. Apparently, deep backfill configuration reduces the percentage of bridges experiencing approach slab settlement. It can be argued that deep configuration allows surface stress to dissipate before it reaches a subgrade or foundation layer beneath the backfill soil. This reduced stress on the subgrade alleviates the settlement contributed by a soft natural soil or secondary compression of the backfill.

The results show that a positive separation between subgrade and backfill material is not specified by 88 percent of the respondents in the EPG, while only New York and Wyoming require the separation. About 60 percent of the GPG and 50 percent of the FPG specify the separation. This finding suggests that a positive separation might not cause approach slab settlement.

Table 37 shows that 82 percent of the states in the EPG and all states in the GPG specify in-situ density tests to ensure proper backfill compaction. On the other hand, only about 17 percent of the states in the FPG specify this requirement. This finding indicates that in-situ density tests required as part of design specifications to assure appropriate backfill compaction control during construction result in better approach slab performance. In-situ density testing can overcome some shortcomings of poor construction, which was shown in Section 4.3.1 to be the dominant cause of settlement. In-situ and laboratory tests specified by each state in the three performance groups are presented in table 39. According to table 39 most states use in-situ test methods to control backfill compaction. The nuclear gauge in-situ method is the most widely used (used by 7 of 18 states in the survey). All states use the standard and modified Proctor test as the laboratory test for backfill compaction control.

Table 39 Types of in-situ and laboratory tests for controlling backfill compaction

Group	State	In-situ test	Laboratory test
Excellent	OR	ODOT TM 158 (In-place deflection density test)	n/a
	HI	Test method HDOT TM 1 (Sand cone method)	n/a
	GA	n/a	Modified Proctor
	VT	Nuclear gage in accordance with AASHTO T 238, Method B	n/a
	MN	Dynamic Cone Penetration (DCP)	n/a
	AK	Compaction with moisture and density control. The maximum density will be determined by WAQTC FOP for AASHTO 180 or ATM 212. Water or aerate as necessary to provide the approximate optimum moisture content for compaction. Compact each layer to not less than 98% of the maximum density. Acceptance densities will be determined by WAQTC FOPs for AASHTO T 310 and T 224	n/a
	MA	n/a	AASHTO Test T 99, method C
	NH	Nuclear gauge	n/a
	VA	Nuclear density gauges	n/a
	OH	ODOT supplement 1015 (Direct transmission method according to AASHTO T-310)	n/a
	NY	Standard Proctor Maximum Density is attained in any portion of an embankment, or 95% in a subgrade area	n/a
	UT	Nuclear density	n/a
Good	NM	Using nuclear methods to determine field densities in accordance with AASHTO T310	AASHTO T180 (Modified Proctor), Method D (TTCP) Modified
	TX	Nuclear gauge	n/a
	SD	n/a	Specified Density - AASHTO T99
	OK	n/a	95% Standard Density in accordance with AASHTO T99
Fair	IA	Backfill is flooded and compacted using specific parameters for water saturation and lift depth	n/a
	CO	Nuclear gauge	Modified proctor data

n/a- not available

Table 37 shows that most of the states in both the EPG and the GPG do not specify a spacer requirement between the backfill and abutment wall, while half of the FPG specify this requirement. In the EPG, only Ohio, New York, and Wyoming, specify this requirement. The spacer requirement might not be directly related to approach slab settlement, but it can reduce lateral backfill pressure imposing on an abutment wall and overcome problems associated with thermal effects as described in Section 4.2.4.

According to table 37, almost all states in the three groups use conventional backfill with no geotextile reinforcement. Only two states, Wyoming (EPG) and Colorado (FPG), use geotextile-reinforced backfill in their designs. This survey result reveals that backfill types do not govern approach slab performance.

