FINITE ELEMENT MODELING OF BURIED ARCHED PIPES FOR THE ESTIMATION OF MAXIMUM FILL COVERS

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Luz María Agudelo Urrego

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Ghadir Haikal, Chair
School of Civil Engineering
Dr. Antonio Bobet
School of Civil Engineering
Dr. Julio Ramirez
School of Civil Engineering

Approved by:
Dr. Dulcy M. Abraham
Head of Lyles School of Civil Engineering Graduate Program

Para mi padres, mis hermosas sobrinas y el amor de Katty y Sammy.

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SYMBOLS

PA	Area of pipe wall section per unit length, in^2/in
PI	Moment of inertia of pipe wall section per unit length, in^4/in
PS	Section Modulus of pipe wall section per unit length, in^3/in
R	Rise, $ft - in$
R_t	Top radius, $ft - in$
R_b	Bottom radius, $ft - in$
R_c	Corner radius, $ft - in$
S	Span, $ft - in$
A	Area of pipe-arch, sft
T	Thickness, in
TL	Tangent length, in
Δ°	Tangent angle, deg
K	Dimensionless magnitude of initial Young's modulus
n	Power-law coefficient for initial modulus
C	Cohesion intercept for failure, psi
ϕ_0	Initial soil friction angle of failure surface
$\Delta\varphi$	Reduction of soil friction angle for 10-fold increase in σ_3, deg
R_F	Failure ratio of actual to model failure stress
P_a	Atmospheric pressure
E_t	Tangent Young's modulus
E_i	Initial tangent Young's modulus
B_t	Tangent Bulk modulus
B_i	Initial tangent Bulk modulus
E_c	Chord moduli of tangent Young's modulus

B_c	Chord moduli of Tangent Bulk modulus
ε_u	Ultimate volumetric strain at large hydrostatic stress
σ_3	Minimum compressive principal stress
σ_m	Average stress
σ	Stress
ε	Stain
$\underline{C}$	Constitutive Function
$\underline{Q}$	Operator Matrix
f	Body force vector
$\underline{K}_G$	Incremental global stiffness matrix
$\Delta\underline{P}_G$	Incremental global load vector
$\Delta\hat{u}_G$	Incremental global displacement vector
H	Height of soil cover measured from top of the pipe, ft
w	density, lb/ft^3
P_f	Design pressure, psi
FP_f	Factored design pressure, psi
P_c	Design pressure using the corner pressure, psi
P_v	Design pressure using the radial pressure, psi
T_f	Factored thrust in pipe wall, lb/in
R_f	Factored resistance for each limit state, lb/in
R_n	Nominal Resistance for each limit state, lb/in
f_c	Critical buckling stress, psi
ϕ	Resistance factor
f_y	Minimum yield strength, psi
f_u	Minimum tensile strength, psi
k	Soil stiffness factor taken as 0.22
r	Radius of gyration of corrugation, in
$\gamma_{max/min}$	Maximum or Minimum standard load factor
$\eta_{DC/EB}$	Composite load modifier for Dead load or Earth fill loading case

ABBREVIATIONS

INDOT	Indiana Department of Transportation
CANDE	Culvert Analysis and Design
FHWA	Federal Highway Administration
FE	Finite Element
FEM	Finite Element Method
SW	Gravelly sand
ASD	Allowable Stress Design
LRFD	Load and Resistance Factor Design
CSPA	Corrugated Steel Pipe-Arch
CAPA	Corrugated Aluminum Pipe-Arch
SPSPA	Structural Plate Steel Pipe-Arch
SPAPA	Structural Plate Aluminum Pipe-Arch
DL	Dead Load
LL	Live Load
IL	Impact Load

ABSTRACT

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The Indiana Department of Transportation implements maximum soil fill covers to ensure the safe installation and operation of buried pipes. Historically, fill cover tables are provided by INDOT, but the methodology for calculating these covers is not well documented. The finite element method enables a comprehensive analysis of the soil-pipe system taking into account soil conditions, pipe type and geometry, and conditions on the pipe-soil interface.

This thesis discusses the calculation of maximum fill covers for corrugated and structural plate pipe-arches using the finite element software CANDE and compares the results with previous estimates provided by INDOT. The CANDE software uses the Finite Element Method, and the Load and Resistance Factored design based on a two-dimensional culvert installation in a soil-pipe model. The model is set up under plain strain conditions and is subjected to factored dead and live load, and provides an analysis of the structure based on safety measures against all factored failure modes associated with the structural material.

Significant issues were encountered when calculating the maximum fill covers for pipe-arches in CANDE, including the inability of standard CANDE (Level 2 mesh) to model pipe-arches, lack of convergence for nonlinear analysis, and fill cover results higher than expected. To solve these issues, the pipe-arches were modeled using Level 3 solution in CANDE. The CANDE analyses were run using small-deformation analysis after buckling was eliminated as a governing failure mode using parallel simulations in Abaqus. Numerical results were compared to analytical solutions following ASTM standards.

The results showed that CANDE and INDOT calculations differ significantly, with the CANDE results yielding higher fill covers than those provided in INDOT specifications. These differences are attributed to the assumed loading pattern at failure. While the CANDE results assume that the maximum fill cover height is defined by the failure of the pipe considering the radial pressure (Pv), the INDOT results are consistent with results obtained by limiting the bearing capacity of the soil around the corner radius (Pc).

1. INTRODUCTION

The nation's underground infrastructure is a 35-million-mile labyrinth of pipes, cables, and conduits used to transport electricity, drinking water, wastewater, natural gas, and drainage. Corrugated Metal Pipe-Aches and Structural Plate Metal Pipe-Arches (an example is shown in Figure 1.1) have been successfully used in the infrastructure for more than 100 years. Their wide range of shapes and sizes, mechanical and geometrical properties that can handle fill heights over 50 ft, service life over 100 years, cost-effectiveness, and recyclability, are proof of the versatility, structural strength, and durability of these pipes.

Corrugated and Structural Plate Pipe-Arches are used in a variety of applications, from drainage applications as sewers (as shown in Figure 1.2), to non-drainage applications such as underpasses for pedestrians and animals (as shown in Figure 1.3). However, they are mostly used where headroom is limited, for improving hydraulic capacity at low flows, due to their aesthetic shape and appearance, and lightweight construction [1].

This project was initiated as a request from the Indiana Department of Transportation (INDOT) to verify the maximum pipe fill covers to ensure the safe installation and operation of buried pipes. This thesis discusses the calculation of maximum fill covers for corrugated and structural plate pipe-arches for different pipe spans and corrugation profiles using the Finite Element Method in the software CANDE (Culvert Analysis and Design) and compares the results with previous results obtained by INDOT.

Minimum and maximum cover height limits are placed on buried pipes to ensure the safety of the pipe during installation and throughout its service life, respectively. Minimum fill heights are determined to ensure a minimum level of confinement for the pipe and a sufficient distance for the transmission of high-stress concentration caused by vehicular point loads during construction. Maximum fill covers represent the maximum soil height that can be placed on a pipe for an embankment of trench installation. This thesis will focus on maximum cover calculations, while minimum fill covers will be assumed to follow INDOT specifications (2 feet).

The two-dimensional combined soil-pipe model shown in Figure 1.4 is used for analyzing the behavior of the pipe under dead and live loading, and with appropriate boundary conditions. Half of the model is used due to symmetry. The parameters needed for the calculations include the pipe type, soil type, soil-pipe interface, and their properties, in addition to live and dead loads, analysis methodology, and design criteria.

Standard sizes and corrugations profiles for the Corrugated and Structural Plate Pipe-Arches discussed in this thesis are summarized in Table 1.1. The soil type used is gravelly sand, with 90% compaction (SW90). The analysis was carried out using the Finite Element Method (FEM) in the software CANDE (Culvert Analysis and Design) with a small deformation analysis and embankment installation, and criteria determined by the Load and Resistance Factor Design (LRFD) method. Careful consideration is required when selecting these parameters as each parameter can lead to a significant change in the fill heights.

Katona et al. [2] developed the software CANDE, and were pioneers in applying FEM to buried pipes problems. CANDE is a free software produced for the structural analysis and design of buried culverts with different shapes, sizes, and materials. The finite element formulation is static and displacement-based, with incremental model buildup representing the embankment installation phases during construction. Plain strain quadrilateral elements, beam elements, and interface elements are used to represent the soil, pipe, and soil-pipe interface, respectively, assuming plain strain conditions.

CANDE's output provides an evaluation of the structural design based on safety measures against all failure modes associated with the structural material, as determined by the LRFD method. The LRFD method provides resistance factors for four strength design criteria: wall area yielding due to thrust stress, global buckling, seam strength, and plastic penetration; and one limit criterion: allowable deflection. The factored capacities need to be higher or equal than the corresponding factored demands for all the strength design criteria.

Significant issues were encountered when modeling pipe-arches. These issues include the inability of standard CANDE (level 2 mesh solution) to model pipe-arches (e.g., generating the mesh for arch shapes and discretizing the model), and lack of convergence for nonlinear analysis that leads to performing small deformation analyses. To ensure that the buckling failure limit is adequately taken into account, calculated fill cover heights were used to perform buckling failure analysis using the finite element software, Abaqus. Results in CANDE showed that, fill cover results were higher than expected. Load and resistant Factor Design (LRFD) calculations based on ASTM standard practices were performed for comparison, to determine the governing assumptions and load patterns. Fill covers were calculated for a total of 624 pipe-arches. The Abaqus buckling analyses and ASTM calculations were performed by fellow students Chatuphat Saviganim and Devansh Gandhi, respectively.

The outline of the thesis is as follows: All the geometrical and mechanical inputs for the pipe and soil, resistance factors, load factors, and general information about the CANDE software and the Finite Element Method can be found in Chapter 2. Chapter 3 discusses the assumptions made for the analysis and the justification behind those assumptions, as well as some of the challenges that were encountered in the project and the proposed solutions. Chapter 4 contains the calculated maximum fill heights, and compares the finite element results with the existing INDOT fill heights as well as with the results obtained using ASTM standards for pipe-arches, and those obtained through the buckling failure mode analysis in Abaqus. Conclusions are discussed in Chapter 5.

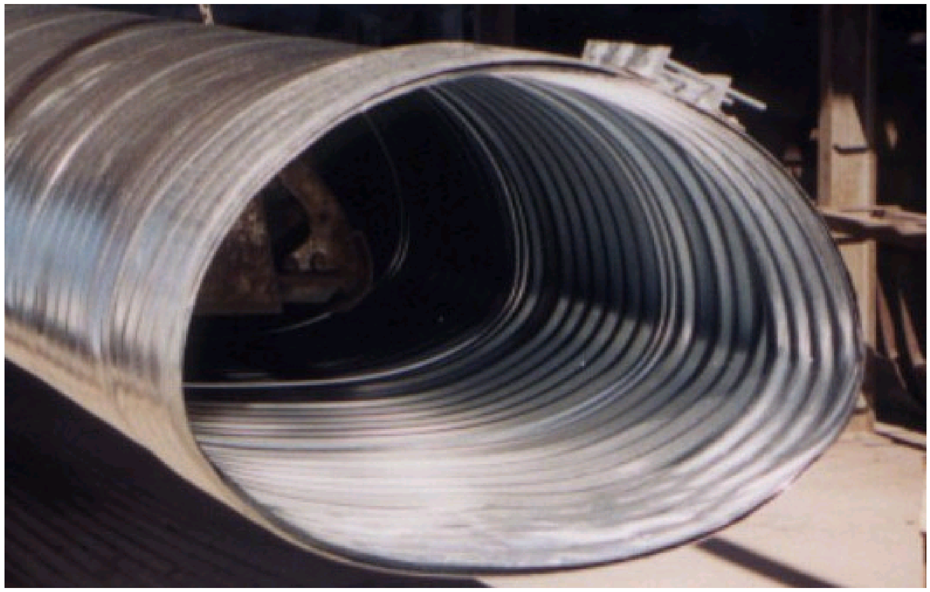


Fig. 1.1. Pipe-Arch [1].

