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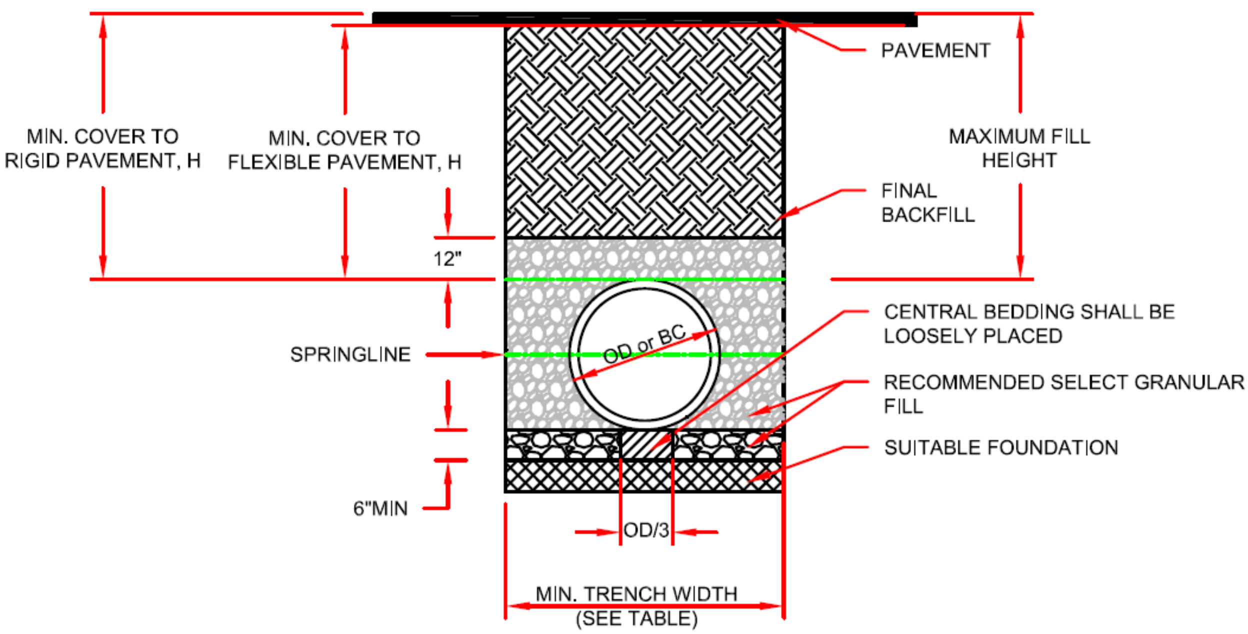

CRITERIA FOR A WYDOT CULVERT SELECTION POLICY

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Supplementary Notes
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Abstract
This report discusses geotechnical and material considerations for culvert design and selection. The purpose of this report is to present the Wyoming Department of Transportation with information in order to alter, improve, and incorporate changes to their standard road and bridge specifications. Research included in this study synthesizes AASHTO, ASTM, State DOT, and NCHRP literature among other technical documentation, as well as State DOT surveys that outline important considerations for culvert design. Additional areas of research discussed in this report include post-installation inspection of pipe culverts and LRFD culvert design procedures. The report concludes with recommendations for changes to WYDOT's specifications related to selection, design, installation, and inspection of culverts.

Key Words	Distribution Statement
Culverts, thermoplastics, soils, Wyoming	Unlimited

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SI* (Modern Metric) Conversion Factors

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	squares miles	Mi^2
Volume				
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yard	Yd^3
Mass				
g	grams	0.035	ounces	Oz
kg	kilograms	2.202	pounds	Lb
Mg	megagrams	1.103	short tons (2000 lbs)	T
Temperature (exact)				
℃	Centigrade temperature	1.8C + 32	Fahrenheit temperature	°F
Illumination				
lx	lux	0.0929	foot-candles	Fc
cd/m^2	candela/m^m	0.2919	foot-Lamberts	Fl
Force and Pressure or Stress				
N	newtons	0.225	pound-force	Lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

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 yards	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
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lbs)	0.907	megagrams	Mg
Temperature (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	℃
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	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

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In addition, the authors would like to acknowledge several state DOT agencies that participated in our study and that provided valued practical information derived from years of experience which no literary piece would otherwise be able to provide. The time spent and information provided by these agencies is much appreciated. States that participated and their representatives are as follows:

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Florida: Rick Renna.

Nebraska: Mark Burham and Kevin Donahoo.

New York: Peter VanKampen.

Ohio: David Riley.

South Dakota: Dean Van DeWiele.

Washington: Jay Christianson.

EXECUTIVE SUMMARY

Culvert systems play an integral part in any transportation inventory. Currently, WYDOT is attempting to revamp their culvert selection and design policies to provide the highest quality transportation infrastructure system to its citizens and visitors of the state. This report intends to provide guidance and recommendations on how the agency can amend their standard specifications to accomplish this task. An extensive literature review and state DOT survey was completed which investigated numerous areas found to significantly influence a culvert's design life. The areas can be categorized into two groups: geotechnical and material considerations. One notable finding is that WYDOT currently does not consider thermoplastic materials as a viable product for culvert installations. It was determined, that if these products are installed with the strictest installation procedures and superior backfill materials, they can provide an equivalent design life compared to traditional culvert materials, especially in areas of highly corrosive and abrasive environments. In addition, the DOT surveys show inclusion of thermoplastics will set economical principals into effect and provide WYDOT with a more competitive price of culvert installations. For these reasons, it is ultimately recommended that thermoplastics should be considered an acceptable material for culvert installations. Other recommendations regarding culvert installations and procedures for all culvert materials are included in this report.

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CHAPTER 1: INTRODUCTION

1.0 Problem Statement

In response to a directive issued by Federal Highway Administration (FHWA), the Wyoming Department of Transportation (WYDOT) is tasked to "develop culvert selection policies that consider all available pipe products judged to be of satisfactory quality and equally acceptable on the basis of engineering and economic analyses." The intent of this federal policy is to require competition in the specification of alternative types of culvert pipes. WYDOT currently has extensive experience using concrete and metal pipe, but little experience with plastic products which are now widely available and are being used in many other states. This report is designed to establish rational procedures for evaluating various culvert materials as to their suitability for a range of drainage applications. These procedures account for all of the factors that affect culvert design and performance, include but are not limited to: design life; consequences of failure; fill height; backfill characteristics; corrosion; abrasion; flow characteristics; and materials specifications. While some of these critical factors are currently addressed in WYDOT standard specifications, some are ill-defined and there is currently no basis for making a rational decision on when and how to allow the use of plastic pipe. The research project described herein is intended to provide a basis for developing engineering standards for the selection and use of all available pipe products.

1.1 Problem Background

Section 5514, Competition for Specification of Alternative Types of Culvert Pipes, of the 2005 *Safe, Accountable, Flexible, Efficient Transportation Equity Act* (SAFETE), requires the Secretary of Transportation to ensure that states provide for competition with respect to the specification of alternative types of culvert pipes. Responsibility for implementation of Section 5514 was assigned to FHWA, which subsequently issued a series of policy documents that includes the April 17, 2006 Notice of Proposed Rule Making, the November 15, 2006 Final Rule, and the July 9, 2007 memorandum that supplements the November 2006 memorandum. Relevant excerpts from the July 9, 2007 memorandum documents include:

> "State DOTs should develop culvert selection policies that consider all available pipe products judged to be of satisfactory quality and equally acceptable on the basis of engineering and economic analyses."

> "Division Offices should now be working with their respective State DOT's to ensure that the State's culvert material selection procedures provide for competition with respect to the specification of alternative types of culvert

> pipes. Division Offices should ensure that the State's procedures are based on sound engineering and economic reasons and not based on arbitrary factors."
>
> "With the potential for significant savings, the implementation schedule should not be based on protracted evaluation periods for experimental or pilot project installations."

While not specifically stated, it is clear that the above policy is intended to ensure that thermoplastic pipes are being considered in the appropriate applications.

WYDOT has been receptive to pilot projects to gain experience with pipes made of thermoplastic materials (referred to herein as plastic). For example, several recent projects have allowed the use of pipe made of high density polyethylene (HDPE). To date, only one project was furnished with HDPE pipe and the contractor decided to provide a select backfill material. WYDOT recently let another project with the HDPE alternative, but it is not yet clear which pipe the contractor will use.

A survey conducted recently on behalf of the Arizona DOT (2006) indicated that most states are allowing HDPE, although many have limitations on the applications. All of the states surveyed are allowing HDPE for culverts under approaches. Beyond that, there is a wide range of implementation strategies among state DOTs.

WYDOT has attempted to address the FHWA directive by forming an internal committee to develop a draft policy. The committee determined that in order to complete its task, it is necessary to conduct a thorough review of current practices to determine if they need to be altered to meet WYDOT needs while addressing the FHWA directive.

1.2 Study Objective

The objective of this study is to provide the WYDOT Culvert Committee with the tools and information they need to draft a policy on culvert selection that satisfies the FHWA directive while also meeting the needs of WYDOT. The policy must be based on rational consideration of costs, performance, and engineering design practice for culverts, constructability, and quality.

1.3 Study Benefits

This work will allow the WYDOT to satisfy the FHWA directive to develop culvert selection policies that consider all available pipe products, in a manner that provides fair competition and which is consistent with acceptable engineering practice. These are the intent of the federal policy. In addition, a new policy is assumed to provide WYDOT with higher quality and more cost-effective culvert installations.

1.4 Work Plan/Scope

The overall scope of this project involves the collection, evaluation, and synthesis of existing data and information, as well as identification of areas or topics for which existing information is inadequate and which may require further research. This project does not involve laboratory or field testing of culverts.

Considering the importance of culvert performance to WYDOT's overall mission of "providing a safe, high-quality, and efficient transportation system to the citizens of Wyoming" and the fact that culvert design requires an interdisciplinary approach, this project has been conducted in close consultation with the WYDOT Culvert Committee comprised of personnel from WYDOT Bridge, Construction, Geology, Hydraulics, and Materials divisions. The end product of this study is a document outlining recommendations for culvert selection and design procedures, which can then be considered for adoption by the WYDOT Culvert Committee.

Initially, this research involved a thorough review and critical evaluation of current WYDOT specifications for culverts. This review was intended to identify strengths of current policies for culvert selection and to identify shortcomings with respect to the procedures for evaluating alternative pipe materials for specific drainage applications. The objective was to determine the degree to which current practices will need to be modified in order to meet future needs and to comply with the FHWA directive, in particular with respect to plastic pipe products.

According to information provided by FHWA, several state transportation agencies have developed policies for culvert selection that comply with the directive to provide fair competition between all suitable products, including plastic pipe. Examples of states identified by FHWA are: Arizona, Florida, New York, Ohio, and Washington. A second task of this research was to conduct a thorough review of the policies and other documents (including research reports) developed by other states, starting with those listed above then expanded to include states bordering Wyoming (Colorado, Nebraska, South Dakota, and Utah). Some of this information is available via the FHWA website and has been reviewed. Key personnel from each of the above states were contacted. To date, interviews have been conducted with representatives from Colorado, Florida, New York, Ohio, South Dakota, and Washington regarding their experience with plastic culvert selection and performance.

Review of WYDOT specifications and other states' policies has been conducted with a focus on specific technical issues that are considered to be critical to the successful design, construction, and performance of culverts. The following discussion of technical issues defines the scope of this project.

1.5 Methodology

The framework for this study consists of information drawn from two sources. First, extensive literature reviews which focused on three different types of material: 1) standard specifications used by State Transportation Agencies; 2) American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM) Standards; and 3) peer reviewed articles. Second, interviews were conducted with State DOT representatives to obtain practical data regarding the use and implementation of HDPE products. The data gathered provided scientific and qualitative facts which are the basis of the recommendations provided in this report.

The objective of this study is to investigate the areas which will have the greatest impact on a successful culvert material selection policy. These include the following:

A. General Design Considerations.
   a. Design Life.
   b. Consequences of Failure.
   c. Pipe Applications / Classifications.
B. Geotechnical Considerations.
   a. Maximum Fill Height.
   b. Minimum Fill Height.
   c. Bedding and Backfill.
   d. Compaction.
   e. Controlled Low-Strength Material.
   f. Construction.
C. Material Selection Considerations.
   a. Durability.
   b. Joints.
   c. End Treatments.
   d. Allowable Pipe Diameter.
   e. Hydraulic Flow Characteristics.
   f. Material Specification.
D. Other Factors Impacting Pipe Selection and Performance.
   a. Deflection.
   b. Control Over Pipe Selection.
   c. Payment for Various Installation Methods.
   d. Ultraviolet (UV) Degradation.
   e. Risk of Fire Destruction.
   f. Roadway Settlement.

E. Introduction to Load and Resistance Factor Design (LRFD) for Culvert Design.
    a. LRFD Background.
    b. LRFD Philosophy.
    c. HL-93 Loads.
    d. AASHTO 2010 LRFD Design.

These categories were the primary components of data collection.

State DOTs, which were included in this study, were selected based on their geographic proximity to Wyoming and/or their particular knowledge and expertise on the use of HDPE pipe. The states included in this study are as follows: Arizona; Colorado; Florida; Nebraska; New York; Ohio; South Dakota; Utah; and Washington. Each state's DOT standard specifications were analyzed and the results are summarized herein.

After a review of state specifications was performed, relevant trends were used to develop preliminary recommendations. Next, interviews of DOT representatives were conducted concurrently with scientific literature reviews. Together this information was used to further justify initial recommendations. All results were compiled, synthesized, and conclusions were drawn to make final recommendations regarding the implementation of HDPE pipe within the current *WYDOT Standard Specifications for Road and Bridge Construction*.

1.5.1 Standard Specifications

It is common for State DOTs to use multiple documents for design. In addition to "Standard Specifications," it is important to note that separate standards such as "highway design manuals," "culvert selection policies," "supplemental specifications," and "standard plans" were included in the literature review. Therefore, the collection of these documents will be referred to as "Standard Specifications."

Standard specifications were used as a starting point of data collection. This investigation revealed how states have implemented plastic pipes within their standard specifications. Pertinent design considerations were tabulated and comparisons were made. These comparisons exposed trends which were the basis of preliminary recommendations.

1.5.2 Peer Reviewed Literature

Findings based on literature review of scientific research were used to support the paper's final recommendations. The findings documented in scientific literature were used to validate the information identified in the review of state standard specifications. In addition to the numerous journal articles reviewed, notable sources in this Report include National Cooperative Highway Research Program (NCHRP), FHWA, and state reports.

1.5.3 AASHTO / ASTM

Many state specifications use ASTM and AASHTO standards as minimum requirements for pipe mechanical properties and installation techniques. The majority of states reference these design guides to serve as quality control for designing HDPE culverts. Notable literature within this area includes AASHTO Standard Specifications, Design Specifications, and Construction Specifications. ASTM literature incorporated within this report includes ASTM D 2321, ASTM D 2487, and ASTM D 3350.

1.5.4 DOT Interviews

All states that were studied include guidelines for the use of HDPE within their specifications, and therefore, deem it as an acceptable material. However, this does not constitute particular success or even ensure that HDPE is actually being used within a particular state. The interviews provided insight into the frequency of use of HDPE products and also exposed specific considerations that are relevant to successful installation of HDPE culverts.

A detailed questionnaire was drafted and emailed prior to conducting phone interviews. This allowed the representatives from each of the states included in this study to familiarize themselves with the questions in order to provide accurate and detailed responses. Details of these interviews are in Appendix A in this Report.

CHAPTER 2: GENERAL DESIGN CONSIDERATIONS

Because culverts comprise a significant portion of a state's infrastructure, it is imperative to provide a system that is both economical and durable. As new materials enter the market, state agencies are faced with the vexing task of ensuring that relatively untested products can provide reliable, long-term service durability in a cost effective manner. Design decisions must include both short-term and life cycle costs. While construction costs are relatively easy to quantify, long-term performance of many emerging products is uncertain.

2.1 Design Life

It is important when selecting a culvert material that it performs properly throughout its anticipated design life. Definitions of design life for different pipe materials are generally inconsistent. Typically, state specifications tie design life to durability considerations including corrosion and abrasion. When considering plastic materials, the structural performance must also be considered. If excessive deflections occur, tension and compressive stresses are likely to result causing pipe cracking (Hsuan and McGrath, 2005). This will result in a reduced expectant design life. Currently, DOTs have considerable experience with concrete and metal structures; however, the long-term performance of plastic products is less certain. Nebulous design parameters place the design life of HDPE products at 50 – 100 years. Table 1 provides the specified design life for HDPE pipe as found within the state specifications. In particular, the long and short-term mechanical properties are not always clearly understood by DOT engineers. Therefore, quantifying a time which a system is guaranteed to perform adequately is difficult due to the variations of site, installation, and product properties. However, AASHTO (2007) states that available research suggests that plastic materials can provide equal service life in more diverse conditions than either steel or concrete material. In addition, it can be assumed that longer design life can be expected if culvert systems are installed with proper installation methods, appropriate joint selection, corrosion and abrasion considerations, and properly designed culvert materials.

AASHTO (2007) states the following:

> "In most instances, no other single factor will positively influence culvert life as much as attaining proper installation in conformance with well developed specifications."

Table 1: Specified Design Life for HDPE pipe

State	Specified Design Life
Arizona	75 years
Colorado	70 years
Florida	100 years
Nebraska	Not specified
New York	70 years
Ohio	75 years
South Dakota	50 years
Utah	Not specified
Washington	Not specified
Wyoming	Not specified

2.2 Consequences of Failure

The consequences of failure must be considered in determining whether a product will meet its intended goals while remaining cost effective. For example, if a culvert corrodes and requires replacement in a high fill, it might require costly methods for lining the pipe which could also reduce flow capacity. When evaluating new products for which the likelihood of failure is more uncertain, it may be best to use them initially in low risk environments where replacement would require less effort until more experience with installation, specifications, and other factors can be fully evaluated.

2.3 Pipe Applications / Classifications

The specific drainage application may dictate what kind of pipe materials would be considered acceptable considering the risk and difficulty of replacement. Applications which are commonly encountered in culvert design are classified as follows:

Cross Drain Culverts

Cross drain culverts convey water from one side of the mainline to the other underneath the roadway. Failure of cross drain culverts could involve detours, traffic delays or more costly methods to rehabilitate the culverts. Some states further define cross drain requirements based on traffic volumes, importance/classification of the roadway, National Highway System versus non-National Highway System, etc.

Parallel Drainage Culverts

Parallel drainage culverts are parallel to the roadway and are used to convey drainage beneath approaches. Because most of these are minor approaches to individual homes, farms, etc., the minimum cover can often be reduced, unless very heavy vehicles traverse the approach. The risk of failure on most of these approaches is fairly low, since replacement could be done away from mainline traffic and in relatively low fills.

Storm Sewers

Storm sewers are generally utilized in congested urban areas with significant pavement cover, high traffic use, and a multitude of other buried utilities in the same vicinity. The consequences of failure can be quite severe, including flooding, blocking of businesses, and of course the impact to traffic and mobility. Storm sewers are also much harder to inspect to determine when failure might occur.

Sanitary Sewers

Sanitary sewers are typically placed under the jurisdiction of local wastewater authorities and will therefore not be addressed by this study.

Edge Drains

Edge drains are used to convey water away from the roadbed to maintain stability of the pavement. These are smaller-diameter pipes and generally are not subjected to traffic loads, but construction practices can frequently crush the pipes, so it is important that they are fully intact after construction. The longevity of these types of pipes should be roughly the time between full reconstruction projects, which may be significantly shorter than many other pipe applications.

Underdrains

Underdrains are frequently used to drain water from medians, embankments, and other areas which might cause the embankment to become unstable or permit water to be conveyed to the roadbed. The consequences of failure and requirements for replacement can vary. Typically the work will be away from traffic, but may substantially affect the embankment in a way that traffic could still be affected. Even worse, if the pipe fails, it could result in a landslide.

Pipe Liners

Pipe liners are typically used to rehabilitate a culvert which has deteriorated to a point where its structural capacity might be in question and/or the hydraulic properties may be compromised. The materials selected must be strong enough to be pushed through the existing culvert and support grouting operations. In addition, it is unclear if this newly created composite structure will withstand the fill heights over time when the existing pipe completely erodes.

Pipe Extensions

Pipe extensions are typically done on widening projects. Usually the existing pipe is still performing adequately. Current WYDOT specifications require pipe extensions to be of the same material as the existing pipe. In general, states included in this study also only allow pipe extensions to be of the same material as the original pipe. Florida and Washington specify that preference should be given to the same material and the existing material should be used when possible; however, dissimilar materials are allowed by their specifications. It appears joining dissimilar pipe can be difficult and research to prove otherwise is lacking. This report suggests the variance in thermal expansion of dissimilar materials may prove difficult for properly joining the pipe. However, if the pipe manufacturer can provide a joint capable of joining the dissimilar material, it is reasonable to be able to use different pipe materials for extensions. Further research is warranted to determine how manufacturers accommodate this irregularity.

Areas of Acceptable Use

Review of state specifications and DOT interviews (Appendix A in this Report) show limited restrictions of HDPE systems use in the various drainage applications. In general, states included in this study allow HDPE culvert systems in the same locations as are allowed by its traditional counterparts. It is a more common practice to limit plastic culvert systems by fill height and allowable pipe diameter rather than specific applications; these limitations are discussed further in Chapters 3 and 4 in this Report. Table 2 is a summary comparing where states deem HDPE as an acceptable material for use.

Table 2: Comparison of Acceptable Drainage Applications by State

Acceptable Applications of HDPE Use		
Specification	**Restrictions**	**Locations**
AZ	no	
CO	**yes**	not allowed for storm drain systems
FL	**yes**	not allowed in the Florida Keys
NE	no	
NY	no	
OH	no	
SD	**yes**	not allowed under mainline
UT	no	
WA	**yes**	not allowed in locations of ditch burning, not allowed for storm drain systems
WY	**yes**	not applicable

CHAPTER 3: DESIGN AND CONSTRUCTION PARAMETERS: GEOTECHNICAL CONSIDERATIONS

Results are organized and presented based on the following categories: maximum fill height; minimum fill height; bedding and backfill; compaction; controlled low-strength material; and construction. Within each section, results are discussed from findings in the AASHTO Specifications, ASTM Standards, standard specifications, and peer reviewed articles.

3.1 Maximum Fill Height

Maximum fill heights for culverts are generally calculated in accordance with the AASHTO LRFD Design Specifications, referred herein as AASHTO (2010b). This specification presents minimum cross sectional properties useful for the calculation of fill heights. This information is discussed in greater detail in Chapter 6 in this Report. Due to the number of suppliers of plastic pipe currently in the marketplace and the complexity associated with producing this material, this report suggests that structural cross sections and mechanical properties could vary significantly from manufacturer to manufacturer. Therefore, designers should verify that the material provided has cross sectional properties that meet or exceed those specified by AASHTO (2010b). When a new type of pipe is evaluated, an AASHTO adopted procedure should be used to calculate maximum fill heights. When conducting an interview with Washington DOT (WSDOT) personnel, it was discovered that this agency required ADS, a leading plastic pipe manufacturer, to supply the agency with LRFD fill height calculations.

When considering fill heights, it is important to understand how culverts perform. There are two main types of culverts: rigid - concrete, solid steel and cast iron; and flexible - corrugated metal and plastic. Rigid pipes carry almost the entire load through the strength of the pipe. Flexible pipes transfer the majority of the load acting on the pipe to the surrounding backfill through arching action. In many situations, a properly installed flexible pipe can be buried much deeper than a similarly installed rigid pipe because of the flexible pipe/backfill interaction. A rigid pipe is often stronger than the backfill material surrounding it, thus it must support earth loads well in excess of the prism load above the pipe. Conversely, a flexible pipe is not as strong as the surrounding backfill; this mobilizes the backfill envelope to carry the earth load. This phenomenon, known as soil arching action, is discussed in greater detail in Chapter 6 in this Report.

Maximum fill height for reinforced concrete pipes is around 30 feet. Corrugated metal culverts can have fill heights of over 100 feet. Therefore, even at sites with corrosive soils, metal pipes may still be necessary with additional mitigation methods including the use of special coatings and adding more metal thickness to account for corrosion loss. State specifications vary considerably with regard to maximum fill heights for plastic pipe. Most states have adopted fill heights in the range of 10 to 20 feet for plastic pipes even though calculations can yield fill heights exceeding this range.

3.1.1 AASHTO / ASTM

As the depth of fill increases, the effects of live loads decrease and geostatic earth pressure and hydrostatic loads become the controlling design considerations. AASHTO Design Specifications establish design procedures to account for live, geostatic earth, and hydrostatic pressures, but imposes no specific maximum fill heights. Using AASHTO equations for plastic pipe, the factored vertical crown pressure and resulting factored thrust can be calculated. The factored wall thrust is then compared to allowable material properties to determine if the pipe can adequately resist buckling, local buckling, and allowable strains in the culvert. A more in depth discussion of AASHTO LRFD design equations are found in Chapter 6 in this Report. No ASTM standards were found specifically addressing maximum fill heights.

3.1.2 State Specifications

All states included in this study, with the exception of South Dakota, impose maximum fill heights for plastic pipe. However, there is little consistency with maximum allowable fill heights varying from 10 to 40 feet. Table 3 is a summary of the maximum fill heights of the states included in this study. This table shows maximum fill height varies significantly from state to state. It should be noted that some states impose criteria for maximum fill height that takes into account the pipe's diameter, type of backfill material, and level of compaction.

Table 3: Specified Maximum Fill Height for HDPE Pipe

State	H_{max} (ft.)	Measured Distance
AZ	10	Top of Pavement
CO*	29	Top of Pavement
FL	17	Top of Pavement
NE	40	Top of Pavement
NY	15	Top of Pavement
OH	20	Top of Pavement
SD	Not Specified	
UT**	17	Top of Pavement
WA	25	Top of Pavement
WY	Under development	

* Varies with compaction

** Varies with pipe diameter

The inconsistencies discussed above can also be noticed when reviewing Arizona DOT (ADOT) Final Report 621 (2006) which investigated various aspects of HDPE design including maximum fill heights. Figure 1 summarizes the specified maximum fill heights reported by 31 states. This figure demonstrates the degree to which maximum fill heights vary, ranging from a few feet to over 30 feet. In general, fill heights between 10 and 20 feet are most common.

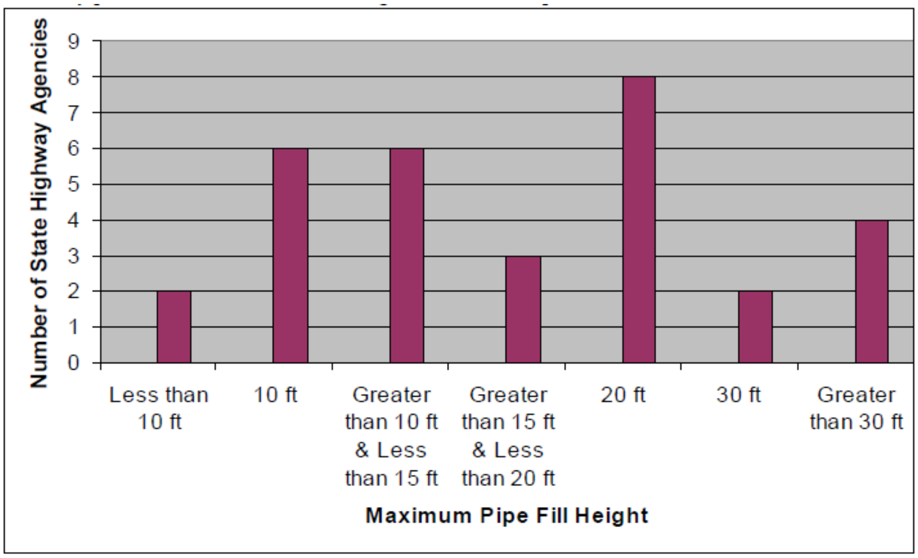

Figure 1: Maximum Fill Height from Various States (ADOT Final Report 621, 2006)

Finally, the Federal Lands Division of the FHWA conducted an investigation of polyvinyl chloride (PVC) and HDPE fill heights. Their recommendations are summarized in the Federal Lands Highway (FLH) Standard Drawing 602-5 and can be found in Appendix B to this Report, and at http://flh.fhwa.dot.gov/resources/pse/standard/. This standard detail shows the maximum fill heights can vary significantly from 10 feet to 57 feet depending on the type of plastic (PVC or HDPE), wall type, and cell classification of pipe used. FLH Standard Drawing 602-5 was the only detail found to calculate fill heights for the individual cell classifications. Also, Colorado DOT (CDOT) supplies a maximum fill height for both PVC and HDPE pipe. The maximum fill height for PVC is 65 feet. This further justifies the need and importance of ensuring proper LRFD fill calculations are performed with each of the corresponding cell classifications. After this procedure is completed, WYDOT should specify a fill height encompassing all plastic pipes and cell classes. If deemed necessary, fill heights could be separated between HDPE and PVC pipes. Cell classifications are discussed in greater detail in Chapter 4 in this Report.

3.2 Minimum Fill Height

Maintaining a minimum fill height is necessary when flexible pipes are used. This cover material ensures that externally applied live loads (vehicle loads) will be distributed in such a way as to not damage the pipe below. Generally, the effects of live loads on a buried structure decrease with depth. Soil stress distribution behavior can be calculated using Boussinesq and Westergard methods, among others. Greater covers have been shown to reduce pipe strains, measured pressures around the pipe, and deflections resulting from imposed live loads (Arockiasamy et al., 2006 & Katona, 1988). Therefore, it is necessary to provide adequate cover over flexible pipes to minimize stresses around the pipe in order to mitigate structural deficiencies.

Arockiasamy et al. (2006) conducted field tests on various types of flexible pipes including HDPE, PVC, aluminum pipe, and corrugated steel pipe (CSP). The study investigated the structural performance of the pipes subjected to live loads with varied minimum cover heights. The minimum cover heights were established by maintaining burial depths of 0.5D, 1.0D, and 2.0D, where D is the pipe diameter. Pipe diameters included in this study are 36 and 48 inches. It is important to also note that all tests included a soil envelope composed of highly compacted, poorly graded sand and silt, and the pipe cover did not include additional rigid or flexible pavement.

As seen in Table 4, the highest pressure occurs in two of the HDPE pipes (PE 36a and PE 36b) installed with the least amount of cover (18 inches). The average stress measured at the crown of the pipe was approximately 16.8 psi (116 kPa). The stress recorded in the HDPE pipe with a cover of 24 inches (PE 48) was 6.7 psi (46 kPa). Therefore, the additional 6 inches of cover relieved the stress by more than 60%. As expected, the greatest deflection was also observed in the pipe with the least amount of cover (PE 36a).

Table 4: Soil pressure measured at crown with burial depth of 0.5D (Arockiasamy et al., 2006)

Pipe Designation	PE36a	PE36b	PE48	PVC 36	AL36	ST36
Modulus of Elasticity (MPa)	760 (110 ksi)	760 (110 ksi)	760 (110 ksi)	2,760 (400ksi)	68,950 (10,000 ksi)	199,960 (29000 ksi)
Soil Pressure (kPa)	125 (18.1 psi)	106 (15.4 psi)	46 (6.7 psi)	90 (13.0 psi)	113 (16.4 psi)	72 (10.4 psi)

Arockiasamy, et al. (2006) also states that of all the 36 inch diameter pipes buried at 0.5D, the HDPE pipes exhibited higher loads at their pipe crowns than the stiffer pipes (PVC 36, AL36, and ST36). However, because PE36b resulted in a pipe crown stress of 15.4 psi (106 kPa) and AL36 resulted in a greater stress of 16.4 psi (113 kPa) and has a modulus of elasticity 90 times greater than that of HDPE, this would suggest a weak correlation. A study conducted by Sargand et al., (2008) further investigates the relationship between pipe stiffness and crown pressure. Table 5 provides a clearer comparison of pipe stiffness and measured crown soil pressure under controlled burial conditions. It is important to note that live loads were not investigated in this study. This data indicate that observed soil pressures are sensitive to backfill type, relative compaction, and fill height; however, decreased pipe stiffness does not necessarily result in increased soil pressure.

Table 5: Soil pressure measured at pipe crown - end of initial study (Sargand et al., 2008)

Pipe No.	Pipe Material	Nom. ID (in.)	Moment of Inertia (in^4/in)	Stiffness (lb/in/in)	Backfill: Type	Backfill: RC	Final Fill Height (ft)	Soil Pressure (psi)
1	PVC	30.0	0.051	44	Sand	96	20	14.8
7	HDPE		0.285	71	Sand	96	20	7.3
2	PVC		0.051	44	C. Rock	96	40	21.7
5	PVC		0.11	95	C. Rock	96	40	27
11	HDPE		0.287	80	C. Rock	96	40	11.8
3	PVC		0.051	44	C. Rock	86	20	17
9	HDPE		0.285	71	C. Rock	86	20	8.9
4	PVC		0.11	95	Sand	86	20	15.1
10	HDPE		0.287	80	Sand	86	20	8.3
6	PVC		0.11	95	C. Rock	96	20	13.4
12	HDPE		0.287	80	C. Rock	96	20	9.7

3.2.1 AASHTO / ASTM

AASHTO (2010b) states the minimum cover of the pipe shall “be taken from the top of rigid pavement or the bottom of flexible pavement, shall not be less than that specified in Table 12.6.6.3-1.” A minimum cover of the greater of 12 inches or the ID/8, D/8, B_c/8 is specified by Table 12.6.6.3-1 (AASHTO (2010b)) for plastic, corrugated metal, and reinforced concrete pipe respectively; 12 inches of cover will control in common applications. If reinforced concrete pipe is installed with compacted granular fill under rigid pavement, a minimum cover of nine inches is acceptable. In addition, AASHTO (2010a) provides recommended minimum cover for construction loads for plastic pipe; this is found below in Table 6. ASTM D 2321 minimum cover heights for plastic pipe vary depending on the type of backfill used. The greater of 24 inches or one pipe diameter is specified as the minimum cover if the backfill material used is of class IA or IB material. If class II, III, or IV-A backfill materials are used, the minimum cover specified is the maximum of one pipe diameter or 36 inches.

Table 6: Minimum Cover of Plastic Pipe for Construction Loads (AASHTO 2010a)

	Minimum Cover, in., for Indicated Axle Loads, kips			
Nominal Pipe Diameter, ft	18.0–50.0	50.0–75.0	75.0–110.0	110.0–150.0
2.0–3.0	24.0	30.0	36.0	36.0
3.5–4.0	36.0	36.0	42.0	48.0
4.5–5.0	36.0	36.0	42.0	48.0

Minimum cover shall be measured from the top of the pipe to the top of the maintained construction roadway surface. If unpaved, the surface shall be maintained.

3.2.2 State Specifications

In general, most states require a minimum cover greater than 12 inches. As seen in Table 7, two out of the nine states investigated implement a one foot minimum cover that does not include pavement. In addition, four states specify a minimum cover of at least two feet. These findings show that states have implemented more conservative minimum cover heights than the AASHTO specifications, especially where rigid pavements are used. In addition, states like Colorado and Nebraska also specify greater fill heights during construction, where loads could be greater than the typical AASHTO design truck. However, when comparing the state specifications to ASTM D 2321, it is clear, that the specified minimum cover of ASTM D 2321 is considerably more conservative; dictating greater minimum covers heights than those of the state specifications.

Table 7: Specified Minimum Cover for Flexible Pipe

State	H_{min} (ft.)	Diam. (in)	Measured Distance
AZ	1	All Sizes	Bottom of Pavement
CO	2	12 to 42	Bottom of Pavement
	3	48 to 60	Bottom of Pavement
FL*	1.25	15 to 60	Bottom of Pavement
NE	1	All Sizes	Bottom of Pavement
NY	2	All Sizes	Top of Pavement
OH	1.5	All Sizes	Bottom of Pavement
SD	1	12 to 96	Subgrade cover
UT*	2	18 to 48	Top of Pavement
	D/2	≥ 48	Top of Pavement
WA	2	All Sizes	Bottom of Pavement
WY	1.75-2.75	Varies	Top of Pavement

*Based on Flexible pavement

It should be noted that in general, the previous table summarizes the installations for flexible culvert systems. Arizona, Nebraska, New York, South Dakota, and Washington specify the same minimum cover for all pipe material. Conversely, Colorado, Florida, Ohio, Utah, and Wyoming specify lesser minimum fill height requirements for rigid versus flexible pipe installations. For example, Florida requires granular fill compacted to 100% for rigid pipe installations, and in doing so allows a minimum cover as small as 7 inches in certain applications. More typical fill height requirements for rigid pipe are approximately 18 inches. Wyoming's minimum specified fill height for flexible pipe range from 21 to 33 inches depending on the type of metal pipe used. Although the minimum covers specified by states are somewhat consistent, it would be prudent to conduct calculations to determine the minimum cover using an LRFD procedure. There is a possibility that LRFD live loads could warrant a greater fill height for some plastic culvert systems. When it is necessary to accommodate lower fill heights, adoption of Washington State's approach, which requires concrete pipe of the following classes: 1.5 feet use Class III, 1.0 foot use Class IV, 0.5 foot use Class V, should be considered.

3.3 Bedding and Backfill

As stated previously, flexible culverts rely on the strength of the surrounding backfill for load carrying capacity. Current WYDOT Standard Specifications do not restrict the material used to backfill culverts as long as 95% compaction can be achieved. This approach differs from current AASHTO specifications, which specify backfill materials (according to AASHTO soil classification categories) based on the type of installation. For example, AASHTO (2010a) specifies backfill materials to be A-1, A-2 or A-3 for corrugated metal pipe (CMP); A-1, A-2-4, A-2-5, A-3 for long spans; A-1, A-3 for long spans with 12 feet or more of fill; and A-1, A-2-4, A-2-5, A-3 for plastic pipes. Concrete pipe fill requirements differ depending on the type of installation (Type 1-4) as specified by AASHTO (2010a). A study on the mitigation of settlements over culverts sponsored by WYDOT (Lundvall and Turner, 2001) also recommended requiring the use of more granular backfills or flowable fill. In drafting a specification for a demonstration project using HDPE as an acceptable alternative, ADS, a leading supplier of HDPE pipe, recommended the use of more granular backfill material and stated further that this should be applied to all pipes. Considering all of the above, it is recommended herein that WYDOT should consider placing restrictions on backfill materials for all culvert installations. Such an approach would also level the playing field for other types of pipe culverts and improve the quality of all culvert installations.

Research has shown that the installation of a properly constructed soil envelope is necessary to mitigate deflections and other deficiencies of flexible pipe. "The long-term performance of deeply buried plastic pipe is largely dictated by the stiffness of the soil enveloping the pipe…" (Sargand et al., 2009). It is well documented that improper installation techniques, including use of low quality backfill, can lead to a soil envelope that is not as stiff as adjacent, undisturbed soils. This lack of stiffness results in an increased potential for detrimental effects, particularly when flexible pipes are concerned (e.g., Zhang et al., 2005 & Gassman et al., 2005).