4.3.4 Approach slab system

Table 40 shows that most states in the EPG use a cast-in-place structural slab system, with a sleeper slab system being the second most common. Although the cast-in-place slab is also most common in the FPG, this group experiences a high percentage of bridges with approach slab settlement problems. However, the first distinct difference between these two groups is that in-situ density tests are performed more by the EPG than the FPG. The second distinct difference is in backfill depth as summarized in table 37. Most states in the EPG use a deep configuration and most states in the FPG use a shallow configuration. Furthermore, the most common system used by the states in the GPG is the sleeper slab. Only two states use the precast slab system. For this reason, it is concluded that the type of approach slab system does not have as critical an impact on approach slab settlement as do design and construction practices.

Table 40 Approach slab system

Group	System	CIP	Sleeper	Precast
Excellent	Quantity	**13**	5	1
	%	**76.5%**	29.4%	5.9%
Good	Quantity	2	**4**	0
	%	33.3%	**66.7%**	0.0%
Fair	Quantity	**4**	2	1
	%	**57.1%**	28.6%	14.3%

CIP−Cast-In-Place slab with no sleeper beam; Sleeper−Sleeper slab system; and Precast−Precast concrete slab system with no sleeper beam.

Table 41 shows the use of integral abutments in the three performance groups. The result shows no clear relationship between the use of integral abutments and approach slab performance.

Table 41 Integral abutment usage in three performance groups

Group	Percent Usage of Integral Abutment					
	0	**0-25**	**25-50**	**50-75**	**75-100**	**100**
EPG	0	8	3	2	2	2
	0%	47%	18%	12%	12%	12%
GPG	0	2	0	2	1	0
	0%	40%	0%	40%	20%	0%
FPG	0	0	2	2	2	0
	0%	0%	33%	33%	33%	0%

4.3.5 Approach slab geometry

Table 42 summarizes the typical thicknesses and lengths of approach slabs used by each group. The geometrical specification of an approach slab is important to the slab’s rigidity. The results show that 65 percent of the states in the EPG use a typical slab thickness of 12-inch to 16-inch. This range is considered at the high end for providing good slab rigidity. As the rigidity increases, its resistance to backfill settlement increases by having the required structural strength to span a void. The results show that the typical slab length for the EPG ranges between 20-ft and 30-ft. Increasing the approach slab length, although the contact area increases and less stress is imposed on backfill material, reduces slab rigidity. Since no states are designing their approach slabs longer than 30-ft, it can be considered the maximum length limit. On the other hand, thinner approach slabs between 10-inch and 12-inch are used by the FPG. It is believed that a combination of a thinner slab and long slab length may have contributed to the poorer approach slab performance in the FPG. The typical slab geometry of the GPG is similar to that of the EPG. This finding reminds us that many factors affect approach slab settlement. It is important to note that steel reinforcement of the approach slab, which was not considered in this study, also affects slab rigidity. Finally, the results conclude that higher rigidity in approach slab means better performance.

Table 42 Approach slab geometry

Excellent	Thickness (in.)	8-10	10-12	**12-16**	Over 16
	Number of Respondent	2	2	**11**	2
	%	11%	11%	**65%**	11%
	Length (ft)	10-15	15-20	**20-30**	Over 30
	Number of Respondent	1	4	**12**	0
	%	6%	23%	**71%**	0%
Good	Thickness (in.)	8-10	10-12	**12-16**	Over 16
	Number of Respondent	1	0	**4**	0
	%	20%	0%	**80%**	0%
	Length (ft)	10-15	15-20	20-30	Over 30
	Number of Respondent	1	2	2	0
	%	20%	40%	40%	0%
Fair	Thickness (in.)	8-10	**10-12**	12-16	Over 16
	Number of Respondent	0	**3**	1	1
	%	0%	**60%**	20%	20%
	Length (ft)	10-15	15-20	**20-30**	Over 30
	Number of Respondent	0	1	**4**	1
	%	0%	17%	**67%**	17%

4.3.6 Retrofitting methods

The survey outcome summarized in table 43 reveals that the overlaying method is the most common retrofitting method, and it was indicated by most respondents as a cost effective method (refer to Section 3.2). However, it is important to note that overlaying a new pavement on an approach slab increases the total dead weight, resulting in higher stress on its backfill material. This method may not permanently solve the settlement problem but it provides a temporary repair of the road and improves drivability.