Fig. 1.2. Pedestrian Underpass [1].

Fig. 1.3. Relining of a failed concrete box with corrugated steel pipe-arch [1].

Table 1.1.
Sizes, corrugation profiles and thicknesses evaluated for corrugated and structural plate pipes.

Type of Pipe	**Span**	**Corrugation Profile (in)**	**Thickness Range (in)**
Corrugated Steel Pipe-Arch (CSPA)	17 in - 83 in	$2\,{}^{2}/_{3} \times {}^{1}/_{2}$	0.064 - 0.168
	60 in - 142 in	3×1	0.079 - 0.168
	60 in - 142 in	5×1	0.109 - 0.168
Corrugated Aluminum Pipe-Arch (CAPA)	17 in - 71 in	$2\,{}^{2}/_{3} \times {}^{1}/_{2}$	0.060 - 0.164
	60 in - 112 in	3×1	0.075 - 0.164
Structural Plate Steel Pipe-Arch (SPSPA)	6 ft - 20 ft	6×2	0.111, 0.140 and 0.280
Structural Plate Aluminum Pipe-Arch (SPAPA)	6 ft - 21 ft	$9 \times 2{}^{1}/_{2}$	0.100 - 0.250

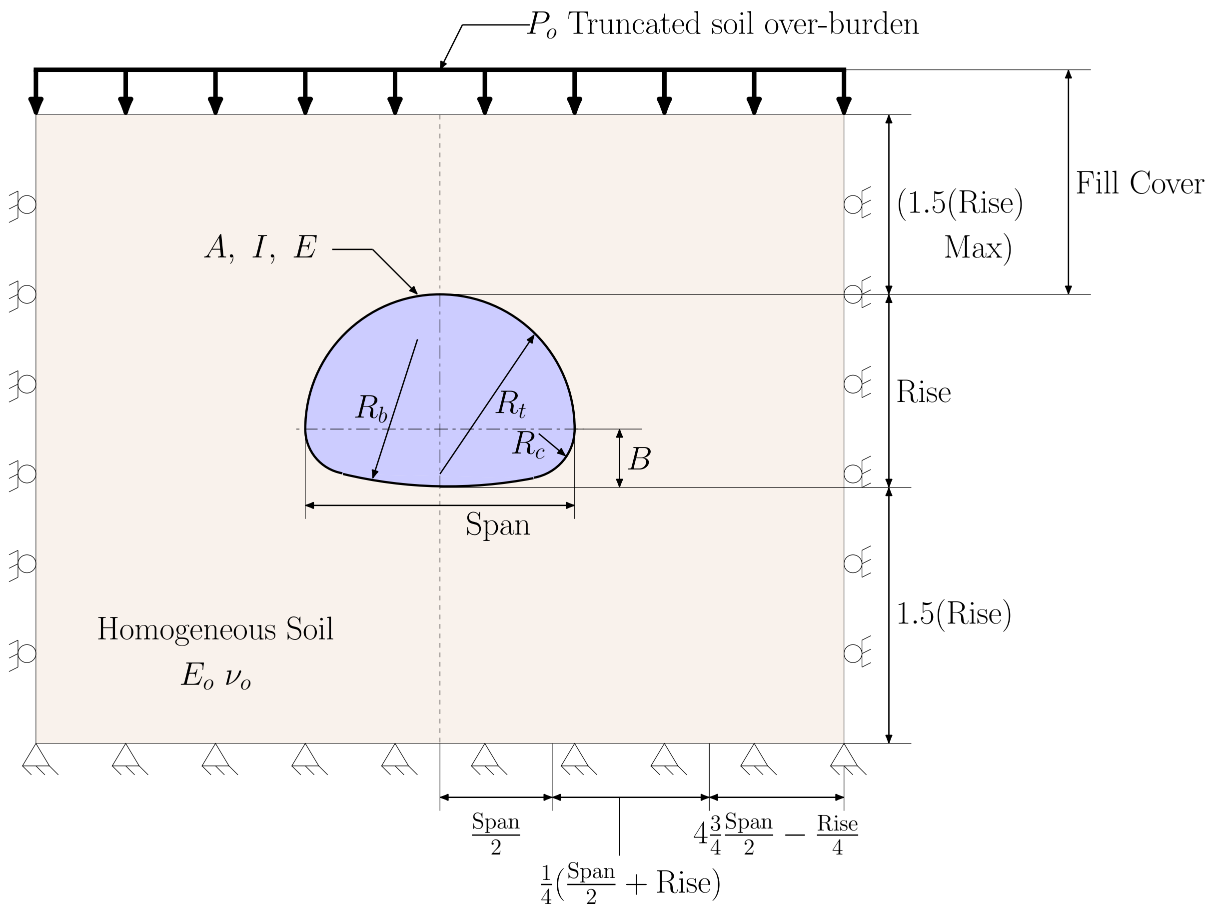


Fig. 1.4. Conceptual soil-structure model with finite boundaries

2. BACKGROUND

This chapter provides an overview of the terms and definitions used in this thesis. Types and materials for the pipe and soil are summarized, and a general overview of the methods and software tools used for the analysis is presented. Also, standard practices for the structural design of buried pipes are detailed. Culverts custom sizes and layout dimensions were extracted from The Modern Sewer Design [3], while corrugation profiles, wall properties, and mechanical properties were obtained from CANDE-2015 User Manual and Guideline [4].

2.1 Pipe-Arches Data

This thesis focuses on Corrugated Steel and Aluminum Pipe-Arches, and Structural Plate Steel and Aluminum Pipe-Arches. In this section, the geometrical and mechanical properties needed for describing this types of pipes are illustrated. The words culvert or pipe will be used to represent a buried pipe structure.

Corrugated Pipe-Arches and Structural Plate Pipe-Arches can be found in a variety of sizes and corrugation profiles that satisfy most requirements in buried systems. They are an economical and reliable choice that provides optimal strength and durability. Corrugated pipes can be helical or annular, depending on if the corrugations and seams run helically or annularly around the pipe respectively. Pipes with helical corrugation can be fabricated with a lock seam method, continuous welding of the seams or attaching a helically corrugated sheet at the lock seam. Annular corrugated pipes are fabricated by riveting, bolting or spot welding the seams. This thesis analyzes corrugated pipes with lock seam or riveted fabrications. Structural plate pipes are used for larger structures requiring field assembly. This type of pipe is manufactured by hot dipping galvanized plates and assembled by bolting plates together. [3]

The mechanical properties of steel and aluminum were selected based on the Culvert Analysis and Design (CANDE) user manual [4], and are summarized in Table 2.1. Table 2.2 summarized the properties for longitudinal seam strength of corrugated pipes.

Table 2.1.
Mechanical properties of steel and aluminum.

Mechanical Properties	**Steel**	**Aluminum**
Young's Modulus (psi)	29,000,000	10,000,000
Yield Stress (psi)	33,000	24,000
Yield Stress of Pipe Seam (psi)	-	24,000
Poisson's Ratio	0.3	0.33
Density (pci)	0.284	0.0975

The geometry of a pipe-arch is defined by its span (S) and rise (R), and by its radii, top radius (R_t), bottom radius (R_b) and corner radius (R_c). Dimension B describes the vertical distance between the measured center for R_c and the bottom of the pipe. The geometrical representation of pipe-arches is shown in Figure 2.1.

A corrugated profile is defined by its thickness (T), pitch, depth, tangent length (TL) and tangent angle (Δ,°), as shown in Figure 2.2. For performing the required analysis, the section properties (cross sectional area (PA), moment of inertia (PI) and section modulus (PS)) should be calculated using the previous dimensions.

The geometrical properties can be found in the appendix. Section A.0.1 lists the sizes, layout and corrugation details for Corrugated Steel and Aluminum Pipe-Arches. Similar details are given in, Section A.0.2 for Structural Plate Steel Pipe-Arches and in Section A.0.3 for Structural Plate Aluminum Pipe-Arches.

Table 2.2.
Ultimate longitudinal seam strength of corrugated pipes.

Corrugation Profile (in)	**Steel**	
	3 x 1	**5 x 1**
Thickness (in)	**Seam Strength Double (lb/ft)**	**Seam Strength Double (lb/ft)**
0.064	28700	28700
0.079	35700	35700
0.109	53000	53000
0.138	63700	63700
0.168	70700	70700
Corrugation Profile (in)	**Aluminum**	
	2 2/3 x 1/2	**3 x 1**
Thickness (in)	**Seam Strength Double (lb/ft)**	**Seam Strength Double (lb/ft)**
0.060	14000	16500
0.075	18000	20500
0.105	31500	28000
0.135	33000	42000
0.164	34000	54500

2.2 Soil Data

The Duncan-Selig model is used for modeling the behavior of the soil, assuming that the soil properties can be represented using a hyperbolic function. The parameters of the model can be found in Table 2.3 and were obtained from the CANDE manual [4]. In this table, K is the dimensionless magnitude of initial Young's modulus, n is the power-law coefficient for initial modulus (these last two parameters are nondimensionalized using the atmospheric pressure, P_a), C is the cohesion intercept for failure, ϕ_0 is the initial soil friction angle of failure surface, $\Delta\varphi$ is the reduction of soil friction angle for 10-fold increase in the minimum compressive principal stress (σ_3), R_f is the failure ratio, defined to be the ratio of actual to model failure stress,

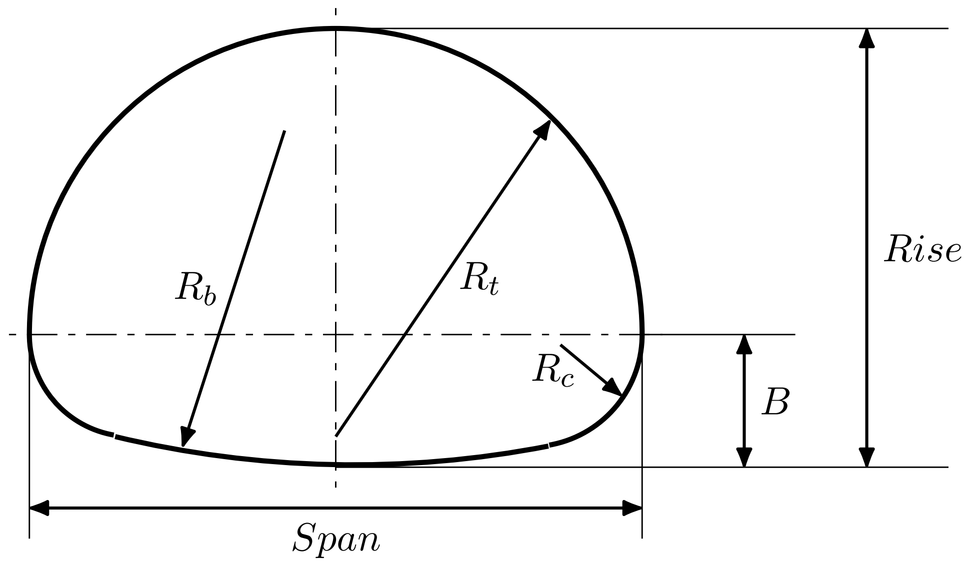


Fig. 2.1. Geometrical representation of pipe-arches.