Identification of soil type and structure is necessary for any culvert installation. Certain soil types exhibit more desirable characteristics that make a stiff soil profile easier to construct. Particle size, propensity of compaction, and water ratios are all characteristics that affect the shear strength of a soil envelope. A soil's modulus of elasticity and stiffness is in turn directly proportional to the shear strength of the soil envelope. In addition, higher shear strength increases the ability to dissipate vertical stresses laterally and therefore, reduce stresses observed in the pipe.

3.3.1 Particle Size / Soil Type

Basic soil mechanics classifies soil into two main broad categories: coarse-grained soils and fine-grained soils. Within these categories four additional classifications exist which are defined by particle size. Coarse-grained soils include gravels, and sands and fine-grained soils include silts and clay. ASTM D 2321 further designates particle size by the percentage of weight that is separated by a sieve analysis. Table 8 gives approximate ranges for typical soil types.

Table 8: Approximate Size Range for Soil Types (McCarthy, 2002)

Soil Type	Upper Size Limit	Lower Size Limit
Gravel	Varies from 80 mm up to about 200 mm (3 in. To 8 in.)	4.76 mm (about 0.20 in.) (as determined by a #4 U.S. Standard sieve) or 2.00 mm (#10 U.S. Standard sieve)
Sand	4.76 mm or 2.00 mm (0.2 in. or 0.08 in.)	0.074 mm (0.003 in.) (#200 U.S. Standard Sieve) or 0.050 mm (0.002 in.) (#270 U.S. Standard sieve)
Silt and clay	0.074 mm or 0.05 mm (0.003 in. or 0.002 in.)	None

3.3.1.1 Fine-grained Soil

Clays and silts share similar particle sizes; however, they possess different mineralogical characteristics. Therefore, fine grained soils are differentiated not only by the size of particle, but also by the plastic characteristics of the soil. Clays are derived from rock that has undergone a chemical change. The resulting material is one that can be easily influenced by electric activity and changes in the water content within the soil mass. Clays are plastic, meaning they are able to change shape in the presence of water. In the presence of large amounts of water, clays behave viscously and act more like a liquid. Conversely, as the presence of water decreases, the same soil will behave more like a plastic substance. A range of water content ratios can be determined to identify when the mass transitions from a liquid to a plastic state, semisolid state, and then finally to a solid state. The transition points between these states are the liquid limit, plastic limit, and shrinkage limit and are collectively known as the Atterberg Limits. The measure of the plasticity of a soil mass is known as the plasticity index (PI), which is the numerical difference of the liquid limit and plastic limit. The lower the PI, the less plastic a mass is and therefore exhibits behavior less indicative of a clay soil. Higher PI's correlate to a higher potential for soil instability. In addition, clays derive their shear strength from a physical reaction with water and are described as cohesive soils. The shear strength can vary depending on the water content within a soil mass. Because water content directly affects shear strength, clays are more prone to cause deficiencies in culvert installations.

Silts are formed from sands and gravels that have been physically broken down into smaller particles. Silts, like sands and gravels, do not exhibit plasticity and are less prone to issues with moisture. However, even though silts are similar to sands and gravels, they are more compressible. Silt particles sizes are also smaller, less angular, and therefore typically possess less shear strength.

3.3.1.2 Coarse-grained Soil

As previously discussed, gravels and sands are non-plastic and therefore do not have the potential to swell or expand; making this type of soil ideal for construction of culvert systems. Gravels and sand, like silts, are broken down soils from larger elements such as boulders and cobbles. Their chemical composition is not changed and no decomposition occurs as in clays. Individual particles are predominately angular and therefore possess better shear strength due to the higher frictional resistance generated between particles (measured by the angle of internal friction). Coarse grained soils are dependent on internal friction and normal stress for shear strength, and are referred to as cohesionless soils.

3.3.1.3 AASHTO / ASTM

AASHTO and ASTM soil standards are used interchangeably within studies and specifications. These standards are discussed in the subsequent sections. To provide a basis for comparison and clarity, Table 9, is supplied below. It is important to note this table provides comparison between AASHTO M 145 and ASTM D 2487 soil types. ASTM D 2321 discusses classes of soils used for plastic pipe installations and provides a comparison between itself and ASTM D 2487. Therefore, it would be reasonable to correlate AASHTO M 145 to ASTM D 2321.

Table 9: Approximate Equivalent ASTM & AASTHO Soil Classifications (AASHTO, 2010b)

Basic Soil Type (1)	ASTM D2487	AASHTO M 145
Sn (Gravelly sand, SW)	SW, SP (2) GW, GP sands and gravels with 12% or less fines	A1, A3 (2)
Si (Sandy silt, ML)	GM, SM, ML also GC and SC with less than 20% passing a No. 200 sieve	A-2-4, A-2-5, A4
Cl (Silty clay, CL)	CL, MH, GC, SC also GC and SC with more than 20% passing a No. 200 sieve	A-2-6, A-2-7, A5, A6

1. The soil classification listed in parentheses is the type that was tested to develop the constrained soil modulus values in Table 12.12.3.4-1. The correlations to other soil types are approximate.
2. Uniformly graded materials with an average particle size smaller than a No. 40 sieve shall not be used as backfill for thermoplastic culverts unless specifically allowed in the contract documents and special precautions are taken to control moisture content and monitor compaction levels.

AASHTO (2010a) establishes which types of soil backfill should be used when considering plastic culvert systems. Section 30.3.2 states: "Bedding and structural backfill shall meet the requirements of AASHTO M 145, A-1, A-2-4, A-2-5, or A-3. Bedding material shall have a maximum particle size of 1.25 inch..." These fills are described as stone fragments, gravel and sand (A-1), fine sand (A-3), and silty or clayey gravel and sand (A-2).

ASTM D 2321 recommends Class I, II, and III fills for plastic culvert installations. These fills consist of angular stone, gravels, and sands with some allowance for clays and silts. Class III materials require greater compaction efforts compared to Class I and II. In addition, Class III materials are not recommended where wet trench conditions exist. Class IV-A fills can be used in optimal conditions and with strict construction limits.

Both AASHTO (2010b) and ASTM D 2321 allow the use of backfills with silts and clays. When using these backfills, a reduced design soil modulus is assigned to lower quality backfills as prescribed by Section 12 of AASHTO (2010b), which further defines these soils as SI (sandy silts, ML) and CL (silty clay). In addition, extra considerations must be taken when using A3 backfills (fine sands) that are uniformly graded with an average particle size smaller than a No. 40 sieve, see note (2) in AASHTO Table 12.12.3.4-2, which is depicted in Table 9 above. ASTM D 2321 does not prescribe any design alterations when using silts and clays; however, general recommendations for installations are discussed when using these fills.

3.3.1.4 State Specifications

States included in this study specify the bedding and backfill gradation requirements in two ways. First, states will specify a particular backfill with the agency's own gradation requirements. States which use this method include Arizona, Colorado, New York, Ohio, South Dakota, and Washington. Individual state gradation matrices of select backfills can be found in

Appendix B in this Report. The second method is specifying a backfill from an AASHTO or ASTM standard. States which use this method include Florida, Nebraska, and Utah. For example, Utah requires all plastic pipes to be backfilled with A-1, A-3, A-2-4, or A-2-5 material. In comparison, WYDOT's Standard Specification Section 206.2.2 states "Use existing material for backfill; do not use material with frozen lumps, chunks of highly plastic clay, stones, or other materials that could damage the structure." This description of materials could include a variety of soils which are not suitable for backfill of culvert systems and in general lacks clarity. For example, even though highly plastic clays are excluded, WYDOT does not exclude clays that are low in plasticity, as well as silts. As discussed in greater detail in Chapter 5 in this Report, fine-grained backfill soils (clays and silts) can be highly compressible and may cause roadway settlement in concrete and steel culverts. When considering all flexible pipe systems, especially plastic, these are composite structures which depend greatly on the shear strength of the soil envelope to ensure an adequate design life. Clays and silts cannot consistently provide as high of shear strength as granular soils. Multiple studies and statements included within this study show the importance of specifying granular backfills in lieu of fine grained soils. WYDOT should consider adopting one of the previously discussed methods for specifying backfills; in doing so, this will provide greater clarity, and will help ensure high quality backfill materials are used.

Analysis of state specifications and DOT surveys (Appendix A) show that four of the nine states (Arizona, Florida, New York, and Ohio) specify that a select granular fill be used for the construction of the entire soil envelope in all culvert installations when constructed in a trench situation. Therefore, requiring reinforced concrete pipe (RCP), CSP, and plastic pipe to be installed with granular materials. This is also true when using an embankment method of construction, with the exception of New York. New York allows a lower quality fill from the pipe springline to the pipe cover for concrete pipe. Colorado, Nebraska, and Utah require select granular fills for RCP installations up to the springline then lower quality fill may be used to complete the installation. Table 10 below, is a comparison table summarizing backfill requirement.

Table 10: Backfill Requirements versus Pipe Type and Location Within Soil

Summary of Backfill Requirements vs. Pipe Type and Location Within Pipe Envelope									
	Bedding (Foundation to Pipe Invert)			**Haunch (Pipe Invert to Springline)**			**Pipe Cover (Springline to Crown + 12")**		
Specification	**RCP**	**Metal**	**Plastic**	**RCP**	**Metal**	**Plastic**	**RCP**	**Metal**	**Plastic**
AZ	Granular Fill - Bedding			Granular Fill - Bedding			Granular Fill - Backfill		
CO	Structural Backfill Class 2[1]	Structural Backfill Class 1	Structural Backfill Class 1	Structural Backfill Class 1[4]		Structural Backfill Class 1	Structural Backfill Class 1 or Class 2	Structural Backfill Class 1 or Class 2	Structural Backfill Class 1
FL	AASHTO A-1, A-2-4, A-3			AASHTO A-1, A-2-4, A-3			AASHTO A-1, A-2-4, A-3		
NE	SW (USCS)[2]	GW, GP, SW,SP,GW-GC, SP-SM, GM, GC, SM (USCS)	GW, GP, SW,SP (USCS)	SW (USCS)[2]	GW, GP, SW,SP,GW-GC, SP-SM, GM, GC, SM (USCS)	GW, GP, SW,SP (USCS)	SW, ML, or CL (USCS)	GW, GP, SW,SP,GW-GC, SP-SM, GM, GC, SM (USCS)	GW, GP, SW,SP (USCS)
NY	Select Granular Fill, Select Structural Fill			Select Granular Fill, Select Structural Fill			Select Granular Fill, Select Structural Fill[4]		
OH	Structural Backfill Type 1, 2, or 3			Structural Backfill Type 1, 2, or 3			Structural Backfill Type 1, 2, or 3[5]		
SD	Class C typical, unless specified		Not Specified	Normal or Imperfect Backfill		Not Specified	Normal or Imperfect Backfill		Not Specified
UT	AASHTO A-1, A-3, or SW	AASHTO A-1, A-2-4, A-2-5, A-3		AASHTO A-1, A-3, or SW	AASHTO A-1, A-2-4, A-2-5, A-3		AASHTO A-1, A-2, A-3, A-4, A-5, A-6 or SW, ML, or CL	AASHTO A-1, A-2-4, A-2-5, A-3	
WA	Gravel Backfill			Pipe Zone Backfill	Gravel Backfill		Pipe Zone Backfill[5]	Pipe Zone Backfill[5]	Gravel Backfill[5]
WY	Class B or Class C		Not Specified	Use existing material		Not Specified	Use existing material		Not Specified
AASHTO (2010a)	SW (USCS)	AASHTO A-1, A-2, A-3[3]	AASHTO A-1, A-2-4, A-2-5, A-3	SW (USCS)	AASHTO A-1, A-2, A-3[3]	AASHTO A-1, A-2-4, A-2-5, A-3	SW, ML, or CL (USCS)	AASHTO A-1, A-2, A-3[3]	AASHTO A-1, A-2-4, A-2-5, A-3

1 - If unyielding foundation exist, use structural backfill class 1

2 - Type 1 installation, ML fill may be used in Type 2 installation with reduced fill heights

3- In locations of long-span structures with greater fill heights than 12 feet, only A-1 and A-3 soils allowed

4 - Standard for trench installations, if embankment procedures are used, a lower class of fill may be used if specified by the engineer

5 - Fill above pipe crown is less than 12 inches

Envelope

3.3.1.5 Literature Review

Gassman et. al, (2005) examined existing HDPE culverts in South Carolina. One key element of the study investigated the backfill material (Type I, II, III, and IV from ASTM D 2321) used in 45 HDPE pipe installations and the correlation of deficiencies observed with the different types of backfill. As shown in Figure 2, the number of culverts that passed a mandrel test was directly proportional to the quality of the backfill. For example, 71% of the pipes tested passed the mandrel test when backfilled with Type II material compared to 33% pass rate of culverts installed with Type IV material.

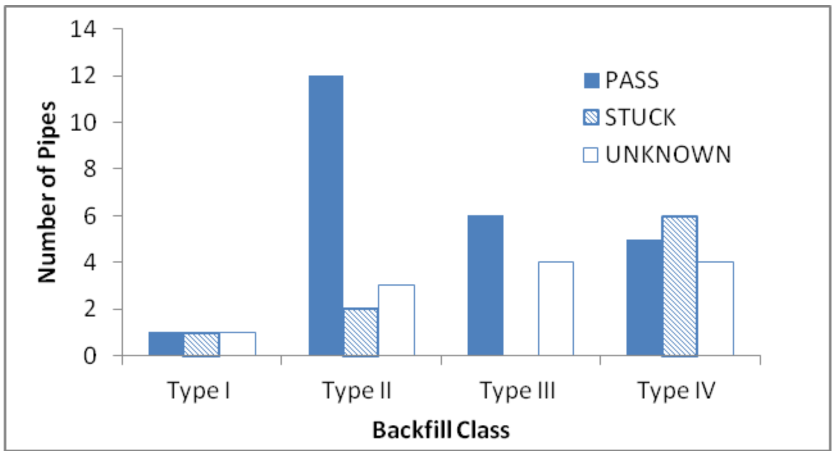

Figure 2: Number of Pipes Passed Mandrel Test vs. Backfill Type (Gassman et al., 2005)

A similar trend exists when examining pipe deficiencies such as cracks, punctures, and bulges. As shown in Figure 3, pipes that were installed with Type II backfill showed no signs of cracks or bulges which can be compared to installations with Type IV backfill where 33% had signs of cracks or punctures.

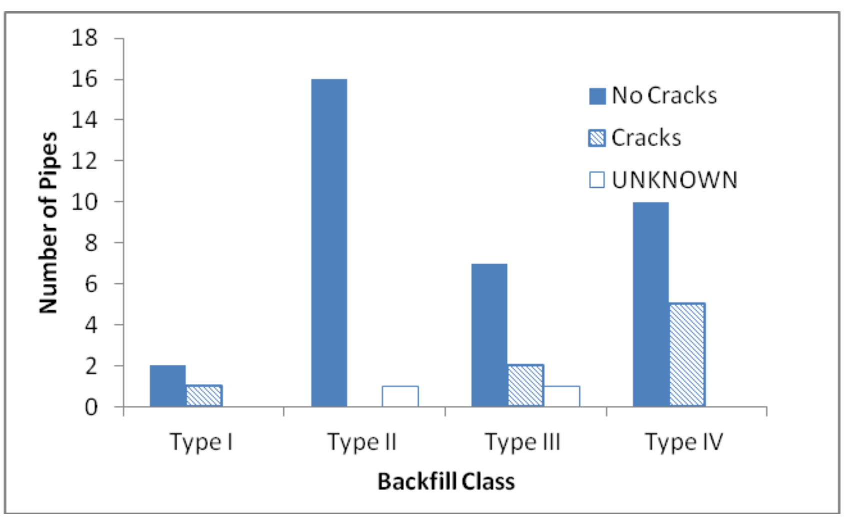

Figure 3: Number of Pipes with Noticeable Cracks vs. Backfill Type (Gassman et al., 2005)

These results display a direct correlation with the performance of HDPE and the type of backfilled used. It is important to note, that significant deficiencies occur when Type IV backfill is used; however, there are reasonable number of instances when no deficiencies were found. These results may suggest HDPE can have adequate performance even when less desirable backfills are used if conditions are optimal and a higher level of care is exercised.

3.3.2 Plasticity

As previously discussed, the plasticity of soil describes the relationship of the water content within a soil and the physical state of the soil (plastic or liquid). Granular soils (sands and gravels) are non-plastic, and when a soil mass is predominantly composed of granular soils, plasticity is a minor concern. Conversely, in soils that have large percentages of fine grained soils, the plastic limit can greatly affect the soil mass and therefore extra consideration should be given when considering its use as backfill. In particular, when soil masses possess large percentages of clays with high plasticity indexes, the potential of significant volume change must be considered.

3.3.2.1 Plasticity effect on Shear Strength

Studies have shown the relationship of the moisture content and plasticity index can significantly affect the corresponding shear strength of fine grained soils and various clays (Sawangsuriya et al., 2009). This study concluded that as the percent moisture content of these particular soils increases, the small-strain shear modulus decreases. In addition, when high levels of moisture where present as the soil mass was compacted, the corresponding shear modulus decreased. Data in this study also shows soils that have a higher plasticity index have less shear strength. This demonstrates the effect of how the moisture content of soil can affect the shear strength. More importantly, clays typically have a higher plasticity index than coarse grained soil and will therefore, have a greater sensitivity to water content and also have a smaller shear modulus.

3.3.2.2 ASTM / AASHTO

As previously discussed, AAHTO (2010a) requires that backfill soil for plastic culverts meet the requirements of AASHTO M 145, A-1, A-2-4, A-2-5, or A-3. Soils A-2-4 and A-2-5 can have a plastic index up to 10 as found in the Soil Classification Chart in AASHTO M 145. ASTM D 2321 allows the use of class IV-A soils; Table 1 from ASTM D 2321 shows these soils can have a plastic index greater than 7 as long as it is above the “A” Line. It is important to note both ASTM and AASHTO do allow the use of some clay mixtures as backfill for HDPE systems. However, these less desirable soils must be installed with strict construction limits and additional consideration. Section 5.3.5 of ASTM D 2321 states:

"Class IV-A materials require geotechnical evaluation prior to use. Moisture content must be near optimum to minimize compactive effort and achieve required density. Properly placed and compacted, Class IV-A materials can provide reasonable levels of pipe support; however, these materials may not be suitable under high fills, surface applied wheel loads, or under heavy vibratory compaction and tampers. Do not use where water conditions in the trench may cause instability and result in uncontrolled water content."

3.3.2.3 State Specifications

Most states included in this study recognize the importance of implementing plasticity limits. Table 11 displays the maximum plastic indexes from the studied state's standard specifications.

Table 11: Specified Plasticity Limits of Backfill

State	P.I. Max	Reference
Arizona	12	AASHTO T 90
Colorado	6	AASHTO T 90
Florida	6	AASHTO T 90
Nebraska	NP	AASHTO T 90
New York	5	AASHTO T 90
Ohio	6	AASHTO T 90
South Dakota	Not Specified	
Utah	NP	AASHTO T 90
Washington	NP	AASHTO T 90
Wyoming	Not Specified	

NP – Denotes Non-plastic

From Table 11, it is clear most states place the maximum PI near 6. These findings can be compared to soil classification A-1 as specified by AASHTO M 145. Therefore, the majority of the states do not allow soils that have large percentages of fines and clays. State DOTs have implemented more strict plastic indexes than those of the AASHTO and ASTM standards. Of the states that specify plastic limits, Arizona is the only state that allows the limit to be greater than 6.

3.4 Compaction

Compaction is a process where energy, usually in the form of vertical pressure, is induced by means of mechanical equipment upon a soil mass. The soil's mass remains constant but the volume decreases, therefore increasing the density of the soil. Granular and sandy soils exhibit better compaction characteristics than silts and clays. A study conducted by Horpibulsuk et al. (2009) concluded that when the same energy is induced upon twenty different soils (i.e., gravels, sands, silts, and clays), the highest unit densities were observed from the gravel and sand samples. The lowest unit density was observed from a sample of bentonite clay. Additional analysis shows the numerical difference of the unit densities of soils when compacted with the lowest energy compared to the highest compaction energy is much smaller in the gravel samples compared to that of the silt and clay samples. This means that the gravel samples reach their maximum unit density with less compaction energy; therefore, less work is needed to compact coarse grained soils than that of fine grained soils.

Table 12 gives a general description of various soil types and their compaction characteristics. Compaction equipment and procedures are necessary considerations given the flexibility of plastic pipe. Some states restrict certain compaction procedures when installing HDPE culverts due to the propensity of damaging the pipe. Therefore, it is important to understand a soil's compaction characteristics in order to avoid difficult and sometimes costly compaction techniques.

Table 12: **Soil Compaction Characteristics (McCarthy, 2002)**

General Soil Description	Unified Soil Classification	Compaction Characteristics
Sand and sand-gravel mixtures (no silt of clay)	SW, SP, GW, GP	Good
Sand or sand-gravel with silt	SM, GM	Good
Sand or sand-gravel with clay	SC, GC	Good to fair
Silt	ML	Good to poor
	MH	Fair to poor
Clay	CL	Good to fair
Organic soil	CH	Fair to poor
	OL, OH, PT	Not recommended for structural earth fill

3.4.1 Compaction Effects on Shear Strength

As previously discussed, the normal force induced upon a soil mass from compaction is directly proportional to the shear strength. Soil masses that are highly compacted exhibited greater shear strength than masses which are loosely compacted. In general, when a soil mass is compacted, individual particles are forced together resulting in a higher degree of mechanical interlock. This results in increased friction between particles. Therefore, the normal force or energy induced upon a soil mass during compaction is proportional to the shear strength of the mass. Highly compacted soils will also have a higher modulus of elasticity. Soils that require less compaction effort in general have larger particles size; these include gravels and sand with little fines. Soils with large percentages of sands, fines, and silts are more difficult to compact and therefore will exhibit lower stiffness.

3.4.2 AASHTO / ASTM

AASHTO (2002) makes the following statement: “A minimum compaction level of 90% standard density per AASHTO T99 shall be achieved.” ASTM D 2321 prescribes various compaction limits based on the type of backfill intended to be used. If the design soil backfill is Class I or II, a minimum density of 85% is allowed, Class III 90%, and Class IV-A 95%.

3.4.3 State Specifications

States included in this study generally specify that compaction limits shall meet the requirements of AASHTO T 99 for determining the relative compaction of the backfill for culvert installations. In general, all states are in agreement and specify the compaction limits from 90 to 96 percent. Colorado’s standard specification bases the level of compaction on the height of fill. Meaning, they will allow greater fill heights if a higher relative compaction of the backfill is achieved for plastic pipe installations. Table 13, displays the individual states and the relative compaction they specify.

Table 13: Specified Compaction of Backfill for Culverts Installations

State	**% R.C.**	**Reference**
Arizona	95	AASHTO T 99
Colorado	90-95	AASHTO T 99
Florida	95	AASHTO T 99
Nebraska	95	AASHTO T 99
New York	95	AASHTO T 99
Ohio	96	AASHTO T 99
South Dakota	95	AASHTO T 99
Utah	90	AASHTO T 99
Washington	95	AASHTO T 99
WY	95	AASHTO T 99

It is important to note that none of the states allowed a compaction limit below 90% which is consistent with the AASHTO Construction Specifications. The majority of the states implement a minimum compaction limit of 95%, suggesting the state DOTs require more strict standards than the AASHTO limits prescribed.

3.4.4 Literature Review

Studies have shown (e.g., Talesnick et al., 2011 & Webb et al., 1996) that the amount of compaction significantly affects the amount of vertical deflection observed in flexible pipes. Pipe deflections measured in the Talesnick study showed that pipe which was installed with highly compacted soil were 70% less than installations with loosely compacted soil. This result is further illustrated in studies by Sargand et al., (2008) discussed below, and is also consistent with NCHRP 631.

One of the most extensive full-scale tests of plastic pipe was conducted by Sargand et al. (2008). This study included 18 pipes, (6 PVC and 12 HDPE) of various diameters installed with different backfill types and compaction levels. Deflections were then measured over the course of five years under two fill heights (20 and 40 feet). Table 14 and Table 15 provide a representative example of the resulting vertical and horizontal deflections. These results demonstrate that pipe deflections are inversely proportional to the level of relative compaction. Furthermore, when comparing pipes number 1 and 4, it is important to note the significant difference in the modulus of elasticity and stiffness. These pipes were installed in very similar conditions and, even though pipe 4 is more than two times stiffer than pipe 1, the maximum deflections occurred in pipe 4 where the soil envelope was compacted to a relative density of only 86%. These results again demonstrate that the performance of a flexible pipe culvert system is affected more by the stiffness of the soil envelope and installation procedures than the mechanical properties of the pipe itself.

Finally, by looking at the differences of the horizontal and vertical deflections, plastic pipes installed in lower compacted envelopes with sand backfill deflect more than those backfilled with crushed rock. This would suggest that plastic pipes installed with sand envelopes create a more sensitive system than that of crushed rock envelopes, and when the envelope's particle size decreases, the propensity of structural deficiencies increase if not installed properly. This is consistent with Webb et al., (1996), where the authors noticed a similar trend and concluded the following:

> "Although acceptable pipe performance can be achieved with the silty sand, the sensitivity to poor installation practices with such backfill is increased, suggesting the need for greater quality control when such backfill materials are specified."

Table 14: Results of Vertical Deflection – 30” Diameter, 20 ft. Cover (Sargand et al., 2008)

Pipe No.	Pipe Material	Modulus of Elasticity (in^4)	Stiffness (lb/in/in)	Backfill:		Vertical Deflection (%)			
				Type	RC	End of Construction	1 Year Later	2 Years Later	5 Years Later
1	PVC	0.051	44	Sand	96	-0.81	-0.86	-1.04	-1.18
4	PVC	0.11	95	Sand	86	-1.27	-1.72	-1.85	-2.07
3	PVC	0.051	44	C. Rock	86	-1.7	-2.39	-2.42	-2.45
6	PVC	0.11	95	C. Rock	96	-0.8	-1.13	-1.23	-1.35
7	HDPE	0.285	71	Sand	96	-0.78	-0.88	-0.9	-1.13
10	HDPE	0.287	80	Sand	86	-3.49	-4.73	-4.75	-4.87
9	HDPE	0.285	71	C. Rock	86	-2.1	-2.44	-2.55	-2.46
12	HDPE	0.287	80	C. Rock	96	-1.43	-2.15	-2.27	-2.17

Table 15: Results of Horizontal Deflection – 30” Diameter,20 ft. Cover (Sargand et al., 2008)

Pipe No.	Pipe Material	Modulus of Elasticity (in^4)	Stiffness (lb/in/in)	Backfill:		Horizontal Deflection (%)			
				Type	RC	End of Construction	1 Year Later	2 Years Later	5 Years Later
1	PVC	0.051	44	Sand	96	.40	.56	.66	.59
4	PVC	0.11	95	Sand	86	.75	.94	.95	.89
3	PVC	0.051	44	C. Rock	86	1.21	2.27	2.28	2.28
6	PVC	0.11	95	C. Rock	96	.98	1.77	1.8	1.81
7	HDPE	0.285	71	Sand	96	.09	.15	.14	.13
10	HDPE	0.287	80	Sand	86	2.35	2.98	2.97	2.99
9	HDPE	0.285	71	C. Rock	86	.58	1.13	1.05	1.18
12	HDPE	0.287	80	C. Rock	96	.63	.67	.58	.62

3.5 Controlled Low-Strength Material

Controlled low-strength material (CLSM) is an alternate to traditional trench and embankment methods that use soil backfill for pipe support. In lieu of using soil as backfill material, CLSM is widely specified as an alternate method of construction. As defined by Farrag (2011a), “Controlled low-strength material (CLSM) also known as flowable-fill, is a self-compacted cementitious material primarily used to replace excavated soil. The components of CLSM are cement, aggregate, water, and fly ash, with an occasional use of admixtures…” Like concrete, the ratios of the previously mentioned components can significantly affect the characteristics of CLSM, including flowability, initial and final compressive strength, and setting time. NCHRP 597 states that the two most important characteristics for fresh and hardened CLSM are flowability and compressive strength respectively. Other characteristics of fresh CLSM include segregation and bleeding, hardening time, and subsidence. Additional characteristics for hardened concrete include excavatability, permeability, shear strength, and consolidation among others. These characteristics are of importance to engineers when considering installation, support, construction schedules, and future excavation of buried culverts.

3.5.1 Materials

In addition to the materials mentioned above, NCHRP 597 states the following are the constituents used in the mixture: Portland cement, supplementary cementitious materials, aggregates, water, chemical admixtures, and other materials. According to NCHRP 597 some materials need not to be analyzed with fine detail; many types of aggregates such as concrete sand, foundry sand, bottom ash, gravel, and crushed stone have been used successfully in CLSM mixes. NCHRP 597 also states that products like foundry sand are commonly disposed of in land-fills. This aggregate has been successfully used in CLSM mixtures and in doing so has reduced the demand on impacted land-fills. Additionally, water appears to not require special attention; "As a general rule, any water that is suitable for concrete will work well for CSLM, including recycled wash water for ready-mix concrete trucks" (NCHRP 597). However, Portland cement and supplementary cementitous materials (fly ash) should be given extra consideration. A common concern with use of CLSM is the mix can have greater compressive strengths than expected which makes future excavation difficult. Use of fly ash in mix designs has been shown to contribute to difficult long-term excavatability (Farrag, 2011a). These results are consistent with a University of Texas-Austin field test as presented by NCHRP 597. Table 16 and Table 17 summarize the mix designs used in the study and findings of direct and indirect measurements discussing the difficulty of manual excavation of various mixtures of CLSM.

Table 16: Mixture proportions for excavation study (NCHRP 597)

Mixture	Type I Cement (kg/m^3)	Fly Ash Type	Fly Ash (kg/m^3)	Concrete Sand (kg/m^3)	Water Content (kg/m^3)	Air Content (%)	Flow (mm)	Mixture Temperature (℃)	Density (kg/m^3)
Flash	0	Class C	224	1672	165	4.0	190	35.2	2179
A1	30	-	0	130	130	29.5	200	33.6	1539
A2	60	-	0	130	130	28.5	220	34.5	1539
PASTE	60	Class F	1195	485	485	1.0	420	42.5	1795
F1	30	Class F	180	175	175	2.25	100	36.8	2051
F2	60	Class F	180	175	175	2.5	140	35.2	2083

"-" = not used

Table 17: Summary of Excavatability of Various CLSM Mixtures at 300 Days (NCHRP 597)

Methods[a]	Flash	A1	A2	Paste	F1	F2
Round-Head shovel	Nearly impossible	Easy	Easy	Nearly impossible	Impossible	Impossible
Square-head shovel	Impossible	Easy	Easy	Impossible	Impossible	Impossible
Pick	Difficult	Easy	Easy	Difficult	Difficult	Very difficult
DCP (mm per blow)	0.2	12.5	5.6	0.3	0.05	Not penetrable
GeoGauge stiffness (MN/m)	41.1	13.7	24.7	29.8	45.8	41.3
Compressive strength[b] (kPa)	7299	86	446	7156	3934	8637
Tensile strength[b] (kPa)	1297	12.4	71.1	761	454	953
Fog room RE[c]	-	0.2	0.8	2.3	2.5	3.4
Field RE[c]	4.9	0.3	0.8	3.6	3.4	4.8
Kelly ball (cm)	4.1	12.7	11.4	4.4	3.5	No dent
Backhoe	Difficult	Very easy	Easy	Difficult (but possible)	Very difficult	Very difficult (nearly impossible)

[a]All testing performed 300 days after trench placement unless otherwise noted.

[b]Cylinders stored for 300 days on site prior to testing.

[c]RE is based on 28-day compressive strength

Finally, components of CLSM which require special attention are chemical admixtures. NCHRP 597 states "Air-entraining agent is the most commonly used chemical admixtures… CLSM with relatively high air contents include low density, improved insulation properties, reduced segregation and bleeding, decreased water and /or cement content, improved frost resistance, and a lower material cost." A concern when using CLSM is the backfill is susceptible to freeze thaw. Farrag (2011a) concluded air-entrained mixtures displayed better freeze thaw durability. Also, mixtures which had higher fly ash content were more susceptible to frost heave and corrosion.

3.5.2 Literature Review

Research suggests that CLSM use as a backfill has significant advantages to conventional soil backfill systems; major benefits include construction and pipe performance benefits. NCHRP 597 identified many benefits when using CLSM. Key factors are summarized below:

- Reduced labor and equipment cost (due to self-leveling properties and no need for compaction).
- Faster construction.

- Ability to place material in confined spaces and therefore smaller trench widths are possible.

In addition, Masada & Sargand (2004) suggests that “CLSM can envelope the pipe completely and provide an ideal installation condition (i.e., perfect haunching).” The effect of haunch support is discussed in further detail later. Masada & Sargand (2004) conducted field and laboratory experiments which investigated financial and installation factors of a pipe system installed with CLSM. The field test included a HDPE pipe system installed with three different types of CLSM mixes; the pipes were then loaded with hydraulic cylinders while deflection and pipe pressure were measured. The authors make comparisons of a similar test they performed with HDPE pipe installed in granular soil backfills, and conclude that pipes which were installed with CLSM performed better than the granular backfill systems, if the ultimate strength of the envelope was not exceeded. Additional analysis of (Webb et al., 1996) test results also makes this conclusion; noting the initial measured HDPE pipe deflections were positive (deflected upwards). The final deflection measurements were approximately equal to zero. This suggests that the pipe did not deviate from its original shape. Webb et al. (1996) concludes, “Pipe tests with controlled low-strength material for backfill performed very well.” An important construction parameter worth noting is both studies installed the pipe in a trench width that was equal to the pipe diameter plus a clear distance of 12 inches on each side of the pipe. Although both tests show the benefits of using CLSM as a backfill, they also acknowledge that flotation must be considered during construction and is a potential problem.

Plastic pipe is relatively light compared to its traditional counterparts. Although, this can be considered a benefit when installing the pipe due to the ease of handling allowing for quick installation; the low density compared to the CLSM backfill can cause the pipe to be lifted from its bedding. Manufacturers and DOT engineers acknowledge pipe floatation can impose a difficulty in construction. Masada and Sargand (2004) suggest this becomes less of a concern when using “common sense” measures to counteract the effect. This study used temporary restraints such as styrofoam blocks and sand bags to maintain horizontal and vertical alignment respectively. A notable difference between the installation procedures in the two studies was the lift thickness used in construction. The Masada & Sargand (2004) installation consisted of an initial lift thickness of approximately 24 inches with no floatation problems. The mix was described as relatively dry and could have resulted in less hydrostatic uplift forces. The Webb et al. (1996) installation placed an initial lift thickness of 6 inches, followed by a secondary lift of approximately 12 inches. In this study, the steel pipe was lifted from its bedding; oddly, the plastic pipe did not have issues with floatation. The authors suggest this could have been due to the deeper corrugations in the plastic pipe. A technical note provided by Hancor Incorporated, recommends lifts for CLSM should be placed in relatively small (4 inches to 22 inches depending on the pipe diameter) incremental lifts. However, Hancor Incorporated states “one continuous lift may be used provided flotation restraints have been properly designed and installed.” (Hancor, 2009)

NCHRP 597 provides recommendations for CLSM characteristics, testing procedures, and additional requirements for specifying CLSM as a backfill material. A summary of these requirements are listed below:

- Slump requirements – 7 to 10 inches (203 to 254 mm) as tested in accordance with ASTM D 6103. Wyoming specifies a minimum of 6 inches.
- 28 day compressive strength – Maximum 100 psi (0.7 MPa), minimum 29 psi (0.2 MPa) as tested in accordance with ASTM D 4832 with alterations to test. Wyoming specifies a minimum of 50 psi and maximum of 100 psi.
- Air Content – Minimum of 6% by volume as tested in accordance with ASTM C 231 with alterations to test. Wyoming specifies a maximum of 15%.
- Trench width – Equal to the outside diameter plus 12 inches for pipes less than 41 inches in diameter or the outside diameter plus 24 inches for pipes greater than 41 inches.
- Place CLSM in lifts such that the hydrostatic pressures do not compromise the integrity of bulkheads, formwork, trench or other soil walls, or other temporary or permanent structures.
- Hardening time is described as the time it takes for a person of average weight and shoe size to be able to walk on the CLSM without creating significant (greater than 3 mm or approximately 1/8 inch) indents in the surface. This time typically takes about 3 to 5 hours, but depending on the construction requirements 1 hour is possible. After this time, construction may continue and additional lifts may be placed.
- Pavements can be placed over CLSM when the compressive strength is 29 psi (0.2 MPa)
- A minimum compressive strength in psi shall be specified to provide structural resistance to traffic loads.

Other benefits can be seen when using CLSM as backfill for metal culvert systems. In addition to providing superior pipe support, CLSM has been shown to reduce corrosion potential in metal culverts known to be particularly susceptible to deterioration. Farrag (2011b) found the corrosion rates of steel specimens installed in CLSM were considerably lower than those installed in envelopes of sand and of silt-clay backfills. Other notable findings show that CLSM mixtures with fly ash tend to increase the corrosion rate when compared to mixtures only using cement. Corrosion rates were also lower in specimens installed using air entrained mixtures. Finally, Lundvall and Turner (2001) note due to the remoteness of some culvert installation sites in Wyoming and a possible lack of WYDOT construction inspectors, inspection can be difficult for this agency. Therefore, the proven superior installation results and characteristics may warrant the cost associated with CLSM to provide extended culvert and roadway design lives.

3.5.3 AASHTO / ASTM

Section 30 of AASHTO (2010a) allows the use of CLSM for pipe backfill and bedding. In addition, it specifies that consideration must be given to floatation by suggested use of restraints, weighting, or placement technique. Plastic Pipe installed in CLSM may have a reduced trench width equal to a minimum of the outside diameter of the pipe plus 12 inches, thus only requiring a clearance of 6 inches on each side of the pipe. However, when this method is used, AASHTO (2010a) states that all joints shall have gaskets; thus cost considerations may warrant further discussion.

3.5.4 States Specifications

States included in this study typically specify a recommended batch design for CLSM within their specifications; in doing so, they also allow contractors to submit a proprietary design for the agency's review. The contractor's design should be submitted prior to the intended date of installation to give the agency ample time to review the design. It was common for states to require the contractor to submit a batch or delivery ticket for each load of CLSM placed; this is also consistent with recommended practice prescribed by NCHRP 597. In addition to recommended batch designs, states typically included a range of allowable compressive strengths of the cured CLSM within their specification. Only a few of the states specified additional requirements for slump and air content limits. Of the states included in this study, Wyoming was the only state to specify limits for slump, compressive strength, and air content for CLSM design. Other requirements found in state specifications include only two states specifying minimum trench widths equal to the outside pipe diameter plus 12 inches (Colorado), and the outside pipe diameter plus 6 inches (New York). Colorado was also the only state to specify a maximum lift thickness of 3 feet.

3.6 Construction

In the previous sections, the identification and study of soil conditions considered for use as bedding and backfill were discussed. In this section, best practices regarding installation procedures and techniques will be identified.