Table 43 Retrofitting methods

Retrofitting method		**Most Used**		**Somewhat Used**	
		Quantity	**%**	**Quantity**	**%**
Excellent	Overlaying	9	75%	7	30%
	Replacement	1	8%	11	48%
	Lifting	2	17%	5	22%
Good	Overlaying	3	50%	2	25%
	Replacement	1	17%	4	50%
	Lifting	2	33%	2	25%
Fair	Overlaying	5	83%	1	9%
	Replacement	1	17%	4	36%
	Lifting	0	0%	6	55%

4.3.7 Summary of survey data analysis

In this chapter, respondents were categorized into three performance groups based on the percentage of their bridges experiencing approach slab settlement. This grouping facilitated the evaluation of approach slab performance based on the survey results. Assessment of the survey results provided the following observations and conclusions:

- For the EPG, approach slab settlement was mostly attributed to insufficient construction practices, natural regional geology, and inadequate design of the approach slab. For the

FPG, poor construction, secondary compression of the backfill, and thermal effects were reported as the main causes of approach slab settlement, while weather and inadequate design were identified as other common causes. The results of the GPG suggest that settlement could be attributed to inadequate approach slab design. Soil volume change, steep approach slab gradient, broken corbels, and steep side slopes were found to be lesser causes of approach slab settlement.

- Uniform settlement is likely to be experienced by both the EPG and the FPG, while both uniform and differential settlements are equally experienced by the GPG. Uniform settlement is a sign of even stress distribution beneath the approach slab. Differential settlement is more likely to occur in cases with inappropriate backfill construction and inadequate approach slab design. As a combined result of poor construction, inadequate design, and environmental factors, the amount of approach slab settlement increases from the EPG to the FPG.
- Since select backfill is mostly used by all three groups, it may not necessarily be the factor causing approach slab settlement. However, percent fines or percent passing a No. 200 sieve is an important factor as all states specify a maximum limit of fines.
- A drainage system is not necessarily specified when select backfill is used.
- Deep backfill (e.g., over 5 ft) configuration reduces stresses distributed to foundation or subgrade soil and could reduce the number of bridges experiencing approach slab settlement.
- A positive separation between backfill material and subgrade soil might not improve the performance of the approach slab.

- The results clearly indicate the importance of controlling compaction quality by conducting in-situ compaction tests during backfill construction.
- A spacer between a backfill and an abutment wall does not directly affect the performance of the approach slab, but it effectively reduces lateral load on the abutment.
- The type of approach slab system does not have an important impact on slab settlement, but design and construction practices are vital.
- No clear relationship was observed between the use of integral abutments and approach slab performance.
- A combination of a thinner and longer slab may have contributed to higher rates of approach slab settlement in the FPG. The results revealed that more rigid approach slabs perform better because they have the structural capacity to span voids created by backfill settlement.
- The overlaying method is the most cost effective retrofitting method. However, this method cannot be considered a permanent solution to approach slab settlement because it imposes additional dead loads on the slab which could increase settlement.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This chapter compares research findings from the literature review and the nationwide survey. Ten components of design and construction of an approach slab system are considered. The research draws the following conclusions:

Causes of Approach Slab Settlement

A main focus of the survey was to determine the causes of the approach slab settlement in various states. The survey results show that the most common cause of approach slab settlement in most states is poor construction practices. For the EPG group the natural geology of the region and inadequate design are the other two most common causes. GPG and EPG shared similar causes: secondary compression of the backfill and thermal effects. Studies documented in the literature review suggest poor drainage and erosion of embankment as the two main causes of approach slab settlement.