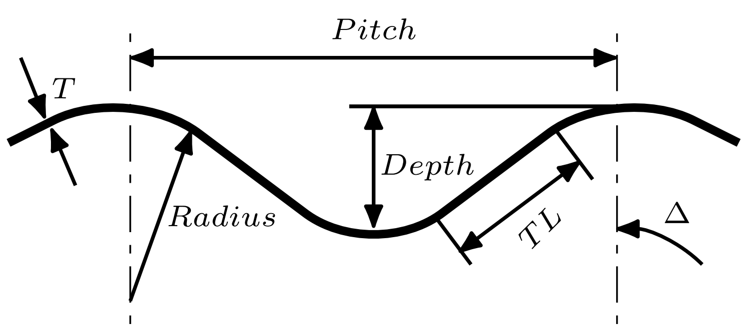


Fig. 2.2. Geometrical representation of the corrugation profiles.

B_i/P_a is the ratio of initial tangent Bulk modulus to the atmospheric pressure and ε_u is the ultimate volumetric strain at large hydrostatic stress. Further explanation of the model is shown in Section 3.3. The type of soil used for the analysis is gravelly sand with 90% of relative compaction (SW90) with embankment installation.

Table 2.3.
Soil Parameters for the Duncan-Selig Model with gravelly sand of 90% compaction. [4]

Soil	Stiffness and Strength						Bulk Modulus		Density
Type	K	n	C (psi)	ϕ_0 (deg)	$\Delta\varphi$ (deg)	R_F	B_i/P_a	ε_u	(lb/ft^3)
SW90	640	0.43	0	42	4	0.75	40.8	0.05	140

2.3 Finite Element Analysis

Modeling a continuum media with numerical methods, such as Finite Elements, has been a problem of interest for many years. A continuum is characterized for its infinitesimal subdivision that only can be solved by mathematical manipulations. Finding an exact solution for the differential equations that represent the continuum is complicated, since the mathematical techniques currently available are limited for oversimplified conditions, and finding a closed-form solution of the partial differential equations governing continuum media is a challenging task. Numerical approaches, such as the finite element method (FEM), seek to find an approximate solution by discretizing the continuum into smaller domains, therefore creating a numerical discretization or mesh in FEM, in which a unique solution for the boundary value problem can be found under specific conditions and in the limit of mesh refinement [5].

Although it is difficult to determine the precise beginning of the FEM, the earliest work that uses the finite element terminology appears to be Clough [6]. The present-day FEM was brought together from the development of variational finite differences [7], piecewise continuous trial functions [8], and direct continuum elements [9]. A detailed process of evolution for the FEM can be found in [5].

The structure of the FEM starts with the definition of a variation method for the mathematical description of the behaviour of the system (Galerkin approximation), continuing with the discretization of the geometry, a process that involves the generation of a finite element mesh, the definition of shape functions that approximate the geometry and deformation fields within each element, and ending with the solution algorithms and post-processing of the data for extraction of the solution and error estimates [10].

The CANDE software uses a static and displacement-based FEM for evaluating the soil-structure interaction problem of underground pipes, with an incremental virtual work approach that mimics the actual build-up of the soil-structure system using the embankment installation. The embankment installation is the physical process of construction by placing and compacting soil layers. This process involves incremental solutions using successive finite element configurations, where each new configuration contains additional soil elements. Material history is accrued during the build-up process to simulate construction conditions in the field. Figure 2.3 shows the schematic of a standard mesh in CANDE, where the different grey shades represent the soil layers and the number inside the element is the construction increment. Further information about the FEM code in CANDE is presented in Section 3.2.

2.4 Standard Practices for the Structural Design of Corrugated Pipes

Standard procedures for the structural design of pipes are based on either the allowable stress design (ASD) or the load and resistance factor design (LRFD), with trench or embankment installation, subjected to earth and live loads. These standards, are provided by ASTM A796/A796M, "Standard Practice for Structural Design of Corrugated Steel Pipe, Pipe-Arches, and Arches for Storm and Sanitary Sewers and Other Buried Applications" for steel [11], and ASTM B790/B790M, "Standard Practice for Structural Design of Corrugated Aluminum Pipe, Pipe-Arches, and Arches for Culverts, Storm Sewers, and Other Buried Conduits" for Aluminum [12]. This practices apply for structures installed according to practice ASTM A798/A798M, "Practice for Installing Factory Made Corrugated Steel Pipe for Sewers and Other Applications" [13] and ASTM A807/A807M, "Practice for Installing Corrugated Steel

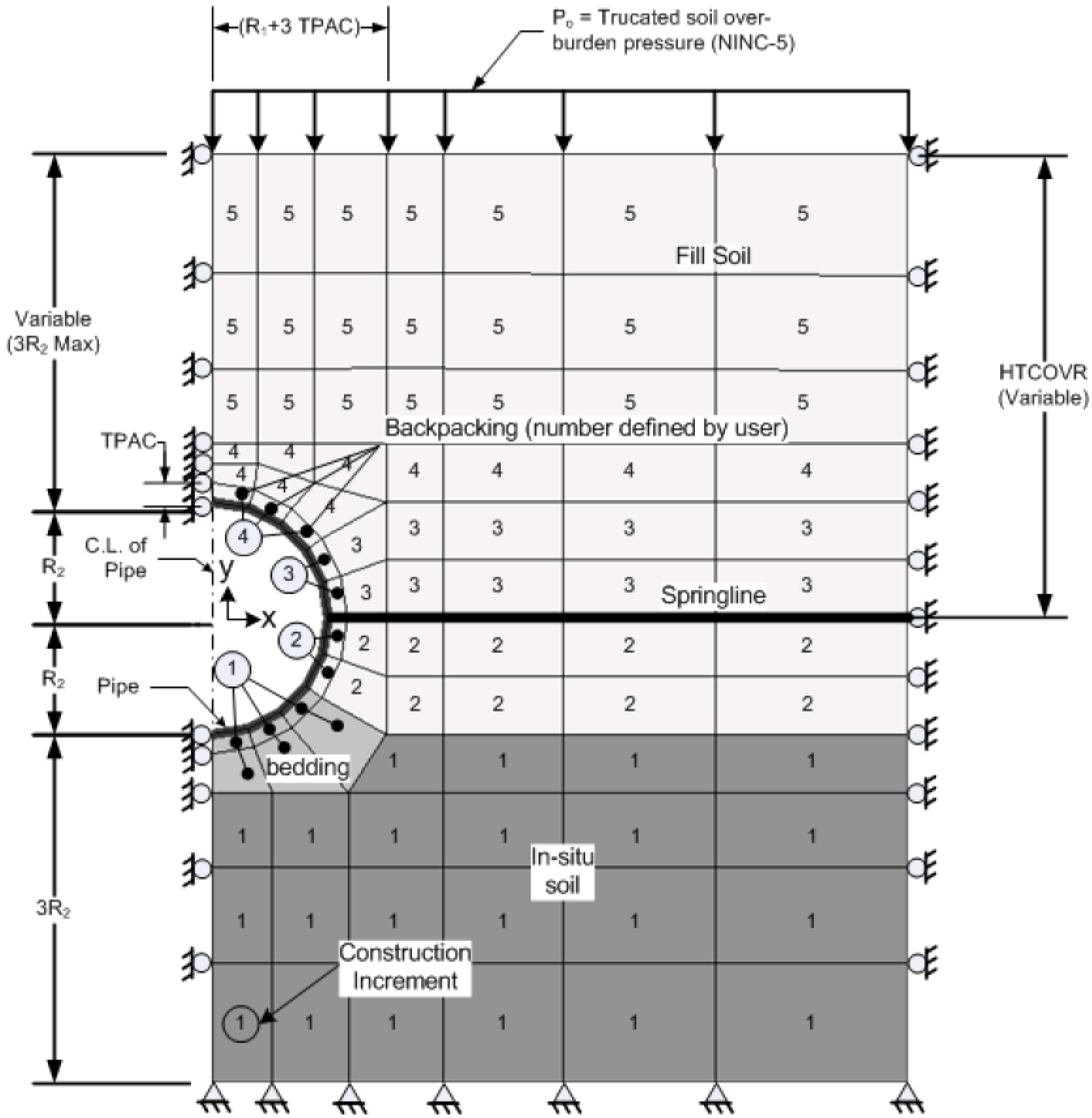


Fig. 2.3. Representation of FE Level 2 mesh (standard) in CANDE with construction increments for the embankment installation [4].

Structural Plate Pipe for Sewers and Other Applications” [14] for steel, and ASTM B788/B788M, ”Practice for Installing Factory Made Corrugated Aluminum Culverts and Storm Sewer Pipe” [15] and ASTM B789/B789M, ”Practice for Installing Corrugated Aluminum Structural Plate Pipe for Culverts and Sewers” [16] for aluminum. These standard practices provide the design considerations for determining the strength requirements for wall strength, buckling strength and seam strength. The formulations include the weight of the entire prism of soil over the pipe, flexibility factors for trench and embankment installation and details about acceptable soil types [3]. For this thesis we considered the embankment installation and the LRFD design methodology.

2.5 CANDE Software

CANDE is a public software developed for the structural analysis and design of buried culverts with different shapes, sizes and materials, including corrugated metal, reinforced concrete and thermoplastic materials. The software uses FEM based on a two dimensional culvert installation with a soil-structure model subjected to dead weight, incremental loading due to the addition of soil layers, temporary construction loads and surface loads due to vehicular traffic. CANDE’s output provide an evaluation of the structural design based on safety measures against all failure modes associated with the structural material. Under the sponsorship of the Federal Highway Administration (FHWA) the software was released in 1976 and updated in 1980 and 1989. Sponsored by AASHTO, CANDE-2007 and CANDE-2011 were released. The last update of the software was in 2019, maintained by Michael G Katona. CANDE is very popular among state Department of Transportation (DOT’s), it also has a variety of users ranging from designers to researchers. Figure 2.4 shows the overall organization of CANDE software, top-level selection and various choices for each top-level category. Those include an execution mode choice (Analysis or Design), a solution level choice (Level 1, 2 or 3, where Level 1 is a elasticity solution based

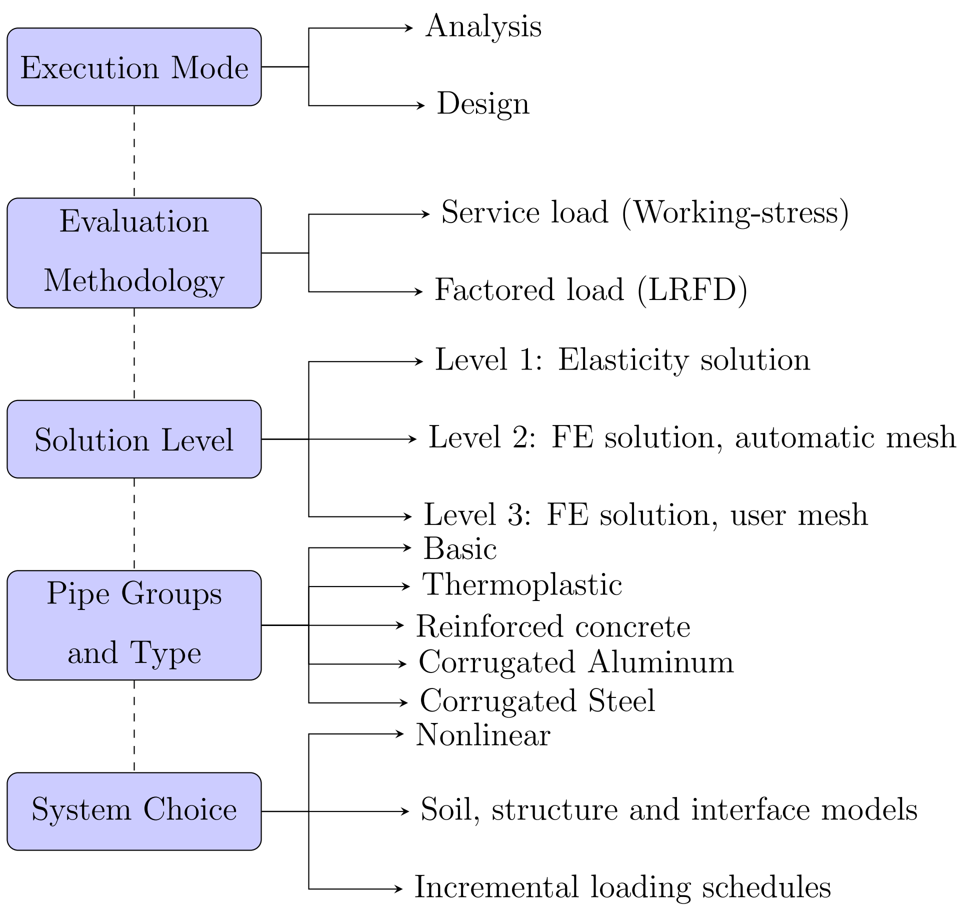


Fig. 2.4. Major options for defining the top-level input data for CANDE [4].