Two basic culvert installations are predominantly used within road construction: trench and embankment construction. While, the final installation procedures are similar; the difference is in the early stages of construction. Embankment installation is required when the proposed final roadway elevation is above the existing grade. Therefore, the roadway will be constructed in lifts to the proposed grade. Trench installations occur when the existing grade is approximately the same as the new proposed roadway elevation. When this occurs, excavation of existing grade commences and forms a trench to allow space for underground utilities.

Both installation types require determination of the horizontal distance measured from the edge of the pipe to the limit of pipe backfill. This dimension is critical in developing the stiffness and strength of the soil envelope. This distance is also necessary to provide adequate space for safe and proper installation and compaction. This distance is defined as the minimum trench width. After the minimum trench width is determined, design and construction of the soil envelope should be addressed.

A soil envelope consists of a proper foundation, bedding, and backfill surrounding the pipe. The particular sections of the soil envelope are summarized in Figure 4. Existing natural soil may or may not be deemed as an acceptable foundation by the engineer. Bedding is a supporting layer of fill between the foundation and the invert of the pipe. A special section of the bedding, known as the central bedding, cradles the pipe and has different compaction requirements than the rest of the bedding section. Backfill is the remaining portion of the soil envelope which starts from the bedding and extends over the pipe crown to a required minimum height. The backfill is installed in prescribed maximum lift thicknesses and then compacted to a specified relative density. Within the backfill zone, a subsection known as the haunch, like the central bedding portion, has special considerations which must be accounted for.

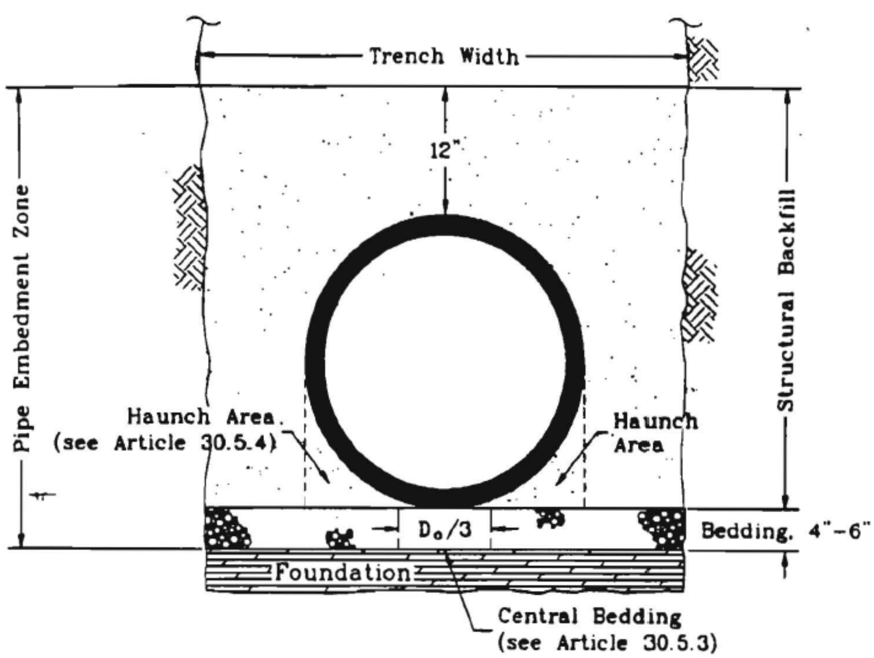

Figure 4: Typical Soil Envelope Geometry (AASHTO, 2002)

3.6.1 Trench Construction

The trench width is determined by the engineer to ensure that adequate space is provided for the contractor to lay and maneuver the pipe to meet horizontal and vertical slope requirements and be able to accommodate compaction equipment to meet the project compaction specifications. In addition, investigation of existing trench walls should be conducted to determine the slope stability to ensure workers' safety.

Adequate trench width can influence the performance of flexible pipe systems; measured stresses occurring at the trench wall interfaces can vary significantly depending on the width of the trench (Web et al., 1996). In a study which investigated full-scale pipe installations of RCP, CSP, and HDPE systems with varying trench widths in addition to other variables, Webb et al. (1996) found that as the final layer of backfill was installed, the springline of the flexible pipes deformed horizontally thus inducing lateral pressure against the soil envelope. These findings are consistent with results found by Masada & Sargand (2007). The authors of the Webb study concluded the pipe will continue to horizontally deflect until the lateral pressure is at equilibrium either within the soil envelope or at the trench wall; testing showed the later occurring in all cases. Webb et al. (1996) discussed this and concluded "This suggests that more stress is developed (in the backfill) in the wide trench during side filling and that less support is required at the trench wall interface because of the greater distance from the pipe." As previously discussed, the importance of selecting backfill which can develop higher shear strengths (e.g., gravels vs. silts) is necessary when using flexible pipe systems; therefore, developing greater lateral soil resistance and in doing so minimizing the pressures observed by the trench wall.

3.6.1.1 AASHTO / ASTM

Section 6.3 of ASTM D 2321 states "Minimum width shall be not less than the greater of either the pipe outside diameter plus 16 in. or the pipe outside diameter times 1.25, plus 12 in." Similarly, AASHTO (2010a) states "Minimum trench width shall not be less than 1.5 times the pipe outside diameter plus 12 inches." Comparing the two standards, it is clear the AASHTO specifications specify greater minimum trench widths than that of ASTM D 2321. These results are summarized in Table 18.

Table 18: Specified Minimum Trench Widths

Nominal Pipe Diameter (inches)	Summary of the Minimum Trench Widths (inches) as Specified by:										
	AZ	CO	FL	NE	NY	OH	SD	UT	WA	WY	ASTM	AASHTO
12	24	48	36	x	36	27	36	x	24	60	28	30
15	27	51	39	31	45	31	39	x	27	63	31	34.5
18	30	54	42	36	54	35	42	44	57	66	34.5	39
24	36	60	48	42	72	42	48	55	66	72	42	48
30	42	66	54	50	78	50	54	66	75	78	49.5	57
36	48	72	60	58	84	57	60	77	84	84	57	66
42	54	78	66	90	90	65	66	88	93	90	64.5	75
48	72	84	72	96	96	72	72	98	102	96	72	84
60	84	96	84	108	108	87	84	120	108	108	87	102

3.6.1.2 State Specifications

The results from Table 18 suggest that there is little to no correlation between state, AASHTO, and ASTM Specifications. It is clear some states, like Arizona, have smaller minimum trench width requirements when compared to the ASTM and AASHTO limits. The converse is true when observing the much larger minimum trench widths prescribed by Utah and Wyoming.

In general, the previous table summarizes the installations for flexible culvert systems. It should be noted Arizona, Colorado, Florida, Ohio, South Dakota, and Washington specify the same trench widths for all pipe material. Conversely, Nebraska, New York, Ohio, and Utah specify smaller trench widths for rigid versus flexible pipe installations. Typical trench widths for concrete culverts as specified by Nebraska, Utah, and AASHTO (2010a) are equal to the outside diameter of the pipe plus one sixth of the outside diameter on each side of the pipe. AASHTO (2010a) installation details for RCP pipe are included in Appendix B.

3.6.2 Embankment Construction

Embankment construction requires lifts to be installed to a specified elevation for roadway construction; the area of this construction is known as the embankment. With regard to culvert installations, the minimum width of the embankment is usually specified as a function of the outside pipe diameter (O_D or B_c). For example, WSDOT (2010b) states “the embankment shall be constructed as in the Plans or designated by the engineer for a distance each side of the pipe location of not less than 5 times the diameter.” The embankment must be constructed to a required height, which is also usually proportional to the pipe’s diameter; at least ½ of the pipe's diameter is typical for rigid pipes. With regards to flexible pipe, the embankment is typically constructed above the pipe crown; this is due to the fact that most states require a select granular fill for flexible pipes above the pipe crown. However, Ohio DOT (ODOT) allows the embankment height to be constructed up to a level of ½ the pipe's diameter for all pipe materials. Then the limits of the select granular fill extend horizontally outward from the sides of the trench width. This allows for all pipe materials to be constructed with granular fill above the pipe crown without requiring the embankment to be constructed to the full height of the pipe. The reader should review ODOT's Standard Detail DM-1.4 for clarification attached in Appendix B. A summary of the required embankment fill heights and total embankment widths are shown below in Table 19 and Table 20 respectively. After the embankment is constructed, a trench will then be cut back into the embankment for pipe installation. If the pipe is not installed with a full embankment method, meaning the embankment is constructed to an elevation greater than the pipe diameter, the remainder of lifts will then be constructed to the prescribed final height. Standards details from state specifications further illustrate this method found in Appendix B.

Table 19: Specified Embankment Construction

Nominal Pipe Diamater (inches)	Summary of the Minimum Embankment Widths (inches)									
	AZ	CO	FL	NE	NY	OH	SD	UT*	WA	WY
12	132	132	48	x	48	60	60	x	132	Not Specified
15	165	165	60	45	48	75	75	x	165	
18	198	198	72	54	54	90	90	54	198	
24	264	264	96	72	72	120	120	72	264	
30	330	330	120	90	90	150	144	90	330	
36	396	396	144	108	108	180	144	108	396	
42	462	462	168	126	126	210	144	126	462	
48	528	528	192	144	144	240	144	144	528	
60	660	660	240	180	180	300	144	180	660	
Summary of the Minimum Embankment Trench Widths (inches)										
12	72	48	36	x	36	27	36	x	24	Not Specified
15	75	51	39	45	45	31	39	x	27	
18	78	54	42	54	54	35	42	44	57	
24	84	60	48	72	72	42	48	55	66	
30	90	66	54	78	78	50	54	66	75	
36	96	72	60	84	84	57	60	77	84	
42	102	78	66	90	90	65	66	88	93	
48	108	84	72	96	96	72	72	98	102	
60	120	96	84	108	108	87	84	120	120	

*Metal only, does not allow embankment construction for plastic pipe

Table 20: Specified Embankment Height

Embankment Height	
AZ	Min. 1’-0” above pipe crown
CO	MIN 0.3*O_D (B_c)
FL	Min. 2'-0" above pipe crown
NE	Min. 1’-0” above pipe crown
NY	Min. 1’-0” above pipe crown
OH	Minimum of 1/2 O_D
SD	Min. 2'-0" above pipe crown
UT	Min. 1’-0” above pipe crown
WA	Minimum of 1/2 O_D
WY	Not Specified

In general, the previous two tables summarize the installations for flexible culvert systems. It should be noted, Arizona, Colorado, Florida, and Washington specify the same embankment trench widths for all pipe material. Conversely, Nebraska, New York, Ohio, and Utah specify smaller trench widths for rigid versus flexible pipe installations. It is clear there is significant variation between the minimum embankment widths specified by the state agencies. AASHTO (2010a) recommends a minimum embankment width equal to three times the outside pipe diameter for concrete pipe only. Since concrete is a rigid pipe and needs little embankment width to develop pipe stability compared to flexible pipes, it appears this width may not be suitable for metal and plastic pipes. FLH Standard Details 602-3 and 602-7 specifies a minimum embankment width of five times the outside pipe diameter for flexible and rigid pipes, which is consistent with ODOT. Other definitive research was not found that proves the adequacy of a minimum embankment width; therefore, additional research in this area is warranted. When the readers should compare Table 18 with Table 19 they will notice Arizona and Nebraska specify greater embankment trench widths than the typical trench installations.

3.6.2 Pipe Foundation

The engineer is to determine if the existing soil is suitable for the culvert system; a proper foundation can affect the performance and life of the system. ASTM D 2321 and AASHTO (2002) identify two conditions where additional consideration must be taken if present. The first is rock and unyielding materials. Unyielding foundations do not allow uniform pressure around the pipe to develop. Instead, a loading more indicative of a single point load at the invert of the pipe is noticed. When unyielding foundations are encountered, a thicker bedding layer is necessary. AASHTO (2002) and ASTM D 2321 refer to this as installing a “cushion of bedding." The second condition is an unstable trench bottom. ASTM D 2321 describes this condition when the foundation is unstable or shows a "quick" tendency. AASHTO and ASTM recommend additional excavation and backfill. ASTM D 2321 further discusses when severe conditions exist; the engineer should consider the use of geotextiles or a foundation system of piles.

Bedding is typically specified to be 4 or 6 inches thick, as shown in Table 21. Where conditions of unyielding foundations exist an additional "cushion bedding" of 2 inches is prescribed by AASHTO (2002) and ASTM D 2321, which results in a total bedding thickness of 6 inches. AASHTO (2002) states the central bedding, which is equal to one-third of the outside diameter of pipe (refer to Figure 4 above) should be "loosely placed" while the remaining portion should be compacted to unit densities discussed in previous sections.

Most states specify 4 inches of bedding for standard installations; however, a more conservative minimum bedding of 12 inches is required for unyielding foundations by several states. State specifications, ASTM D 2321, and AASHTO (2002) require that the bedding be shaped to provide stable uniform support to prevent distortion, damage to, or displacement of the pipe. Also, recesses in the bedding are required to accommodate protrusions such as bell ends in a bell and spigot joint system.

Table 21: Specified Minimum Bedding Thickness

Specification	Typical Bedding Thickness (inches)	Unyielding Foundation Bedding Thickness (inches)
Arizona	6	12
Colorado	0 (if not rock)	12
Florida	4	12
Nebraska	6	6
New York	0.1D (min.) not less than 3	12
Ohio	6	6
South Dakota	0.15D (min) not less than 3	Not Specified
Utah	4	6
Washington	6	6
Wyoming	6	Not Specified
ASTM D 2321	4	6
AASHTO	4	6

In general, the previous table summarizes the installations for flexible culvert systems. It should be noted, Arizona, Florida, and Washington specify the same bedding thickness for all pipe material. Conversely, Colorado, Nebraska, New York, Ohio, and Utah specify a thinner bedding thickness for normal and unyielding foundations in rigid pipe installations, typically 3 and 6 inches respectively. AASHTO (2010a) states bedding thickness for concrete culverts shall be Bc/24 not less than 3 inches for normal foundations and Bc/12 not less than 6 inches for unyielding foundations. It is important to provide appropriate bedding conditions for rigid pipes to avoid large stress concentrations.

3.6.4 Haunch Support

The haunch backfill section begins at the top of the bedding and extends vertically to the springline of the pipe with the horizontal limits being equal to the pipe diameter (see Figure 4 earlier). The haunch zone is one of the most important areas of the soil envelope with regard to a pipe's design life. The lack of adequate compaction within the haunch zone can lead to irregular strain distributions around the pipe with the largest strains occurring between the invert and springline of the pipe (Rogers et al., 1996). ASTM D 2321 states: "Lack of adequate compaction of embedment material in the haunch zone can result in excessive deflection, since it is this material that supports the vertical loads applied to the pipe." These statements are consistent with other studies that have shown the lack of haunch support and compaction directly influences the deflections observed in flexible pipe systems (Webb et al., 1996 and NCHRP 631). NCHRP 631 reported on two 24 inch diameter HDPE pipes which were installed in a laboratory test apparatus, one experiment thoroughly compacted the haunch area, and the second test did not implement proper compaction of the haunch. As expected, results from the study showed the maximum vertical deflection occurred in the pipe installation where inadequate haunch support was provided with a value of -0.50 inches (-12.6 mm). This can be compared to a specimen where adequate haunch support was implemented, which resulted in a deflection of -0.18 inches (-4.5mm).

Four out of the nine states included in this study discuss the term "haunch" within their specification (Arizona, Florida, Ohio, & Washington). In general, these standard specifications state that backfill shall be placed to provide adequate support under the haunch areas. Also, the soil must be compacted to the prescribed density. Standard specifications further suggest compaction equipment cannot be easily maneuvered in the haunch area without causing damage or distortion of the pipe, and therefore should be manually compacted which can result in difficulty with regard to achieving the necessary soil densities. Additional recommendations found within state specifications suggest the haunch area should be compacted using hand tampers and spud bars; ODOT (2010) states the following:

> “Provide compaction equipment that compacts the material under the haunch of the pipe. If the compaction equipment cannot fully compact the material under the haunch, supplement the compaction equipment by using shovel slicing, spud bars, or mechanical spud bars to compact the material under the haunch of the pipe. Use shovel slicing and spud bars in conjunction with the compaction operations to compact the material and to manipulate the material under the haunch of the pipe.”

ASTM D 2321 states that the haunch material should be placed and compacted prior to the remaining embedment in the pipe zone. Finally, when compacting the haunch area up to the springline, there is a reasonable concern that the pipe may be lifted off the bedding layer and precautions must be taken to prevent this from happening. AASHTO (2002) discusses the backfill material should be compacted by hand and special compaction techniques should be used.

Since the haunch area of the backfill has been shown to significantly affect the shape and deformation of the pipe coupled with the difficulty of properly installing the backfill; this area should be thoroughly inspected to ensure the installation is adequate.

<u>3.6.5 Backfill Lift Thickness</u>

Lifts, or sometimes referred to as layers, are thicknesses of soil which the contractor places in loose layers that are then compacted. After the required density of each layer is achieved, the next successive layer is installed. AASHTO, ASTM, and state standard specifications are in agreement that (1) layers shall be loosely placed; and (2) layers should be simultaneously and evenly placed on both sides of the pipe. Rogers et al. (1996) found when asymmetrically installing lifts, a horizontal displacement of the pipe was observed. Also, “prominent” voids in the haunch area were reported, and excessive vertical displacements were observed. All specifications studied prescribe maximum lift thicknesses. A summary of these results are found below in Table 22. From the results, the difference between the maximum lift thickness is 2 inches. Little research is available which investigates pipe-soil interaction and the effect of the soil envelope where differences in the lift thicknesses were this negligible. Therefore, the differences seen above are unlikely to have a considerable effect on pipe performance. However, one can deduce that the lift thicknesses are a factor when obtaining the required relative density of backfill soils. Thicker lifts require more compaction energy to achieve the prescribed density. As previously discussed, the density of the soil envelope is vital to the performance of flexible pipe systems.

Table 22: Specified Maximum Lift Thickness

Specification	Maximum Lift Thickness (inches)
Arizona	8
Colorado	6
Florida	6
Nebraska	6
New York	6*
Ohio	8
South Dakota	6
Utah	6
Washington	6
Wyoming	8
ASTM D 2321	6
AASHTO 2010a	8

* NYDOT allows various fill limits based on the type of compaction, backfill, and number of passes contractor must use. In general, a Type A installation specifies a maximum 6" lift thickness.

3.6.6 Literature Review

A 2009 study by Sargand investigated a HDPE pipe which, at the time, was 20 years old. The particular facts of the installation are as follows:

- 24 inch diameter HDPE pipe.
- (29) 20 foot sections of type C and S pipe giving a total pipe length of approximately 580 feet.
- Cross culvert located under Interstate Highway 279.
- Maximum fill height of 100 feet.
- Culvert is installed in a crushed rock backfill compacted to 100% of the Standard Proctor maximum dry unit weight.

The investigation included visual observations as well as deflection measurements taken at pipe sections 14 and 15, as shown in Figure 5, located under the maximum fill height. The results of the test are a continuation of an earlier study. Visually, the pipe appears to be circular from the inlet until approximately 40 feet where the cover is about 15 feet in height, and then it becomes slightly oval in shape. There is localized pipe wall cracking in sections 12, 13, and 14 of the pipe where the maximum fill height occurs. Other signs of structural stress are not found in sections of pipe where the fill height was less than the maximum 100 feet. The maximum vertical deflections taken at sections 14 and 15 are less than 5% of the diameter. The authors of the report stress all the deficiencies recorded were already observed in the 15 year study and no new significant signs of distress or deflection is noticed from then.

This particular installation used backfill described as crushed rock compacted to 100% of the Standard Proctor maximum dry unit weight. Today, the pipe has been installed for approximately 25 years. It is important to note this study is presented to discuss the observations of a HDPE pipe installed with what are considered best practices with regard to construction methods for this particular material, and the relative successful performance of this pipe is not necessarily meant to be used to deduce any particular trends of general success with HDPE pipe. It is also important to note that the pipe is relatively young with regard to the expected design life for this type of structure.

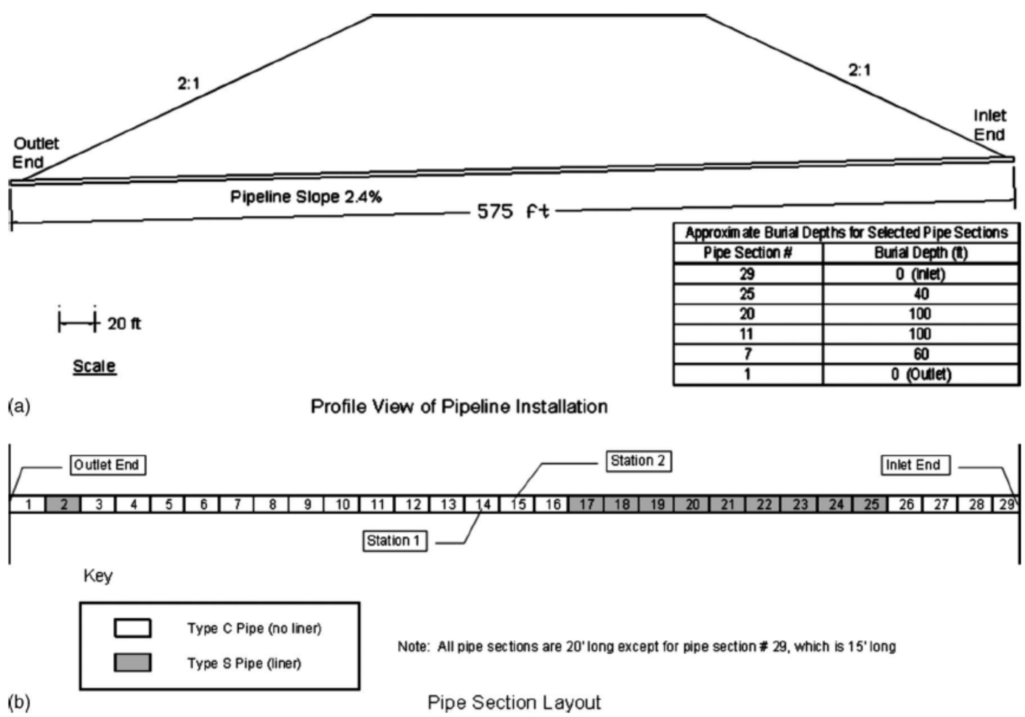

Figure 5: Schematic of Pennsylvania Deep Burial Installation (Sargand, 2009)

3.7 Summary Bedding and Backfill

From the previous studies and specifications, it is important to understand the significance of the particle size, density, and plastic limits of the soil intended to be used as backfill for flexible pipe culvert systems. These characteristics can affect the installation cost, compaction effort, and the long term-performance of the installed system. Ultimately, choosing an appropriate class of backfill with good compaction characteristics and minimal plastic indexes will result in a soil mass with greater shear strength. This will provide a stiffer soil envelope and greater design soil modulus. A stiffer soil envelope will minimize deflections in flexible pipes and other structural deficiencies such as local bulges and cracking (Gassman et al., 2005 and Sargand, et al., 2008). This is also consistent with information found within the American Water Works Association Manual of Practice M45 Pipe Design (1996) which states "bending strains are highest in low stiffness pipe backfilled in soils that require substantial compactive effort (silts and clays), and is lowest in high stiffness pipe backfilled in soils that require little compactive effort (sands and gravels)." Finally, Zhang et al. (2005) concludes when a soil envelope is less dense than the adjacent soil for any culvert installation, structural deficiencies, and roadway settlement are expected.

Review of all state specifications, AASHTO (2010a), and standard details of pipe installations, summarized in section 3.3.1.4, show that all specifications require either a select, AASHTO, or USCS granular backfill for all pipe installations up to a minimum of the pipe's springline with the exception of South Dakota and Washington. It should be noted, it is common for these specifications to then allow less coarse grained materials with higher percentages of fines from the springline up to the remainder of the soil envelope.

CHAPTER 4: DESIGN AND CONSTRUCTION PARAMETERS: MATERIAL SELECTION CONSIDERATIONS

Results are organized and presented based on the following categories: durability; joints; end treatments; allowable pipe diameters; hydraulic flow characteristics; and materials specification. Within each section, results are discussed from findings in the AASHTO Specifications, ASTM Standards, standard specifications, and peer reviewed articles.

4.1 Durability

"Culvert material durability is as important a consideration to culvert installation as proper hydraulic and structural design. The two largest factors affecting durability of culverts are corrosion and abrasion" (NDOR, 2006). The previous sections address considerations which affect the structural performance of a culvert system. In addition, state DOT engineers should consider the environmental conditions which affect the durability of the pipe. NCHRP 254 defines durability as "A material's ability to resist degradation as a result of forces or chemical or electrochemical corrosion and mechanical abrasion" (NCHRP Synthesis 254). Culverts which are installed in soil are subjected to natural chemical reactions. Water which flows through culverts can have varying pH levels. Both soil and water can have significant effects on the integrity of a pipe system, and therefore an understanding of the corrosion resistance of the pipe material should be considered. In addition to the pH level of water which flows through culverts, the material that is transported via water must be considered. Abrasive materials carried by water damage the interior surface of culverts; the effect is increased with velocity of flow through the system. NCHRP 254 asserts corrosion and abrasion acting together is considerably more detrimental to a culvert than when acting alone.

4.1.1 Corrosion

Corrosion is the leading cause of pipe deterioration. Corrosion is particularly detrimental to metal pipes, although there are coatings to help retard the corrosion process. Concrete pipe is much more resistant to corrosion, but may require special cement and epoxy coated rebar when placed in more corrosive soils. Plastic pipes are highly resistant to corrosion, a characteristic that could favor the use of plastic for corrosive soil sites.

Currently WYDOT conducts soils testing to determine the pH and resistivity of the soils. In addition, soil saturation is estimated since moisture is required for corrosion to occur. Based on these parameters, the Materials Program assigns a corrosion resistance (CR) number to each pipe location.

NCHRP 254 states “corrosion is a cause of deterioration, dissolution or destructive attack on material resulting in degradation of material properties by chemical or electrochemical reaction with the environment.” Environmental surroundings which typically are in contact with the culvert are soil, runoff water, ground water, and bed loads. Other agents include marine and mine or industrial run off. All of these surroundings may contain various acids, sulfates, and alkalis which may cause corrosion. Since a culvert is exposed to these compounds on the inside and outside of the pipe, corrosion is a factor that must be considered.

Two predominant types of corrosion are of particular concern: chemical and electrochemical. A basic understanding of both types of corrosion can be determined through a review of NCHRP 254. Electrochemical corrosion exists where natural occurring electric current is present in soils, when a difference of energy potential occurs, current passes through soil and culverts. The current causes galvanic corrosion. Soils with low resistivity, low pH values of interacting soil and water, higher moisture contents, and oxygen levels are all cited to increase current and therefore corrosion. Table 23 summarizes resistivity values for different soil and water types.

Table 23: Typical Resistivity Values (NCHRP 254)

Soil		Water	
Classification	Ohm-cm	Source	Ohm-cm
Clay	750-2,000	Seawater	750-2,000
Loam	2,000-10,000	Brackish	2,000-10,000
Gravel	10,000-30,000	Drinking water	10,000-30,000
Sand	30,000-50,000	Surface water	30,000-50,000
Rock	50,000-Infinity*	Distilled water	50,000-Infinity*

*Theoretical

When metal culverts are manufactured, electric energy is created and is stored internally. This energy increases the likelihood for a difference in energy potential to exist, and therefore opportunity is present for corrosion. Coupled with the fact that most metals used for culverts are natural conductors; electrochemical corrosion is an important consideration for metal culverts. A similar result occurs in reinforcing steel when used in concrete culverts.

Chemical corrosion is of particular concern in concrete pipes. RCP which is exposed to salts and acids may lead to a higher potential of corrosion. Products from cement hydration are hydrated lime and hydrated calcium carbonate. Runoff water which possesses various types of salts permeates into RCP. The products (hydrated lime and hydrated calcium carbonate) of RCP react with these salts forming new compounds. These new compounds form larger crystals which create internal tensile forces, and the result is cracking and deterioration of RCP. This then leads to greater exposure of the reinforcing steel which is susceptible to electrochemical corrosion. Also, hydrated cement possess large amount of calcium hydroxide, which is a very basic material with a pH value of approximately 13. When exposed to highly acidic water, a change in the pH of the pipe occurs resulting in further corrosion.

Numerous studies and literature suggest HDPE and other plastic compounds used for culverts are particularly resistant to electrochemical and chemical corrosive attacks (NCHRP 254, 631, and Cooney et al., 2011).

4.1.1.1 State Specifications

All states included in the study mention the importance of corrosion resistance with regard to material selection. Results from state specifications vary regarding how individual states control corrosion limits. South Dakota Department of Transportation (SDDOT) obtains soil samples and then consults with the Natural Resources Conservation Service for corrosion ratings and design. States such as Arizona, Colorado, Utah, and Washington set corrosion limits based on sulfate, pH, and resistivity values from soil and water samples. Then all allowable pipe is assigned a corrosion level or a resistance number depending on the characteristics of the material. For steel, various coatings and thicker metal gages are required for higher corrosive categories. Concrete pipe also requires special coatings and treatments in highly corrosive environments. Plastic pipe does not require additional treatments in corrosive environments and is placed in the highest corrosive categories in all states that specify corrosion categories. States including Ohio, Nebraska, and Florida acknowledge plastic pipe's superiority and do not specifically include it in corrosion tables. Table 24 and Table 25 shown below, are representative of the corrosion level determination and corresponding allowable materials included in CDOT's state specifications. Additional tables, which address corrosion and abrasion limits, are provided in Appendix B in this Report.

Table 24: CDOT's Corrosion Levels (CDOT Pipe Material Selection Guide)

Guidelines for selection of corrosion resistance levels

	SOIL			WATER		
CR Level	Sulfate (SO_4) % max	Chloride (Cl) % max	pH	Sulfate (SO_4) ppm (max)	Chloride (Cl) ppm (max)	pH
*CR 0	0.05	0.05	6.0-8.5	50	50	6.0-8.5
CR 1	0.10	0.10	6.0-8.5	150	150	6.0-8.5
CR 2	0.20	0.20	6.0-8.5	1,500	1,500	6.0-8.5
CR 3	0.50	0.50	6.0-8.5	5,000	5,000	6.0-8.5
CR 4	1.00	1.00	5.0-9.0	7,500	7,500	5.0-9.0
CR 5	2.00	2.00	5.0-9.0	10,000	10,000	5.0-9.0
CR 6	>2.00	>2.00	<5 or >9	>10,000	>10,000	<5 or >9

*No special corrosion protection recommended when values are within these limits. Concrete pipe used when the pH of either the soil or water is less than 5 shall be coated in accordance with subsection 706.07. When needed, specify the coating in a special provision or plan note.

Table 25: CDOT Material Allowed for Class of Pipe (CDOT Pipe Material Selection Guide)

Material Allowed**	Class of Pipe*										
	0	1	2	3	4	5	6[4]	7	8	9	10[4]
CSP	Y	N	N	N	N	N	N	N	N	N	N
Bit. Co. CSP	Y	Y[1]	N	N	N	N	N	N	N	N	N
A.F. Bo. CSP	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
CAP	Y	Y[2]	Y[2]	Y[2]	Y[2]	Y	N	N	N	N	N
PCSP – both sides	Y	Y	Y	Y	N	N	N	N	N	N	N
PVC[6]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
PE[6]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
RCP (SPO)[3,5]	Y	Y	N	N	N	N	N	Y	N	N	N
RCP (SP1)[3,5]	Y	Y	Y	N	N	N	N	Y	Y	N	N
RCP (SP2)[3,5]	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N
RCP (SP3)[3,5]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

* As determined by the Department in accordance with the CDOT *Pipe Selection Guide*. Determination is based on abrasion and corrosion resistance.

** Y=Yes; N=No.

1 Coated Steel Structural Plate Pipe of equal or greater diameter, conforming to Section 510, may be substituted for Bit. Co. CSP at no additional cost to the project.

2 Aluminum Alloy Structural Plate Pipe of equal or greater diameter, conforming to Section 510, may be substituted for CAP at no additional cost to the project.

3 SP= Class of Sulfate Protection required in accordance with subsection 601.04 as revised for this project. RCP shall be manufactured using the cementitious material required to meet the SP class specified.

4 For pipe classes 6 and 10, the RCP shall be coated in accordance with subsection 706.07 when the pH of either the soil or water is less than 5. The Contract will specify when RCP is to be coated.

5 Concrete shall have a compressive strength of 4500 psi or greater.

6 In accordance with subsection 712.13.

From the tables above, it is clear that HDPE, PVC, and RCP are the only materials allowed when extreme levels of corrosion or abrasion are anticipated. CDOT's class 10 pipe designation is for a class of pipe located in areas with the highest abrasion and corrosion level. However, when RCP is used, CDOT requires the pipe to have a compressive strength of 4500 psi. In addition, the pipe is required to be coated with asphalt mastic with a total thickness of 50 mils and provide a Class 3 sulfate protection as specified by section 601.04 of CDOT's Standard Specification. Pipe class 6 is the highest allowed level for any metal pipe regardless of coating. HDPE and PVC pipe may be used as a class 10 pipe without any additional requirements. Utah and Washington also permit plastic pipe in their highest corrosion levels, Level C and Level III, respectively. Arizona states that HDPE is allowed within pH limits of 1.25 and 14.

4.1.2 Abrasion

Abrasion is defined as "the wearing away of pipe material by water carrying sands, gravel and rocks (bed load) and is dependent upon size, shape, hardness, and volume of bed load in conjunction with volume, velocity, duration, and frequency of stream flow in the culvert" (CDOT-2009-11). It is clear from the previous definition that abrasion is a factor of many variables that when coupled together requires an understanding of the global system and not simply individual parameters. Material resistance (culvert material) can be characterized by hardness, fracture energy, and plain strain hardness (Zok and Miserez, 2007). All of these characteristics are a function of Young's Modulus and Poisson's Ratio. The media which are transported through culverts are typically hard and have geometric variances which can induce yielding and/or crack formation in the softer pipe material. Finally, the velocity of flow through a pipe increases deteriorations. NCHRP 254 states that abrasion is a function of the square of the velocity; therefore, the abrasive power will quadruple when the velocity doubles.

4.1.2.1 AASHTO/ASTM

AASHTO (2007) states that concrete and especially steel culverts are susceptible to damage in highly abrasive sites. Methods to combat this effect include specifying a thicker gauge of pipe for steel culverts and sacrificial concrete cover for concrete pipe (minimum of 2.0 inches for highly abrasive sites). In contrast, this document also states that plastics including PVC and HDPE exhibit excellent abrasive resistance, especially in highly corrosive environments. However, AASHTO (2007) also states that PVC is shown to have slightly lower abrasion resistance compared to HDPE, particularly in environments where pH is ≤ 4. In general, AASHTO and ASTM specifications are vague when discussing methods of combating the effects of abrasion for plastic pipe. ASTM D 2321 does not mention abrasion within its text. Section 17.1.7 (AASHTO, 2002) states "Extra thickness may be required for resistance to abrasion. For highly abrasive condition, a special design may be required." Although the AASTHO specification suggests that extra thickness should be included, the "term highly abrasive conditions" is unclear. A recognized guideline used to determine abrasion levels is presented in Table 26. This information is defined by the Federal Lands Highway Division of the FHWA.

Table 26: Abrasion Design Guidelines (NCHRP Synthesis 254)

Abrasion Level	Site Conditions
Nonabrasive	no bed load and very low velocities
Low abrasive	minor bed loads of sand and velocities less than 1.5m/s (5 fps)
Moderate abrasive	moderate bed loads of sand and gravel and velocities between 1.5 and 4.5 m/s (5 and 15 fps)
Severe abrasive	heavy bed loads of sand, gravel and rock and velocities exceeding 4.5 m/s (15fps)

4.1.2.2 State Specifications

Like the AASHTO specifications, most states included in this study are not clear what design limits for abrasion are and how to design for them. For instance, Nebraska clearly identifies the importance of abrasion considerations; however, provides minimal guidance on abrasion levels. ADOT (2007) states when the bed flow velocity is greater than 6.6 ft/s (2 m/s) abrasion may cause problems. Possible methods to address abrasion include increasing metal gage thickness, adding a concrete invert, or using polyethylene pipe. ADOT (2007) suggests when flow is greater than 39 ft/s (12 m/s), increasing the compressive strength of RCP is an economical solution to higher abrasive bed flow. The standard specification also states that HDPE has a high resistance to abrasion problems; therefore, the engineer should consider using HDPE. Steel or aluminum pipes are not allowed for bed flow velocity greater than 39 ft/s (12m/s). Additional examples of states that clearly address abrasion design procedures are Colorado and Washington. Figure 6 and Figure 7 are from Washington State and Colorado's Standard specifications, respectively.

Abrasion Level	General Site Characteristics	Recommended Invert Protection
Non Abrasive	• Little or no bed load • Slope less than 1% • Velocities less than 3 ft/s (1m/s)	Generally most pipes may be used under these circumstances, if a protective treatment is deemed necessary for metal pipes, any of the protective treatments specified in Section 8-5.3.1 would be adequate.
Low Abrasive	• Minor bed loads of sands, silts, and clays • Slopes 1% to 2% • Velocities less than 6ft/s (2 m/s)	For metal pipes, an additional gage thickness may be specified if existing pipes in the vicinity show a susceptibility to abrasion, or any of the protective treatments specified in Section 8-5.3.1 would be adequate.
Moderate Abrasive	• Moderate bed loads of sands and gravels, with stone sizes up to about 3 inches (75 mm) • Slopes 2% to 4% • Velocities from 6 to 15ft/s (2 to 4.5 m/s)	Metal pipes shall be specified with asphalt paced inverts and the pipe thickness shall be increased on or two standard gauges. The designer may want to consider a concrete-lined alternative. Concrete pipe and box culverts should be specified with an increased wall thickness or an increased concrete compressive strength. Thermoplastic pipe may be used without additional treatments
Severe Abrasive	• Heavy bed loads of sands, gravel and rocks, with stones sizes up to 12 inch (300 mm) or larger • Slopes steeper than 4% • Velocities greater than 15 ft/s (4.5 m/s)	Asphalt protective treatments will have extremely short life expectancies, sometimes lasting only a few months to a few years. Metal pipe thickness should be increased at least two standard gages, or the pipe invert should be lined with concrete. Box culverts should be specified with an increased wall thickness or an increased concrete compressive strength. Sacrificial metal pipe exhibits better abrasion characteristics than metal or concrete. However, it generally cannot be reinforced to provide additional invert protection and is not recommended in this condition.

Pipe Abrasion Levels

Figure 6: WSDOT Abrasion Design Guidelines (WSDOT 2010a)

Step II: Determine Abrasion Level – An estimate of the potential for abrasion is required to determine acceptable pipe types and whether there is a need for invert protection. Four levels of abrasion are referred to in this guidance, and the following guidelines are established for each level:

- Abrasion Level 1 – This level applies where the conditions are nonabrasive. Nonabrasive conditions exist in areas of no bed load and very low velocities. This is the level assumed for the soil side of drainage pipes. This is also the level assumed for the inverts of cross drains and side drains installed in typically dry drainages.
- Abrasion Level 2 – This level applies where low abrasive conditions exist. Low abrasive conditions exist in areas of minor bed loads of sand and velocities of 5 fps or less.
- Abrasion Level 3 – This level applies where moderately abrasive conditions exist. Moderately abrasive conditions exist in areas of moderate bed loads of sand and gravel and velocities between 5 fps and 15 fps.
- Abrasion Level 4 – This level applies where severely abrasive conditions exist. Severely abrasive conditions exist in areas of heavy bed loads of sand, gravel, and rock and velocities exceeding 15 fps.