Types of Approach Slab Settlement

The survey results show that the most common type of settlement observed by the EPG and the FPG is uniform settlement while both uniform and differential settlements are equally experienced by the GPG. The severity of the settlement (i.e., amount of settlement) increases from the EPG to the FPG, indicating the performance of the approach slab in these groups. It is concluded that settlement severity is a result of a combination of poor construction, inadequate design, and environmental factors.

Backfill

Backfill design and construction is the most important factor affecting approach slab settlement. The use of poorly graded materials and poor compaction are among the main causes of approach slab settlement. The survey results reveal that special attention should be given to backfill design and construction. The percentage of fine particles and the plasticity of backfill material should be reduced, and bulking moisture content of a granular backfill should be avoided. Survey results clearly reveal that construction control of backfill directly relates to approach slab performance as compaction increases backfill stiffness. Although reinforcing the backfill alone is not capable of completely eliminating the approach slab settlement problem, a combination of geosynthetic-reinforced backfill and spacer between abutment and backfill yields good performance under a service load. Survey results indicate that backfill types (i.e., conventional and geotextile-reinforced) do not influence approach slab performance. Specifically, reinforcing backfill beneath a sleeper beam improves slab performance. Alternatively, expanded polystyrene or flowable fill can be used as a backfill to lessen immediate settlement. Deep backfill configuration reduces surface stresses distributed to foundation soil or subgrade while high embankment increases backfill weight and severity of settlement. It is important to note that deep backfill configuration is commonly used by the EPG while shallow backfill configuration is mostly used by both the GPG and FPG.

Approach Slab System and Structural Slab

The stiffness of an approach slab is one of the important factors controlling approach slab settlement. Both the literature and survey indicate that a stiffer approach slab shows better performance in alleviating settlement. According to the literature, Precast Prestressed Concrete Pavement (PPCP) improves the ability of an approach slab to span voids. Furthermore, the literature review indicates that integral abutments improve approach slab performance. However, survey results do not show any noticeable difference in slab performances based on the type of abutments.

The survey results do not show a strong preference for any particular approach slab system. However, the literature recommends using a sleeper slab system. Additionally, the literature mentioned that a steep approach gradient could increase the severity of approach slab settlement.

Foundation

Foundation soil plays an important role in approach slab performance. As stated in the literature, approach slabs with granular and stiff foundations are less prone to settlement. Also, the survey results show that a soft soil foundation is a main cause of settlement in several states.

Drainage

As stated in the literature review, poor drainage could cause undermining of a sleeper slab of an approach slab. It is recommended to maintain the drainage behind a backwall. On the other hand, the survey results reveal that the GPG and FPG, which experienced more approach slab settlement problems, have a drainage system beneath the approach slab in the design.

Erosion

The literature identifies embankment erosion as a major cause of approach slab settlement. Erosion in the backfill leads to faulting of approach slab, failure of slope protection, and exposure of the bridge foundation's supporting abutment.

Spacer

A spacer constructed between the backfill and abutment wall reduces lateral loads on the abutment and mobilizes the resistance of backfill geosynthetic reinforcement. The survey results do not show a distinct difference in slab performance among the three groups in terms of using the spacer. However, usage of the spacers is recommended by the literature to lower the lateral load on abutments.

Construction

Construction sequence plays an important role in approach slab settlement as indicated in the literature review. Better slab performance was observed when construction of the approach slab preceded backfill compaction. The survey results obtained from most states indicate that poor construction practice is the main cause of approach slab settlement. Texas DOT suggests that, for a closed spill-through and integral abutment, the approach slab's embankment should be constructed before the abutment. For a perched abutment, however, the approach slab should be constructed after the abutment. The survey results show that performing in-situ tests to control and verify backfill compaction decreases approach slab settlement. However, as stated in the literature, achieving a specified soil compaction close to an abutment is a major construction challenge. Therefore, it is concluded that construction practice is one of the most important factors affecting approach slab settlement.