on Burns and Richard [17], Level 2 is a finite element solution with an automated mesh for circular culverts, and Level 3 is a finite element solution with a user defined mesh), pipe type choice (corrugated steel or aluminum, reinforced concrete, plastic or basic), soil model choice (linear elastic, overburden dependent, and nonlinear hyperbolic model), and interface choice (bonded, frictionless, or friction at soil-structure interface). [4]

2.6 Design Criteria and Load Factors

CANDE uses the LRFD methodology, based on the AASHTO LRFD Bridge Design Specifications [18]. The strength limit states, include the yield strength, ultimate strain, or global buckling capacity of the soil-structure system. For this limit states, the LRFD method assigns net multiplying factors to the service loads. For the resulting structural response to be satisfactory, the factored capacities need to be greater or equal than the corresponding factored demands for all the strength-state design criteria.

AASHTO LRFD has specific design criteria for different materials. Corrugated metal pipes have four design criteria and one performance limit criterion. The design criteria for corrugated metal pipes are: 1) Thrust stress; 2) Global Buckling; 3) Seam strength; and 4) Plastic Penetration (considered as 0.9 for steel pipes and 0.85 for aluminum pipes). The performance limit criterion is the allowable deflection considered as 5% for all pipe types. The resistance factor for each of these design criteria is also incorporated in CANDE, and is based on the AASHTO LRFD specifications, Table 2.4 shows the resistance factors applied to the strength values. Once a given analysis is completed in CANDE, the user needs to check that, for each of the design criteria, the factored capacities are greater or equal than the corresponding factored demands (an evaluation ratio should be less than 1.0 for the design criterion to be considered safe) and that the performance limit criteria are met (e.g. the maximum deflection is below 5%). Table 2.5 lists the load factors for buried structures according to AASHTO LRFD specifications [18], as stated in the CANDE user manual [4]. Where, γ_{max} is the maximum standard load factor, γ_{min} is the minimum standard load factor, η_{DC} is the composite load modifier for DC, and η_{EB} is the composite load modifier for EB.

Table 2.4.
Resistance Factors (φ) used in the Analysis. [4] [11] [12]

Type of Pipe	**Limit State**	**Resistance Factor**
CSPA and CAPA Lock Seam	Thrust Stress	1
	Global Buckling	1
	Seam Strength	1
CSPA and CAPA Riveted	Thrust Stress	1
	Global Buckling	1
	Seam Strength	0.67
SPSPA and SPAPA	Thrust Stress	1
	Global Buckling	1
	Seam Strength	0.67

Table 2.5.
Load Factors and Modifiers Used in the Analysis. [4]

Culvert Type	**Dead Load Culvert DC**			**Earth fill Loading EB**			**Live Load LL**	
	γ_{max}	γ_{min}	η_{DC}	γ_{max}	γ_{min}	η_{EB}	γ_{max}	η_{LL}
Corrugated metal arch	1.25	0.9	1.05	1.95	0.9	1.05	1.75	1

3. METHODOLOGY

3.1 Solution Technique

As was discussed in Section 2.5 -Figure 2.4- the methodology in CANDE requires selecting the type of analysis wanted for each top-level feature. Top-level options include execution mode, evaluation methodology, solution level, pipe types, and system choices. In this section, we will discuss the options used for evaluating the performance of buried pipe-arches under loading conditions.

3.1.1 Execution Mode

The Execution Mode top-level has the option of choosing between Design or Analysis. The design mode implies that CANDE will arrive to a design solution for the culverts cross-sectional properties based on the desire safety factors, pipe shape, materials, and loading conditions.

For this project, the **analysis** mode is selected, since the main goal is assessing the safe performance of a specific corrugated pipe-arch for all failure modes prescribed by LRFD corresponding with the shape of the pipe and structural material. The pipe and soil are defined in terms of geometry (shape and cross-sectional properties), material properties and loading conditions, and the mesh is created by CANDE (Level 2) or through a custom user-defined procedure (Level 3), depending on solution level.

3.1.2 Evaluation Methodology

The CANDE software allows the user to select a service (working-stress) or factored (LRFD) load design method. The **LRFD** design method is used for the evaluation of the culverts performance. The solution is provided in terms of ratios of factored demand-to-factored capacities for each design criterion related to the pipe type. For this solution, the user must assign load factors for every load step depending on the type of load being applied (dead loads, earth loads, and live loads) as required by AASHTO LRFD specifications.

3.1.3 Solution Level

The Level 2 mesh in CANDE is an option with an automatic generation of the finite element mesh, i.e, the numbering and coordinates of the nodes, and connectivity of elements. This solution level can be used with three different shapes of pipes, round or elliptical, rectangular and arches culverts, by using the pipe-mesh, box-mesh or arch-mesh options respectively. The input parameters include, pipe dimensions, embankment or trench installation type, bedding dimensions, height of soil cover, and the number of incremental construction layers. For performing an analysis on a common shape culvert, this is usually the most convenient option [4].

Since the main focus of this work is on pipe-arches, the Level 2 arch-mesh options was first considered. However, performing the analysis with Level 2 mesh option encountered severe limitations, including:

- The standard CANDE capabilities, do not allow for the geometric properties of pipe-arches (arc radii R_c, R_b and R_t, B, span and rise, described in Figure 2.1) to be provided as input for Level 2 solution.
- Since CANDE uses built-in models for default geometric shapes, the pipe-arches listed in Table 1.1 do not fall strictly within these default models, and therefore simulation results for pipe-arch models created by modifying the regular pipe-mesh in CANDE, may not be accurate.
- Furthermore, the software's inability to accommodate mesh refinement raised concerns about the accuracy of the results, especially for maximum fill covers with flexible pipes.

The majority of the problems were solved by using the **Level 3** solution instead of Level 2. Level 3 uses a user defined mesh with the same finite element solution methodology as Level 2. With Level 3, one can model unlimited structural shapes, soil systems and loading conditions. The process for creating and running the model, includes the discretization of the mesh using another FEM software (Abaqus), then a custom-made software created in Matlab is used to have the Abaqus output in a format that can be read by CANDE, and finally the CANDE code created using Level 3 solution is run. Detailed information of the process used is described in Section 3.4.

3.1.4 Pipe Types

Corrugated Aluminum or **Corrugated steel** pipe-type is selected, along with the material properties and wall properties (cross-sectional area, moment of inertia and section modulus), listed in the CANDE manual [4] for a linear material and commercial corrugation sizes. With this input information the initial stiffness of the overall pipe is computed, then the pipe element stiffness properties are modified during nonlinear iterations, and the design criteria are evaluated at the end of each converged load step. Aluminum or steel material behavior is simulated in CANDE with a bilinear stress-strain model, initially elastic until yield stress followed by the plastic response (identical in tension and compression) and the unloading is assumed to be linear elastic" [4]. The design criteria for metal pipes include thrust stress, global buckling and seam strength, and a performance limit on the allowable defection.

3.1.5 System Choices

From the different soil models offered by CANDE, the hyperbolic **Duncan Selig** model is selected. This model is available in the software with predefined parameters that characterize sands, clays, silts, and crushed rock for a range of compaction conditions. The user also may define the interface conditions (bonded or friction) between the pipe and the soil. A **friction interface** with coefficient of friction of 0.5 and tensile force of 10lb/in is selected for the analysis.

Furthermore, one can choose to run a Small Deformations or a Large Deformations analysis. The large deformation analysis allows evaluating large and flexible pipes under heavy load. Additionally, it predicts the global buckling capacity of the soil-structure system. When using the Large Deformation feature in CANDE, however severe convergence problems were encountered, and fill heights for a large number of pipes could not be obtained. After consultation with the project sponsors, it was decided to obtain the fill heights using **Small Deformation** analysis. This analysis option provides estimates for buckling capacity, but it was not clear from the CANDE manual how these estimates were computed. To ensure that buckling was not the cause of failure and that it was reasonably well captured in CANDE, selected cases were verified separately for buckling capacity through large deformation analysis using Abaqus. Further explanation of the Abaqus analysis is shown in Section 3.5.

Moreover, fill heights were checked against analytical solutions for all the cases following analytical solutions provided by ASTM A796/A796M [9] for steel and ASTM B790/B790M [10] for aluminum. Additional explanation is shown in Section 3.6.

3.2 Finite Element code CANDE

The FEM formulation described in CANDE Solution Methods and Formulations [19] is a displacement-based static formulation, based on incremental virtual work. This method allows the load to be applied in a sequence of steps representing increments of overburden pressure and the culvert structure to be assembled. The incremental virtual work is expressed in Equation 3.1, where the increment of internal virtual strain energy is equal to the increment of external virtual work of body and traction loads when the system is subjected to a virtual displacement. Using the incremental stress-strain equation ($\Delta\sigma = \underline{C}\Delta\varepsilon$), and writing strains in terms of displacement ($\Delta\varepsilon = \Delta\underline{Q}(u) = \underline{Q}(\Delta u)$), the virtual work equation can be expressed in terms of the global displacements as follows:

$$\int_V \underline{Q}(\delta u)^T \underline{C}\underline{Q}(\Delta u) dV = \int_S \delta u^T \Delta\tau dS + \int_V \delta u^T \Delta f dV \tag{3.1}$$

In this equation σ is the stress vector, ε is the strain vector, u is the displacement vector, τ is the surface-traction vector, f the body-force vector, S is the surface area of traction loads at load step $i+1$, V is the volume of structural system at at load step $i+1$, $\underline{C}$ is the constitutive function, and $\underline{Q}$ is the operator matrix composed of partial derivatives. The last two components, $\underline{C}$ and $\underline{Q}$, depend on the element type, material behaviour and the kinematic assumptions.

CANDE employs quadrilateral solid elements for representing the soil, while interface elements are used for the contact between the culvert and the soil and the culvert structure is discretized by beam elements. The quadrilateral element consists of a four-node quadrilateral with a 8×8 stiffness matrix, where each node has two degrees of freedom for horizontal and vertical displacements. The interface element allows the parts connected to slip relative to each other and is composed of three nodes with coordinates that share a common contact point, one associated to the soil, the other one to the pipe, the third node carries the normal and tangential interface forces; two nodes have two degrees of freedom for horizontal and vertical displacements, producing a 6×6 stiffness matrix, the third node has 2 interface forces. The beam element is defined by two nodes and three degrees of freedom per node, rotation, horizontal and vertical displacements, bending and axial deformation are approximated by a cubic and linear interpolation respectively. Figure 3.1 illustrates these elements.

The equilibrium Equation 3.2 must be satisfied at every load step, is composed of a set of linear algebraic equations that are solved for $\Delta\hat{u}_G$ in CANDE by the computational method Gauss Elimination.