The Project Manager will estimate and document the abrasive forces that will have an effect on the drain or sewer.

- Measure or calculate the velocity of the water based upon 2-year flow and less.
- Estimate the bed-loading as:
  - No bed load
  - Minor bed load – silt and sand
  - Moderate bed load – silt, sand, and gravel
  - Heavy bed load – silt, sand, gravel, and rock
- Determine whether the abrasion level is 1, 2, 3, or 4 as defined above.

Figure 7: CDOT Abrasion Design Guidelines (CDOT 2010)

WSDOT specifications states "Laboratory testing indicates that the resistance of plastic pipe to abrasive bed is equal to or greater than that of other types of pipe material. However, because plastic pipe cannot be structurally reinforced, it is not recommended for severely abrasive conditions…" (WSDOT, 2010a). Colorado approves HDPE material as an acceptable product for its highest Abrasion Level 4.

None of the states included require physical testing or sampling. However, many states suggest the stream bed should be visually examined and recorded to determine the slope and average particle size of the stream bed. In doing so, a more accurate determination of the abrasion level is assumed.

Caltrans Final Report FHWA/CA/TL-CA01-0173 is a study which investigates abrasion resistance of various pipe materials. A test apparatus was created which anchored 12 inch by 12 inch test specimens installed in a concrete frame. The test specimens were randomly placed within the fame. The apparatus was located at an outlet of a drainage pipe with the intention that all specimens would be subjected to the same environmental conditions, see Figure 8 and Figure 9 below. The location of the culvert was downstream of a former mining operation which altered the watershed and was transporting bed loads consisting of gravel and sands; the authors describe the test site as "extremely aggressive from an abrasion standpoint." Each test specimen was removed once a year to be visually inspected and measured for loss of thickness. The specimens were re-installed and the following year were removed again; the test was conducted over a five year period. The authors of the study make the following conclusions:

- Polyethylene coating to CSSRP outperformed all of the other metal coatings.
- Smoother profiles evidenced less abrasive wear than did corrugated profiles.
- All pipe materials tested evidenced significantly less abrasive wear than did concrete pipes.
- PVC evidenced less abrasive wear than did HDPE.

Further analysis from results of the study show that overall coated steel pipes experienced less abrasive wear than plastic and RCP pipes during lower run-off seasons, especially when considering the polyethylene coated pipes. However, during the fifth year, there was a significant difference in the peak and average flow, see Table 27. During this year, 18 of the test specimens were completely destroyed from the high run-off. The authors suggest that the HDPE specimen outperformed most other materials when exposed to an extreme run-off event such as in the (5) test season. Figure 10, seen below, are photographs of test specimens from row A-C. The authors point out row D consistently experienced less flow than A-C due to an irregularity in the natural flow and suggests results in row D are not typical and therefore are not presented.

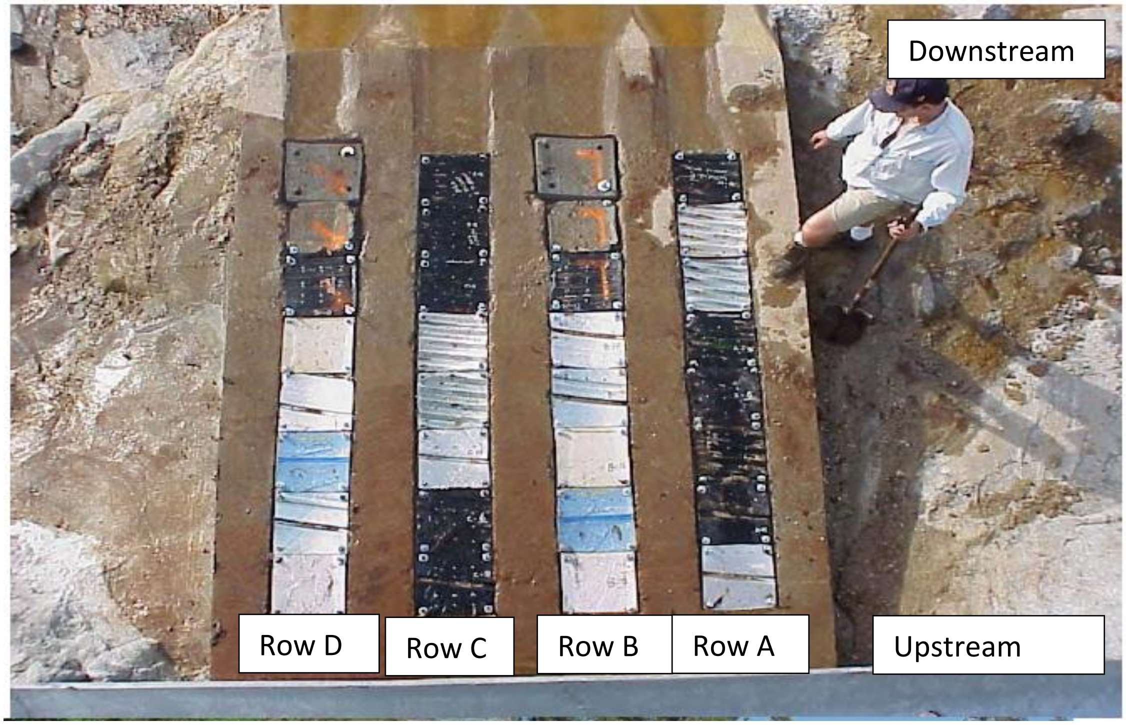

Figure 8: Test Setup from FHWA/CA/TL-CA01-0173 September 2001 – Begin Year 1

Figure 9 Test Setup from FHWA/CA/TL-CA01-0173 June 2006 – End Year 5

HDPE Row B

Front

Back

PVC Row B

Front

Back

CSSRP Row B CSP Bit.

Front

Back

Coated & Paved Row A

Front

Back

CSP Bit. Coated & Paved Row C

Front

NO IMAGE

AVAILABLE

CSP w/ Polymerized Asphalt Row A

Front

Back

CSP w/ Polymerized Asphalt Row C

Front

Back

CSP w/ Polymeric Coating Row A

Front

Back

CSP w/ Polymeric Coating Row C

Front Back

CSP w/ Polymeric Coating & Polymerized Asphalt Row A

Front Back

CSP w/ Polymeric Coating & Polymerized Asphalt Row C

Front Back

Aluminized CSP Row A

Front Back

Aluminized CSP Row C

Front Back

Galvanized CSP Row A

Front Back

Galvanized CSP Row A

Front Back

Galvanized SSRP Row B

Front Back

Figure 10: Coupon Results from FHWA/CA/TL-CA01-0173 June 2006– End Year 5

Table 27 : Summary of Run-off by Year (FHWA/CA/TL-CA01-0173)

( )Rain Year:	(1) 2001/2	(2) 2002/3	(3) 2003/4	(4) 2004/5	(5) 2005/6
Ave. peak flow (cfs)	110	135	92	152	309
Ave. peak velocity (fps)	12.8	13.6	12	14.3	17.7
Peak flow (cfs)	300	500	300	1000	1200
Peak velocity (fps)	16.9	19.3	16.9	20.4	21.4

The authors of this study also note the effect of consistent UV exposure in this experiment had an "immeasurable" effect on pipe samples that are significantly affected by UV degradation (PVC, HDPE, bituminous, polymeric and polymerized asphalt coatings). The RCP specimens were almost destroyed in year four, except in Row D. The aluminized and galvanized specimens performed poorly. From the figures above, it is clear that even though many of the samples remained, they were significantly damaged with major perforations in the specimen. Notable exceptions to this observation are the HDPE and CSP w/ Polymeric Coating & Polymerized Asphalt specimens. As a result of this study, a table of recommended abrasion levels and corresponding allowable culvert materials and treatments is included in Appendix B in this Report.

4.1.3 Conclusion

From the previous studies and specifications, it is clear corrosive and abrasive environments influence the durability of culvert systems, greatly influencing the design life more so than the structural performance of the pipe as suggested by some studies. When coupled together, the deterioration effects from abrasion and corrosion are considerably magnified compared to when acting individually, (Cooney et al., 2011.) NCHRP 254 suggests these effects are of particular concern in metal and concrete culvert systems. The previous standard specifications show plastic pipe performs better in corrosive and abrasive environments. Appendix B in this Report gives additional information and guidance when addressing these issues.

4.2 Joints

Out of all design categories researched in this study, joints have the largest discrepancies on how they are specified within the state specifications. In addition, there is little scientific research which studies the performance of joints (NCHRP Project Report 20-07). Although literature that discusses joint design and specification appears to be lacking, this design category can have one of the largest impacts on the pipe and installation design life. "Experience has shown that the component responsible for many culvert and sewer performance problems and failures can be traced back to the pipe joint" AASHTO (2009). Despite the relative lack of scientific literature, the specifications found have proven to provide valuable and accurate insight.

The literature review of the state specifications indicates that the methods of joining pipe are numerous. Methods of joining pipe include bell and spigot, elastomeric seals, rubber gaskets, coupling bands, solvents, geotextile wraps, and heat fusion. These methods must produce a system that is either soil-tight, silt-tight, leak-resistant, or water-tight. A description of these systems can be found in AASHTO (2009) and are as follows:

Leak-resistant – Refers to a system that is not completely (100 percent) water-tight. The acceptable leakage rate to provide a leak-resistant joint is a maximum rate of 200 gallons/inch-diameter/mile/day for the specified head or pressure.

Silt-tight – A joint that is resistant to infiltration of particles that are smaller than particles passing the No. 200 sieve. Silt-tight joints provide protection against infiltration material containing a high percentage of fines (more than 35 percent passing the No. 200 sieve), and typically utilize some type of filtering or sealing component, such as an elastomeric rubber seal or geotextile

Soil-tight – A joint that is resistant to infiltration of particles larger than those retained on the No. 200 sieve. Soil-tight joints provide protection against infiltration of backfill material containing a high percentage of coarse grained soils, and are influenced by the size of the opening (maximum dimension normal to the direction that the soil may infiltrate) and the length of the channel (length of the path along which the soil may infiltrate). Additional requirements include the length of channel must be at least four times the size of the opening if greater than 1/8 inch. In no case shall the opening be greater than 1 inch.

Water-tight – A joint that provides zero leakage or infiltration and exfiltration for a specified head or pressure application. Water tight joints typically utilize a resilient rubber seal of some type and are capable of passing a laboratory hydrostatic pressure and vacuum test of at least 10.8 psi without leakage.

When determining what type of joint system should be specified, the designer should consider the applicability of the previous definitions to the specific location of the pipe installation. Additional considerations the designer should take into account are summarized by NRC (1998) and are as follows:

- Resistance to infiltrations of groundwater or soil.
- Resistance to exfiltration.

- Flexibility to accommodate lateral deflection or longitudinal movement without creating leaking problems.
- Resistance to shear stresses between adjacent pipes.
- Hydraulic continuity.
- Ease of installation.

The state specifications regularly specify joints by stating "Joints and fittings specified by the manufacturer." When this occurs, it is reasonable to suggest many state DOTs do not know which type of joints are being installed as well as a general lack of understanding in the differences between them. The numerous joining systems, methods, and considerations can be daunting for a designer. AASHTO (2009) provides a flow chart (included in Appendix B in this Report) intended to aid designers for joint specification.

In addition to the description of the four different joint systems discussed above, AASHTO (2009) also outlines particulars for joint specification by different pipe material. A description of these requirements for the various pipe materials are discussed below:

Concrete Pipe

> Soil-tight Joints: Plain joints that use mortar, mastic, external geotextile wraps, and rubber gaskets meet the requirements of soil tight joints when assembled properly.
>
> Silt-tight Joints: Should utilize a rubber gasket, mastic filler, or an external joint wrap. If a gasket or mastic filler is chosen for the sole method of sealing, the joints shall meet the testing requirements of AASHTO M 315 with the exception the maximum hydrostatic test pressure shall not be greater than 2 psi for both straight and deflected positions. If a wrap is chosen for the sole method of sealing, the wrap must cover the entire circumference of the pipe and must be either an external sealing band that meets the requirements of ASTM C 877 or a 12 inch wide geotextile separation fabric.
>
> Leak-resistant Joint: Should utilize a rubber gasket, mastic filler, or an external joint wrap. If a gasket or mastic filler is chosen for the sole method of sealing, the joints shall meet the testing requirements of AASHTO M 315 with the maximum test pressure equal to 10.8 psi for straight alignment and 10 psi for the deflected alignment. If a wrap is chosen for the sole method of sealing, the wrap must cover the entire circumference of the pipe and must be either an external sealing band that meets the requirements of ASTM C 877 Type 1 or Type 2.

Corrugated Metal Pipe

Soil-tight Joints: The joint is considered soil-tight if it meets the requirements of Article 26.4.2.4 of AASHTO (2010a), discussed below. Joints should utilize an externally banded corrugated or partially corrugated metal pipe band with a minimum width of 7.5 inches, or a bell and spigot design that meets the requirements of Section 9.1.7 of AASHTO M 36.

Silt-tight Joints: The joint is considered silt-tight if it meets the requirements of Article 26.4.2.4 of AASHTO (2010a), discussed below. Joints should utilize an externally banded corrugated or partially corrugated metal pipe band with a minimum width of 10.5 inches. Also a bell and spigot design that meets the requirements of Section 9.1.7 of AASHTO M 36 is considered silt-tight if wrapped with a 12 inch minimum width geotextile wrap the entire circumference, or an elastomeric gasket meeting the requirements of ASTM D 3212, with the exception that the hydrostatic test pressure shall be a minimum of 2 psi.

Leak-resistant Joint: AASHTO (2009) states that currently there is not an acceptance criteria for a corrugated metal pipe joint. However, it does note if a leak-resistant joint is needed for this material, it should demonstrate the ability to meet the same testing requirements of concrete and plastic pipe for this joint type.

Plastic Pipe

Soil-tight Joints: All measurements and requirements shall meet the respective AASTHO and ASTM standards.

Silt-tight Joints: Shall utilize an elastomeric rubber seal meeting the requirements of ASTM F 477. External joint wraps are an acceptable alternative if the joint meets the requirements of ASTM D 3212, with the exception that the hydrostatic test pressure shall be a minimum of 2 psi.

Leak-resistant Joint: Shall utilize a bell and spigot design with an elastomeric rubber seal meeting the requirements of ASTM F 477. External joint wraps are an acceptable alternative if the joint meets the requirements of ASTM D 3212, with the exception that the hydrostatic test pressure and vacuum shall be 10.8 psi.

The previous paragraphs are a summary outlining the more important criteria for joint requirements of different pipe materials. WYDOT should review AASHTO (2009) for additional requirements for items such as gaskets, geotextile wraps, and testing requirements. Important conclusions from this specification show soil-tight joints for concrete and plastic pipe are ill defined; however, it appears most joining methods for these materials are to be considered acceptable for soil-tight criteria. The requirements for a soil-tight joint for corrugated steel pipe are better defined, and gaskets appear to not be required. The specific requirements for water-tight joints for the individual materials were not included in this specification. Also, WYDOT should note AASHTO (2009) is a provisional AASHTO standard, and review of the adopted specification was not possible due to cost and a relatively new publication date. However, review of the material shows to be consistent with other AASHTO publications and its quality is considered accurate.

Although not every referenced specification by AASHTO (2009) can be included in this report, AASHTO (2010a) Section 26 provides prudent information for joint requirements as discussed above, and therefore warrants inclusion. A summary of Sections 26.4.2.3 and 26.4.2.4 (AASHTO, 2010a) are as follows:

Section 26.4.2.3 Soil Conditions

- The type of joint is dependent upon the type of backfill used.
- Piping action is a term used which describes a situation when the backfill soil surrounding the pipe will infiltrate the pipe through the joints.
- Backfill that is subjected to piping action is known as "Erodible," these include fine sands and silts.
- Backfill not subjected to piping action, "Nonerodible," includes coarse sand, small gravel, and cohesive soils.

26.4.2.4 Joint Properties – Divided into six categories

- Shear Strength – The shear strength of a joint must be able to withstand a percentage of the pipe's calculated shear strength.
- Moment Strength – The moment strength of a joint must be able to withstand a percentage of the pipe's calculated moment strength.
- Tensile Strength – Strength required to withstand longitudinal forces. 5000 lbs. for pipe diameters 0 to 48" and 10,000 lbs. for pipe diameters 48" to 84".
- Joint Overlap – In lieu of meeting the moment strength requirements, a sleeve which overlaps the joining pipe ends may be used (10.5").
- Soiltightness – No opening may exceed 1.0 inch. If an opening of 0.125 inches exists, the length of the channel shall be at least four times the size of the opening. For nonerodible and erodible soils the ratio of D_{85} soil size to the opening size must be greater than a particular ratio which varies depending on the soil size. Alternatively, joints that pass a 2-psi hydrostatic test without leakage are also considered soil tight.
- Watertightness – The pipe ends must not vary in diameter by more than 0.5 inches in diameter or 1.5 inches in circumference. Must meet a 10.8 psi laboratory test per ASTM D 3212 and utilize a bell and spigot design with a gasket meeting ASTM F 477.

From the research conducted via DOT phone interviews, there is a general consensus that plastic joint systems are superior compared to RCP joints. Also due to the longer lengths of pipe, there are fewer joints within the system. Therefore, reducing the number of instances where failures could occur.

Typically states included in this study only specify water tight joints when an agency feels a lower tolerance joint is necessary. When this is done, it is usually phrased as “when specified” and is followed with a statement requiring the joint to meet a particular ASTM or AASHTO specification. AASHTO (2010a) states joints for plastic pipe shall meet the requirements for soiltightness (discussed above) unless water tight joints are specified. However, some states do specify particular instances when the joint is to be water-tight. A summary of this is found below in Table 28. WYDOT follows the procedure of specifying water tight joints when the agency feels it is necessary. In addition, like many other states, WYDOT specifies water tight joints for concrete pipe shall meet AASHTO M 198. Also, water tight joints for corrugated steel pipe shall meet AASHTO M 36 in conjunction with applicable sections of AASHTO M 198. ASTM C 443 is another reference WYDOT should consider for review that is commonly specified by other states which discusses requirements for gasketed joints of concrete pipe. In addition to the testing requirements previously discussed, certain states will require further testing procedures to be conducted for water tight joints. For example, CDOT states the following:

> “Sanitary sewer lines, when completed, shall be tested for water-tightness before backfill is placed. The installations shall not show infiltration or exfiltration in excess of 0.6 gallon per inch of internal pipe diameter per 100 feet of sewer line per hour when tested at 10 psi by hydraulic means.”

WYDOT ultimately needs to investigate and determine which type of joint is necessary for specific locations. For example, it was found through the Florida DOT (FDOT) interview, the state has considerable problems with ground water pollution. The agency has adopted a zero leak policy for their culverts. Therefore, FDOT requires that all pipe systems are to have water tight joints. It is assumed the greater precision of water-tight joints correlate to an increase in cost. If a lower tolerance of water infiltration/exfiltration can be tolerated, the additional cost of water-tight joints may not be necessary. WYDOT should consider the cost and benefits to determine the necessity for each joint type.

Table 28: Requirements for Water Tight Joints

Application for Required Water Tight Joints		
	Location	Reference & Material
AZ	When specified	RCP: AASHTO M 198 Metal: AASHTO M 36, M 198 Plastic: ASTM D 3212
CO	When specified for culverts and sanitary sewers	RCP: Meet AASHTO M 198 Metal: AASHTO M 198 Plastic: By manufacturer
FL	Storm sewers, cross culverts, and gutter drains	RCP: ASTM C 443 Metal: ASTM D 3212 Plastic: ASTM D 3212
NE	Cross culverts under roadways and storm sewers	Water tight joint by NDOR Approved products list
NY	When specified	RCP: Passes NYDOT Leak Test Metal: Not specified Plastic: By manufacturer
OH	When specified	RCP: ASTM C 443 Metal: AASHTO M 36 Plastic: AASHTO M 294
SD	When specified	RCP: AASHTO M 198 Metal: Not specified Plastic: By manufacturer
UT	Cross culverts: sustain 3 psi test storm drains & irrigation pipes: sustain 5 psi test	RCP: AASHTO M 198 Metal: AASHTO M 36 Plastic: ASTM D 3212, F 477
WA	Culverts and sewer pipe	RCP: Meet AASHTO M 198 Metal: AASHTO M 198 Plastic: ASTM D 3212, F 477
WY	When Specified	RCP: AASHTO M 198 Metal: AASHTO M 36 Plastic: Not specified

4.3 End Treatments

Insignificant scientific research has been found which determines the adequacy of plastic end sections. AASHTO (2006) states "When polyethylene pipe is to be used in locations where the ends may be exposed, consideration should be given to protection of the exposed portions due to combustibility of the polyethylene and the deteriorating effect of prolonged exposure to ultraviolet radiation." When studying the individual state's standard specifications it appears they are consistent with the previous statement. From the states included in this study, only Ohio and Washington allow the use of plastic end sections. The remaining states specifically dictate that plastic end sections are not allowed.   Section 8-2.3 of WSDOT (2010a) states when HDPE end sections are used, they should be beveled to match the slope but not flatter than 4:1; in addition, this section discusses the difficulty securing the pipe to the ground due to hydrostatic uplift forces.

Although the lack of scientific research regarding HDPE use as an end treatment is present, AASHTO and state specifications appear to be consistent with the notion that plastic end sections are vulnerable to environmental elements and should not be used. Therefore, use of plastic end sections should be carefully considered.

4.4 Allowable Pipe Diameter

Typical diameters for HDPE pipe range from 4 to 60 inches and can be as large as 144 inches with even larger custom diameters available. By limiting pipe diameters, DOT engineers can control the use of specific materials in certain applications. Table 29 displays allowable pipe diameters by state. As seen in this table, the maximum allowable pipe diameter is 60 inches. Six out of the nine states studied, allow 60 inch diameter pipe. While, three of nine specify 36 inch diameter as the maximum size allowable.

Table 29: Specified Allowable HDPE Pipe Diameters

State	Min. (in.)	Max. (in.)
Arizona	12	36
Colorado	3	60
Florida	12	60
Nebraska	15	36
New York	12	60
Ohio	4	60
South Dakota	Not Specified	36
Utah	18	60
Washington	12	60
Wyoming	Not Specified	

4.5 Hydraulic Flow Characteristics

Concrete and plastic pipes provide roughly equivalent Manning's values. Metal pipe with helical or annular corrugations have a higher Manning's value. This is also true with plastic pipe which have corrugations. FDOT (2012) reports single wall (corrugated) polyethylene pipe has a Manning's Number equal to 0.024, which is twice that compared to smooth wall pipe. Typical design Manning's numbers can be found below in Table 30. Smooth wall corrugated plastic pipe, should be considered as an acceptable alternative to RCP or metal pipe with respect to hydraulic flow characteristics.

Table 30: Manning's Values (ADOT, 2007)

Pipe Type	"n"
Concrete Pipe:	0.012
Cast-in-Place Concrete	0.014
Smooth Plastic: Polyethylene	0.012
Spiral Rib: Galvanized Steel	0.014

4.6 Materials Specification

The AASHTO Standard Specifications for Transportation Materials establishes standard specifications for a host of products used in highway construction. It is critical that the AASHTO Subcommittee on Materials has reviewed, adopted, and published specifications regarding the material properties of any candidate materials. Provisions for quality control and other criteria to ensure adequate performance must also be available. AASHTO M 294 or referred to as AASHTO (2006) in this document and ASTM D 3350 are two publications which places minimum standards on HDPE pipe. First, AASHTO (2006) discusses general classifications of pipe type (C, S, and D among others), pipe dimensional tolerances, mechanical properties, etc. ASTM D 3350 discusses and places minimum standards for various cell classes of plastic pipe. This cell classification is designated by ASTM D 3350 described below in Figure 11.

CELL CLASSIFICATION
3 4 5 4 3 4 C

Density
Melt Index
Flexural Modulus
Tensile Strength at Yield
Environmental Stress Crack Resistance
Hydrostatic Design Basis at 23° C (73.4° F)
Color and UV Stabilizer

EXPLANATION OF
CELL CLASSIFICATION VALUES (see Table 1)

3 = 0.0941 to 0.955
4 = <0.15
5 = 110,000 to < 160,000 psi
4 = 3000 to < 3500 psi
3 = Condition C/ 192h; 20% Max Failure
4 = 1600 psi
C = Black with 2% Min Carbon Black

Table 1 of ASTM D 3350 lists the primary properties of the Cell Classification and paragraph 6.2 of D 3350 indicates the color and UV stabilizer codes.

Table 1 Primary Properties - Cell Classification Limits

Property	Test Method	0	1	2	3	4	5	6
Density, g/cm	D1505	-	0.910-0.925	0.926-0.940	0.941-0.955	>0.955	-	-
Melt Index	D1236	-	>1.0	1.0 to 0.4	<0.4 to 0.15	<0.15	A	B
Flexural modulus, MP_s(psi)	D790	-	<136 (<20000)	136-<276 (20000 to <40000)	276-<552 (40000 to <80000)	552<758 (80000 to <110000)	758-<1103 (110000 to <160000)	1103 <160000)
Tensile strength at yield, MP_s (psi)	D538	-	<15 (<2200)	15-<18 (2200-<2600)	18-<21 (2600-3000)	21-<24 (3000-<3500)	24-<28 (3500-<4000)	>28-(>4000)
Environmental Stress Crack resistance: a. Test Condition b. Test Duration, h c. Failure, max %	D1693	-	A 48 50	B 24 50	C 192 20	-	-	-
Hydrostatic design basis, MP_s (psi), (23°C)	D2537	NPRc	5.52(800)	6.89(1000)	8.62(1250)	11.03(1600)	-	-

A. Refer to 10.1.4.1 B. Refer to 10.1.4.2 C. NPR = Not Pressure Rated

Code Letter	Color and UV Stabilizer
A	Natural
B	Colored
C	Black with 2% min. carbon black
D	Natural with UV stabilizer
E	Colored with UV stabilizer

Figure 11: ASTM D 3350 Cell Classification Limits

Currently, most states and AASHTO (2010b) Table 12.12.3.3-1 specify a minimum cell class for the various plastic pipes. A summary of the required specifications and cell classes are presented below in Table 31. It is typical for states to only allow HDPE products that meet the specification of AASHTO M 294 even though AASHTO (2010a) and (2010b) allow use of the ASTM classifications; these classifications are discussed further in Chapter 6 in this Report. However, it is difficult to know whether these parameters are met; coupled with the fact that numerous plastic pipe manufacturers exist, it is difficult for DOT engineers to guarantee the quality of pipe being installed. CDOT and Utah DOT (UDOT) for instance, also specify the pipe must come from a plant that is certified by the National Transportation Product Evaluation Program (NTPEP). NTPEP tests and evaluates HDPE pipes to ensure they meet the minimum specifications of both AASHTO M 294 and ASTM D 3350.

Table 31: Plastic Pipe Specification by States

Specification for HDPE and PVC as Required by States						
HDPE for Culverts & Storm Drains				PVC for Culverts & Storm Drains		
State	**Specification**	**Cell Class**	**Wall Profile**	**Specification**	**Cell Class**	**Wall Profile**
AZ	AASTHO M 294			Not specified for culvert/storm drain systems		
CO	AASTHO M 294		Type S, SP	AASHTO M 304		
	ASTM F 894	334433C or 335434C		ASTM F 794		
	ASTM F 714	335434C		ASTM F 949		
FL	AASTHO M 294		only annular corrugations	AASHTO M 278		
				ASTM F 949		
NE	AASHTO M 294	335420C	Type C or S	ASTM F 794		
				ASTM F 949		
NY	AASHTO M 294		Type S	Not specified for culvert/storm drain systems		
OH	AASHTO M 294		Type S, SP, D	AASHTO M 304		
				ASTM F 794		
SD	AASHTO M 294			Not specified for culvert/storm drain systems		
UT	AASHTO M 294			AASHTO M 304	12454C	
WA	AASHTO M 294		Type S or D	ASTM F 794		
WY	Under Development					

Note: AASHTO M 294 specifies a minimum cell class of 435400C per ASTM D 3350

CHAPTER 5 OTHER FACTORS IMPACTING PIPE SELECTION AND PERFORMANCE

5.1 Deflection

Studies have brought to light instances where HDPE pipes have experienced frequent and excessive structural deformations (Montahari and Abolmalli, 2010). This test randomly measured deflections of 96 pipelines in five states using a laser ring profile system. The results from the test indicate 63% of pipes studied experienced deformations larger than the specified 5% AASHTO limit. It is important to note, no mention of the construction procedure or backfill type was noted when examining the pipe. However, the previously mentioned studies (Sargand et al., 2008 & 2009, and Webb et al., 1996) showed good deflection results in tests and laboratory experiments where strict construction standards were used. This would suggest structural performance of plastic pipe is directly proportional to the installation procedure in which the pipe was installed. This is consistent with the following statement: "Achieving 100 year service life on HDPE pipe requires control of tensile stresses, which are directly related to deflection. Deflections are controlled by backfill and control of construction practices" (Hsuan and McGrath, 2005).

5.1.1 Deflection Testing

Seven of the nine states included in this study require deflection testing of plastic pipe. South Dakota does not require deflection testing and it is unclear what tests are required by Arizona. AASHTO (2010a) prescribes deflection of an installed plastic pipe not be greater than 5% of the original ID (inside diameter) measured not less than 30 days following completion of installation. All of the states that do require deflection tests specify that testing must occur at least 30 days after installation. ASTM D 2321 continues to state "as a quality control measure, periodic checks of deflection may be made during installation." Additionally, Nebraska requires periodic deflection tests during construction. If a pipe fails a deflection test, consequences vary depending on the state. Three states specify the contractor is to replace the pipe if deflection exceeds 5%. One state, Ohio, allows a 7.5% deflection before replacement is required. Utah, allows 10% deflection before replacement; in addition, a 25% deduction of the contractor's unit bid price is enforced when deflections are greater than 5%. Kentucky imposes a 50% reduction of the contractor's unit bid price resulting from a failed mandrel testing procedure where the deflection is found to be greater than 5%. Removal and replacement is required if the deflection is greater than 10%. Also, Virginia imposes a 25% reduction of the contractor's unit bid price resulting from a failed mandrel testing procedure where the deflection is found to exceed 5%. AASHTO (2010a) requires an evaluation by the contractor that uses a professional engineer to review and evaluate the pipe in installations where deflections exceed 5%. Areas that should be investigated include the severity of deflection, structural integrity, environmental conditions, and the design service life of the pipe. Replacement or remediation is required if deemed to be problematic. Furthermore AASHTO (2010a) requires remediation or replacement for pipes that fail a 7.5% test. A test program in Ohio is studying (14) HDPE pipe installations. ODOT had to replace one of the fourteen pipes due to excessive deflection. ODOT's representative stated "We did not have perfect results," but expressed his satisfaction with the program, and is confident the supplemental specification will be adopted into their standard specification. FDOT openly admits they are aggressive with their deflection testing protocols. FDOT specifies all pipe, regardless of material, less than or equal to 48 inches in diameter are required to be laser ring and video tested.

Out of the seven states that do require deflection testing for plastic pipe, four (Florida, Nebraska, Ohio, and Utah) also require deflection testing for metal pipes. Ohio and Nebraska allow a 7.5% deflection limit for metal culverts. Florida and Utah impose the same deflection standards on metal pipe as they do for plastic pipe. AASHTO (2010a) requires a deflection test of metal culverts and places the maximum limitation of 7.5%, if failed remediation or replacement is required. AASHTO (2010a) states metal pipes that fail a deflection test should be considered as indicative of poor backfill materials, poor workmanship or both. Metal pipes smaller than 24 inches in diameter are not required to be tested as specified by AASHTO (2010a).

Deflection testing is not necessary for concrete pipe. However, states that use a laser profiling system can measure crack widths and lengths occurring in pipe. Ohio requires measurement of all crack lengths whose width is greater than 0.1 inches. Florida requires this for all sizes of cracks in the pipe. AASHTO (2010a) recommends concrete pipe should be inspected 30 days after installation for cracks inside of the pipe. AASHTO (2010a) considers longitudinal and transverse cracks that are less than or equal to 0.01 inches to be minor and should be noted in an inspection report. If cracks are greater than 0.1 inches, it could be indicative of poor bedding, overloading, or poor installation procedures, especially under the haunch area. However, the reader should be aware the AASHTO (2010a) commentary states pipes installed in noncorrosive environments (pH> 5.5) with cracks 0.10 inches or less can be considered acceptable. From review of the state specifications, it was found a concrete inspection of this nature was not typical. Although it seems reasonable to conduct a manual inspection of larger diameter pipes, it appears outside of the normal procedures by states included in this study. Further research in this area is warranted.

In addition to the testing procedures of the different pipe material discussed above, AASHTO (2010a) recommends a general inspection procedure for all pipes. The suggested areas of investigation include joint quality, alignment, localized distortions, and backfill materials.

Deviations in these areas may significantly affect the design life of the pipe. Additional information regarding inspection protocols, forms, and equipment can be found in Chapter 14 of AASHTO (2007).

Different types of deflection tests include: mandrel, laser, physical measurement, and video with the most common being the mandrel testing. Physical measurement can be very difficult in pipe diameters less than 48 inches. Few national standards exist which dictate how the test should be performed and what constitutes failure. In 1986 the FHWA published the FHWA Culvert Inspection Manual. It was determined that there was a need to have inspection of culvert systems which can be tied to a numerical rating system. It should be noted that this manual does not include all pipe materials, most notably plastics. Also, more recent development of video and laser ring technology provides sophisticated tools for culvert inspection. For these reasons, it was determined that the FHWA manual was considerably out of date. In response to this, NCHRP Project Report 14-26 is currently in development. This report intends to provide AASHTO with a policy that addresses the following: (1) catalog for distressed conditions, (2) inspection techniques, (3) condition assessment and rating criteria, (4) inspection reporting, and (5) best practices to help agencies manage their culvert inventory. WYDOT should be aware of this report and review its contents when published. Currently, it appears laser ring deflection testing mostly occurs in eastern states and the equipment is costly. When laser ring technology becomes more readily available, WYDOT should consider its use for implementation within their specification. For the purposes of this report, mandrel testing appears to be the most practical tool available for WYDOT. Currently, KDOT provides the most comprehensive literature (KM 64-114-12) found discussing deflection testing. This document includes requirements for the mandrel size and construction, outlines the testing procedure, and describes the report format and submittal. The report in its entirety can be found at *transportation.ky.gov/Materials/Documents/KM114_12.pdf*. It is our recommendation that the WDOT consider adopting the KDOT testing procedure as a practical, interim measure. As additional testing technologies and further research become available WYDOT should consider adopting new test standards. In addition to KM 64-114-12, Virginia publishes a post installation manual for buried culverts and storm drains (Virginia Test Method-123) and should be considered for review by WYDOT.

Although repeatable scientific literature which outlines standardized procedures for deflection testing is lacking; the practice has been shown to have significant merit. It is the opinion of this report that WYDOT should consider requiring culvert inspections for future installations.

5.1.2 Deflections of HDPE Pipe

As previously discussed, plastic pipe is sensitive to construction and installation procedures which can lead to excessive pipe deflections. In addition, a discussion of types of deflections and the AASHTO design equations which predict this behavior is discussed below.

5.1.3 Peaking Deflections at Installation

Deflections which occur during installation are a result of the compaction energy induced within a soil envelope. The energy results in lateral or horizontal pressure which typically deflects the pipe upward. As the final layers of the backfill are placed, the pipe will then deflect in the opposite direction, returning the pipe close to its original shape. Masada & Sargand (2007) suggest this initial peaking deflection is necessary to consider when predicting the long term deflections. This is because the deflection, which is a result of the final backfill layer placement, would theoretically cause greater vertical deflections if induced upon a culvert which does not have this initial upward peaking deflection. The current AASHTO design equations do not take into account initial peaking deflections.

5.1.4 Long term Deflections

Excessive long-term deflections may cause large combined bending strains within a pipe profile. The strains are limited by current AASHTO design equations and if not controlled local buckling or rupture may occur (NCHRP 631). AASHTO design equation (12.12.3.5.4b-1) is used to calculate the anticipated vertical deflection due to bending. When calculating the factored thrust, as specified by AASHTO eq. 12.12.3.4-1, it is not clear whether the engineer should use the short or long-term section modulus. Within AASHTO (2010b) commentary C12.12.3.3, an explanation of the short and long term section modulus is provided which states that HDPE and PVC have a non-linear stress/strain relationship which is dependent upon time. The commentary asserts this relationship is not synonymous with material softening. The commentary points to the engineer to judge which modulus to use depending on the load application. However, AASHTO C12.12.3.3 states “Response to live loads will reflect the initial modulus, regardless of the age of the installation.”

5.2 Control Over Pipe Selection: Contractor versus Designer

Currently, when the bid item “Pipe” is used, any alternate allowed in the standard specifications can be used as long as it meets the CR Number and the allowable minimum and maximum fill heights. In some instances, states have also implemented abrasion guidelines with which the pipe must also be approved within certain limits to be deemed as an acceptable material. From the DOT surveys, it was determined Colorado, Florida, Ohio, and Washington use performance based specifications. DOT engineers consistently mention this system introduces free market principles into the pipe selection process by allowing the contractor to determine the means and method of installations; therefore a reduction in price of culvert installations have been noticed by the individual agencies. This allows the individual pipes to compete against each other based on their particular strengths and weaknesses; which in turn alleviates much of the external pressure imposed upon DOT agencies by various manufacturers. In general, the DOT surveys show an overall level of satisfaction when implementing performance based specifications. However, the surveys show by choosing to implement this system, it is not uncommon for agencies to not know which types of pipe have been installed. This disconnect may lead to insufficient knowledge of the overall culvert inventory. If WYDOT chooses to implement a performance based specification, consideration should be given to implementing a system to record the type and method of culvert installations.

5.3 Payment for Various Installation Methods

Within the state specifications, multiple methods exist for measuring and calculating completed work. This calculation then translates to pay items where the contractor may receive full or partial payments depending on the percentage of the work completed. Typical methods of measurement are as follows:

- Lump Sum. This method does not include calculation of individual effort or materials for completion of the work. Instead this method encompasses all of the cost incurred and then combines them together in order to provide a simplified cost analysis. An example of this method is a mobilization cost.
- Per Unit or Each. This method counts the number of particular instances of an installation and then determines a cost per installation. End sections or treatments are a common example of this method.
- Length. The length measured with respect to a datum, then a cost per length is used. Culverts or drainage pipes in general are typically paid for by a cost per foot basis rounded to the nearest foot.
- Area. A two dimensional area is calculated, then a cost per area is submitted.
- Volume. A three dimensional volume is calculated, then a cost per volume is submitted. Excavation and backfill quantities are typically priced by this method and submitted as a cost per cubic yard.