Retrofitting

The literature recommends several retrofitting methods, such as excavation and replacement, preloading and surcharge, and dynamic compaction. Abu al-Eis and LaBarca (2007) concluded that the URETEK method, a lifting and realigning method, is an effective retrofitting method. However, the survey results indicate that URETEK is not cost effective, while the commonly used overlaying method is the most economical.

5.2 Recommendations for Implementation

To improve approach slab performance in the State of Wyoming, conclusions drawn from this research were used to propose recommendations for changes to current WYDOT design and construction specifications. Several changes to the current WYDOT Bridge Applications Manual Chapter 4, Section 4.14 (WYDOT, 2008) by the WYDOT's Bridge Program are suggested as described in table 44. The detailed requirements for approach slab are documented in the WYDOT Bridge Applications Manual Chapter 4, Section 4.14 (WYDOT, 2008).

Table 44 Suggestions and potential changes to current WYDOT bridge applications manual Chapter 4

Section 4.14	Current Specifications	Suggestions and Potential Changes
General Design and Detail Information	The thickness of the concrete slab shall be 10-in.	Based on the finding described in Section 4.3.5, it is recommended to increase the thickness of the approach slab to 12-in. to16-in. The depth of corbel should be considered when a thicker slab is designed. If the recommended change to the approach slab geometry is implemented, the steel reinforcement of the slab should be designed accordingly to maintain its structural stiffness.
	Approach slabs are constructed using backfill material, geotextile, and an underdrain pipe.	It is recommended to keep the current drainage system. However, the effectiveness of the drainage system requires further investigation.
	Slabs are typically 25-ft long on a normal bridge .	No change is necessary at this time.
Bridge Approach Backfill	Bridge approach backfill is a pervious material consisting of crushed gravel, crushed rock, or manufactured sands.	Poorly-graded backfill materials are currently specified. It is suggested to change it to a well-graded pervious backfill material to enhance compaction without scarifying the drainage. Based on the United Soil Classification System, well-graded backfill should have a coefficient of gradation (C_c) between 1 and 3. It is recommended that the backfill should be compacted to a minimum 95% of the standard Proctor density.
	The approach backfill is divided into lifts separated by Geotextile, Embankment and Retaining Wall.	It is recommended to keep the geotextile reinforcement in the design.
	Each lift is governed by a minimum and a maximum thickness designated by the Geology Program as: Minimum: 8-in.; Maximum: 2-ft.	It is recommended to reduce the maximum lift thickness to assure a better compaction.
	There shall be a 2-in. to 4-in. gap between the abutment and the geotextile to help keep earth pressure off the backwall	No change is necessary at this time.

Table 44 Suggestions and potential changes to current WYDOT bridge applications manual Chapter 4 (Continued)

Section 4.14	Current Specifications	Suggestions and Potential Changes
Geotextile, Emb and Retaining Wall	One layer of geotextile shall line the bottom and extend up the side limits of the excavation to the bottom of the first layer of the geotextile and up the back limit of excavation to the bottom of the roadway subgrade.	No change is necessary. Further investigation will be required to evaluate the effectiveness of the design and construction procedures of the geotextile reinforced backfill.
Limits of Excavation and Backfill	If the backwall is 5-ft or less below the top of the corbel, a shallow configuration is used. If the backwall is greater than 5-ft below the top of the configuration, a deep configuration is used.	Although the backfill configuration is governed by the depth of backwall, it is recommended to evaluate the effects of backfill weight by determining its geostatic vertical stress and surface stress distribution using a method, such as Boussinesq's solution, on foundation soils, especially a relative soft foundation soil.
Sleeper Slab	The sleeper slab is typically used when performed elastomeric compression joint seals are not used between the concrete pavement section.	It is recommended to design a reinforced foundation underneath the sleeper slab.

Since construction plays a significant role in approach slab performance, changes are also proposed for the WYDOT Standard Specifications for Road and Bridge Construction Manual (WYDOT, 2010), as presented in table 45.