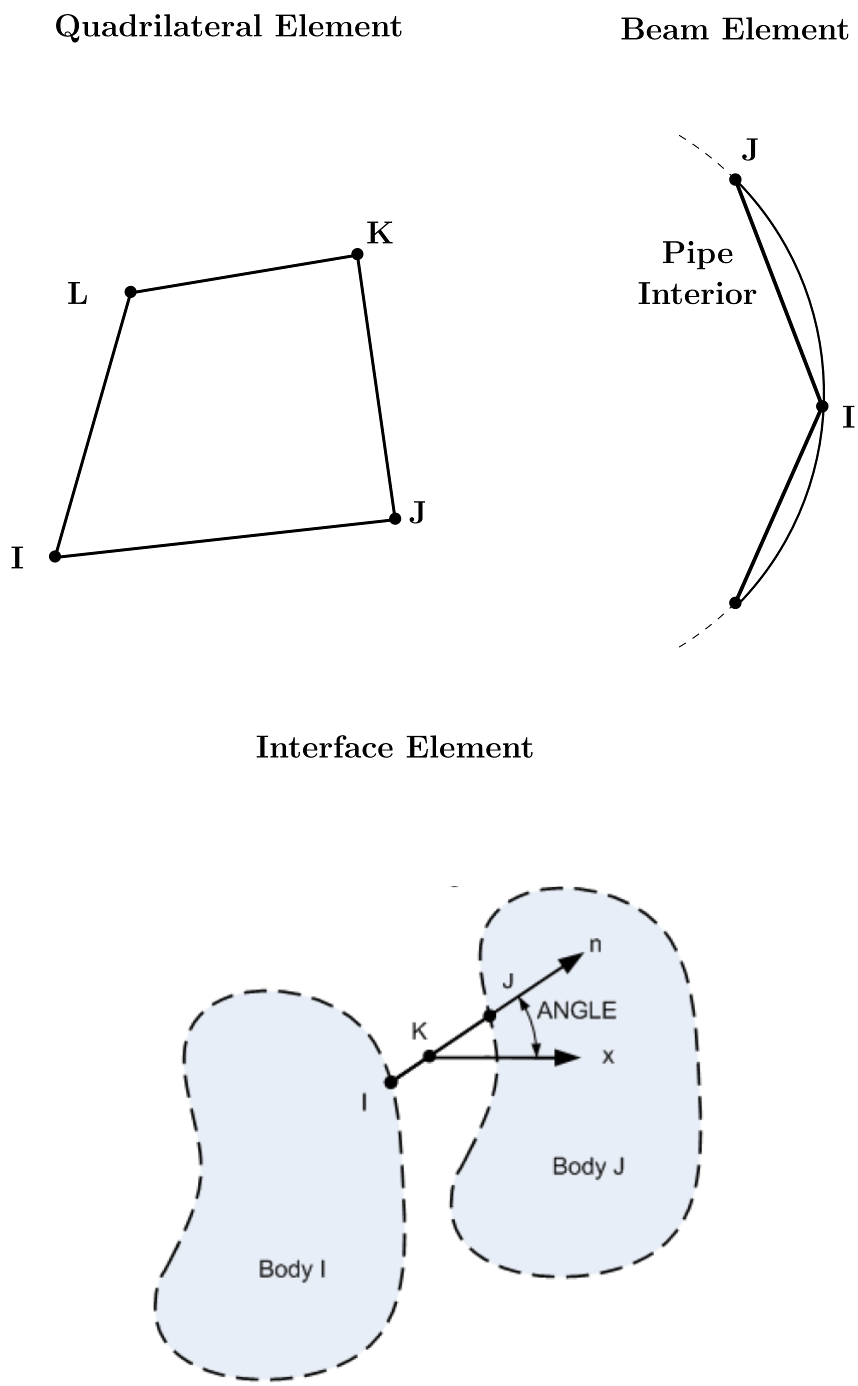


Fig. 3.1. CANDE Elements with nodal connectivity for Quadrilateral, beam and Interface elements. [4]

$$\underline{K}_G \Delta \hat{u}_G = \Delta P_G \tag{3.2}$$

Where $\underline{K}_G$ is the incremental global stiffness matrix, ΔP_G is the incremental global load vector and $\Delta \hat{u}_G$ is the increment of global displacement vector.

3.3 Duncan/Selig Soil Model

The Duncan/Selig soil model formulated in CANDE Solutions Methods and Formulations [19] is based on the elasticity formulations of Duncan [20] for the Young's modulus and Selig [21] for the Bulk modulus, both stress dependent and based on hyperbolic stress-strain relationships.

The Young's modulus formulation developed by Duncan is based on experimental observations of soil behavior from a tri-axial test. The experimental curve is approximated to the deviatoric stress $(\sigma_1 - \sigma_{3)}$ with a hyperbolic function of axial strain. The equation for the Tangent Young's modulus that represents the soil behavior is:

$$E_t = E_i \left[1 - \frac{R_F (1 - \sin\varphi)(\sigma_1 - \sigma_3)}{2(C\cos\varphi + \sigma_3 \sin\varphi)} \right]^2 \tag{3.3}$$

Where the initial Young's modulus (E_i) is in Equation 3.4, and the angle of internal friction (φ) is in Equation 3.5; σ_1 and σ_3 are the principal stresses, and P_a is the atmospheric pressure. See Table 2.3 in Section 2.2 for the material properties specific values.

$$E_i = K P_a \left(\frac{\sigma_3}{P_a} \right)^n \tag{3.4}$$

$$\varphi = \varphi_0 - \Delta\varphi \log_{10} \left(\frac{\sigma_3}{P_a} \right) \tag{3.5}$$

Selig's Tangent Bulk modulus was developed based on hydrostatic tests, where the soil specimen is compressed under increasing pressure applied equally in all directions.

A hyperbolic equation describes the experimental curve that relates the mean stress to the volumetric strain. The hyperbolic Selig form for the Tangent Bulk modulus is:

$$B_t = B_i\left[1 + \frac{\sigma_m}{B_i/\varepsilon_u}\right]^2 \tag{3.6}$$

Where σ_m is average stress, B_i is the initial Tangent Bulk modulus and ε_u is the ultimate volumetric strain. See Table 2.3 in Section 2.2 for specific values on the material properties.

The Duncan/Selig equations described before are used to define the nonlinear components of an isotropic and elasticity-based constitutive matrix for plane-strain conditions, as shown in Equation 3.7. In this Equation, the stress increments in x and y directions and shear components ($\Delta\sigma_x,\ \Delta\sigma_y,\ \Delta\tau$, respectively) are related to the strain increments in x and y directions and shear components ($\Delta\varepsilon_x,\ \Delta\varepsilon_y,\ \Delta\gamma$, respectively) by the constitutive matrix of nonlinear components dependent on the Young's and Bulk modulus ($C_{11},\ C_{12},\ C_{33}$). Equations 3.8 and 3.9 show the chord moduli for the Tangent Young's modulus (E_c) and Bulk modulus (B_c) respectively, the chord moduli forms showed in these equations define the constitutive matrix nonlinear components in average formulations, suitable for the iteration cycle. The iteration cycle consists of determining the constitutive matrix (in Equation 3.7) of a soil element, where the principal stresses from the last iteration are used to developed closer estimations of the chord moduli (average formulations of constitutive matrix components) until convergence occurs. The algorithm converges when two successive iterations have a difference of less than 1%.

$$\begin{bmatrix} \Delta\sigma_x \\ \Delta\sigma_y \\ \Delta\tau \end{bmatrix} = \begin{pmatrix} C_{11} & C_{12} & 0 \\ C_{21} & C_{11} & 0 \\ 0 & 0 & C_{33} \end{pmatrix} \begin{bmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\gamma \end{bmatrix} \tag{3.7}$$

$$E_c = (1 - r)E_{t_i} + rE_{t_{i+1}} \tag{3.8}$$

$$B_c = (1 - r)B_{t_i} + rB_{t_{i+1}} \tag{3.9}$$

where, E_{t_i} and $E_{t_{i+1}}$ is the Tangent Young's modulus at step i and i+1 respectively, B_{t_i} and $B_{t_{i+1}}$ is the Tangent Bulk modulus at step i and $i + 1$ respectively, and r is the averaging ratio (usually 0.5).

3.4 CANDE Level 3 Solution

The Level 3 mesh option requires providing a user-defined mesh for the soil-structure system. Figure 3.2 illustrates the process needed for creating the finite element mesh. First, the geometry of the model is generated and discretized in Abaqus scripting (command interface of the FEM software Abaqus). The conceptual 2D soil-structure model under boundary conditions is shown in Figure 1.4 and the conceptual mesh used with soil steps, dimension of the soil and boundary conditions is shown in Figure 3.3. Only half the domain is modeled, thanks to symmetry. To be able to obtain the mesh information (nodes coordinates and element connectivity) the file created in Abaqus scripting should now be open in Abaqus Standard (graphic interface of the FEM software Abaqus), then this input is written for obtaining the mesh data. Moreover, a subroutine created in Matlab reads the data collected from Abaqus Standard and writes this data with the commands, spaces, and parameters understood by CANDE. Input commands C-1 and C-2 define the control variables, command C-3 defines all nodal coordinates, and it should be at the beginning of every line that contains nodal coordinates information. Similarly, command C-4 is used repeatedly to describe all element properties, and finally, command C-5 defines all displacement and load boundary conditions. [4]