Due to the complexities of projects, a combination of the previously discussed methods is used with hopes to provide a simplified and accurate cost analysis. For example, a lump sum per length method is used by ADOT for calculation of pipe installations. ADOT 2008 states the following:

> "…no separate measurement or payment will be made for excavating trenches and for furnishing, placing and compacting bedding and backfill material as specified herein and on the project plans, the cost thereof being considered as included in the contract unit price per foot of pipe."

This method considers the bedding, backfill material, significant construction and installation cost incidental to the pipe installation. Therefore, this method requires the contractor to account for these costs when determining his or her bid. A lump sum method does appear to provide a simple and efficient procedure of tracking pipe installation cost and may be determined advantageous by the agency. However, a more common method as specified by the states is to break down the excavation, bedding, and backfill on a cost per volumetric basis. This volume is typically calculated from the dimensions shown on the construction drawings. Calculated volumes may or may not encompass work for compaction, transportation (hauling), or other construction cost. Theoretical volumes and areas are typically calculated using "neat lines" determined from the construction drawings. Then the pipe material is separate and paid for by a price per linear foot of pipe.

Although the previous method is more common within state specifications, AASHTO (2010a) suggest the method of payment for all pipe installations should be more similar to Arizona's method of payment discussed above. AASHTO (2010a) states the following:

> "…the length determined as herein given shall be paid for at the contract unit prices per linear foot bid for culverts of the several sizes and shapes, as the case may be, which prices and payments shall constitute full compensation for furnishing, handling, and installing the culvert and for all materials, labor, equipment, tools, and incidentals necessary to complete this item. Such price and payment shall also include excavation, bedding material, backfill, headwalls, endwalls, and foundations for pipe."

No scientific literature was found that proves which method or combination of methods of payments correlate to fewer change orders, lawsuits, or in general less financial discrepancies between agencies and the general contractors. Ultimately, WYDOT should decide what areas of pipe installation the agency believes to be necessary to keep record of and then specify how to pay for installations.

5.4 Ultraviolet Degradation

UV degradation is a process where ultraviolet rays alter or break down polymer strains resulting in altered mechanical properties of the material. This process is accelerated in the presence of oxygen (Gijsman et al., 1999). Plastic is subject to degradation in direct sunlight also known as photo-oxidation. NRC (1998) states the effects from UV degradations include a color change, a slight increase in tensile strength and elastic modulus, and a decrease in impact strength. FHWA/CA/TL-CA01-0173 notes that pipes such as PVC and HDPE are prone to UV degradation and notes an adverse “immeasurable” effect to the durability of the pipes when exposed to sunlight. To combat UV effects, plastic pipe is treated with a UV inhibitor such as carbon black and antioxidants to retard UV effects and reduce the acceleration of the degradation from the presence of oxygen. Hsuan and McGrath (2005) state the mechanical properties and ultimately the design life of HDPE pipe can only be maintained by properly formulated antioxidants. Although both the additives help prevent degradation, they will eventually dissipate if sun light exposure is prolonged. The chemical aging process of HDPE polymers is described in Figure 12 by Hsuan and Koerner (1998) below.

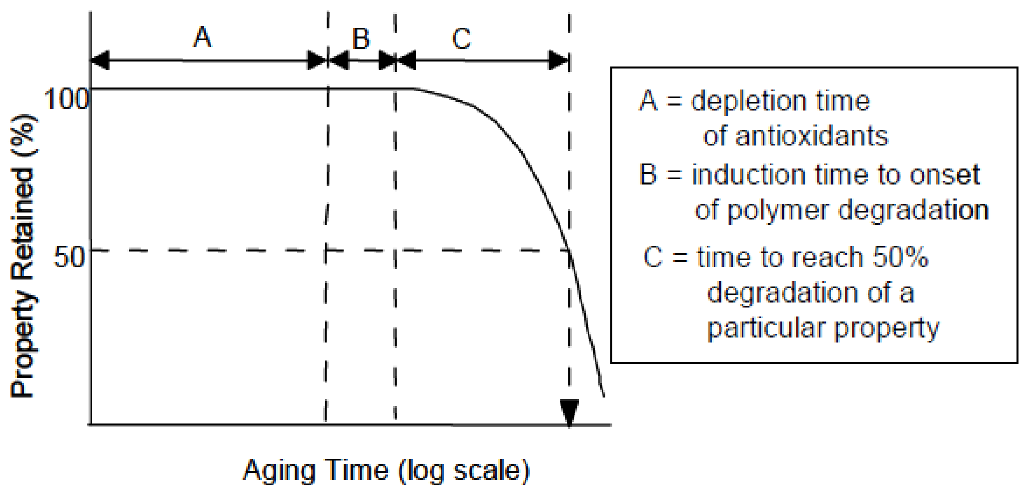

Figure 12: Conceptual Chemical Aging of HDPE Polymers (Hsuan and Koerner, 1998)

This graph shows when all antioxidants are depleted (Stage A) and the material cannot resist degradation any longer (Stage B), degradation of the pipe material will result (Stage C); at this time, mechanical properties will begin to decline exponentially. ASTM D 3895 outlines an accelerated oxidation induction time test (OIT) which measures the number of hours to reach the individual stages. To ensure an adequate time period is met, ASTM D 3350 (previously discussed) provides minimum values for meeting a specified cell class.

Therefore, it is necessary to ensure carbon black is always stipulated for applications where the product will sit in the sun while stockpiled or in its final location. ASTM D 3350 specifies this by the last character input “C” of the cell classification. This designation requires the pipe to be black in color and be composed of a minimum of 2% carbon black. NRC (1998) indicates the concern of UV degradation is minimal for concrete and steel, and no scientific literature was found to prove otherwise.

5.5 Risk of Fire Destruction

Plastic pipe is not flammable (i.e., will not sustain combustion on its own), but if a fire fuel source such as tumbleweed and other debris accumulates inside the pipe, the structure can be consumed in a fire. A case in point occurred in Badlands National Monument when a grass fire ignited tumbleweeds in an HDPE culvert. The fire moved very quickly, but when done, all that could be seen were the corrugations in the backfill material which hadn't moved yet. Most states using HDPE have apparently treated this as a fairly low risk potential, but this concern may preclude its use in certain areas where a fuel source may be present and/or frequent controlled burns close to the highway are anticipated. For example, WSDOT specifically addresses this issue by adding the following statement within their specification "If maintenance practices such as ditch or field burning is anticipated near the inlet or outlet of a pipe, it is recommended that PE not be allowed as a pipe alternate." Also, as previously mentioned in Chapter 4, AASHTO (2006) recommends that agencies should give consideration when using plastic end sections due to combustibility. Little scientific research is present specifically addressing this issue; however, this section still warrants consideration by WYDOT.

5.6 Roadway Settlement

In general, pipe culverts in Wyoming have been structurally sound unless damaged by corrosion or abrasion, but roadway settlement over culvert installations has occurred in some locations. Roadway settlement is the result of vertical deformation which occurs in the pipe foundation, the pipe itself, or in the backfill soil; the problem is well-documented in WYDOT Research Report FHWA-WY-97/01 (Lundvall and Turner, 2001). This can result in a vertical deformation in the roadway commonly known as a "dip", which in turn, may lead to minor or significant safety concerns for motorists. Lundvall and Turner, (2001) cite three probable causes for this and are as follows:

- Inadequate compaction.
- Shallow cover of fill above culverts.
- Use of plastic, compressible soils derived from bentonitic Cretaceous shales as fill.

The previous study investigated a particular area (in addition to three other sites) in Wyoming shown to have significant roadway settlement, located at WYO 487 between Medicine Bow and Casper. This location is described to have severe roadway settlement problems occurring at approximate mile post 51.18, 50.47, 50.24, and 47.97. Analysis of the geological soil conditions in this area show it is underlain with a Steele Shale formation consisting of several bentonite beds. A statement which describes this formations composition is as follows: "Bentonite consists primarily of the clay mineral montmorillonite, and often indicates soils with high plasticity, high compressibility, low shear strength, and undesirable volume change characteristics (shrinking and swelling)." In addition, these locations had the least amount of cover. Soil samples from this area were analyzed at the University of Wyoming and were classified as A-7-6 according to AASHTO classification system. This soil was then used as backfill for a laboratory experiment which induced cyclic and static loading tests upon a buried steel culvert in various fills. Deflections occurring within the pipe due to the loading were then measured and recorded. From these results the authors conclude the soil taken from the Shirley Basin site classified as A-7-6 should not be used as backfill around structures. In addition, well compacted granular soil or CLSM would provide better material or subgrade and therefore minimize roadway settlement. Finally, the results show the smallest measured deflections occurred in the pipe installed with CLSM backfill.

Final recommendations include select backfill material, such as granular or sand backfill, should be considered and that better quality control of backfill compaction is needed. CLSM should also be considered as an option to mitigate settlement. These results and conclusions are consistent with previously mentioned studies included in this report. The authors note most of the settlements were observed in metal pipes, but some occurred with concrete pipe as well. Therefore, it is important to note that roadway settlement is a concern for both rigid and flexible structures.

CHAPTER 6: INTRODUCTION TO LRFD FOR CULVERT DESIGN

6.1 Load and Resistance Factor Design Background

The first LRFD code introduced by AASHTO was published in 1991 followed by the first applied version in 1994 (Dasenbrock, 2009). This code received little attention and was rarely used. In response to this, a mandate was imposed by AASHTO requiring all bridge projects after October 2007 to be engineered using LRFD procedures in lieu of traditional Allowable Stress Design (ASD). WYDOT currently is in the process of converting culvert fill heights to the LRFD Specifications. A brief discussion of LRFD procedures including the current HL93 design truck loads is presented below.

6.2 LRFD Philosophy

Allowable Stress Design (ASD) is based on the application of a single factor of safety to the resistance of the material, which is suggested to be based on experience and not necessarily mathematical reasoning (Huaco et al., 2012). In this approach, the uncertainty and variability associated with both load and resistance are lumped into a single parameter, the factor of safety. This approach has several shortcomings, the most significant of which is that it does not provide a consistent and rational framework for incorporating the individual sources of risk into the design. No consideration is given to the fact that each component of load and resistance has a different level of variability and uncertainty, i.e, load and resistance are independent variables. These criticisms of ASD were the impetus for developing the LRFD approach. As its name implies, LRFD imposes separate factors upon the loads and material resistances and therefore accounts for uncertainties in both. Resistance factors are derived from rigorous statistical analyses to achieve a target reliability index (β) which is related to the probability that the structure will reach a 'limit state'. A limit state is defined as a condition for which the structure does not fulfill its design function. A limit state can be defined in terms of strength, for example based on yield strength of the material, or in terms of serviceability, for example a limiting value of deformation. One of the advantages of the LRFD approach is that all components of the structure, including the geotechnical components, can be designed to a uniform level of safety. In other words, for a given limit state, the probability of failure is approximately the same for all components of the structure. This approach is expected to result in designs that are more cost-effective and with a more clearly defined and uniform level of safety.

Barker and Puckett (2007) summarize the uncertainties accounted for within LRFD bridge design procedures, as follows:

Υ_i load factors, typically greater than 1:

- Magnitudes of loads.
- Arrangement (positions) of loads.
- Possible combinations of loads.

ϕ resistance factors, typically less than 1:

- Material Properties.
- Equations that predict strength.
- Workmanship.
- Quality Control.
- Consequence of failure.

Accounting for these uncertainties statistically allows the probability of achieving a limit state to be calculated. The use of resistance factors that provide a sufficiently low probability of reaching a limit state forms the basis of achieving a "safe" design. The basic LRFD design requirement, as implemented in AASHTO (2010b), can be stated as follows: *for each limit state, the summation of factored force effects may not exceed the summation of factored resistances*, or:

$$\Sigma \eta_i \Upsilon_i Q_i \leq \phi R_n \qquad \textbf{Equation 1}$$

where:

Υ_i = load factor: a statistically based multiplier applied to force effects.

ϕ = resistance factor: a statistically based multiplier applied to nominal resistance.

η_i = load modifier: a factor relating to ductility, redundancy, and operational classification.

Q_i = force effect.

R_n = nominal resistance.

It is important to note different load combinations are coupled with different load factors depending on which AASHTO (2010b) load combination and which sources of load are being considered (dead, live, earth, etc.). In addition, resistance factors vary depending on which culvert material is used. These are discussed in further detail later in this chapter.

6.3 HL-93 (highway load, developed in 1993)

HL-93 loading configuration encompasses three different types of live load, which include a design truck, design tandem, and a design lane (see Figure 13 for loading configuration). Although these loads are very similar to the old standard design loads known as highway semitrailer 20 ton loads (HS20), the methodology of their application varies. To determine maximum load effects using current LRFD procedures, AASHTO (2010b) requires the greatest load effect from the design truck or tandem superimposed onto the design lane. ASD procedures do not require design trucks to be combined with design lanes. This a major difference between the two codes. The HL-93 design loads were the result of multiple studies. One particular example is Kulicki and Mertz (1992), which investigated the effects of truck loads (exclusion trucks) and compared them to HS20 loads. The study measured the force effects of trucks passing over single and multiple span bridges. Areas which were monitored include positive and negative shear adjacent to the exterior supports, negative shear adjacent to the interior support, positive and negative moments at the 4/10 spans, moment over the interior support, and moment at the midspan of a simply supported bridge. The ratio of the measurable effects from the exclusion trucks to the HS20 loads is shown below in Figure 14 and Figure 15. These results consistently show a ratio much greater than one meaning that measurable load effects are greater than the design effects of the HS20 loads and therefore not conservative. The ratio of the measured force effects were then compared to the HL-93 loads, the results of which are shown in Figure 16 and Figure 17. These figures show the maximum ratio for both shear and moment is less than 1.2, which is considerably less than the maximum HS20 ratio of approximately 1.85. In addition, the variation is considerably less when comparing the HL-93 loads. As a result of this, the HL-93 loads were adopted and are used within the current LRFD code, AASHTO (2010b).

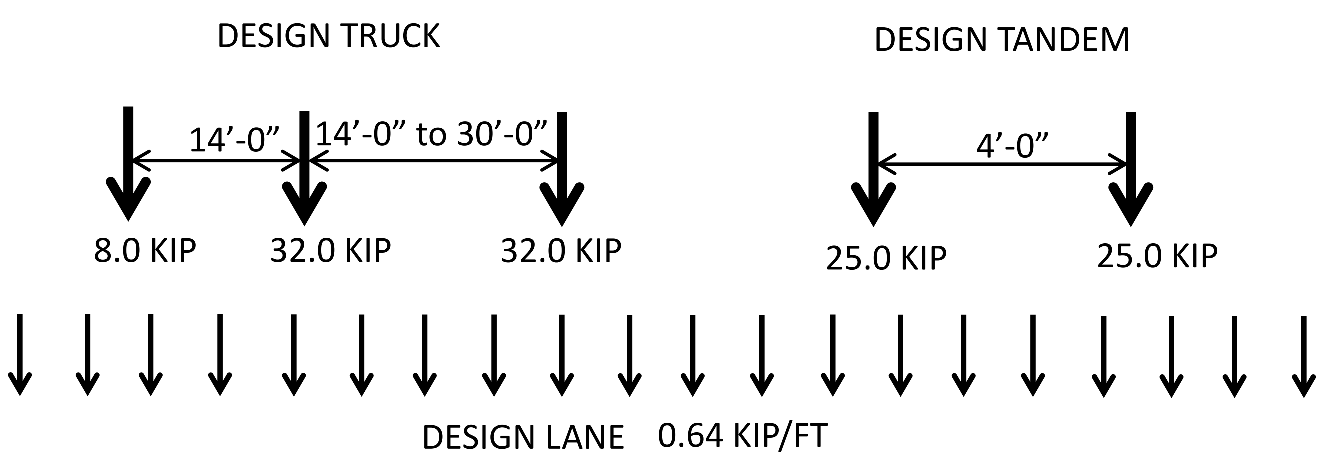

Figure 13: Schematic of AASHTO HL-93 Loads

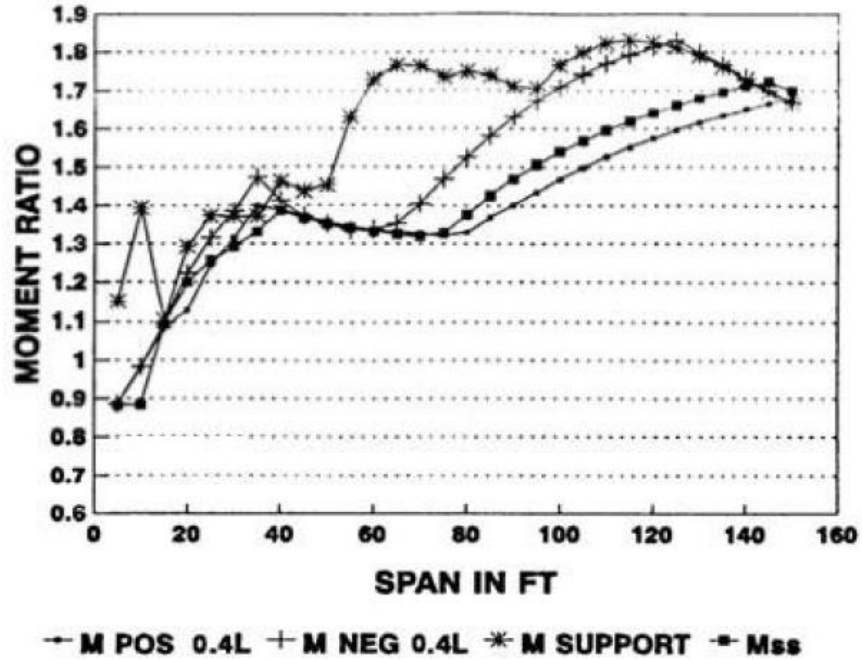

Figure 14: Moment Ratios: Exclusion Vehicles to HS20 (truck of lane) or Two 24.0-kip axels at 4.0 ft (AASHTO, 2010b)

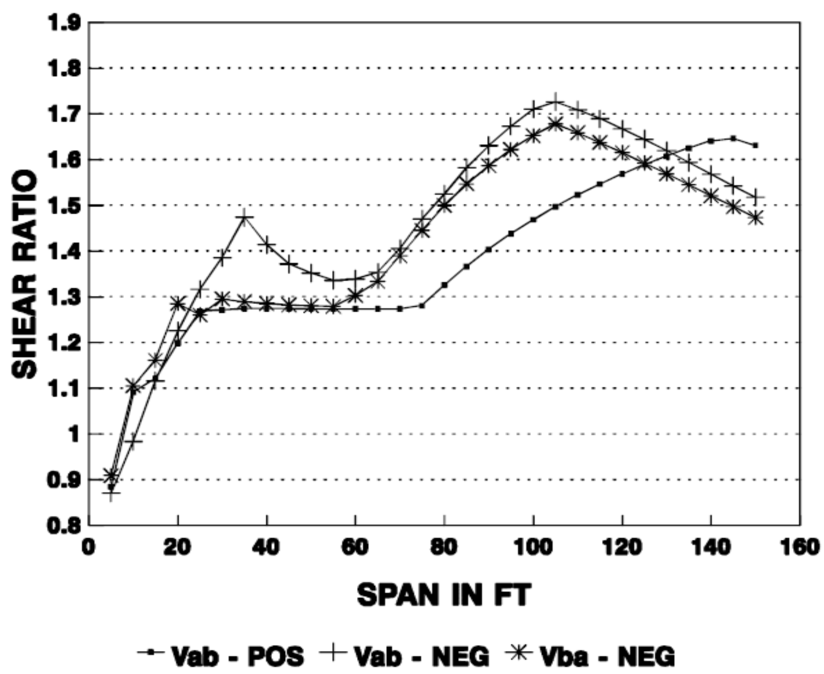

Figure 15: Shear Ratios: Exclusion Vehicles to HS20 (truck of lane) or Two 24.0-kip axles at 4.0 ft (AASHTO, 2010b)

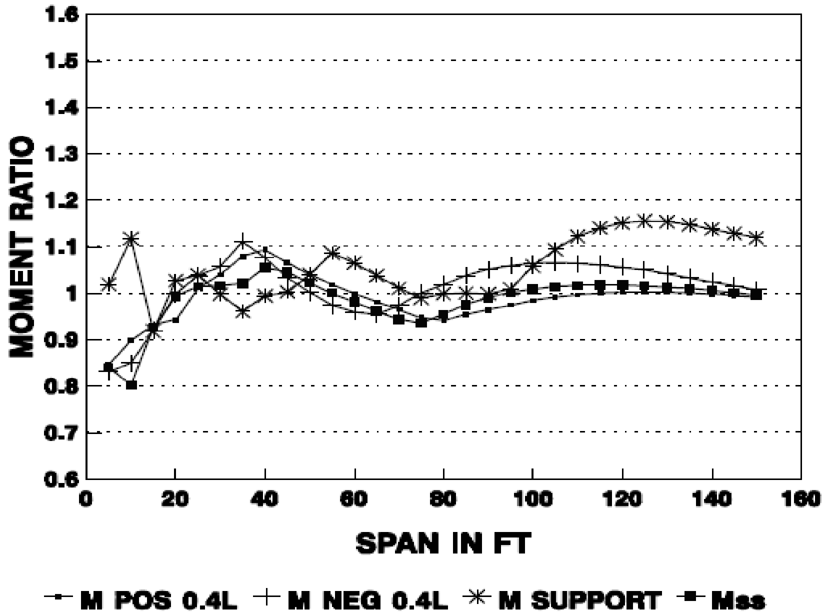

Figure 16: Moment Ratios: Exclusion Vehicles to HL-93 Loads (AASHTO, 2010b)

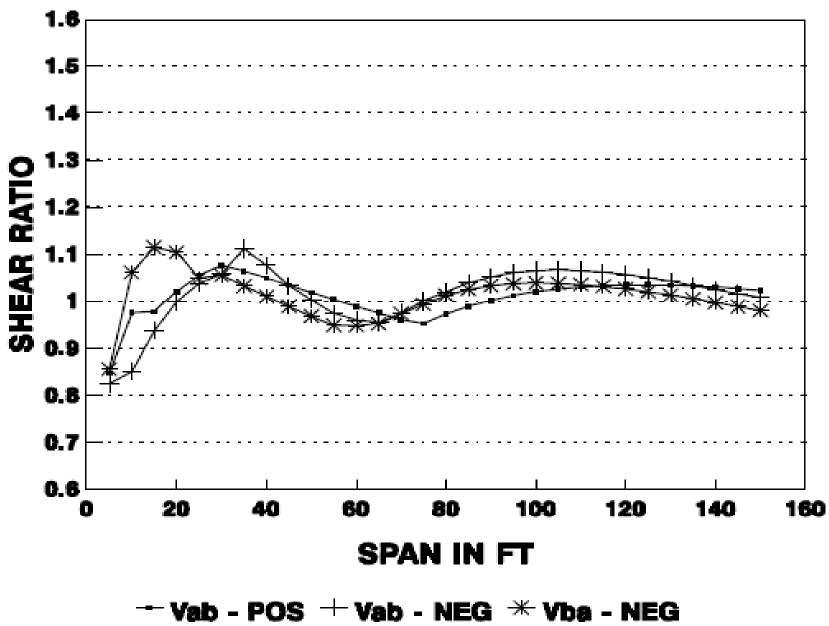

Figure 17: Shear Ratios: Exclusion Vehicles to HL-93 Loads (AASHTO, 2010b)

6.4 AASHTO 2010 LRFD Design

AASHTO (2010b) requires investigations of multiple limit states for serviceability, strength, fatigue, and extreme loading for general bridge applications. However, AASHTO (2010b) asserts fatigue and extreme events do not control the design of culverts and therefore only particular serviceability and strengths checks need to be considered. A summary of the required limit state checks for culvert design prescribed by AASHTO (2010b) are as follows:

Service Limit State: Imposes restrictions on stresses, deflections, and cracking under regular service conditions.

Service Load Combination I – Basic load combination assuming normal vehicle use with all loads taken as their nominal values.

Strength Limit State: Requires adequate material resistance of the entire system to be greater than applied loads.

Strength Load Combination I – Basic load combination assuming normal vehicle use.

Strength Load Combination II – Load combination assuming special or permit vehicles specified by the agency.

As previously discussed, these individual load combinations use different factors for the various loads which must be considered. For the purposes of this report, loads which require attention for culvert design include hydrostatic (WA), earth (EV), and live (LL) vehicle loads. Other required considerations prescribed by AASHTO (2010b) include multiple presence factors (m), dynamic impact factors (IM), and live load distribution factors (C_L for culverts). This can be summarized by an expanded version of Equation 1, shown below in Equation 2.

$$\boldsymbol{\eta_I\, \eta_R\, \eta_D\, [\Upsilon_{wa}\, WA + \Upsilon_{ev}\, EV + m\, C_L\, \Upsilon_{LL}\, (LL_{TR}\, (1+IM) + LL_{LN}\,)] \leq \phi\, R_n} \qquad \textbf{Equation 2}$$

Where:

η_I = operational importance factor, varies from 1.05-0.95 based on the location of installation.

η_R = redundancy load modifier, 1.0 for typical installations.

η_D = ductility load modifier, 1.0 for typical culvert materials.

Υ_p = load factor for permanent loads, varies see AASHTO 3.4.1-1 and 3.4.1-2.

Υ_{wa} = load factor for hydrostatic pressure, see AASHTO 3.4.1-1.

WA = force effect from hydrostatic load.

Υ_{ev} = load factor for geostatic earth pressure, 1.95 for flexible buried structures see AASHTO 3.4.1-1.

EV = force effect from vertical geostatic earth load.

m = multiple presence factor, see AASHTO 3.6.1.1.2-1.

C_L = live load distribution coefficient L_w / D_o.

L_w = horizontal live load distribution width in the circumferential direction, at the elevation of the crown (ft.).

Υ_{LL} = load factor for live loads, varies see AASHTO 3.4.1-1 and 3.4.1-2.

LL_{TR} = force effect from the greater of the design truck or design tandem.

IM = dynamic impact load factor = $33(1.0-0.125D_E) \geq 0\%$.

D_E = the minimum depth of earth cover above the structure (ft.).

LL_{LN} = force effect from the design lane.

ϕ = resistance factor, varies depending on culvert material, see AASHTO 12.5.5-1.

To reiterate, the above equation is an expansion of the general LRFD equation (Equation 1) where individual load modifiers (η_i) and load factors (Υ_i) are applied to each component of load. The load factors are derived from statistically-based probabilistic analyses, and give designers the ability to refine their analysis by increasing the load factors in areas of higher uncertainty. For example, the load factor for geostatic earth pressure (Υ_{ev}) is 1.95 for buried structures; the load factor for hydrostatic pressure (Υ_{wa}) is 1.30. This suggests that designers believe the force effects from earth pressure could vary significantly when compared to the effects from the hydrostatic pressure, and therefore justify a greater load factor. Similarly, the resistance factors (ϕ) for reinforced concrete pipe range from 0.82 to 1.0 depending on the installation and loading condition. The resistance factor for plastic pipes is 1.0; again suggesting a higher level of uncertainty for different material strengths. This reasoning forms the underlying basis of LRFD and is why some designers believe a more consistent design can be achieved by using this method.

6.4.1 LRFD for Plastic Pipe

Section 12.12 of AASHTO (2010b) outlines the design equations and procedures for plastic pipe design. Thrust, buckling, and flexibility limits are the three governing design checks required by AASHTO (2010b). Detailed examples of LRFD procedures for plastic pipes can be found in NCHRP 631. In addition, through DOT surveys (Appendix A), it was determined that WSDOT required plastic pipe suppliers to submit LRFD calculations for review. These sources are valuable design aids for determining LRFD fill heights. Although the exact design equations are outside the scope of this report and not discussed, particular factors that warrant comment are included. These factors can significantly affect fill height calculations and their implementation is left to the discretion of the engineer. Often, these factors can be improperly used if careful review of the AASHTO (2010b) commentary is not exercised.

VAF (vertical arching factor): This is designated within AASHTO (2010b) as VAF. VAF is a phenomenon of pipe/soil interaction theory, and is summarized by Sargand and Masada (2003). When a flexible pipe is installed, the stiffness of the pipe is less than that of the adjacent soil. As flexible pipe deforms under induced loads, the result is a differential shear interface between the soil column above the pipe and the adjacent soil. For flexible pipes, there is an upward shear force; therefore, the calculated soil pressure (P_{sp}) is reduced. This is referred to as positive arching action. The opposite reaction is seen when rigid pipes are installed, resulting in negative arching action, or an increase in soil pressure. Graphical representation of VAF is presented below in figure 18. NCHRP 631 design examples show this factor can reduce the soil pressure by as much as 75%, which is considerable. Conservatism may be adopted by using a VAF equal to 1.0. If WYDOT elects to require pipe manufacturers to supply design equations or use equations supplied by NCHRP 631, it is important to note AASHTO (2010b) only allows use of this factor if embankment type installations are used. VAF is not applicable for trench installations. This is discussed in the AASHTO (2010b) interim specifications and is unclear in the design equations.

$K_{\gamma E}$ (Load Installation Factor): This factor is applied to the calculated soil pressure and ranges in value from 1.0 to 1.5. It is intended to impose an additional factor of safety for plastic pipe installation due to the sensitive nature of the material's dependence upon strict installation standards. This factor is also discussed in the AASHTO (2010b) interim specifications commentary and is not included in the current design equations. The commentary states the factor must be 1.5 unless the designer ensures additional testing, monitoring, construction controls, bedding and backfill requirements, and compaction requirements are met.

Compaction Design Practice: As previously discussed, greater design life of plastic pipe depends greatly upon the type of backfill and compaction of the soil envelope. The soil modulus (M_s) significantly affects the design of this pipe and is clearly shown in the AASHTO design equations. Typical values are shown in AASHTO (2010b) Table 12.12.3.4-1. However, within the commentary it is suggested that the relative design compaction of the soil be 5% less than the specified compaction requirements. Therefore, when conducting fill height calculations, a 90% compaction should be used in design while still specifying a minimum 95% compaction for construction. Applying this procedure will result in a conservative design soil modulus, again affecting fill height calculations.

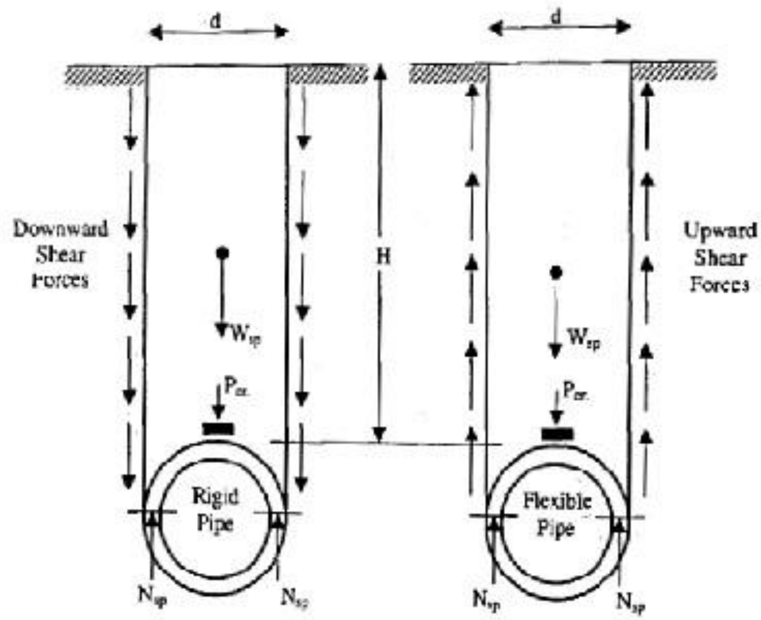

Figure 18: VAF Theory (Sargand and Masada, 2003)

6.4.2 Plastic Pipe Specifications

AASHTO (2010b) includes two different plastic pipe materials within its specification for design, polyethylene (PE) and PVC. Each pipe material has subcategories which are designated by either an AASHTO or ASTM specification. A brief summary of the classification of plastic pipes included in AASHTO (2010b) is as follows:

Polyethylene

Solid Wall - *ASTM F 714: Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Outside Diameter*

ASTM F 714 discusses three standard outside diameter sizing systems used for specification of solid wall pipe. These systems are known as ISO metric system, IPS system, and the DIPS system. These different systems give dimensional properties such as the outside diameter of the pipe, tolerances, and wall thicknesses. This specification also outlines material, workmanship, tolerances, and testing requirements.

Corrugated - *AASHTO M 294: Corrugated Polyethylene Pipe, 300-mm to 1500-mm Diameter*

AASHTO M 294 (referred to in this report as AASHTO 2006) discusses the material, dimensional properties, workmanship, testing procedures and pipe tolerances. This specification outlines the various wall classifications of pipe, which include Type C, Type S, and Type D. Type C pipe consists of corrugations on the interior and exterior surfaces. Type S possesses an outer corrugated pipe wall and a smooth interior. Type D is constructed with a smooth interior and outer wall. In addition, all of these classifications may be perforated, in which case they are designated as CP, SP, and DP. This specification is similar to ASTM F894 with regard to the type of wall construction. However, AASHTO M 294 specifies the minimum cell classification to be 435400C per ASTM D 3350. It is important to note, within AASHTO M 294 and AASHTO (2010b), pipes are required to pass the notched constant ligament-stress (NCLS) test according to ASTM F2136. This test measures the slow crack growth resistance. Most states require pipe that shall meet the minimum specifications of AASHTO M 294.

Profile - *ASTM F 894: Standard Specification for Polyethylene (PE) Large Diameter Profile Wall Sewer and Drain Pipe.*

ASTM F 894 discusses the two different types of profile wall type construction for polyethylene pipe. They are referred to as closed and open profile wall. The closed profile wall system provides a smooth internal and external surface. The open profile wall system provides a smooth interior surface with ribbed or corrugated external surface. The specification discusses requirements for material, dimensional properties, workmanship, testing procedures and pipe tolerances. In addition, the various methods of joining systems are summarized along with their respective testing protocols.

Poly Vinyl Chloride (PVC)

Solid Wall – *AASHTO M 278: Class PS46 Poly(Vinyl Chloride) (PVC) Pipe*

Profile Wall – *AASHTO M 304: Poly(Vinyl Chloride) (PVC) Profile Wall Drain Pipe and Fittings Based on Controlled Inside Diameter*

AASHTO M 278 and 304 discuss the material, dimensional properties, workmanship, and pipe tolerances. Both specifications are very similar. The largest difference between the two specifications is the additional requirements for the profile wall geometry in AASHTO 304. Both reference ASTM D 1784, which is the specification that governs the minimum cell classification for PVC pipe.

A typical cross section of a pipe that is specified by AASHTO M 294 is a corrugated pipe wall that is trapezoidal. The ASTM specifications discuss a profile wall. A profile wall may have multiple profile types; these include annular or helical projections or ribs on the outside of the pipe. Figure 19 below, depicts various profiles. The difference between corrugated and some of the profile wall types is not clear, and it is suggested that wall profiles may be visually similar. According to one plastic pipe supplier contacted by the first author, AASHTO M 294 pipe is manufactured by extruding the pipe through a continuous mold in a single process. Profile walls are manufactured by extrusion of the wall into a sheet, and then that material is wound around a mandrel to finalize the process.

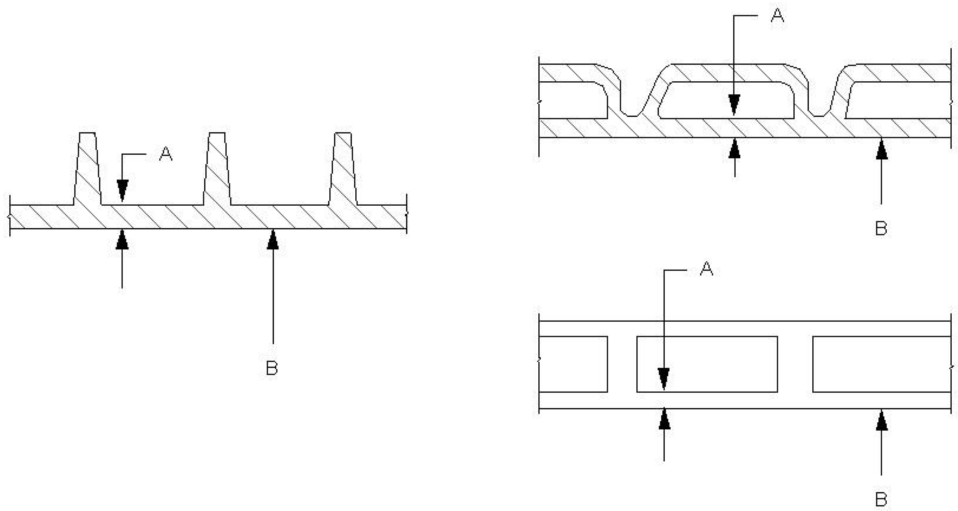

Figure 19: Typical Profiles (Cross Sections): A-Waterway Minimum Wall, B-Average Inside Diameter (Other Configurations of Ribs and Spacing Are Permissible) (AASHTO M 304)

6.4.3 Minimum Cross Sectional Properties

AASHTO (2010b) provides tables of minimum cross sectional properties for AASHTO M 294, ASTM F 894, and AASHTO M 304 specifications, and are presented below in Table 32, Table 33, and Table 34 respectively. These tables should be used as guidance when calculating LRFD cover heights. Actual cross sectional properties could vary significantly and should be checked.

Table 32: Minimum Cross Sectional Properties of PE Corrugated Pipe, AASHTO M 294 (AASHTO, 2010b)

Nominal Size (in.)	Min. *ID* (in.)	Max. *OD* (in.)	Min. *A* (in.^{2}/ft)	Min. *c* (in.)	Min. *I* (in.^{4}/in.)
12	11.8	14.7	1.5	0.35	0.024
15	14.8	18.0	1.9	0.45	0.053
18	17.7	21.5	2.3	0.50	0.062
24	23.6	28.7	3.1	0.65	0.116
30	29.5	36.4	3.9	0.75	0.163
36	35.5	42.5	4.5	0.90	0.222
42*	41.5	48.0	4.69	1.11	0.543
48*	47.5	55.0	5.15	1.15	0.543

For the 42.0-in. and 48.0-in. pipe, the wall thickness should be designed using the long-term tensile strength provision, i.e., 900 psi, until new design criteria are established in the AASHTO bridge and structures specifications.