Table 45 Suggestions and potential changes to current WYDOT Standard Specifications for Road and Bridge Construction Manual (2010)

Section	Suggestions and Potential Changes
212	It is recommended that the backfill should be compacted to a minimum 95% of the standard Proctor density.
	It is strongly recommended to perform in-situ tests to control and verify the quality of the backfill compaction during construction. The current construction procedure to ensure an adequate compaction near to the backwall or areas that are not easily accessible to compaction equipment should be reviewed.
	Construction sequence is not mentioned in any of the approach slab design and construction manuals. It is recommended to review the construction sequence and develop a section specifying the required construction practices for the approach slab system.
217	No change is necessary at this time.
507	It is recommended that a well-graded pervious backfill material requirement should be added to this section. Lifting and realigning method could be a viable retrofitting method since its cost is likely to be lesser than the replacement method.

It is important to emphasize that the aforementioned suggestions and recommendations are based solely on the outcomes obtained from the literature review and nationwide survey completed in this research. Neither experimental, field, nor computational analyses were performed in this research. Although most of the recommendations are conceptual, they provide a basis for future investigations to collect quantitative information for the improvement of WYDOT’s approach slab system specifications.

5.3 Recommendations for Future Research

With respect to the limitations of this research, recommendations for future studies are suggested as follows:

- Experimental and/or computational studies are suggested to quantitatively evaluate the effects of various factors influencing approach slab settlement.
- Future research should investigate the maximum lift thickness of backfill, compaction procedure, and quality control and assurance during construction to ensure adequate compaction.
- The ability of geotextile to mobilize its resistance and drain water should be investigated since no information on these topics was discovered in this research.
- The effectiveness of a positive separation between backfill and foundation soil requires further investigation.
- Experimental studies are suggested to evaluate the suitability of select backfill material for drainage and the effectiveness of drainage systems.
- The effect of shallow versus deep configuration on approach slab performance has yet to be determined. This effect should be investigated for different foundation soil conditions, backfill materials, depths, and dynamic load conditions related to traffic.
- Few studies have been conducted to evaluate the effectiveness of different retrofitting methods, and no guidelines exist for selecting and using the various methods. Experimental studies are suggested to evaluate the effectiveness of the three common retrofitting methods: overlaying, replacement, and lifting methods. Economic analysis should be conducted in conjunction with these studies.

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APPENDIX A – Survey Questionnaire

1- What is the name of your agency?
   [Text Box]

2- Has your state conducted research on approach slabs? If possible, please provide the reference.
   a. Yes
   b. No
      [Text Box]

3- What percentage of the bridges use an approach slab system?
   a. 0
   b. 0-25%
   c. 25-50%
   d. 50-75%
   e. 75-100%
   f. 100%

4- What percentage of bridges with approach slab system use an Integral abutment?
   a. 0
   b. 0-25%
   c. 25-50%
   d. 50-75%
   e. 75-100%
   f. 100%

5- Which approach slab system(s) are currently used in your state? (Choose all that apply)

	Mostly used	**Occasionally used**	**Not used**
Cast-In Place (no sleeper slab)	○	○	○
Precast (no sleeper slab)	○	○	○
Sleeper Slab	○	○	○
Other: [Text Box]	○	○	○

6- What percentage of bridges have approach slab settlements?

a. 0
b. 0-25%
c. 25-50%
d. 50-75%
e. 75-100%
f. 100%

7- What are the causes to approach slab settlement?

	Most Common	**Somewhat Common**	**Least Common**
High embankment fill	○	○	○
Soft natural soil foundation or subgrade	○	○	○
Primary compression of backfill material (During and immediately following grading operations)	○	○	○
Secondary compression of backfill material (After completing the grading operations)	○	○	○
Soil volume change due to moisture content change or erosion of embankment material	○	○	○
Weather effect (e.g., heavy rain storms, extreme freeze-thaw cycles)	○	○	○
Steep approach slab gradients	○	○	○
Poor construction practices (e.g., not compacting embankment fill)	○	○	○
Thermal effect (expansion and contraction of the bridge decks and girders)	○	○	○
High average daily traffic or high induced traffic load	○	○	○
Broken corbels	○	○	○
Inadequate design (e.g., not providing efficient drainage system, not placing proper expansion joints)	○	○	○
Steep side slope of the approach slab embankment	○	○	○

8- What type(s) of settlements have you experienced [approximate maximum settlement in inches]?