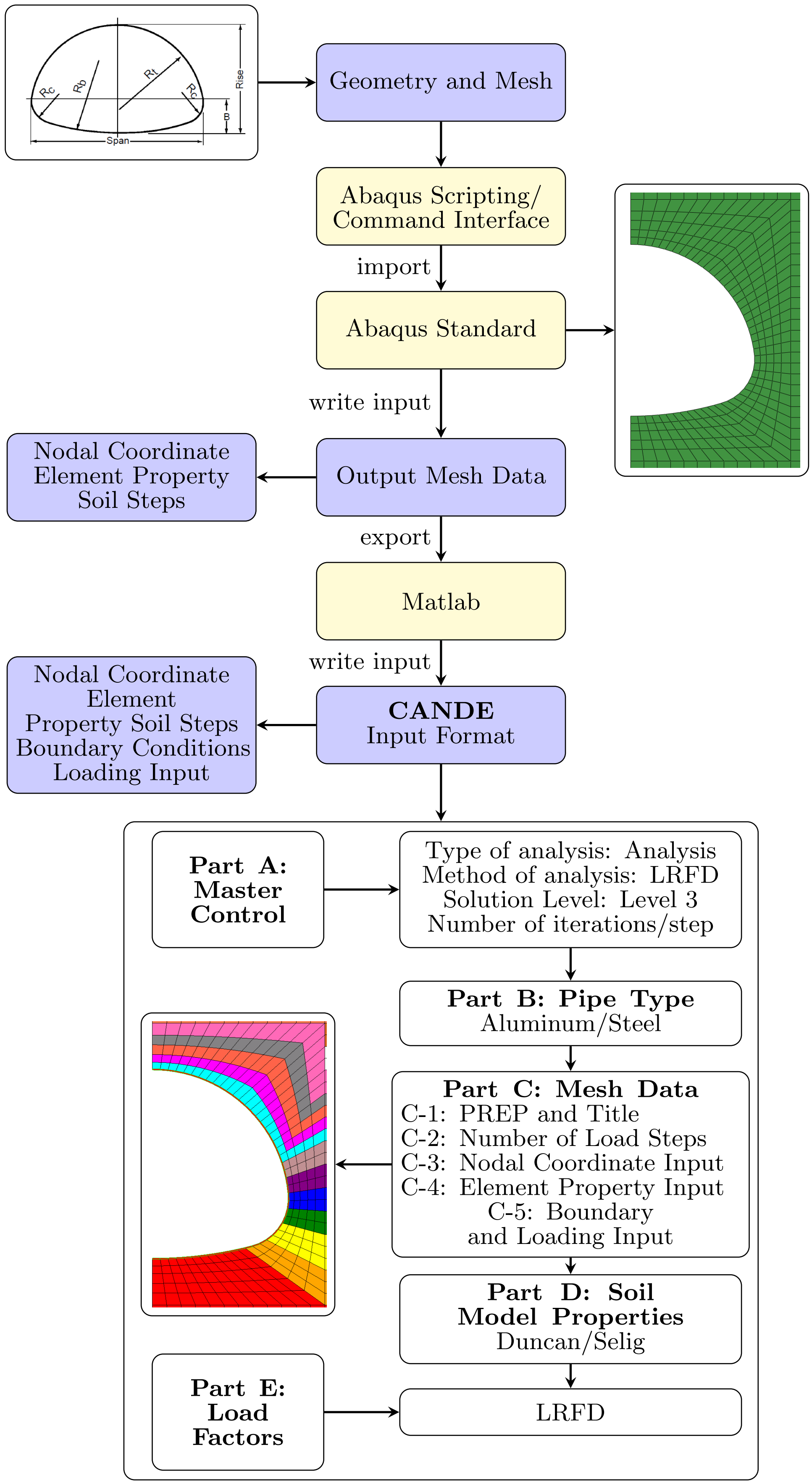


Fig. 3.2. CANDE level Three Input Data Flow Chart

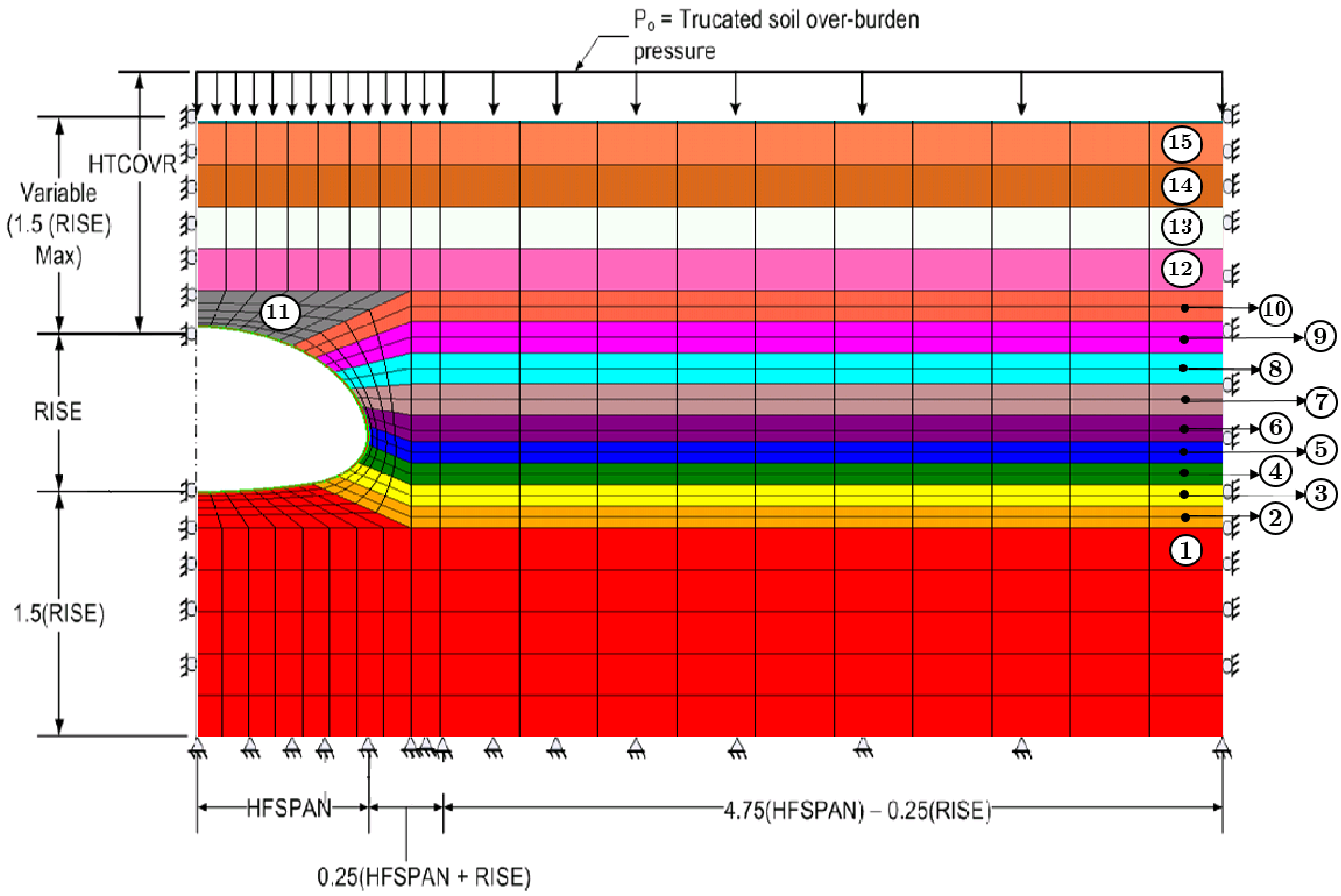
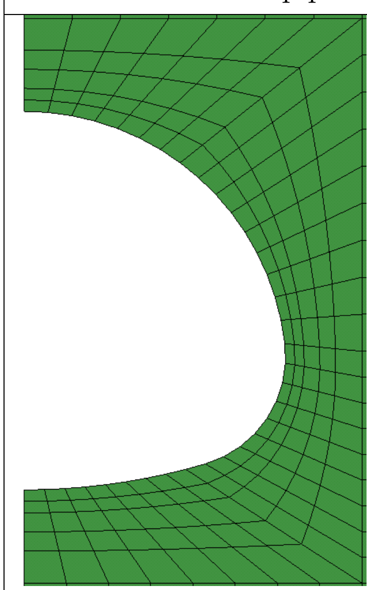
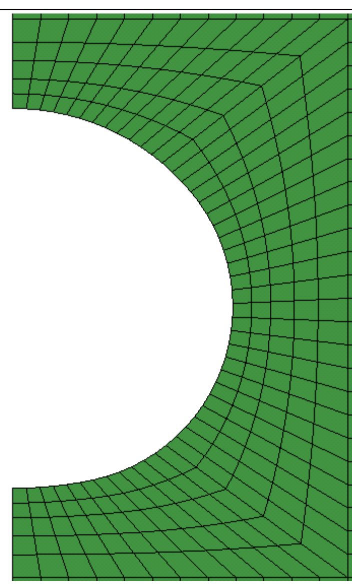
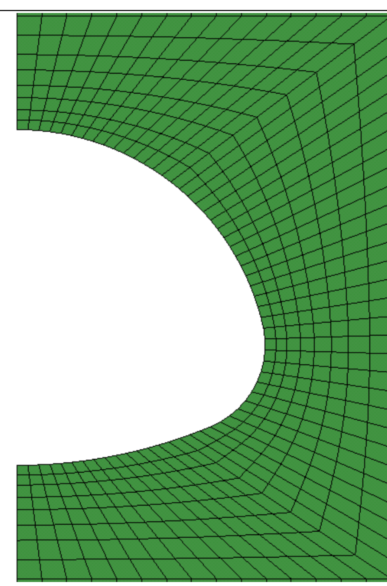


Fig. 3.3. Conceptual embankment mesh used for Level 3 Mesh Calculations. The different colors represent the soil steps. HTCOVR is the height of soil cover above the top of the arch and HFSPAN one-half of the arch span.

Details on CANDE input (.cid file) for Level 3 mesh are shown in Figures B.1 and B.2, and Table B.1 in Appendix B; where the specifications on the row number belong to Mesh 2 (Table 3.1) and are used as an example. The row number varies according to the mesh, the number of nodes, and elements used; typically for small sizes of pipe-arches Mesh 1 is used, for medium sizes Mesh 2 and large sizes Mesh 3. The column numbers remain the same for all pipe sizes regardless of the number of nodes used. Moreover, in Table B.1 some specifications are made over the number of nodes, elements, and boundary conditions, these specifications belong to Mesh 2 in Table 3.1 and also vary according to the mesh used. Lines beginning with D-1, D-2, and E-1 in Table B.1, should be repeated as necessary for characterizing the soil properties and LRFD factors per step thoroughly.

Table 3.1.

Mesh Sizes.

Mesh 1 - Small Pipes	**Mesh 2 - Medium Pipes**	**Mesh 3 - Large Pipes**
Span $\leq 6ft$	$6ft <$ Span $\leq 20ft$	Span $> 20ft$
34 nodes around pipe	49 nodes around pipe	61 nodes around pipe
		

3.5 Buckling Analysis in Abaqus

Buckling is one of the failure criteria in the finite element analysis via the CANDE software, in the form of LRFD strength-limit ratios at the final step of each analysis. This section intends to evaluate the CANDE buckling analysis using Abaqus finite element software. Abaqus evaluation of the buckling failure mode was performed by Chatuphat Savigamin, a Ph.D. student in Civil Engineering at Purdue University. This analysis allowed the elimination of buckling as a critical failure mode in cases studied in this thesis, which enabled the use of the small-deformation analysis in CANDE.

For each Abaqus finite element model, the embankment mesh configuration is built according to the CANDE-2017 User Manual and Guideline [4]. The maximum fill heights obtained from the CANDE finite element analysis were used in the analysis. The finite element meshes in Abaqus are built individually for each cross-section to allow an appropriate mesh refinement as suitable for each specific geometry. Figure 3.4 shows an example of the mesh for 6 x 2 Structural Plate Steel Pipe-Arch (Bolted) with 18 Rc (in) and 7-8 Span (ft-in).

3.6 ASTM LRFD Design Methodology

The standard practices ASTM A796/A796M [11] for steel and ASTM B790/B790M [12] for aluminum provide analytical estimates for pipe fill covers. Figure 3.6 summarizes the process for finding the maximum fill cover. First the design pressure (P_f) is calculated using Equation 3.11 for two different approaches, using the radial pressure (P_v) that depends on the height and weight of the soil; and using the pressure at the corners (P_c), where the pressure is approximately inversely proportional to the radius of curvature of the top (R_t) and corner (R_c) radius, as shown in Figure 3.5.

Next, the factored load (FP_f) is computed using the first part of Equation 3.12 ($FP_f = 1.95(P_f)$), multiplying the dead load (DL) by the load factor (calculated using the factors in Table 2.6). The second part of this equation considers the Live

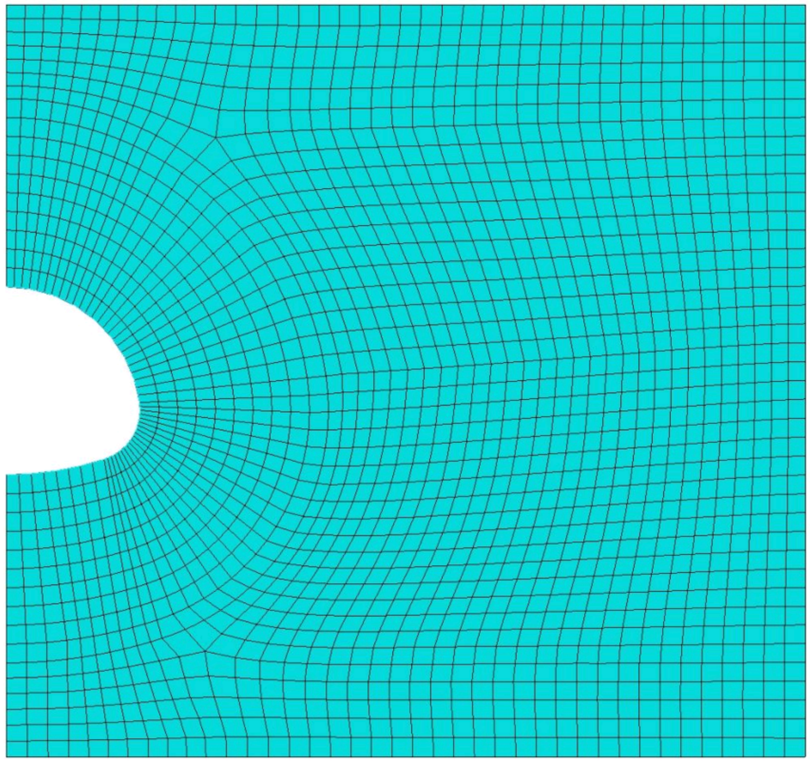


Fig. 3.4. Abaqus finite element meshes for 6 x 2 Structural Plate Steel Pipe-Arch (Bolted) with 18 Rc (in.) and 7-8 Span (ft.-in.).