Table 33: Minimum Cross Sectional Properties of PE Ribbed Pipes, ASTM F894 (AASHTO, 2010b)

Nominal Size (in.)	Min. *ID* (in.)	Max. *OD* (in.)	Min. *A* ($in.^2/ft$)	Min. *c* (in.)	Min. *I* ($in.^4/in.$) Cell Class 334433C	Min. *I* ($in.^4/in.$) Cell Class 335434C
18	17.8	21.0	2.96	0.344	0.052	0.038
21	20.8	24.2	4.15	0.409	0.070	0.051
24	23.8	27.2	4.66	0.429	0.081	0.059
27	26.75	30.3	5.91	0.520	0.125	0.091
30	29.75	33.5	5.91	0.520	0.125	0.091
33	32.75	37.2	6.99	0.594	0.161	0.132
36	35.75	40.3	8.08	0.640	0.202	0.165
42	41.75	47.1	7.81	0.714	0.277	0.227
48	47.75	53.1	8.82	0.786	0.338	0.277

Table 34: Minimum Cross Sectional Properties of PVC Profile Wall Pipes, AASHTO M 304 (AASHTO, 2010b)

Nominal Size (in.)	Min. *I.D.* (in.)	Max. *O.D.* (in.)	Min. *A* ($in.^2/ft$)	Min. *c* (in.)	Min. *I* ($in.^4/in.$) Cell Class 12454C	Min. *I* ($in.^4/in.$) Cell Class 12364C
12	11.7	13.6	1.20	0.15	0.004	0.003
15	14.3	16.5	1.30	0.17	0.006	0.005
18	17.5	20.0	1.60	0.18	0.009	0.008
21	20.6	23.0	1.80	0.21	0.012	0.011
24	23.4	26.0	1.95	0.23	0.016	0.015
30	29.4	32.8	2.30	0.27	0.024	0.020
36	35.3	39.5	2.60	0.31	0.035	0.031
42	41.3	46.0	2.90	0.34	0.047	0.043
48	47.3	52.0	3.16	0.37	0.061	0.056

CHAPTER 7: SUMMARY AND RECOMMENDATIONS

An extensive literature review was conducted to investigate which items should be considered when implementing new culvert materials or when updating WYDOT's *Standard Specification for Road and Bridge Construction*. The framework for this study consists of information drawn from two sources. These include an extensive literature review which focused on three different types of material: DOT's standard specifications; AASHTO and ASTM Standards; and peer reviewed/professional articles. Second, interviews were conducted with state DOT representatives to obtain practical data regarding the use and implementation of HDPE products. Currently, all states which were selected to be included in this study have been contacted to participate in the phone interview. Out of these states, six have participated.

In general, from the research presented within this study it is clear that plastic products are regularly used for open-flow drainage applications with good results depending on the quality of installation. States intentionally specify plastic pipe materials in locations of adverse corrosive and abrasive environments. Only South Dakota does not allow plastic pipe for cross culvert applications. Therefore, it is recommended that HDPE should be regarded as an acceptable material for use in highway drainage applications **if** installed and inspected with strict construction practices. In addition, particular limitations and restrictions should be placed to control the areas of its applicability. The practices and areas of applications which should be considered and implemented are as follows:

7.1 Maximum Fill Height

With the exception of South Dakota, all states specify maximum fill heights that range from 10 feet to 40 feet with an average of 22 feet. AASHTO specifies that pipe must be able to withstand forces and strains from the factored pipe thrust. Research shows plastic pipes installed with strict construction practices performing very well in fill heights up to 40 and even 100 feet. It is recommended that WYDOT review the FLH Standard Drawings as a starting point for maximum fill heights. Ultimately, WYDOT should conduct LRFD fill height calculations to verify the adequacy of any proposed fill height. In addition, it is recommended this distance is to be measured from the top of the pipe (crown) to the top of the pavement.

7.2 Minimum Fill Height

All states included within this study specify minimum fill heights that range from 12 inches to 36 inches. Five of the nine states, Colorado, Ohio, New York, Utah, and Washington specify a minimum fill height of at least 18 inches. AASTHO (2010a) specifies a minimum fill height of 12 inches for all pipe materials for typical pipe installations. ASTM D 2321 specifies minimum fill heights depending on the type of backfill used, which is taken as the greater of 24 inches or one pipe diameter. Studies included in this report show increasing the fill height over a plastic pipe from 18 inches to 24 inches, dramatically reduces deflections and crown soil pressures from live loads. Therefore, it is recommended the minimum fill height for all allowable pipe diameters implemented by WYDOT be 24 inches. In addition, it is recommended that this distance be measured from the top of the pipe (crown) to the top of rigid pavement or the bottom of flexible pavement. It is the opinion of this report that the minimum fill heights should always be maintained. However, in locations where this cannot be accomplished, it is recommended that a method similar to that adopted by Washington State be implemented. Washington State currently requires concrete pipe of the following classes when fill heights are less than 2 feet: 1.5 feet use Class III, 1.0 foot use Class IV, 0.5 foot use Class V.

7.3 Bedding and Backfill

The type of backfill and the manner in which it is installed is one of the most important considerations when using plastic pipe. Research presented in this study shows the soil envelope must be able to develop high shear strengths in order to resist lateral pressure induced by vertical loads. In general, granular, coarse-grained soils with little to no fines typically develop greater shear strength. Also, soils with higher plasticity indexes have been shown to have lower shear strength, be sensitive to changes in water contents, and are more compressible.

AASHTO (2010a) specifies that bedding and backfill soils shall meet the soil classifications of A-1, A-2-4, A-2-5, or A-3 as specified by AASHTO M 145 for plastic pipe installations. These soils include various gravel and sand mixtures with less than 20% fines (GW, GP, SW, SP, GM, SM). The state specification charts indicate that no state allows soils with greater than 20% fines. With the exception of Colorado and Florida, every state limits the fines content to be less than 15%. ASTM allows the use of Class III and IV-A soils if evaluated by a geotechnical engineer, as well as if located in areas of ideal conditions (areas of near optimum moisture content). Although not specifically stated, it is reasonable to assume that ASTM D 2321 suggests Class I and II backfill material only should be used. Studies included in this report show that plastic pipes installed with coarse-grained materials with little fines perform well structurally. With the exception of Arizona, every state consistently specifies a maximum plasticity index of 6 or specifies the backfill to be non-plastic.

AASHTO (2010a) specifies that bedding and backfill soils shall meet the soil classifications of A-1, A-2, or A-3 as specified by AASHTO M 145 for metal pipe installations. However, in long span structures with fill heights greater than 12 feet, only A-1 and A-3 soils are allowed. State specifications show it is common to require a select granular fill for metal pipe installations. Since metal pipes are considered a flexible pipe, although not as flexible as plastic pipe, the system is still dependent upon the backfill soil and therefore relies on a soil envelope that can develop high shear strengths.

AASHTO (2010a) specifies that bedding and backfill soils up to the springline shall meet the soil classifications of an SW type soil as specified by the Unified Soil Classification System (USCS) for Type I RCP installations. A SW soil is comparable to an AASHTO A-3 soil or a Type II soil as specified by ASTM D 2321. Specifying a select granular fill for RCP up to a springline is also typical in state specifications. Furthermore, states including Arizona, Florida, New York, and Ohio continue to specify a granular fill for the remainder of the pipe installation. However, the reader should be aware that most states and AASHTO (2010a) allow fine grained soils with higher percentages of clays (ML and CL) to be used for fill in this area. Various standard details can be found in Appendix B in this Report. Although these specifications commonly allow for lower quality soils, and it is also suggested in this report that this type of installation may provide adequate pipe support, there is always a concern for roadway settlement when using these fills. Silts and clays are more compressible and their performance is highly time dependent. Clays can be sensitive to water content, and silts are subject to piping action. When used as backfill around rigid structures, there is a reasonable concern roadway settlement may occur. In addition, with regard to RCP and steel pipe, backfill soils consisting of rock, sand, and gravel (A-1, A-3 or GW, GP, SW, SP) are recommended due to their lower electric conductivity, thus reducing the chances of corrosion.

Therefore, it is recommended that only select granular soils with less than 10% fines and a maximum PI of 6 be used as bedding and backfill materials for all pipes. The backfill should have a maximum particle size of 1.5 inches. It is recommended the select granular fill satisfy the gradation requirements found below in Table 35. Table 35 is the result of gradation analysis from states, AASHTO M 145, and ASTM D 2321 specifications. The bedding should extend below the invert of the pipe to the specified thickness discussed later in this Chapter. The backfill shall begin from the top of the bedding and continue above pipe crown a minimum of 12 inches. See recommended standard pipe installation detail in Appendix C in this report for further clarification.

Table 35: Recommended Select Granular Fill Gradation

Sieve Size	Percent Passing
1 1/2"	100
1"	75-100
No. 4	20-80

No. 200	10 max.

7.4 Compaction

Compaction is one of the most consistent areas when comparing all specifications. AASHTO (2010b) specifies a minimum relative compaction of 90%. All states with the exception of Utah also specify a minimum compaction of 95%. Colorado allows a lesser compaction of 90% if smaller fill heights are present. Currently, WYDOT specifies a minimum compaction of 95%; therefore, no alteration to WYDOT's Standard Specifications are warranted herein.

7.5 CLSM

Studies have shown that plastic pipe performs better structurally when installed in CLSM compared to traditional soil envelopes. All states allow pipe to be installed with CLSM. Additional, benefits for all pipe installations include accelerated construction time and reduced labor and equipment costs. Because of these advantages, it is recommended that use of CLSM be allowed for plastic pipe installations in Wyoming. It is the opinion of this report, that CLSM should always be considered a viable option for all pipe installations unless the designer has reason to preclude its use. Like typical soil backfill, CLSM should be installed with evenly placed lifts on both sides of the pipe to limit vertical and horizontal deviations. Particular consideration should be given to floatation of the pipe when installed with CLSM. Restraints are recommended to counteract buoyancy forces and alignment deviations. It is recommended a maximum lift thickness of 24 inches be specified, provided restraints are adequate to resist hydrostatic forces.

Comparison of WYDOT's CLSM specification to other state specifications shows the agencies' requirements are somewhat consistent. In general, WYDOT's specification is more detailed and prescribes more characteristics of CLSM recommended by NCHRP 591 than most other states. However, review of NCHRP 597 and studies discussed in Chapter 4 in this Report warrant the alterations to Section 206.4.5.2 of WYDOT Standard Specification; the recommendations are as follows:

- Include a lower bound to the air content equal to 6%.
- Include an upper bound to the maximum slump equal to 10 inches.
- Add a statement requiring CLSM to set for a minimum of 24 hours prior to allowing vehicle loads to travel over the fill.
- Add a statement requiring the contractor to submit mix designs to the agency a minimum of 30 days prior to installation for review.

- Add a statement requiring the contractor to provide a "delivery" ticket along with each batch of CLSM. The ticket should provide information such as the project designation, date, time, compressive strength, yield and unit weight, and flowability.

It should be noted that some states limit or only allow the use of fly ash with permission given by the engineer. Although fly ash does provide benefits such as reduced segregation and bleeding, studies discussed in this report show that fly ash can result in higher than anticipated compressive strengths, greater susceptibility to frost heave, and increased corrosion rates when used for metal pipes. Therefore, reducing the amount of fly ash and/or not allowing it unless approved by the engineer should be considered. Finally, it is recommended that WYDOT should ensure aggregates used in mix designs are non-toxic and not environmentally hazardous due to the possibility of CLSM leaching.

7.6 Trench Width

Trench width should be established on the basis of safety. This issue is addressed adequately by Occupational Safety and Health Administration (OSHA) Safety Standards and is therefore not addressed further in this report. In addition, studies show that wider trench widths may resist greater horizontal earth pressures, requiring less support at the trench wall. Currently, WYDOT's existing recommended trench widths are reasonable when compared to other states and are consistently greater than AASHTO recommendations. In fact, when considering pipe diameters of 48 inches or less, WYDOT consistently specifies greater trench widths compared to all other states. No recommendation regarding altering WYDOT's specifications are warranted herein.

If CLSM is used in trench installations, it is recommended the trench width may be reduced to a minimum width equal to the outside pipe diameter plus 24 inches, or maintain a minimum clearance of 12 inches on each side between the pipe and trench wall.

7.7 Embankment Construction

The horizontal limits of embankment construction vary significantly between state specifications, ranging from a maximum of eleven times the outside pipe diameter to three times the outside pipe diameter. The limit of eleven times the pipe diameter was the most consistently specified by the states. AASHTO (2010a) only makes recommended embankment widths for concrete pipe that is equal to three times the outside pipe diameter. Although this limit appears to be adequate for concrete pipe, it may not be suitable for flexible pipe. It is recommended WYDOT implements a **tentative** minimum embankment width equal to five times the pipe diameter for all pipe materials. Additionally, it is recommended further research be conducted in this area. Typically states specify the vertical limit for embankment construction to be a minimum of ½ the pipe diameter for concrete pipe, or the pipe crown plus 12 inches for flexible pipe. Due to the previous recommendation requiring all pipe to be installed with the Select Granular Fill, it is recommended the vertical limit of the embankment be constructed to a minimum height of 12 inches above the pipe crown for all pipe materials. See recommended standard pipe installation detail in Appendix C in this Report for further clarification.

7.8 Pipe Foundation / Bedding Thickness

AASHTO and ASTM state that when rock or unyielding pipe foundations are present, additional bedding thickness should be provided. Research suggests that if unyielding foundations exist and inadequate thickness is provided, irregular pipe strain can result which can affect the adequacy of the pipe.

State DOT, ASTM, and AASHTO specifications vary somewhat in prescription of bedding thicknesses. All specifications state that bedding thickness shall be 4 or 6 inches for flexible pipe in typical locations. Where unyielding foundations exist, specifications state the bedding thickness shall be 6 or 12 inches. It is recommended that 6 inch and 12 inch bedding thickness be specified in locations of typical and unyielding foundation locations, respectively for all types of pipe installations. Also, it is recommended that central bedding shall be loosely placed. A statement should be added within WYDOT’s specification that requires the bedding to be shaped to accommodate protrusions occurring in the pipe.

It is recommended WYDOT’s existing Class B and Class C bedding be replaced by the proposed Select Granular Fill discussed above for all pipe installations.

7.9 Haunch

Compaction of the haunch area has been shown to significantly affect the structural performance of flexible pipe, and is one of the most crucial areas to ensure properly installed and compacted backfill. The haunch area is considered part of the soil envelope and therefore specific compaction requirements are specified in previous recommendations. However, it is recommended that discussion of the importance of adequate haunch support be provided within the WYDOT’s specifications.

7.10 Backfill Lift Thickness

The lift thicknesses should be considered to ensure that adequate compaction of the backfill is achieved. Thicker lifts require greater energy to reach the specified compaction. All specifications included in this study state the maximum lift thickness as either 6 or 8 inches, with the vast majority of them requiring 6 inch lifts. Currently, WYDOT uses 8 inch maximum lift thickness, which is consistent with AASHTO. Currently, some pipe installations in Wyoming have not been achieving adequate compaction, and therefore may warrant an alteration to WYDOT's specification requiring a 6 inch lift thickness. However, with the adoption of Select Granular Fill, it is suggested that the relative compaction will be attained with less effort; thus alteration to the current lift thickness may not be necessary if compaction is being achieved. Research discussed in Chapter 4 in this Report demonstrates that if the lifts are not brought up simultaneously, horizontal deviations and prominent voids within the haunch area would not be uncommon. Therefore, it is recommended that specifications express the importance of evenly placed lifts.

7.11 Corrosion

WYDOT's Corrosion Resistance Acceptability Table (Table 603.4.2-1) provides adequate if not superior information on guidance of corrosion resistance. Additional information for corrosion of steel and concrete pipe is included in Appendix B in this Report, and is provided for review. It is widely accepted that plastic is superior to metal and concrete materials in corrosive applications. All states included in this study that utilize corrosion tables for aid in culvert design place plastic pipe within the highest level of acceptable materials. Interviews indicate that states intentionally specify HDPE in areas with adverse corrosive environments such as acid mine run-off and salt water with good results. Therefore, it is recommended that plastic pipe be specified as an acceptable material for WYDOT's CR9 of Table 603.4.2-1.

7.12 Abrasion

Like corrosion, plastic pipe is noted for its high abrasion resistance. All states included in this study that utilize abrasion tables for aid in culvert design place HDPE within the highest level of acceptable materials, with the exception of Washington. WSDOT notes that HDPE abrasion resistance is equal to or greater than any type of material, but also notes that it cannot be structurally reinforced. Therefore, WSDOT specifies HDPE as an acceptable material for moderately abrasive conditions. Currently, WYDOT does not use abrasion tables for use in culvert design. Since abrasion is one key factor when estimating service life of culvert materials, it is recommended that WYDOT incorporate the abrasion guidelines set forth by NCHRP 254 discussed in Chapter 4 in this Report for design. According to the NCHRP guidelines plastic pipe is acceptable for severely abrasive site conditions which includes bed loads consisting of sands, gravels, and rocks traveling in excess of 15 ft/sec. If bed load consisting of larger sized particles including cobbles and boulders are encountered, plastic pipe is not recommended. In locations where this situation does occur, it is recommended that WYDOT consult with the abrasion guidelines set forth by (FHWA/CA/TL-CA01-0173) attached in Appendix B in this Report. Specific guidelines WYDOT should consider for adoption of highly abrasive sites include specifying an increased gauge thickness of either 1 or 2 standard gages depending on the corrosivity of the site conditions and location of the installation. Adding a minimum 2.0 inch sacrificial concrete cover for concrete culverts, this can be accomplished by specifying a different wall class of pipe and/or adding an invert paving. For plastic pipe, specify only a smooth interior wall type.

7.13 Joints

Research on the adequacy of pipe joints and the relative advantages and disadvantages of various joint types is limited. States regularly defer to AASHTO, ASTM, and manufacturer's specifications. Specifications that are particularly useful when researching the various types of joints are discussed in Chapter 4 in this Report. From the limited research, it has been found piping action can erode the surrounding backfill soil and possibly lead to roadway settlement. To combat this effect, it is recommended that soil-tight joints be specified as a minimum joint system for culvert installations. In locations deemed as higher risk installations, or in situations where groundwater contamination is a possibility, it is recommended a water tight joint be considered for all pipe materials. If water tight joints are required for plastic pipe, it is recommended they meet the requirements set forth by ASTM D 3212 and ASTM F 477.

7.14 End treatments

AASHTO specifically gives caution regarding exposed HDPE end treatments for its potential susceptibility to UV deterioration and combustion. Only two states, Ohio and Washington, allow the use of HDPE end treatments. Within Ohio and Washington's specification, it is noted the plastic end sections can also be susceptible to floatation. It is commonly accepted practice by all other states to use either concrete or metal end sections. It is recommended that HDPE end sections not be permitted for use and only concrete or metal end sections shall be allowed.

7.15 Allowable Pipe Diameter

The minimum allowed pipe diameter for plastic pipes is somewhat consistent as specified by the states and has not been found to have significant design impacts or challenges. It is recommended the allowable minimum pipe diameter is to be 12 inches. The maximum pipe diameter should be carefully considered, as this is another way to limit or promote plastic pipes use. Six of the nine states allow a maximum pipe diameter of 60 inches. Arizona, Nebraska, and South Dakota limit the maximum pipe diameter to 36 inches. Although no scientific research has been found that proves larger plastic pipes to be more problematic, the recommended maximum pipe diameters are limited to smaller diameter pipes. See interim recommendations discussed later in this Chapter for actual maximum allowable pipe diameters.

7.16 Deflection Testing and Inspection

Methods which can measure deflections occurring in pipe installations included laser profiling, mandrel, and physical measurement. Laser profiling is the most sophisticated and accurate method for determining deflections and provides agencies with detailed analysis which can be used to rate a culvert installation. This method can also provide measurement of cracks, joint gaps, and other structural deficiencies occurring within the pipe. Currently, this method appears to be costly and used predominately in eastern and mid-west states and is not readily available for use in Wyoming. It is the recommendation of this report that this method should be strongly considered for implementation within WYDOT's specifications when it is financially reasonable and more readily available. Due to the recommended allowable pipe diameters included in this report, mandrel testing is recommended for implementation for deflection testing of all plastic pipe installations.

This study shows that deflection testing and inspection is necessary when using plastic pipe. The most experienced State DOTs stress the importance of this and enforce the policy with aggressive measures. Research clearly shows that if deflections are not controlled, excessive strains can result and therefore limit the design life of plastic pipe. Some states do allow deflections exceeding 7%. However, AASHTO (2010a) suggests the maximum deflection should be limited to +/- 5% of the original pipe diameter. This is also consistent with the majority of state specifications. In addition, AASHTO (2010a) and all states which specify deflection testing require the test be conducted 30 days after installation. It is recommended that WYDOT implement deflection testing of all plastic pipe installations and that maximum deflection not exceed 5% of the original pipe diameter. Kentucky Method 64-114-12 has been found to provide detailed procedure for conducting mandrel testing. It is recommended WYDOT use this specification as guidance for drafting its own supplemental specification. Additional consideration should be given to video inspection. This can provide WYDOT with visual qualitative data and can be used in conjunction with mandrel testing to validate its results. The test should be conducted not prior than 30 days after installation and a maximum of 90 days. A statement should be added which dictates if the pipe does not meet the 5% limitation, the contractor is to provide an evaluation made by a professional engineer which may result in the removal and replacement of the pipe. The evaluation should investigate areas such as the severity of deflection, structural integrity, environmental conditions, and the design service life, or with regard to WYDOT's specification, the location of the pipe installation. After the evaluation is conducted, a stamped report written by the engineer should be submitted to the agency outlining the findings along with the engineer's recommendation. It is recommended that WYDOT include a statement declaring the agency shall have final acceptance of all pipe material. Conducting a 7.5% mandrel test should be used as additional guidance for the engineer's evaluation if the 5% test fails. AASHTO (2010a) states that if a plastic pipe is found to have greater than 7.5% deflection, the pipe is required to be replaced or remediated. A statement should be added which dictates the contractor is to replace the pipe at no cost to WYDOT. The test should be completed prior to paving; the contractor should be made aware of this policy in order to provide good incentive for proper installations.

Finally, if deflection testing is chosen not to be enforced within WYDOT's specification, it is recommended that plastic pipe not be implemented with the specification.

Deflection testing of metal pipe is also required by many of the states included in this study in addition to AASHTO (2010a). It is recommended that all metal pipes greater than 24 inches in diameter be tested for deflection following a similar procedure discussed above. AASHTO (2010a) recommends the limitation for round metal pipes is 7.5% of the nominal diameter of the pipe plus the manufacturing tolerance of either 1.0% of the nominal diameter or 0.5 inches, whichever is greater.

7.17 Interim Recommendations

As stated in the previous section, long-term success of HDPE is heavily dependent upon the manner in which it is installed. Hsuan and McGrath (2005) state the following:

> "Since deflections are in fact controlled more by construction practice than by design, it is increasingly becoming practice to place responsibility for control of deflections on the contractor, rather than the designer."

Therefore, strict inspections of installation should be conducted. If all of these practices and areas of applications are met, good results can be expected for cross drain applications. However, results from DOT surveys show there is a learning curve for contractors. Therefore, it is recommended that implementation occurs first through use of pilot projects. Interim specifications should be implemented which do not allow the use of plastic pipe in the following locations:

- Under interstates.
- Within the confines of bridge or building foundations.
- Within the confines of mechanically stabilized earth (MSE) walls.
- Other areas where deemed high-risk implementations (e.g., storm sewers and highways with high ADTT values).
- Pipe diameters greater than 36 inches.
- HDPE pipe meet the specifications of AASHTO M 294 and only be supplied by manufacturers certified by the NTPEP.

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APPENDIX A – RESPONSES FROM DOT SURVEY

Dole Grebenik – Colorado Department of Transportation 4/25/2012

Study of the use and limitations of high density polyethylene pipe in underground burial applications

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1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?
    - No restrictions for culvert applications
    - Are not allowed for storm drain systems
2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.
    - No, with the exception of the T-REX project
3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.
    - The pipe will float during installations
    - Extra care must be given to ensure proper alignment
4. Within your state's projects, has your agency experienced particular benefits with the use of HDPE pipe? If so, please explain.
    - In general, the increased number of viable options has forced RCP to drop in prices
5. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.
    - Not seen any notable benefits
6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?
    - Do not track which type of pipe is installed
    - CDOT does track the class of pipe and diameter used, but this information does not specify what type of material was installed
7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?
    - Yes, plastic pipe requires "Class I Structural Backfill", different from RCP fill
8. When using HDPE pipe, do you require a specific compaction of your fill?
    - 95% or 90% based on fill height
9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?
    - Yes, 5% limitation. Removal and replacement is required if greater than the limit

- Test is conducted after 30 days

10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?
    - It is the opinion of the CDOT representative that deflection testing has discouraged contractors from choosing to use HDPE
11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?
    - No information warranting comment
12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?
    - The CDOT representative suggest WYDOT should start considering polypropylene and DuroMAXX products
    - CDOT's pipe type selection document allows the contractor to select any pipe material that meets the performance criteria. (Abrasion and corrosion). The contractor selects the product, so CDOT does not have a comprehensive record of current HDPE installations. However, with the pipe type selection policy reaching the 2 year mark, not a single contractor has selected HDPE over RCP.

Rick Renna – Florida Department of Transportation 2/15/2012

Study of the use and limitations of high density polyethylene pipe in underground burial applications

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1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?
    - Currently, FDOT implements interim specifications. These includes under main line, in locations where failure would also cause a structural failure of a bridge or building, and not allowed in the Florida Keys.
    - The higher ambient temperature adversely effects the slow crack growth resistance and depletion of anti-oxidants
    - These interim specifications will be lifted with the exception of the Florida Keys specification.
2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.
    - No
3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.
    - The pipe will float during installations
    - Misalignment is not uncommon if you do not backfill simultaneously on both sides and if you do not use restraints during installation
4. Within your state's projects, has your agency experienced particular benefits with the use of HDPE pipe? If so, please explain.
    - Noticed financial benefits from having additional products
    - HDPE is noted for being a superior product in salt water applications
5. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.
    - No mentionable benefits
    - Longer pipe lengths, "sticks"
6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?
    - Have informal records
    - The contractor must declare which method of installation he/she will use
    - When Florida decided to use "optional pipe" the agency made a conscience effort not to track which types of pipe where used
7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?

- FDOT uses that same backfill for all pipes. Either A-3 or an A-2-4 fill
- A-2-4 requires greater energy to achieve density

8. When using HDPE pipe, do you require a specific compaction of your fill?
    - 95% flexible pipe
    - 100% for concrete, noticed historical problem with settlement around rigid structures
    - Because of the 100% relative compaction requirement, RCP receives a “break” on the LRFD culvert fill heights
9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?
    - Yes, 5% limitation. 100% laser ring and video test all pipes that are less than or equal to 48” in diameter.
    - FDOT suggest, if contractors construct their backfill envelope properly, they should not see deflections greater than 5%
    - Also, holds steel pipe to 5%
10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?
    - Moving towards early inspection, fill height greater than 3’-0”, this will provide an early warning system for excessive deflection
    - This intends to eliminate issues if the pipe is required to be replaced at a later date if failed
    - The inspection is the responsibility of the contractor
11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?
    - FDOT representative suggest Dr. Grace Hsuan is a valuable resource and her research are particularity useful
12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?
    - Admits FDOT is aggressive with their post-installation inspection policies.
    - The FDOT representative states: “I am not sure I would want to use a pipe this flexible if we weren’t inspecting it and did not have the ability to enforce it.”
    - Plastic pipe installations require additional care.
    - FDOT representative suggest WYDOT should consider PVC and suggest is less problematic than HDPE
    - PVC is installed more than HDPE
    - FDOT representative stated Florida has problems with ground water pollution. Therefore, FDOT has a zero leak policy and water-tight joints are required for storm drains and culverts
    - FDOT representative notes the superior joint performance of the bell and spigot type joints with HDPE products
    - Contractors are allowed to pick the pipe type and method of installation as long as the pipe meets corrosion and fill heights. Florida refers to this as “optional pipe”

- FDOT representative asserts it is important to use sound technical research to make unbiased decisions when implementing culvert materials

Mark Burham– Nebraska Department of Roads

Note, the phone interview was not completed prior to the completion of this report. The following are the written responses from the agency

Study of the use and limitations of high density polyethylene pipe in underground burial applications

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1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?

    Yes, no general limitations—(assuming proper installation). See attached Policy Link   and included Policy Flowchart. (End of survey document)

2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.

    No.

3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.

    No.

4. Within your state's projects, has your agency experienced particular benefits with the use of HDPE pipe? If so, please explain.

    Ease of installation without heavy equipment. Excellent for use in high corrosion areas.

5. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.

    Same as above. Also, speed of installation using granular backfill materials.

6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?

    Yes.

7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?

    Yes, see attached policy link and plans.

8. When using HDPE pipe, do you require a specific compaction of your fill?

    Yes, see policy.

9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?

    Yes—during installation and 30 days post installation.

10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?

    No.

11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?

Contact NCHRP.

12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?

See following link for application of HDPE and other flexible pipes:

http://www.dor.state.ne.us/docs/pipe-policy-english.pdf

Peter VanKampen – New York State Department of Transportation 2/10/2012

Study of the use and limitations of high density polyethylene pipe in underground burial applications

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1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?
    - No restrictions allowed anywhere that satisfies the cover limits
2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.
    - Originally the contractors had difficulties installing the pipe. Apparent learning curve, now there are no problems
3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.
    - Similar to previous answer
4. Within your state's projects, has your agency experienced particular benefits with the use HDPE pipe? If so, please explain.
    - Cost is lower compared to concrete. It is quicker, cheaper, and requires fewer people to install
5. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.
    - Speed is a major factor in New York, HDPE is quicker to install. Also seems to be safer
6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?
    - Do catalog pay items, but does not specifically track the types of pipe installed
7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?
    - NYDOT uses the same backfill for all pipe.
8. When using HDPE pipe, do you require a specific compaction of your fill?
    - 95% relative compaction
9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?
    - Yes, 5% limitation.
10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?
    - Not aware of any.
11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?
    - Manufacturer's specifications are good references
12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?

- CLSM is used in locations of difficult installations, i.e. next to utility lines.
- Floatation with CLSM is a problem
- Use HDPE for culvert rehabilitations with good results

David Riley – Ohio Department of Transportation 2/1/2012

Study of the use and limitations of high density polyethylene pipe in underground burial applications

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1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?
    - Thermoplastic pipes were not allowed originally for TYPE "A" culverts until Supplemental Specification 802.
    - SS 802 is a performance based specification allows the contractor to determine the means and method on installation. HDPE is acceptable for TYPE "A" installations.
    - ODOT allow the use of plastic end treatments
2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.
    - No significant deficiencies
3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.
    - Achieving the required densities is a problem. The effort is much more significant.
    - Each pipe type has its own concerns with installation
4. Within your state's projects, has your agency experienced particular benefits with the use HDPE pipe? If so, please explain.
    - The increased number of viable products for consideration introduces more competition and therefore financial benefits are noticed.
5. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.
    - HDPE is intentionally specified in locations of high acid mine run-off due to its superior corrosive resistance.
    - HDPE has given ODOT a better life expectancy than RCP and CSP in these areas.
6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?
    - Does not keep record
    - The contractor is free to pick any pipe material they want to use and the Department has no way to track what was used.
7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?
    - Do not correlate to ASTM or AASHTO Standards. ODOT's backfill requirements are based on research conducted by the Ohio University.

- ODOT's specification requires select backfill material for a height of at least 12 inches above the pipe.

8. When using HDPE pipe, do you require a specific compaction of your fill?
   - All of pipe requires 96% relative compaction

9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?
   - SS 802 requires testing after 30 days of final fill placement and before 90 days.
   - The limits are as described in AASHTO 5% must be evaluated by a PE to see how big of a problem it is and over 7.5 % replacement.
   - Due to the manner which ODOT's specification are written, the contractor is given a range for how the pipe is installed. Therefore, post construction inspection is necessary to hold the contractor responsible for the quality of installation.
   - The inspection is the responsibility of the contractor
   - If 7.5% deflection is not meant, the agency has no problem requiring the contractor to replace the pipe

10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?
    - The test projects so far have not yielded a problem.

11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?

    Research Office Contact information

    Vicky Fout, 614-387-2710, Vicky.fout@dot.state.oh.us

    State Job Number 14797

    Long Term Monitoring of Pipe Under Deep Cover. Review can be found at:

    http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Pages/HydraulicReports.aspx

12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?
    - The AASHTO design equations are somewhat problematic should have been 100% based on pipe stiffness which is easily measured and is an indirect way to measure the pipe profile elements.
    - HDPE is the pipe of choice for contractors in Ohio.
    - HDPE pipe is more sensitive to the backfill and its compaction
    - SS 802 studied 14 installations which used the specification. One pipe was replaced.
    - Contractors choose to install pipes with flowable fill due to smaller trench widths and no compaction requirements
    - Using cover tables takes the design away from the engineers which results in faster and cheaper designs.
    - Due to the lack of information discussing the maintenance cost of culverts, and therefore design life is difficult to quantify.

- Significant amounts of HDPE are installed within Ohio, have been using it since 1985.
- An HDPE bell is required; this bell has the same shape as a concrete pipe and is therefore given the same hydraulic inlet coefficient (Ke). This allows the HDPE culvert size to be equal to the concrete culvert size. An inlet coefficient is required for proper hydraulic design (size).
- Specifications require select backfill material for a height of at least 12 inches above HDPE pipe outside pavement.
- If the trench under the pavement is greater than 4 feet in depth then regular backfill material can be used above 4 feet.

Dean Van DeWiele – South Dakota Department of Transportation 2/9/2012

Study of the use and limitations of high density polyethylene pipe in underground burial applications

1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?
    - Do not disallow HDPE
    - Not allowed under the mainline. Concrete is the only material allowed under the mainline.
    - HDPE has a difficult time getting a reasonable market share within the state.
2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.
    - Installations are rare, no comment is warranted
3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.
    - Similar to the previous answer
4. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.
    - See benefits with using it as a liner
5. Within your state's projects, has your agency experienced particular benefits with the use HDPE pipe? If so, please explain.
    - Seen benefits with using it as a liner
6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?
    - South Dakota does not keep record.
7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?
    - Normal backfill is used
8. When using HDPE pipe, do you require a specific compaction of your fill?
    - Ordinary compaction methods are used to achieve 95% compaction
9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?
    - Deflection testing is not required
10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?
    - Not applicable
11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?

- No

12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?
    - Very little experience with HDPE
    - HDPE liners have been used regularly for re-lining projects, with good results
    - South Dakota has conducted cost analysis and determined new pipe installations will not compete financially with re-lining projects
    - Very little new projects
    - Acknowledges quickness of installations and would be beneficial in urban cities.

Jay Christianson – Washington State Department of Transportation 6/1/2012

Study of the use and limitations of high density polyethylene pipe in underground burial applications

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1. Does your agency limit or not allow the use of HDPE pipes in certain applications (e.g., under interstates, roads with high adt values, cross culverts, etc.)?
    - No restrictions for culvert applications if meets fill height limitations, 25'-0"
    - Not allowed in some areas where ditch burning occurs
2. Within your state's projects, do you know of reoccurring deficiencies with HDPE pipe? If so, please explain.
    - Some instances of pipe did not pass WSDOT air pressure test. This was attributed to installation procedures, not issues relating to pipe material
3. Within your state's projects, do you know of reoccurring difficulties with installing HDPE pipe? If so, please explain.
    - No notable difficulties
4. Within your state's projects, has your agency experienced particular benefits with the use of HDPE pipe? If so, please explain.
    - Notes the joints are better compared to RCP. HDPE uses a positive joint system that allows the contractor to know when the pipe is properly connected
5. Within your state's projects, has your agency experienced any particular benefits with installing HDPE pipe? If so, please explain.
    - The pipe is lighter and therefore requires smaller equipment and less man power to install
    - The lighter products seem to be safer to install
    - Washington has "hot" soils, HDPE performs better than other materials in these conditions due to its corrosive resistance
    - HDPE performs better in abrasive conditions compared to other pipe material
6. Does your agency keep record how many instances HDPE pipe has been installed within your state? If so, may we obtain this information?
    - WSDOT records the "Pipe Schedule", but does not particularly monitor which type of pipe was installed
    - WSDOT representative suggest this could be a deficiency with the performance based specification
7. When using HDPE pipe, do you specify a particular bedding and backfill? Do they correlate to fills specified by ASTM or AASHTO Standards?
    - WSDOT specifies a different backfill for rigid and flexible pipes
    - The backfill requirements are more stringent compared to ASTM and AASHTO standards
8. When using HDPE pipe, do you require a specific compaction of your fill?

- All pipe is installed with 95% compaction

9. Does your agency require deflection testing of HDPE pipe? If so, when is the test conducted; what are the allowable deflections limits you specify?
    - (Follow up with Jay to see what limitation is placed)
    - A mandrel "go, no go" test is required only for thermoplastic pipe
    - Air pressure test are require on all pipes
10. Has imposing deflection tests lead to difficulties during the installation or impeded projects?
    - No information is present to suggest so
11. Are you aware of any publications that are particularly prudent regarding the use of HDPE pipe?
    - ASTM and AASHTO standards
12. Do you have any other general comments/thoughts regarding the use of HDPE pipe for in culvert applications?
    - The contractor may choose the type of pipe he wants to work with, allowing him flexibility in materials, bidding, etc
    - WSDOT required ADS to submit LRFD fill height computations
    - WSDOT representative suggests WYDOT start considering polypropylene products, they are "more contractor friendly" however it is more expensive compared to HDPE
    - WSDOT will implement into their standard specification that HDPE pipe will be required to come from a NTPEP plant

APPENDIX B – STANDARD SPECIFICATIONS

UDOT's Pipe Selection Flow Chart (UDOT 2004)

REGION MATERIALS LAB
Responsible for the collection of the following data at each pipe location:
Soil pH
Soil Resistivity
Soluble Salts in the soil

↓

UDOT Region Materials Engineer
Determine the pipe class required for the pipe location soil conditions using UDOT corrosion charts and the required Minimum Design Life as shown below:

- Storm Drain = 50 years
- Cross Culverts on Interstates = 40 years
- Remaining Culverts = 30 years

↓

Design Engineer
- Locates and sizes culverts for the proper drainage area and flow.
- Prepare separate Summary Sheets for cross culvert and storm drains.
- Summaries shall include at least:
  -Pipe Class
  -Type of joints for pipes
  -Pipe diameter
  -Pipe length
  -Any other job specific requirement for the project

↓

Contractor

Selects pipe culvert according to Standard Specifications, Drawings and the information given in the Summary Sheets.

Informs UDOT of the pipe selection at the Preconstruction Meeting.