	Most common	**Somewhat common**	**Not common**	**Approximate Maximum Settlement (in)**
Uniform settlement	○	○	○	[Text Box]
Differential settlement	○	○	○	[Text Box]
Other: [Text Box]	○	○	○	[Text Box]

9- What type(s) of approach slab backfill are currently used in your state?

	Mostly used	**Somewhat used**	**Not used**
Conventional (Non-reinforced compacted soil)	○	○	○
Geotextile or Fabric reinforced	○	○	○
Light weight material	○	○	○
Mechanical stabilized earth	○	○	○
Other: [Text Box]	○	○	○

10- Is select backfill material used beneath the approach slab? If yes, please indicate the section(s) describing the gradation in your specifications requested in Question 19?

a. Yes [Sections]

b. No

11- What is the typical Geometry Specification (Average Depth) of your backfill?

a. Shallow configuration (Under 5 ft);

b. Deep configuration (Over 5 ft);

12- Is a drainage system used beneath the approach slab?

a. Yes

b. No

13- Is a positive separation between subgrade and backfill provided?

a. Yes

b. No

14- Is in-situ density test performed on compacted backfill? If yes, what is/are the in-situ test methods?

   a. Yes; [in-situ test methods]
   b. No

15- Are spacers being used between the backfill and the abutment wall to minimize the lateral load on abutment? If yes, what is the specification of this spacer?

   a. Yes; [specification of this spacer]
   b. No

16- What is the typical thickness of the structural approach slab?

   a. Under 8"
   b. 8-10"
   c. 10-12"
   d. 12-16"
   e. Over 16"

17- What is the typical span length of the approach slab?

   a. Under 10'
   b. 10-15'
   c. 15-20'
   d. 20-30'
   e. Over 30'

18- What retrofitting method(s) are used for approach slab settlement? What is the average cost of each method per bridge?

	Mostly used	**Somewhat used**	**Not used**	**Average Cost ($)**
Overlaying	○	○	○	[Text Box]
Replacement	○	○	○	[Text Box]
Lifting and realigning the approach slab by filling and sealing the void under the approach slab	○	○	○	[Text Box]
Other: [Text Box]	○	○	○	[Text Box]

19- What is the current specification used for design and construction of approach slabs? (If possible please attach the electronic version or provide the online URL link)

    [Text Box]

    [Upload File]

20- If you are using typical template drawings for constructing the approach slabs, please upload them into the following boxes?

    [Upload File]

21- Are you satisfied with your current design or are you planning on improving it? Please provide any useful comments in this manner, in the specified box.

    a. Satisfied – NO further improvement needed;
    b. Not Satisfied – further improvement needed;
    c. Comments: [Text Box]

22- Please provide your contact information if you wish to receive results of this survey.

APPENDIX B – Survey Results

All responses received from the survey are contained in an accompanied CD.

ACNOWLEDGEMENTS

The authors would like to thank the Wyoming Department of Transportation (WYDOT) for sponsoring the research project described in this report. The authors would like to specially thank the project champion, Mr. Michael Menghini, and WYDOT Bridge Program’s State Bridge Engineer, Mr. Keith Fulton, who initiated this research. Also, special thanks to Mr. Timothy McDowell and Ms. Enid White from the WYDOT’s Research Center, Mr. Kirk Hood from the WYDOT’s Geology program and the WYDOT’s research advisory committee members for supporting this research project. Furthermore, the authors would like to thank the DOTs that participated in the nationwide survey.