(LL) and Impact (IL) loads and is only used when the maximum fill cover is less than 8ft.

Then, the Factored thrust (T_f) is computed with Equation 3.14 and the factored resistances (R_f) with Equation 3.15. This analysis includes calculations for Wall Resistance (R_n) in Equation 3.16, Resistance to buckling (f_c) in Equation 3.13 and Seam Resistance in Table 2.2. The resistances values should then be factored using Equation 3.15. Finally, the minimum value of the factored resistances calculated should be compared to the factored thrust, the factored resistance shall equal or exceed the factored thrust $R_f \geq T_f$, and the required height is back calculated. The ASTM fill cover heights were calculated by Devansh Gandhi, a Masters student in Civil Engineering at Purdue University.

$$DL = Hw \tag{3.10}$$

$$P_f = \begin{cases} P_v = DL & \textbf{A. } \text{Considering the radial pressure} \\ P_c = DL \times R_t/R_c & \textbf{B. } \text{Considering the pressure at the corners} \end{cases} \tag{3.11}$$

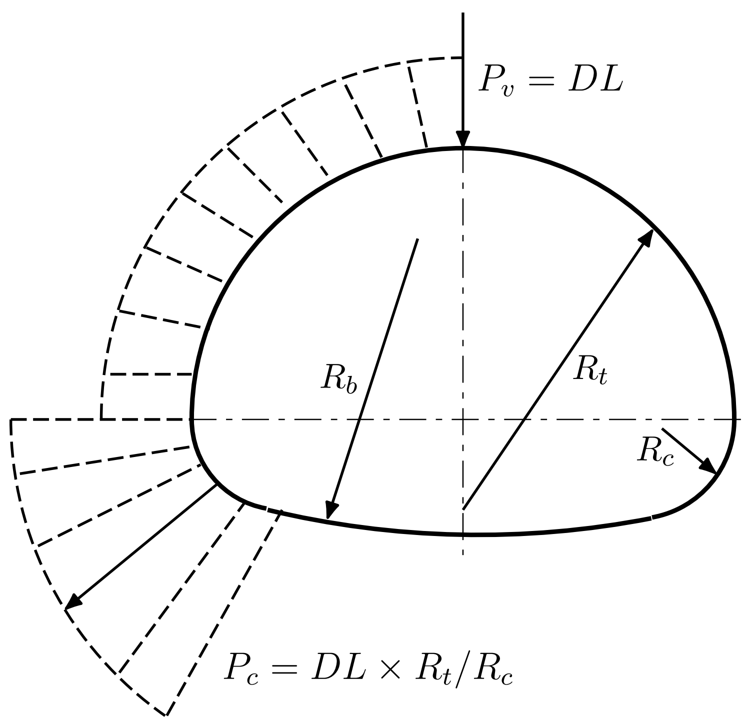


Fig. 3.5. Pressure on a pipe-arch.

$$FP_f = 1.95(P_f) + 1.75(LL + IL) \tag{3.12}$$

$$f_c = \begin{cases} f_u - \frac{{f_u}^2}{48E}(\frac{kS}{r})^2 & \text{if } S < \frac{r}{k}\sqrt{\frac{24E}{f_u}} \\ \frac{12E}{(\frac{kS}{r})^2} & \text{if } S > \frac{r}{k}\sqrt{\frac{24E}{f_u}} \end{cases} \tag{3.13}$$

$$T_f = P_f S/2 \tag{3.14}$$

$$R_f = \varphi R_n \tag{3.15}$$

$$R_n = f_y PA \tag{3.16}$$

In these equations, f_u is the minimum tensile strength, k is the soil stiffness factor taken as 0.22, r is the radius of gyration of corrugation, E is the Young's modulus, f_y is the minimum yield strength, PA is the cross-sectional area, and S is the span.

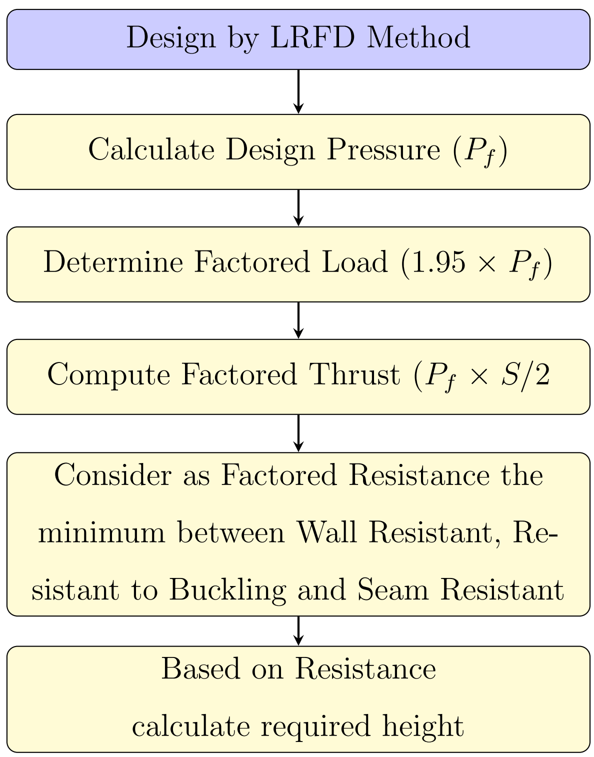


Fig. 3.6. Steps for performing an ASTM LRFD analysis according to [11] and [12]

4. RESULTS & DISCUSSION

This chapter includes the maximum fill heights of Corrugated Steel and Aluminum Pipe-Arches, and Structural Plate Steel and Aluminum Pipe-Arches obtained with CANDE. The finite element analysis in CANDE was performed with the resistance factors shown in Table 2.4, a factor of 2.05 for the load, a coefficient of friction of 0.5, and a tensile force of 10 lb/in. The maximum fill height tables include results previously published by INDOT, results obtained with CANDE, ASTM calculations considering the pressure around the corners (P_c) and the overall pressure (P_v). Tables are color-coded according to the critical failure criterion, and results are plotted in figures for better comparison. In these figures, the red curve represents INDOT results, the grey curve shows the ASTM P_c results, the blue curve is the ASTM P_v results, and the black curve represents CANDE results. Results obtained for specific cases analyzed in Abaqus over the buckling failure mode are also shown.

The chapter is divided in three sections, Section 4.1 discusses the buckling analysis with Abaqus, Section 4.2 shows the CANDE results for Corrugated Steel and Aluminum Pipe-Arches and Section 4.3 discusses results for Structural Plate Steel and Aluminum Pipe-Arches.

4.1 Buckling Analysis via Abaqus Software

Three different cross sections of the 6 x 2 structural plate steel pipe-arch are selected to perform the buckling analysis in Abaqus as detailed in Table 4.1. For each cross-section, the study is done separately for three thicknesses: 0.111, 0.140, and 0.280 inches. The analysis was carried out using the maximum fill heights obtained from the CANDE finite element analysis.

Table 4.1.
Selected cross sections and thicknesses of 6” $\times$ 2” Structural Plate Steel Pipe-Arch to perform Abaqus buckling analysis.

Rc (in)	SPAN (ft-in)	RISE (ft-in)	A (sft)	T (in)
18	6-1	4-7	22	0.111
18	6-1	4-7	22	0.140
18	6-1	4-7	22	0.280
18	7-8	5-5	33	0.111
18	7-8	5-5	33	0.140
18	7-8	5-5	33	0.280
31	18-7	12-0	172	0.111
31	18-7	12-0	172	0.140
31	18-7	12-0	172	0.280

The Abaqus buckling analysis results show that all the selected cross sections and thicknesses do not fail due to buckling, which is in agreement with the CANDE results. An example of the results is illustrated in Figure 4.1. The eigenvalues obtained for each analysis were greater than one, indicating that the model did not fail because of buckling. Furthermore, when performing buckling analysis in Abaqus, the equivalent plastic strain was evaluated. Results helped in determining the amount of permanent strain in the soil surrounding the pipe, as shown in Figure 4.2. The concentrated equivalent plastic strain in the soil located at the corner radius of the pipe indicates a significant effect on the overall strength of the pipe-soil interaction as a result of the soil compaction at the corner area. In other words, if the soil compaction at the corner radius of the pipe is not carried out properly, the bearing capacity of the soil at the pipe-arch corner will limit the maximum fill height of soil over the pipe-arch.

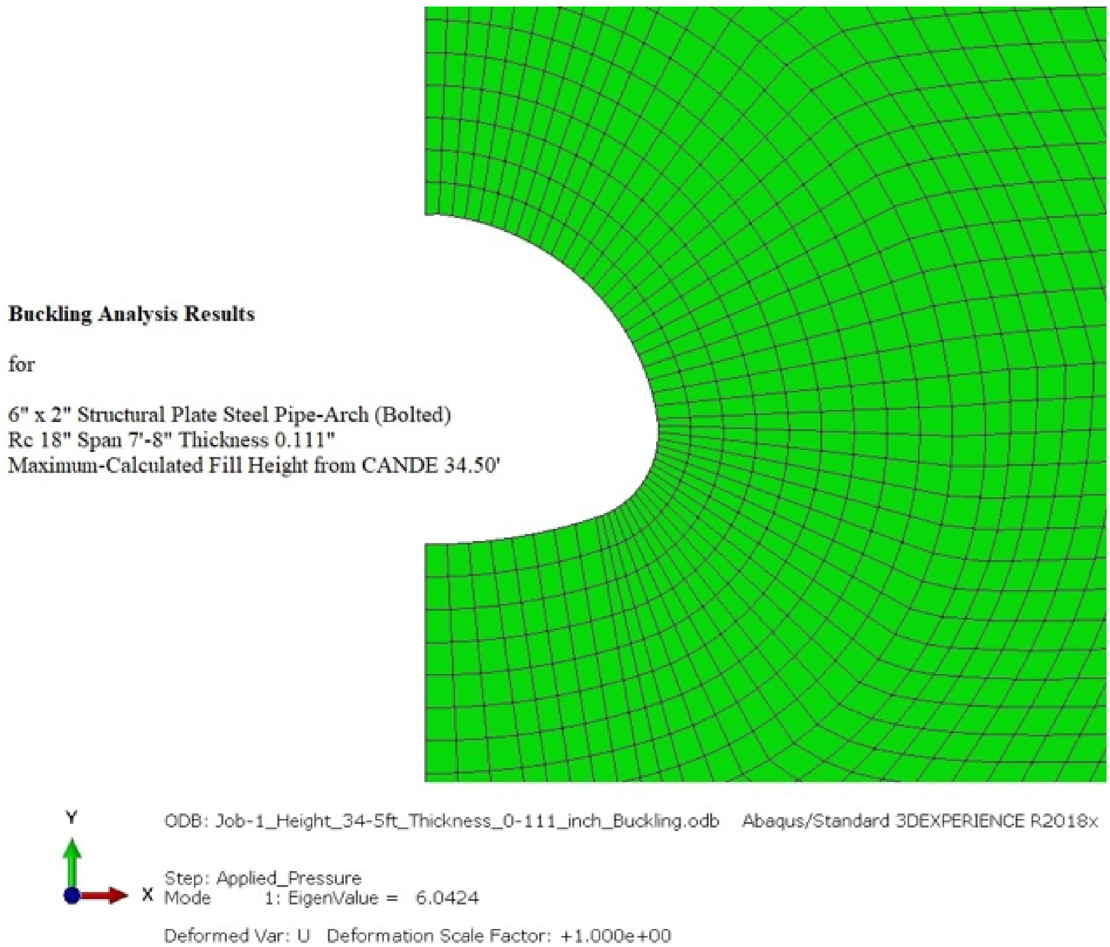


Fig. 4.1. Abaqus buckling analysis results for 6” ×2” Structural Plate Steel Pipe-Arch (Bolted) with 18 R_c (in), 7-8 Span (ft-in), and 0.111 Thickness (in).