UDOT Pipe Classes*

Pipe Class	Pipe Materials
A (non-reactive/ Non-corrosive)	-Galvanized Steel -Aluminum -Concrete (Type II Cement) -Polyethylene
B (Reactive/Corrosive)	-Steel Bituminous and Pitch -Resin (polymeric) Coated -Aluminum -Polyethylene -Concrete (Type II Cement)
C (Highly Reactive Soils)	-Steel, Fiber Bonded Bituminous Coated -Polyethylene -Concrete (Type V Cement)

Pipe Arch Classes*

D (non-reactive/ Non-corrosive)	-Steel (plain corrugated) -Aluminum Plate and Pipe Arch
E (Reactive/Corrosive)	-Structural Steel (asphalt coated) -Aluminum Plate Pipe and Pipe Arch

*See UDOT Standard Specifications

Figure 9-1 – UDOT Pipe Selection Flow Chart

Anticipated Service Life for Corrugated Metal Pipe (ODOT 2011)

pH	Under 6.5	6.5	7.0	7.5	8.0	8.5	9.0 and Above	Steel Conduit Size & Type	Protection
Gage Required for 75 year Design Service Life							B	707.01 or 707.02	Galvanized
				10	12	14	16	707.01 or 707.02, Aluminum Coated	Aluminized
					10	12	12	≤ 48” 707.05 or 707.07	Galvanized – Asphalt coated an paved
						10	12	≥ 54” 707.05 or 707.07	Galvanized – Asphalt coated an paved
			12	14	16	16	16	≤ 48” 707.05 or 707.07 Al-Coated	Aluminized – Asphalt coated an paved
				12	12	16	16	≥ 54” 707.05 or 707.07 Al-Coated	Aluminized – Asphalt coated an paved
			12	14	16	16	16	707.04 (1/2” corr.) 707.04 (1” corr.)	Polymer Coated
	10	12	14	16	16	16	16	707.04 (1/2” corr.) paved per 707.07 707.04 (1” corr.) paved per 707.07	Polymer coated- Asphalt coated and paved
	16 w/ CFP **	16 w/ CFP	16 w/ CFP	16 w/ CFP	16 w/ CFP	16 w/ CFP	16 w/ CFP	707.02 w/ field paving	Galvanized – Concrete field paved invert
	12 w/ CFP **	12 w/ CFP	12 w/ CFP	1 (or 12 w/ CFP)	3 (or 12 w/ CFP)	8 (or 12 w/ CFP)	10 (or 12 w/ CFP)	707.03 (Invert Plates)	Structural Plate

* Concrete field paving shall be epoxy coated per 706.03 for pH < 5.0

** Externally coated per AASHTO M243

w/CFP With concrete field paving of invert

REQUIREMENTS FOR CORRUGATED METAL PIPE THICKNESS AND PROTECTION AT ABRASIVE SITES – 75 YEAR DESIGN SERVICE LIFE

1002-6(75)

REFERENCE SECTION 1002.3.I

Revised October, 2001

WSDOT Corrosion Level III Chart (WSDOT 2010a)

Pipe Classifications and Materials

Culverts	Storm Sewers
Schedule Pipe: Schedule____Culvert Pipe_____in Diam. If Schedule pipe not slected then: **Concrete:** • Plain Concrete Culvert Pipe • Cl___Reinf. Concrete Culvert Pipe **PVC:** • Solid Wall PVC Culvert Pipe • Profile Wall PVC Culvert Pipe **Polyethylene:** • Corrugated Polyethylene Culvert Pipe **Aluminum:** • Plain Aluminum Culvert Pipe[1]	**Concrete:** • Plain Concrete Culvert Pipe • Cl___Reinf. Concrete Storm Sewer Pipe **PVC:** • Solid Wall PVC Storm Sewer Pipe • Profile Wall PVC Storm Sewer Pipe **Polyethylene:** • Corrugated Polyethylene Storm Sewer Pipe **Aluminum:** • Plain Aluminum Storm Sewer Pipe with gasketed seams[1] **Aluminum Spiral Rib:** • Plain Aluminum Spiral Rib Storm Sewer Pipe with gasketed seams[1]

1. Can be used if the requirements of Section 8-2.2.6 are met

Corrosion Zone III

Acceptable Pipe Alternatives and Protective Treatments

Figure 8-4.3B

CalTrans Guide for Protection of Concrete Pipe (AASHTO 2007)

Soil or Water pH[a]	**Sulfate Concentration of Soil or Water(ppm)**[a]	**Cementitious Material Restrictions**[b]	**Water Content Restrictions**
7.1 to 14	0 to 1500	No Restrictions	No Restrictions
5.6 to 7.0	Greater than 1500 to 2000	No Restrictions	Maximum water-to-cementitious material ratio of 0.45
3 to 5.5[c]	Greater than 2000 to 15,000[c]	400 kg/m^3 (675 lbs/yd^3) Minimum: 75 percent Type II Mod. Or Type V 25 Percent mineral admixture[d]	Maximum water-to-Cementitious material ratio of 0.40

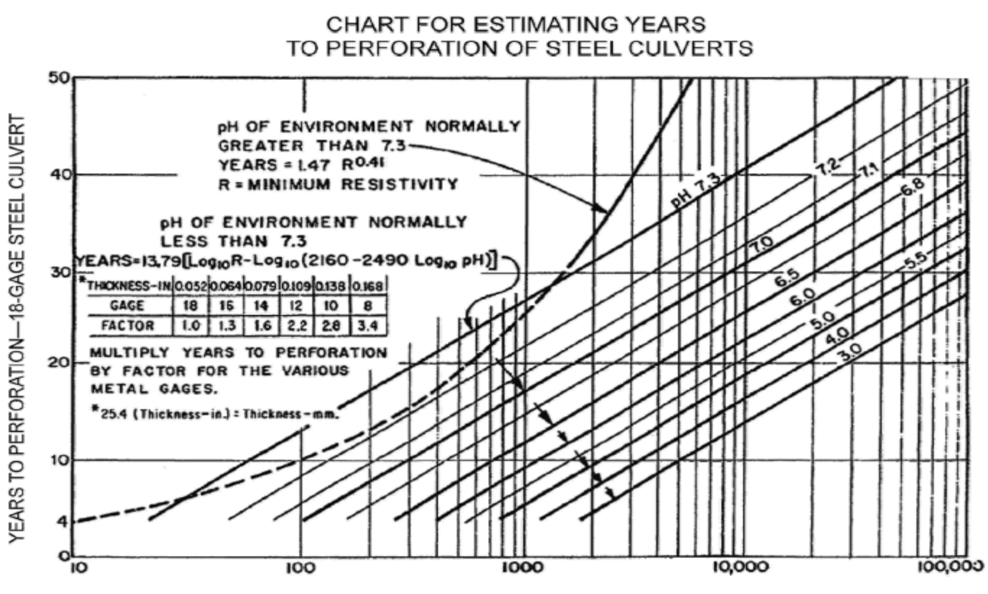
[a] The table lists soil/water pH and sulfate concentration in increasing level of severity starting from the top of the table. If the soil/water pH and the sulfate concentration are at different levels of severity, the recommendation for the more severe level will apply. For example, a soil with a pH of 4.0, but with a sulfate concentration of only 1600 ppm, would require a minimum of 400 kg/m^3 (675 lbs/yd^3) of cementitious material. The cementitious material would consist of 75 percent by mass Type II Modified or Type V cement plus 25 percent by mass mineral admixure. The maximum water-to-cementitious material ratio would be 0.40.

[b] Recommendations shown in the table for the cementitious material restrictions and water content restrictions should be used if the pH and/or sulfate conditions in Column 1 and/or Column 2 exist. Sulfate testing is not required if the minimum requirement resistivity is greater than 1,000 ohm-cm.

[c] Additional mitigation measures will be needed for condition where the pH is less than 3 and/or the sulfate concentration exceeds 15,000 ppm. Mitigation measures may include additional concrete cover and/or protective coatings. For additional assistance, contact the Corrosion Technology Branch or the Office of Rigid Pavement Materials and Structural Concrete of the Division of Materials Engineering and Testing Services (METS) at 5900 Folsom Boulevard, Sacramento, CA 95819.

[d] Mineral admixtures shall conform to ASTM C 618 and Section 90-2.04 of the Caltrans Standard Specifictions.

CalTrans Service Life Chart (AASHTO 2007)



Abrasion Table (FHWA/CA/TL-CA01-0173)

ABRASION LEVELS AND MATERIALS TABLE		
Abrasion Level	**General Site Characteristics**	**Invert/Pipe Materials**
Level 1	• Virtually no bed load with velocities less than 5ft/s* * Where there are increased velocities with minor bed load volumes (e.g. urban storm drains systems or culverts ≤ 30" diam.), significantly higher velocities may be applicable to level 1	All pipe materials listed in HDM Table 853.1A allowable for this level. No abrasive resistant protective coatings listed in HDM Table 854.3A needed for metal pipe.
Level 2	• Bed loads of sand, silts, or clays regardless of volume • Velocities ≥ 3 ft/s and ≤ 8 ft/s* * Where there are increased velocities with minor bed load volumes (e.g. urban storm drains systems or culverts ≤ 30" diam.), significantly higher velocities may be applicable to level 2	All allowable pipe materials listed in HDM Table 853.1A with the following considerations: Generally, no abrasive resistant protective coatings needed for steel pipe. Polymeric, polymerized asphalt or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements in inadequate for abrasion potential.
Level 3	• Moderate bed load volumes of sands and gravels (1.5" max). • Velocities > 5ft/s and ≤8 ft/s* * Where there are increased velocities with <u>minor</u> bed load volumes ≤ 1.5" (e.g. urban storm drains systems or culverts ≤ 30" diam.), higher velocities may be applicable to level 3	All allowable pipe materials listed in HDM Table 853.1A with the following considerations: Steel pipe may need one of the abrasive resistant protective coatings listed in HDM Table 854.3A or additional gauge thickness if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential. Aluminum pipe may require additional gauge thickness for abrasion or concrete invert protection if thickness for structural requirements is inadequate for abrasion potential. Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (equivalent to galv. Steel) where pH<6.5 and resistivity < 20,000. Lining alternatives: PVC, Corrugated or Solid Wall HDPE, CIPP (with min. thickness of abrasion specified)
Level 4	• Small to moderate bed load volumes of sands, gravels, and/or small cobbles/rocks with maximum stone sizes up to about 6 in. • Velocities > 8ft/s and ≤ 12 ft/s	All allowable pipe materials listed in HDM Table 853.1A with the following considerations: Steel pipe will typically need one of the abrasive resistant protective coatings listed in HDM Table 854.3A or may need additional gauge thickness if thickness for structural requirements is inadequate for abrasion potential. Aluminum may require additional gauge thickness or concrete invert protection if thickness for structural requirements is inadequate for abrasion potential. Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. Increase concrete cover over reinforcing steel for RCB (invert only) RCP generally not recommended. Lining alternatives: Closed profile or SDR 35 PVC (corrugated and ribbed PVC limited to 36" min. diameter. Machine-wound PVC <u>not</u> recommended. SDR HDPE (corrugated HDPE Type S limited to 48" min. diameter, corrugated HDPE Type C not recommended). CIPP (min. thickness for abrasion specified), concrete.
Level 5	• See next page	Aluminum may require additional gauge thickness or concrete invert protection if thickness for structural requirements is inadequate for abrasion potential (see lining alternatives below). Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. Closed profile and SDR 35 PVC liners allowed but not recommended.

Level 5	• Moderate bed load volumes of sands, gravels, and/or small cobbles with maximum stone sizes up to about 6 in. For larger stone sizes within this velocity range, see Level 6 • Velocities > 12 ft/s and ≤ 15 ft/s	for upper range stone sizes in bed load if freezing conditions are often encountered, otherwise OK for stone sizes up to 3 in. Most abrasive resistant coatings listed in HDM Table 854.3A are not recommended for steel pipe. A concrete invert lining or additional gauge thickness is recommended if thickness for structural requirements is inadequate for abrasion potential. See lining alternatives below. Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended. Lining alternatives: Closed profile (≥30 in) or SDR 35 PVC (corrugated and ribbed not recommended. Machine-wound PVC not recommended). SDR HDPE (corrugated Type S and Type C not recommended.) RPMP, CIPP (with min. thickness for abrasion specified), concrete.
Level 6	• Heavy bed load volumes of sands, gravel and rocks, with stones sizes 6 in or larger • Velocities > 12 ft/s and ≤ 20 ft/s or • Heavy bed load volumes of sands, gravel and small cobbles, with stones sizes up to 6 in • Velocities > 15 ft/s and ≤ 20 ft/s* *Very limited data on abrasion resistance for velocities > 20 ft/s; contact District Hydraulics Branch.	Aluminum pipe requires additional gauge thickness and concrete invert protection (see lining alternatives below). Aluminized steel (type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 None of the abrasive resistant protective coatings listed in HDM Table 854.3A are recommended for protecting steel pipe. A concrete invert lining and additional gauge thickness is recommended. See lining alternatives below. Corrugated HDPE not recommended. Corrugated and closed profile PVC pipe not recommended. RCP not recommended. Increase concrete cover over reinforcing steel recommended for RCB (invert only) for velocities up to 15 ft/s. RCB not recommended for bed load stones sizes > 3 in and velocities greater than 15 ft/s unless concrete lining with larger, harder aggregate is placed (see lining alternatives below). SDR 35 PVC liners (≥ 36 in) allowed but not recommended for upper range of stone sizes in bed load if freezing conditions are often encountered, otherwise OK for stone sizes up to 3 in. Lining/replacement alternatives: SDR 35 PVC (see note above) or HDPE SDR (minimum wall thickness 1"), CIPP (with min. thickness for abrasion specified), class 2 concrete with embedded aggregate (e.g. cobbles or RSP (facing)): (for all bed load sizes a larger, harder aggregate than the bed load, decreased water cement ration and an increased concrete compression strength should be specified). Alternative invert lining may include steel plate, rails or concreted RSP, and abrasion resistant concrete (Calcium Aluminate). For new/replacement construction, consider "bottomless" structures.

Plastic Pipe Culvert Federal Lands Highway Detail 602-5

STATE	PROJECT	SHEET NUMBER

POLYETHYLENE (PE) PLASTIC ROUND PIPE CULVERT

FILL HEIGHT TABLE AND MINIMUM CELL CLASSIFICATION NUMBER PER ASTM D 3350

SMOOTH WALL (SOLID WALL)

PIPE SIZE	MINIMUM COVER	CELL CLASSIFICATION NUMBER 335434C						
		MINIMUM WALL THICKNESS (INCHES)						
		0.607	0.857	0.923	1.154	1.385	1.292	1.477
DIAMETER INCHES	INCHES	MAXIMUM FILL HEIGHT (FEET)						
12	12	57						
18	12		52					
24	12			38				
30	12				38			
36	12					38		
42	12						27	
48	12							27

CORRUGATED

PIPE SIZE	MINIMUM COVER	CELL CLASS. NO. 435400C
DIAMETER INCHES	INCHES	MAXIMUM FILL HEIGHT (FEET)
12	12	10
15	12	10
18	12	10
24	12	10
30	12	10
36	12	10

RIBBED

PIPE SIZE	MINIMUM COVER	CELL CLASS. NO. 334433C	CELL CLASS. NO. 335434C
DIAMETER INCHES	INCHES	MAXIMUM FILL HEIGHT (FEET)	
18	12	18	24
24	12	22	28
30	12	22	28
36	12	25	31
42	12	21	27
48	12	21	26

NOTE:

1. When directed, camber pipe culverts upward from a chord through the inlet and outlet inverts an ordinate amount equal to 1% of the pipe length. Develop camber on a parabolic curve. If the midpoint elevation on the parabolic curve as designed exceeds the elevation of the inlet invert, reduce the amount of camber or increase the pipe culvert gradient.
2. Measure minimum cover from the top of the pipe culvert to the subgrade for flexible pavements, and to the top of the pavement for rigid pavements. Measure maximum fill height from the top of the pipe to the top of the pavement for both flexible and rigid pavement.

POLYVINYL CHLORIDE (PVC) PLASTIC ROUND PIPE CULVERT

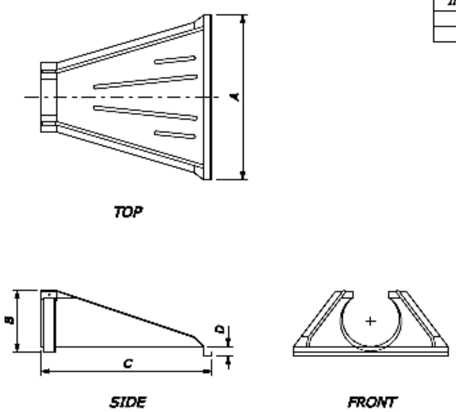
FILL HEIGHT TABLE AND MINIMUM CELL CLASSIFICATION NUMBER PER ASTM D 1784

SMOOTH WALL (SOLID WALL)

PIPE SIZE	MINIMUM COVER	CELL CLASS. NO. 12454		CELL CLASS. NO. 12364	
		MINIMUM WALL THICKNESS (INCHES)			
		0.358	0.438	0.358	0.438
DIAMETER INCHES	INCHES	MAXIMUM FILL HEIGHT (FEET)			
12	12	65		69	
15	12		62		66

RIBBED

PIPE SIZE	MINIMUM COVER	CELL CLASS. NO. 12454C	CELL CLASS. NO. 12364C
DIAMETER INCHES	INCHES	MAXIMUM FILL HEIGHT (FEET)	
12	12	37	26
15	12	32	22
18	12	33	23
24	12	29	21
30	12	28	20
36	12	27	19
42	12	26	18
48	12	24	17



PLASTIC PIPE END SECTION

END SECTION DIMENSIONS

PIPE SIZE DIAMETER INCHES	DIMENSIONS INCHES A	B	C	D
12	42	14.5	33	6
15	46	24.5	45.5	6
18	54	29	55	6
24	64	37	65	6
30	88	36	63.5	6
36	88	43	66.5	6

NO SCALE

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
FEDERAL LANDS HIGHWAY

U.S. CUSTOMARY STANDARD

PLASTIC PIPE CULVERT

STANDARD APPROVED FOR USE 12/1999
REVISED: 4/1994 8/2008
DRAFT 12/2008

STANDARD 602-5

ADOT Pipe Bedding Gradation Table (ADOT 2008)

Sieve Size	Percent Passing
1-1/2 inch	100
1 inch	90 - 100
No. 8	35 - 80
No. 200	0 - 8.0

The plasticity index of the bedding material for all pipe shall not exceed 8 when tested in accordance with the requirements of AASHTO T 90.

ADOT Pipe Backfill Gradation Table (ADOT 2008)

Pipe backfill material shall conform to the following gradation:

Sieve Size	Percent Passing
3 inch	100
3/4 inch	60 - 100
No. 8	35 - 80
No. 200	0 - 12.0

The plasticity index shall not exceed 12 when tested in accordance with the requirements of AASHTO T 90.

CDOT Class I Structural Backfill Gradation Table (CDOT 2011)

703.08 Structure Backfill Material.

(a) Class I structure backfill shall meet the following gradation requirements:

Sieve Size	Mass Percent Passing Square Mesh Sieves
50 mm (2 inch)	100
4.75 mm (No. 4)	30-100
300 µm (No. 50)	10-60
75 µm (No. 200)	5-20

In addition this material shall have a liquid limit not exceeding 35 and a plasticity index of not over six when determined in conformity with AASHTO T 89 and T 90 respectively.

CDOT Class II Structural Backfill Gradation Table (CDOT 2011)

(b) Class 2 structure backfill shall be composed of suitable materials developed on the project. To be suitable for use under this classification, backfill shall be free of frozen lumps, wood, or other organic material. If the material contains rock fragments that, in the opinion of the Engineer, will be injurious to the structure, the native material shall not be used for backfilling and the Contractor shall furnish Class 1 structure backfill material at the contract unit price. If contract unit price does not exist for Class I structure backfill, it will be paid for in accordance with subsection 104.03.

ODOT Structural Backfill Type 2 (ODOT 2010)

B. Structural Backfill Type 2.

1. Furnish Type 2 structural backfill that meets the gradations of 703.05.A, 703.02.A, or one of the gradations below:

Sieve Size		Total Percent Passing	
2 1/2 inch	(63 mm)	–	100
1 inch	(25.0 mm)	–	70 to 100
3/4 inch	(19.0 mm)	100	–
3/8 inch	(9.5 mm)	80 to 100	–
No. 4	(4.75 mm)	60 to 100	25 to 100
No. 8	(2.36 mm)	45 to 95	–
No. 40	(425 µm)	–	10 to 50
No. 50	(300 µm)	7 to 55	–
No. 200	(75 µm)	0 to 15	5 to 15

2. Physical properties:

Percent of wear, Los Angeles test, maximum (CCS or gravel)	50 %
Loss, sodium sulfate soundness test, maximum	15 %

Ensure that the portion of the material passing through the No. 40 (425 mm) sieve has a maximum liquid limit of 25 and a maximum plastic index of 6.

NYDOT Select Granular Fill (NYDOT 2008)

C. Select Granular Fill and Select Structural Fill. Materials furnished under these items shall be suitable, well graded, and conform to the following requirements:

1. Gradation. Except when used as backfill material for aluminum pipe with Type IR corrugations (Spiral Rib Pipe), the material shall have the following gradation:

Sieve Size	Percent Passing by Weight
4 inch	100
No. 40	0 to 70
No. 200	0 to 15

When used as backfill for Corrugated Aluminum Pipe, Type 1R (Spiral Rib Pipe) 100% of the material shall also pass the 2 inch sieve.

2. Soundness. The materials shall be substantially free of shale and soft, poor durability particles. A material with Magnesium Sulfate Soundness Loss exceeding 30% will be rejected.

3. Composition. RAP shall not be used.
When used as backfill for aluminum pipe, the material shall be free of Portland cement or Portland cement concrete.

4. pH. Where the State elects to test for this requirement, a material with pH of less than 5 or more than 10 shall be rejected.

WSDOT Gravel Backfill (WSDOT 2010b)

9-03.12(3) Gravel Backfill for Pipe Zone Bedding

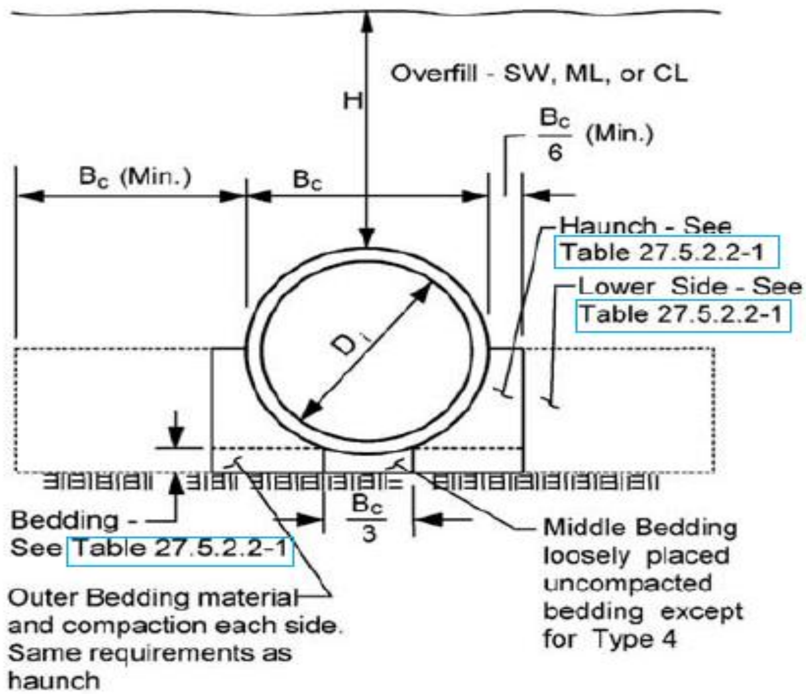
Gravel backfill for pipe zone bedding shall consist of crushed, processed, or naturally occurring granular material. It shall be free from various types of wood waste or other extraneous or objectionable materials. It shall have such characteristics of size and shape that it will compact and shall meet the following Specifications for grading and quality:

Sieve Size	Percent Passing
1½"	100
1"	75-100
⅝"	50-100
No. 4	20-80
No. 40	3-24
No. 200	10.0 max.
Sand Equivalent	35 min.

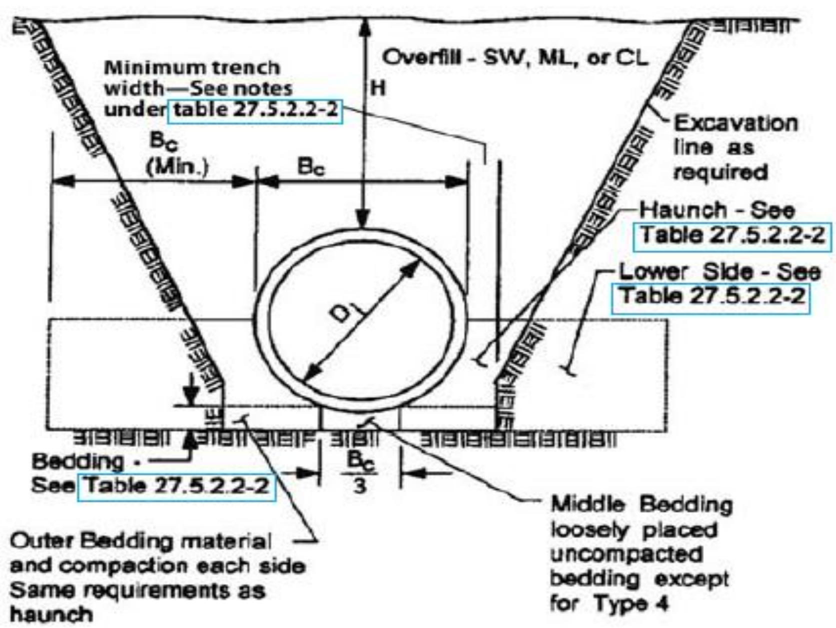
All percentages are by weight.

If, in the opinion of the Engineer, the native granular material is free from wood waste, organic material, and other extraneous or objectionable materials, but otherwise does not conform to the Specifications for grading and Sand Equivalent, it may be used for pipe bedding for rigid pipes, provided the native granular material has a maximum dimension of 1½-inches.

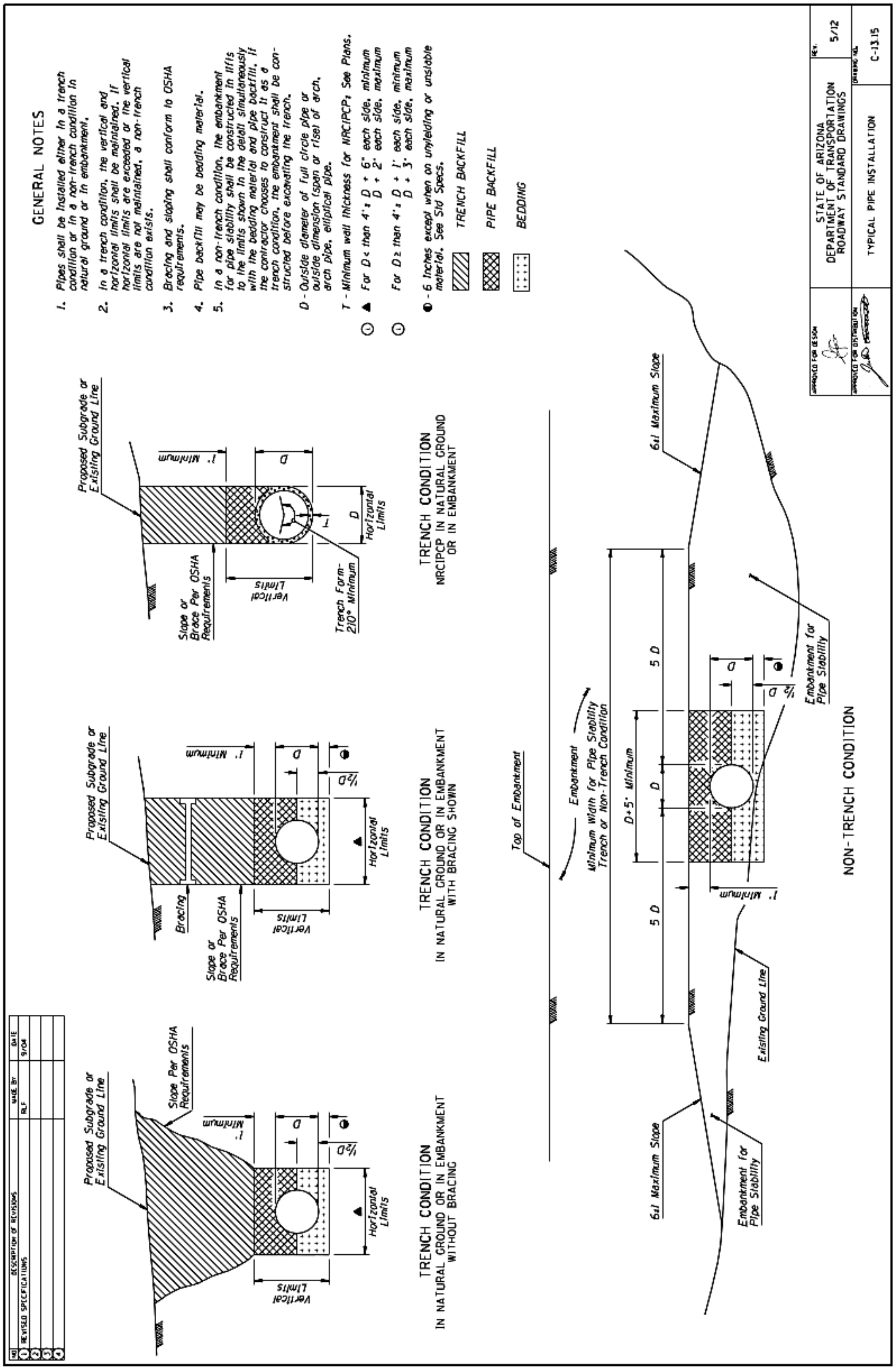
Concrete Pipe Embankment Installation Detail (AASHTO 2010a)



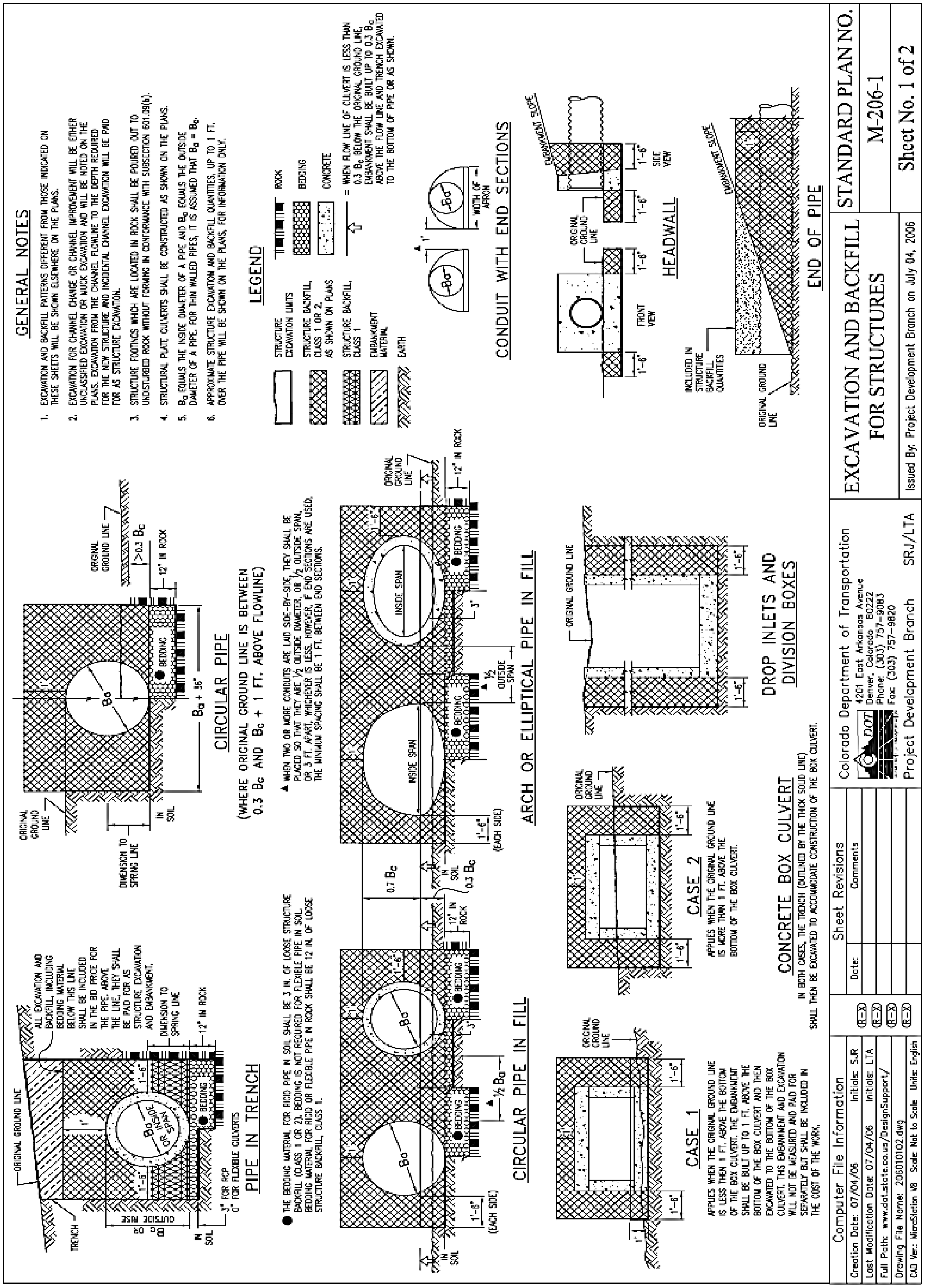
Concrete Pipe Trench Installation Detail (AASHTO 2010a)



Typical Pipe Installation Detail (ADOT 2012)



Typical Pipe Installation Detail (CDOT 2012)



Concrete Pipe Embankment Installation Detail (NDOR 2008)

TABLE 1
STANDARD INSTALLATIONS, SOILS AND MINIMUM COMPACTION REQUIREMENTS

INSTALLATION TYPE	BEDDING THICKNESS	HAUNCH AND OUTER BEDDING	LOWER SIDE
TYPE 1	DO/24 MINIMUM, NOT LESS THAN 3 IN. IF ROCK FOUNDATION, USE DO/12 MINIMUM, NOT LESS THAN 6 IN.	95% SW	90% SW, 95% ML, OR 100% CL.
TYPE 2		90% SW OR 95% ML	85% SW, 90% ML, OR 95% CL.
• TYPE 3		85% SW, 90% ML, OR 95% CL	85% SW, 90% ML, OR 95% CL.

TABLE 1 NOTES:

• THE TYPE 3 INSTALLATION SHOWN IS THE NDOR MINIMUM STANDARD, USING EITHER A SHAPED TRENCH ACCORDING TO THE STANDARD SPECIFICATIONS, OR AT THE OPTION OF THE CONTRACTOR, THE BEDDING WITH COMPACTIONS AS SHOWN.

ALLOWABLE FILL HEIGHTS FOR THE TYPE 1, 2, AND 3 INSTALLATIONS ARE SHOWN IN TABLE 4.

TABLE 2
PIPE DIMENSIONS

NOMINAL PIPE DIAMETER (INCHES)	STANDARD OUTSIDE PIPE DIAMETER, DO (SPAN)			
	ROUND PIPE	ARCH PIPE	H. ELLIP. PIPE	V. ELLIP. PIPE
15	19.5	22.5		
18	23	27	28.5	
21	26.5	31.5		
24	30	34.5	36.5	
27	33.5		41	
30	37	43.25	45.5	
36	44	51.75	54	38
42	51	60.13	63	44
48	58	68.5	71	49
54	65	76	80	55
60	72	85	89	61
66	79		97	67
72	86	102	106	73
78	93		114	79
84	100	118	123	85
90	107			
96	114			
102	121			
108	128			

TABLE 3
SOIL CLASSIFICATION FOR BEDDING & BACKFILL

ASTM SOIL GROUP SYMBOL D 2487	DESCRIPTION	PERCENTAGE PASSING SIEVE SIZES		
		1½ IN. (40 mm)	NO. 4 (4.75 mm)	NO. 200 (0.075 mm)
SW	WELL GRADED SANDS AND GRAVELLY-SANDS: LITTLE OR NO FINES. NON PLASTIC	100%	> 50% OF "COURSE FRACTION"	< 5%
ML	INORGANIC SILTS AND VERY FINE SANDS, ROCK FLOUR, SILTY OR CLAYEY-FINE-SANDS, SILTS WITH SLIGHT PLASTICITY		100%	> 50%
CL	INORGANIC CLAYS OF LOW TO MEDIUM PLASTICITY, GRAVELY-CLAYS, SANDY-CLAYS, SILTY-CLAYS, LEAN CLAYS			

NOTES FOR EMBANKMENT INSTALLATIONS:

1. COMPACTION AND SOIL SYMBOLS, I.E. 95% SW, REFER TO SW SOIL MATERIAL WITH A MINIMUM STANDARD PROCTOR COMPACTION OF 95%.

2. SOIL IN THE OUTER BEDDING, HAUNCH, AND LOWER SIDE ZONES, EXCEPT WITHIN THE DO/3 MIDDLE BEDDING, SHALL BE COMPACTED TO AT LEAST THE SAME COMPACTION AS THE MAJORITY OF THE SOIL IN THE OVERFILL ZONES.

3. SUBTRENCHES

3.1 A SUBTRENCH IS DEFINED AS A TRENCH WITH ITS TOP AT AN ELEVATION LOWER THAN 1 FT. BELOW THE BOTTOM OF THE PAVEMENT BASE MATERIAL.

3.2 THE MINIMUM WIDTH OF A SUBTRENCH SHALL BE 1.33DO, OR WIDER IF REQUIRED FOR ADEQUATE SPACE TO ATTAIN THE SPECIFIED COMPACTION IN THE HAUNCH AND BEDDING ZONES.

3.3 FOR SUBTRENCHES WITH WALLS OF NATURAL SOIL, ANY PORTION OF THE LOWER SIDE ZONE IN THE SUBTRENCH WALL SHALL BE AT LEAST AS FIRM AS AN EQUIVALENT SOIL PLACED TO THE COMPACTION REQUIREMENTS SPECIFIED FOR THE LOWER SIDE ZONE, AND AS FIRM AS THE MAJORITY OF SOIL IN THE OVERFILL ZONE, OR SHALL BE REMOVED AND REPLACED WITH SOIL COMPACTED TO THE SPECIFIED LEVEL.

GENERAL NOTES:

WHEN IN-SITU LATERAL SOIL RESISTANCE IS NEGLIGIBLE, E.G. PEAT, MUCK, OR HIGHLY EXPANSIVE SOIL, EMBEDMENT SHALL BE PLACED AND COMPACTED AT THE DIRECTION OF THE ENGINEER.

TO PROTECT THE PIPE AND BACKFILL DURING CONSTRUCTION, PROVIDE A MINIMUM OF 36 IN. OF COMPACTED FILL MATERIAL OVER THE TOP OF THE PIPE BEFORE ALLOWING ANY HEAVY EQUIPMENT TO TRAVERSE OVER THE PIPE. EXTREMELY HEAVY EQUIPMENT MAY REQUIRE LARGER COVER AS DETERMINED BY THE CONTRACTOR.

THE PIPE VOLUME SHOULD NOT BE SUBTRACTED FROM THE VOLUME OF EXCAVATION.

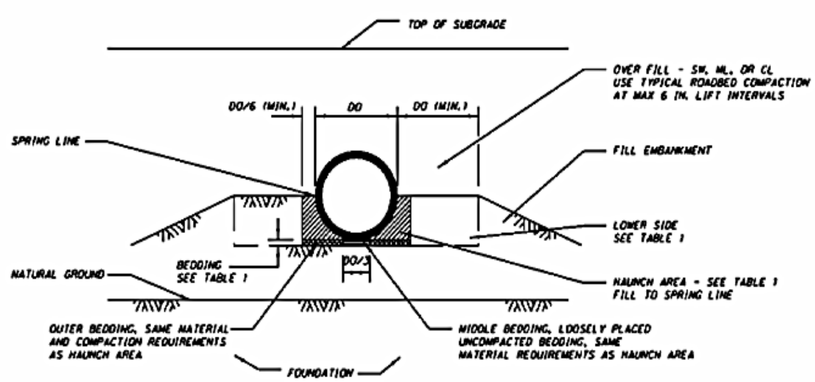
THESE DESIGN STANDARDS ARE MINIMUM. IF A MORE RESTRICTIVE DESIGN IS REQUIRED BY THE ENGINEER OR CULVERT MANUFACTURER, THEN THESE STANDARDS SHALL BE MODIFIED. CHANGES TO PAY ITEM QUANTITIES DUE TO UNFORESEEN SITE CONDITIONS SHALL BE CALCULATED AND INCORPORATED INTO THE CONTRACT THRU A CHANGE ORDER.

BOTH ENDS OF THE PIPE SHALL BE SEALED WITH COHESIVE SOIL (AROUND THE PIPE EXTENDING 3 FT. TO 4 FT. FROM EACH END) TO PROTECT AGAINST INFILTRATION AND EROSION.

BEDDING AND BACKFILL MATERIAL IS NOT PAID FOR DIRECTLY, BUT IS SUBSIDIARY TO THE LINEAR FEET OF CULVERT.

BEDDING AND BACKFILL MATERIAL SHALL MEET ASTM D 2487 (SOIL GROUPS AS SHOWN IN TABLE 3).

PERCENT COMPACTION SHALL BE DETERMINED IN ACCORDANCE WITH NDOR STANDARD TEST METHOD T 99.



TYPICAL EMBANKMENT INSTALLATION

REV. NO.	DATE	DESCRIPTION OF REVISION

NEBRASKA DEPARTMENT OF ROADS
STANDARD PLAN NO. 411
BEDDING AND BACKFILL REQUIREMENTS FOR CONCRETE PIPE

FHWA APPROVED:
DATE
ORIGINAL: JUNE 6, 2008
DATE

2/4

Typical Flexible Pipe Installation Detail (NDOR 2008)

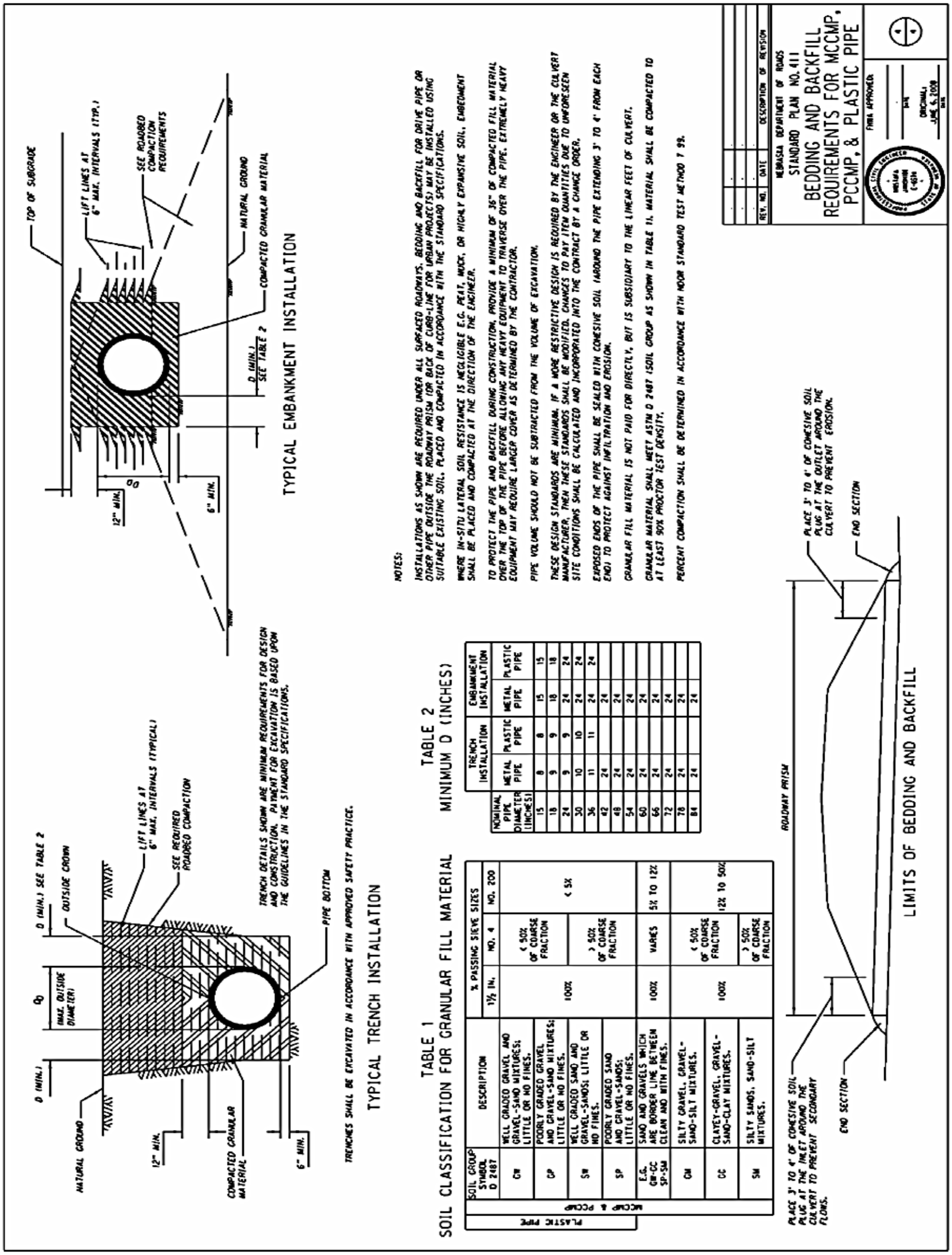


TABLE 1
SOIL CLASSIFICATION FOR GRANULAR FILL MATERIAL

	SOIL GROUP SYMBOL D 2487	DESCRIPTION	% PASSING SIEVE SIZES 1½ IN.	NO. 4	NO. 200
PLASTIC PIPE; MCCMP & PCCMP	GW	WELL GRADED GRAVEL AND GRAVEL-SAND MIXTURES; LITTLE OR NO FINES.	100%	< 50% OF COARSE FRACTION	< 5%
	GP	POORLY GRADED GRAVEL AND GRAVEL-SAND MIXTURES; LITTLE OR NO FINES.			
	SW	WELL GRADED SAND AND GRAVEL-SANDS; LITTLE OR NO FINES.		> 50% OF COARSE FRACTION	
	SP	POORLY GRADED SAND AND GRAVEL-SANDS; LITTLE OR NO FINES.			
MCCMP & PCCMP	E.G. GW-GC SP-SM	SAND AND GRAVELS WHICH ARE BORDER LINE BETWEEN CLEAN AND WITH FINES.	100%	VARIES	5% TO 12%
	GM	SILTY GRAVEL, GRAVEL-SAND-SILT MIXTURES.	100%	< 50% OF COARSE FRACTION	12% TO 50%
	GC	CLAYEY-GRAVEL, GRAVEL-SAND-CLAY MIXTURES.			
	SM	SILTY SANDS, SAND-SILT MIXTURES.		> 50% OF COARSE FRACTION	

TABLE 2
MINIMUM D (INCHES)

NOMINAL PIPE DIAMETER (INCHES)	TRENCH INSTALLATION METAL PIPE	TRENCH INSTALLATION PLASTIC PIPE	EMBANKMENT INSTALLATION METAL PIPE	EMBANKMENT INSTALLATION PLASTIC PIPE
15	8	8	15	15
18	9	9	18	18
24	9	9	24	24
30	10	10	24	24
36	11	11	24	24
42	24		24	
48	24		24	
54	24		24	
60	24		24	
66	24		24	
72	24		24	
78	24		24	
84	24		24	

NOTES:

INSTALLATIONS AS SHOWN ARE REQUIRED UNDER ALL SURFACED ROADWAYS. BEDDING AND BACKFILL FOR DRIVE PIPE OR OTHER PIPE OUTSIDE THE ROADWAY PRISM (OR BACK OF CURB-LINE FOR URBAN PROJECTS) MAY BE INSTALLED USING SUITABLE EXISTING SOIL, PLACED AND COMPACTED IN ACCORDANCE WITH THE STANDARD SPECIFICATIONS.

WHERE IN-SITU LATERAL SOIL RESISTANCE IS NEGLIGIBLE E.G. PEAT, MUCK, OR HIGHLY EXPANSIVE SOIL, EMBEDMENT SHALL BE PLACED AND COMPACTED AT THE DIRECTION OF THE ENGINEER.

TO PROTECT THE PIPE AND BACKFILL DURING CONSTRUCTION, PROVIDE A MINIMUM OF 36" OF COMPACTED FILL MATERIAL OVER THE TOP OF THE PIPE BEFORE ALLOWING ANY HEAVY EQUIPMENT TO TRAVERSE OVER THE PIPE. EXTREMELY HEAVY EQUIPMENT MAY REQUIRE LARGER COVER AS DETERMINED BY THE CONTRACTOR.

PIPE VOLUME SHOULD NOT BE SUBTRACTED FROM THE VOLUME OF EXCAVATION.

THESE DESIGN STANDARDS ARE MINIMUM. IF A MORE RESTRICTIVE DESIGN IS REQUIRED BY THE ENGINEER OR THE CULVERT MANUFACTURER, THEN THESE STANDARDS SHALL BE MODIFIED. CHANGES TO PAY ITEM QUANTITIES DUE TO UNFORESEEN SITE CONDITIONS SHALL BE CALCULATED AND INCORPORATED INTO THE CONTRACT BY A CHANGE ORDER.

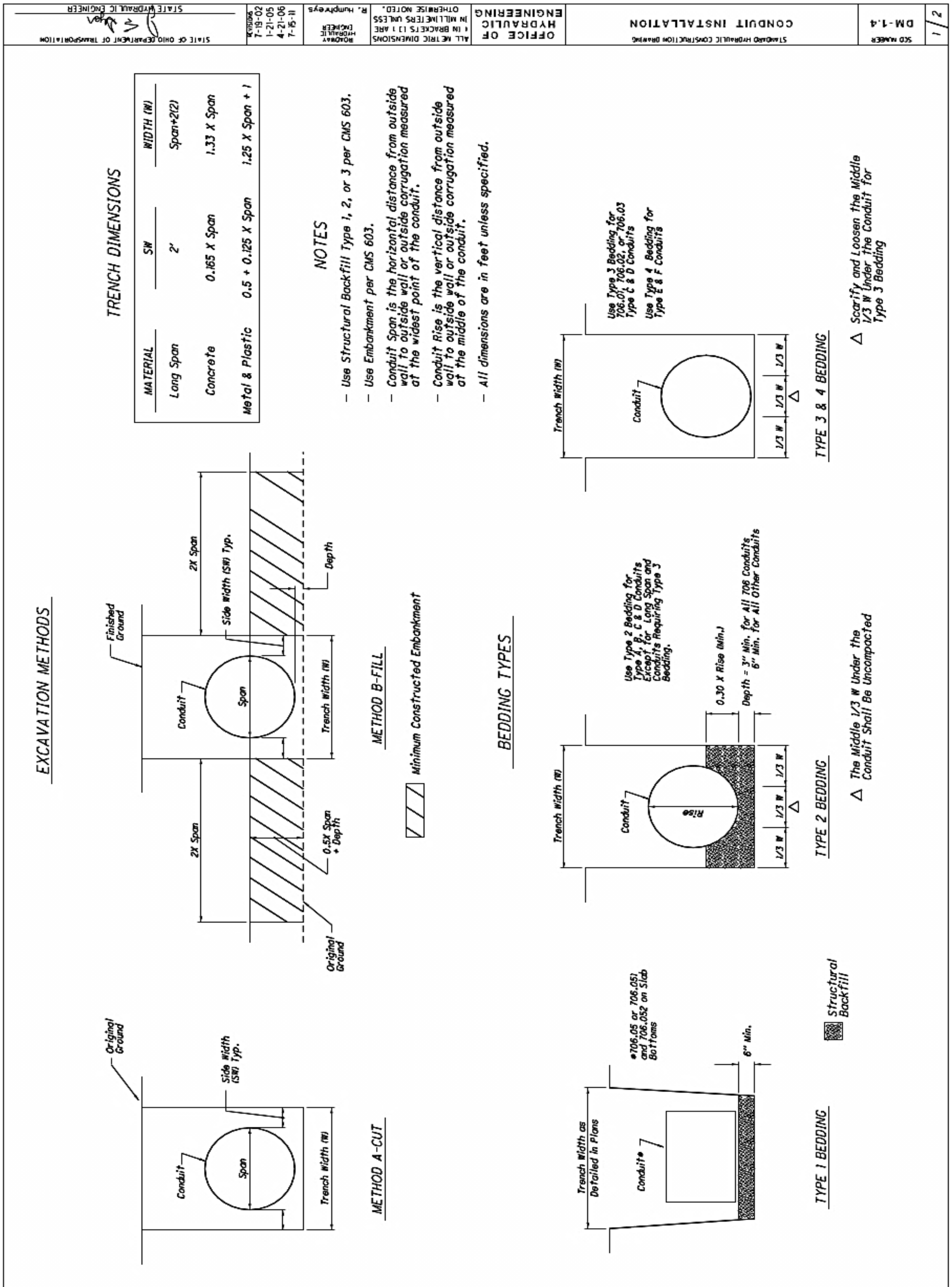
EXPOSED ENDS OF THE PIPE SHALL BE SEALED WITH COHESIVE SOIL (AROUND THE PIPE EXTENDING 3' TO 4' FROM EACH END) TO PROTECT AGAINST INFILTRATION AND EROSION.

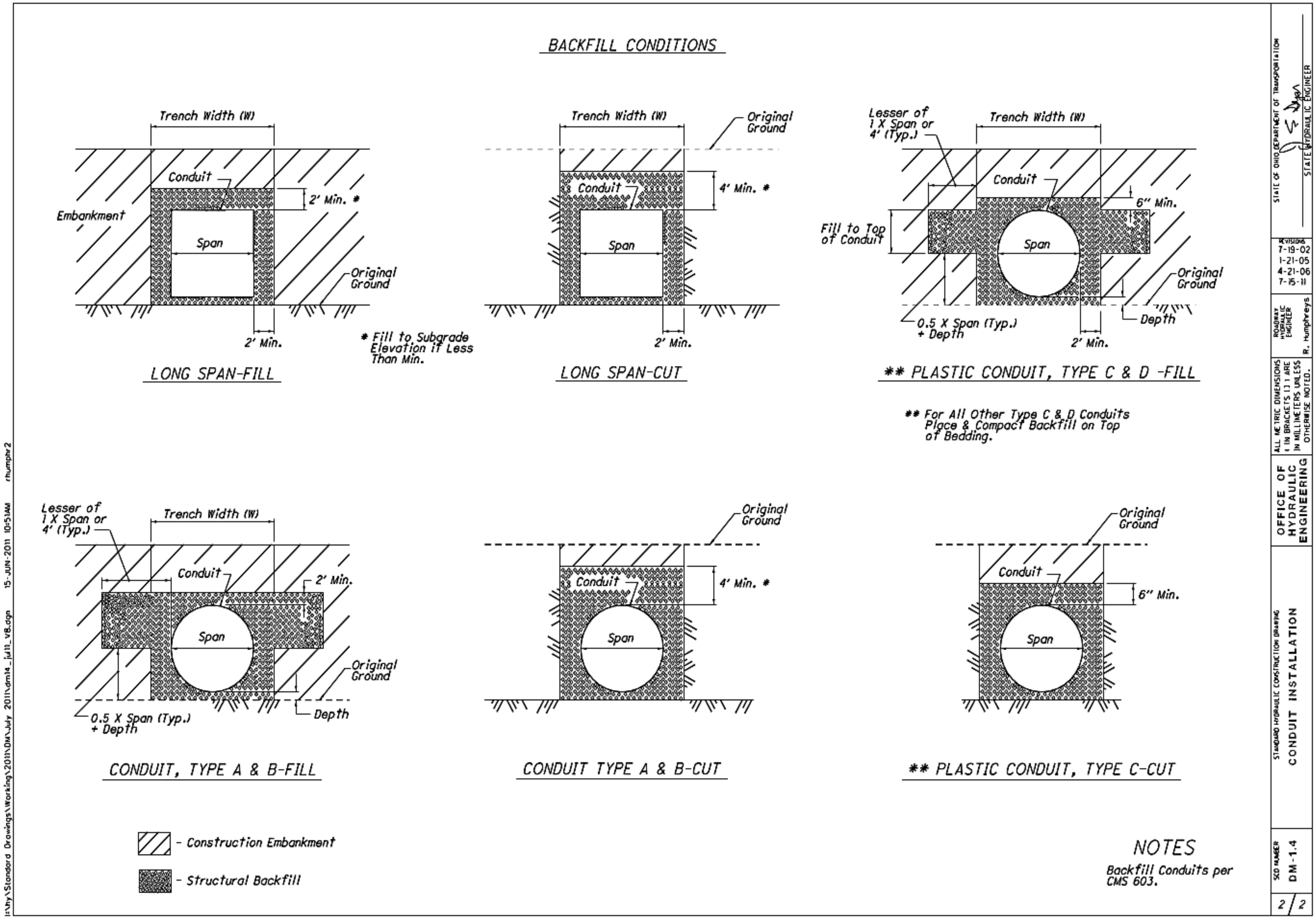
GRANULAR FILL MATERIAL IS NOT PAID FOR DIRECTLY, BUT IS SUBSIDIARY TO THE LINEAR FEET OF CULVERT.

GRANULAR MATERIAL SHALL MEET ASTM D 2487 (SOIL GROUP AS SHOWN IN TABLE 1). MATERIAL SHALL BE COMPACTED TO AT LEAST 90% PROCTOR TEST DENSITY.

PERCENT COMPACTION SHALL BE DETERMINED IN ACCORDANCE WITH NDOR STANDARD TEST METHOD T 99.

Typical Concrete Pipe Installation Detail (ODOT 2010)




BACKFILL CONDITIONS
Trench Width (W)
Conduit
2' Min. *
Embankment
Span
Original Ground
2' Min.
* Fill to Subgrade Elevation if Less Than Min.
LONG SPAN-FILL
Trench Width (W)
Original Ground
Conduit
4' Min. *
Span
2' Min.
LONG SPAN-CUT
Lesser of 1 X Span or 4' (Typ.)
Trench Width (W)
Conduit
6" Min.
Fill to Top of Conduit
Span
Original Ground
0.5 X Span (Typ.) + Depth
Depth
2' Min.
** PLASTIC CONDUIT, TYPE C & D -FILL
** For All Other Type C & D Conduits Place & Compact Backfill on Top of Bedding.
Lesser of 1 X Span or 4' (Typ.)
Trench Width (W)
Conduit
2' Min.
Span
Original Ground
0.5 X Span (Typ.) + Depth
Depth
CONDUIT, TYPE A & B-FILL
Original Ground
Conduit
4' Min. *
Span
CONDUIT TYPE A & B-CUT
Original Ground
Conduit
6" Min.
Span
** PLASTIC CONDUIT, TYPE C-CUT
- Construction Embankment
- Structural Backfill
NOTES
Backfill Conduits per CMS 603.
STATE OF OHIO DEPARTMENT OF TRANSPORTATION
STATE HYDRAULIC ENGINEER
REVISIONS
7-19-02
1-21-05
4-21-06
7-15-11
ROADWAY HYDRAULIC ENGINEER
R. Humphreys
ALL METRIC DIMENSIONS (IN BRACKETS [ ]) ARE IN MILLIMETERS UNLESS OTHERWISE NOTED.
OFFICE OF HYDRAULIC ENGINEERING
STANDARD HYDRAULIC CONSTRUCTION DRAWING
CONDUIT INSTALLATION
SCD NUMBER
DM-1.4
2/2
i:\hy\Standard Drawings\Working\2011\DM\July 2011\dm14_jul11_V8.dgn 15-JUN-2011 10:51AM rhumphr2

Typical Concrete Pipe Installation Detail (UDOT 2008)

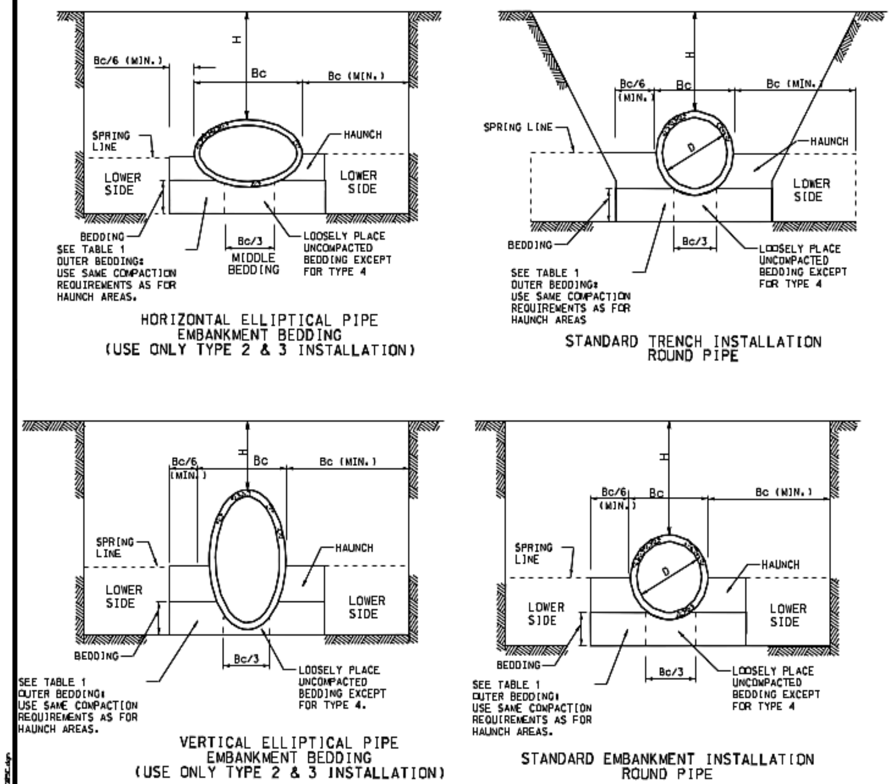


TABLE 1. SOILS AND MINIMUM COMPACTION REQUIREMENTS FOR STANDARD EMBANKMENT AND TRENCH INSTALLATIONS.

INSTALLATION TYPE	BEDDING THICKNESS	HAUNCH & OUTER BEDDING			LOWER SIDE		
		MINIMUM COMPACTION	AASHTO SOIL CLASS	USCS	MINIMUM COMPACTION	AASHTO SOIL CLASS	USCS
TYPE 1	SOIL FOUNDATIONS: Bc/24 IN. MIN., NOT LESS THAN 3 IN. ROCK FOUNDATIONS: Bc/12 IN. MIN., NOT LESS THAN 6 IN.	95%	A1,A3	SW	90% 95% 100%	A1,A3 A2,A4 A5,A6	SW ML CL

NOTES:

1. COMPACT BACKFILL ACCORDING TO TABLE 1. REFER TO AASHTO T 99. REMOVE BOULDERS OR ROCKS WITHIN BEDDING AREAS. PROVIDE SUFFICIENT TRENCH WIDTH TO FIT COMPACTION EQUIPMENT.
2. RECESS THE BEDDING TO RECEIVE CULVERT JOINTS WHERE APPLICABLE.
3. FILL AND COMPACT HAUNCH AREAS UNDER PIPE ACCORDING TO SPECIFICATIONS. REMOVE ANY VOIDS WITHOUT DISTURBING THE PIPE FROM SPECIFIED LINE AND GRADE.
4. SEAL CONNECTIONS TO JUNCTIONS BOXES, MANHOLES, AND INLETS ACCORDING TO MANUFACTURER'S RECOMMENDATIONS.
5. PROTECT PIPES DURING CONSTRUCTION. REPLACE ANY PIPES DAMAGED DURING CONSTRUCTION.
6. DO NOT USE DAMAGED PIPES THAT HAVE CRACKS WIDER THAN 0.01 INCHES.
7. REMOVE AS DIRECTED BY THE ENGINEER UNSTABLE SOILS SUCH AS PEAT, BOG, SILTS, CLAYS, AND UNCEMENTED SANDS WHOSE WATER CONTENT EXCEED THEIR LIQUID LIMITS FROM THE PIPE BEDDING AREA. REPLACE WITH SUITABLE BACKFILL MATERIAL.
8. FOLLOW STANDARD SPECIFICATION SECTION 00820 AND "THE UDOT CONSTRUCTION SAFETY AND HEALTH MANUAL" FOR MINIMUM SAFETY TRENCH REQUIREMENTS.

REINFORCED CIRCULAR PIPE MAX. FILL HEIGHT

PIPE DIA. Inch	PIPE CLASSES II ft.	III ft.	IV ft.	V ft.
18	20	27	41	61
21	20	27	41	61
24	20	27	40	61
27	20	27	40	61
30	20	27	40	60
33	19	27	39	60
36	19	26	39	59
42	19	26	39	59
48	19	26	39	59
54	18	25	39	58
60	18	25	38	58
66	18	25	38	57
72	18	24	38	57
78	17	24	37	57
84	17	24	37	56
90	17	24	37	56
96	17	24	36	56
102	17	23	36	55
108	16	23	36	55
114	16	23	35	55
120	16	23	35	54
126	16	23	35	54
132	16	22	35	54
138	15	22	34	53
144	15	22	34	53

ELLIPTICAL PIPE MAX. FILL HEIGHT

PIPE DIA. Inch	PIPE CLASSES II ft.	III ft.	IV ft.	V ft.
14x23	20	27	41	61
19x30	20	27	41	61
22x34	20	27	40	61
24x38	20	27	40	61
27x42	20	27	40	60
29x45	19	27	39	60
32x49	19	26	39	59
34x53	19	26	39	59
38x60	19	26	39	59
43x68	18	25	39	58
48x76	18	25	38	58
53x83	18	25	38	57
58x91	18	24	38	57
63x98	17	24	37	57
68x106	17	24	37	56
72x113	17	24	37	56
77x121	17	24	36	56
82x128	17	23	36	55
87x136	16	23	36	55
92x143	16	23	35	55
97x151	16	23	35	54
106x166	16	23	35	54
116x180	16	22	35	54

NON-REINFORCED CIRCULAR PIPE MAX. FILL HEIGHT

PIPE DIA. Inch	PIPE CLASSES I ft.	II ft.	III ft.
18	19	27	30
21	18	25	30
24	17	24	29
27	16	23	27
30	15	22	25
33	14	21	23
36	14	19	21

REVISIONS			
NO.	DATE	APPR.	REMARKS

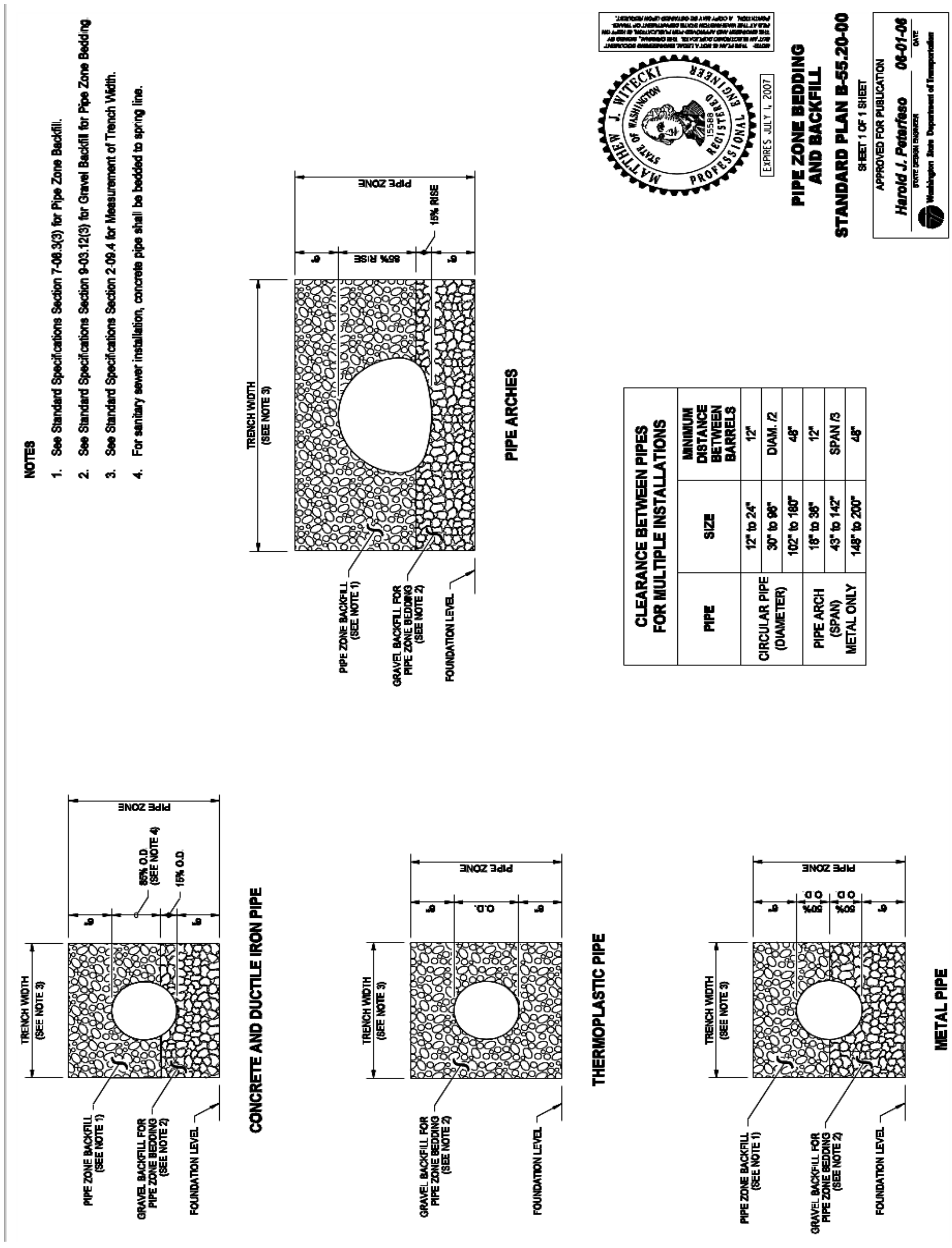
UTAH DEPARTMENT OF TRANSPORTATION
STANDARD DRAWINGS FOR ROAD AND BRIDGE CONSTRUCTION
SALT LAKE CITY, UTAH

RECOMMENDED FOR APPROVAL — JAN.01,2008 DATE
CHAIRMAN STANDARDS COMMITTEE APPROVED — JAN.01,2008 DATE
DEPUTY DIRECTOR

STANDARD DRAWING TITLE
PRECAST CONCRETE PIPE CULVERT INSTALLATION

STD DWG
DG 5C

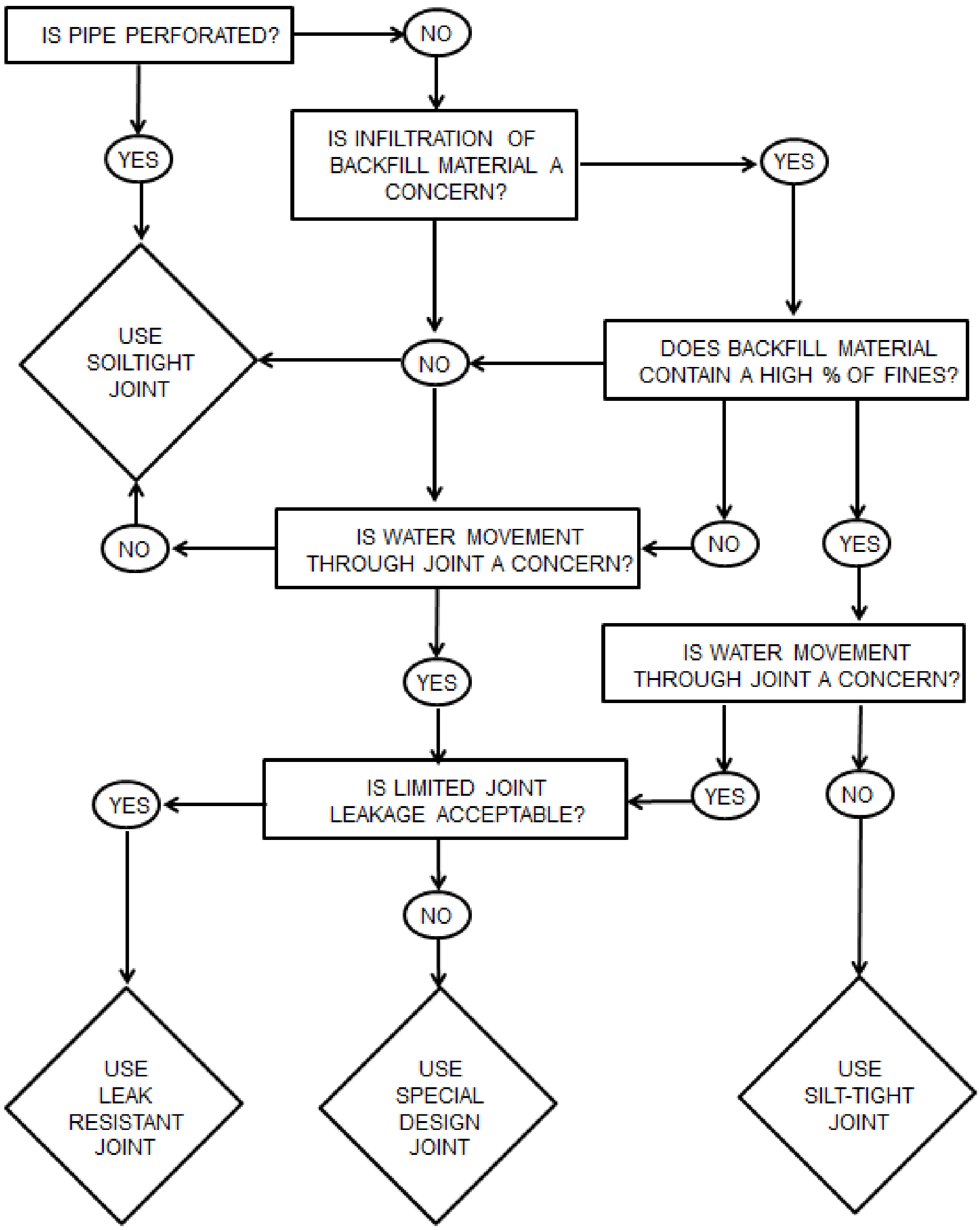
Typical Pipe Installation Detail (WSDOT 2006)



CLEARANCE BETWEEN PIPES FOR MULTIPLE INSTALLATIONS

PIPE	SIZE	MINIMUM DISTANCE BETWEEN BARRELS
CIRCULAR PIPE (DIAMETER)	12" to 24"	12"
	30" to 96"	DIAM. /2
	102" to 180"	48"
PIPE ARCH (SPAN) METAL ONLY	18" to 36"	12"
	43" to 142"	SPAN /3
	148" to 200"	48"

Pipe Joint Selection Flowchart (AASHTO 2009)

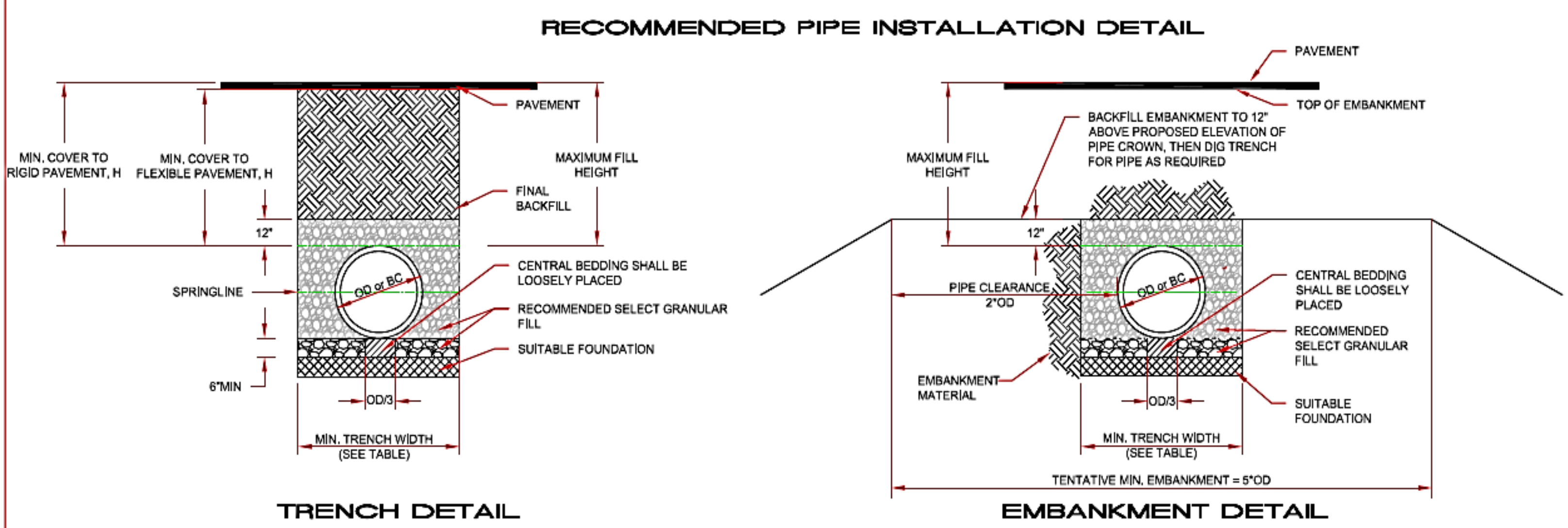


LEAKAGE RATE (MAXIMUM)

-200 gal/in.-diam/mi/day

Figure 1-Pipe Joint Selection Process Flowchart

APPENDIX C – RECOMMENDED PIPE INSTALLATION DETAIL



CURRENT WYDOT MINIMUM TRENCH WIDTHS

PIPE DIAM.	MIN. TRENCH WIDTH
12"	60"
15"	63"
18"	66"
24"	72"
30"	78"
36"	84"
42"	90"
48"	96"
60"	108"

TYP. PIPE INSTALLATION

NOTES:

1. ALL PIPE SHALL MEET THE REQUIREMENTS AND IN ACCORDANCE WITH AASHTO SPECIFICATIONS
2. MINIMUM BEDDING THICKNESS SHALL BE 6", IF PIPE IS LOCATED ABOVE ROCK FOUNDATION MINIMUM BEDDING THICKNESS SHALL BE 12".
3. MATERIAL SHALL BE INSTALLED IN MAXIMUM OF 8" LIFTS COMPACTED TO 95% STANDARD PROCTOR.
4. MINIMUM COVER SHALL BE 24". ADDITIONAL COVER MAY BE REQUIRED DURING CONSTRUCTION.

WYOMING DEPARTMENT OF TRANSPORTATION

RECOMMENDED DETAIL TYPICAL PIPE INSTALLATION DETAILS

603-1A

SHEET X of X

XXX-X

XXX-X