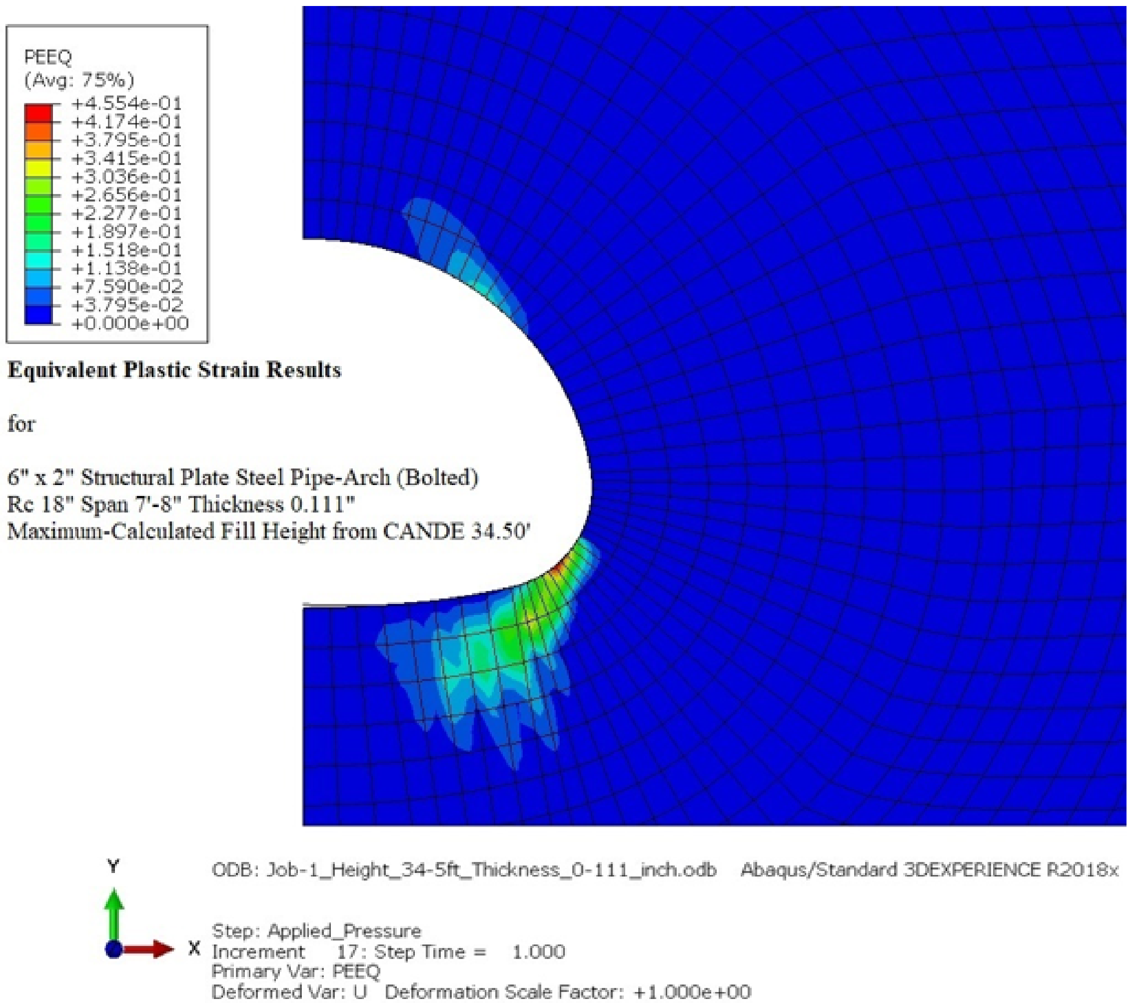


Fig. 4.2. Abaqus equivalent plastic strain results for 6” × 2” Structural Plate Steel Pipe-Arch (Bolted) with 18 R_c (in), 7-8 Span (ft-in), and 0.111 Thickness (in).

4.2 Corrugated Pipe-Arches

The mechanical and geometrical properties for CSPA and CAPA are summarized in Table 2.1 and 2.2, and Section A.0.1.

From the results on 2²/3" × 1/2" Corrugated Steel and Aluminum Pipe-Arch with Riveted and Lock Seam, shown in Tables 4.2 and 4.5, one can see that previous results determined by INDOT for steel and aluminum are identical, and also remain constant for all corrugation thicknesses.

Even though it was not specified where these results came from, comparing these heights with those calculated using Equation 4.1 listed in ASTM B790/B790M [12] shows a general agreement for the structural design of corrugated aluminum pipes. Since Equation 4.1 only depends on the span (S) and the corner radius (R_c), the INDOT calculated maximum fill heights do not vary when the cross-sectional corrugation increases, neither when the fabrication differs (riveted or lock seam). This result is counter-intuitive, as steel and aluminum results should vary since Equation 4.1 is only specified for aluminum pipes.

$$H = \frac{66.7R_c}{S} \text{ (for } 2tons/ft^2 \text{of soil bearing pressure)} \tag{4.1}$$

Similarly for 3" × 1" Corrugated Steel and Aluminum Pipe-Arch with Riveted and Lock Seam, and for 5" × 1" Corrugated Steel Pipe-Arch with Lock Seam (shown in Tables 4.3, 4.6 and 4.4) INDOT results were obtained using Equation 4.1.

In the plots shown in Figures 4.3, 4.4, the red curve represents INDOT results, the grey curve the ASTM P_c results, the blue curve ASTM P_v results, and the black curve CANDE calculations. The results determined using FEM in CANDE are higher than INDOT results. Nonetheless, the results obtained in CANDE are closer to the results calculated using Equation 3.11 for the radial pressure, and INDOT results are closer to the results calculated using Equation 3.11 for the corner pressure. This behavior repetitively appears in the results obtained for for 3" × 1" Corrugated Steel and Aluminum Pipe-Arch with Riveted and Lock Seam, and for 5" × 1" Corrugated Steel

Pipe-Arch with Lock Seam, shown in Figures 4.5, 4.6, 4.10 and 4.11 for 3" × 1" pipe-arches, and Figure 4.7 for 5" × 1" pipe-arches. Some curves representing CANDE results (black curve) are not smooth (a smooth curve is a curve with no peaks or valleys). Non-smooth curves are due to the change in the mesh needed when varying the pipe-arches dimensions; even though the number of nodes and elements in most of the cases remain the same, the size of the elements does not remain constant, affecting the smoothness of the results. The results were used to obtain smooth best fit curve approximations in cases where the curve is not smooth; the best fit values also appear in the tables.

Overall, the maximum fill cover decreases when increasing the span, and increases when increasing corrugation thickness. Most of the cases failed because of the seam strength failure mode, and only a few cases failed because of the vertical deflection. Other failure modes (global buckling, wall yielding, and plastic penetration) were not decisive for determining the maximum depth of pipe-arches. In addition, all Corrugated Steel Pipe-Arches (CSPA) and Corrugated Aluminum Pipe-Arches (CAPA) cases converged thanks to the sizes of these pipes, where the span of the biggest pipe-arch is not higher than 7ft, allowing to run the analysis with Mesh 2 in Table 3.1 and 49 nodes around the pipe, which simplifies the analysis.

4.2.1 $2^2/_3$” × $^1/_2$” Corrugated Steel Pipe-Arch

Table 4.2.
Maximum Soil Cover for $2^2/_3$” × $^1/_2$” Corrugated Steel Pipe-Arch Riveted and Lock Seam.

2 2/3'' x 1/2'' Corrugated Steel Pipe-Arch Riveted - Cover Limit (ft)

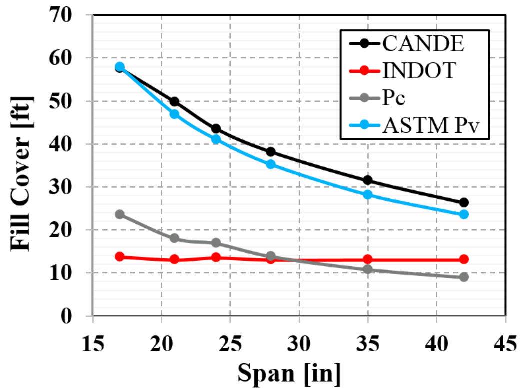
Rc (in)	SPAN (in)	RISE (in)	AREA (sft)	Thickness (in) 0.064					0.079				0.109				0.138				0.168			
				INDOT	ASTM	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
3 1/2	17	13	1.1	13.70	13.73	23.48	57.86	57.48	13.70	25.59	63.06	64.77	13.70	32.90	81.08	79.30								
4 1/8	21	15	1.6	13.00	13.10	17.97	46.84	49.65	13.00	19.59	51.05	53.40	13.00	25.18	65.63	71.70								
4 7/8	24	18	2.2	13.50	13.55	16.83	40.99	43.44	13.50	18.34	44.67	46.90	13.50	23.58	57.43	63.95								
5 1/2	28	20	2.9	13.00	13.10	13.80	35.13	38.10	13.00	15.04	38.29	41.90	13.00	19.34	49.22	54.00								
6 7/8	35	24	4.5	13.00	13.10	10.81	28.10	31.46	13.00	11.78	30.63	34.20	13.00	15.15	39.38	40.27	13.00	15.86	41.23	44.58				
8 1/4	42	29	6.5	13.00	13.10	8.99	23.42	26.30	13.00	9.79	25.52	28.60	13.00	12.59	32.82	34.80	13.00	13.18	34.36	37.30	13.00	13.78	35.90	39.80
9 5/8	49	33	8.9						13.00	8.38	21.88	24.56	13.00	10.78	28.13	30.40	13.00	11.28	29.45	32.00	13.00	11.79	30.77	33.80
11	57	38	11.6										12.80	9.29	24.18	27.03	12.80	9.73	25.32	28.18	12.80	10.17	26.45	29.43
12 3/8	64	43	14.7										12.80	8.26	21.54	24.10	12.80	8.65	22.55	25.10	12.80	9.04	23.56	26.20
13 3/4	71	47	18.1														12.90	7.55	20.33	22.40	12.90	8.17	21.24	23.40
15 1/8	77	52	21.9																		13.00	7.22	19.58	20.66
16 1/2	83	57	26																		13.20	6.63	18.17	18.60

2 2/3'' x 1/2'' Corrugated Steel Pipe-Arch Lock Seam - Cover Limit (ft)

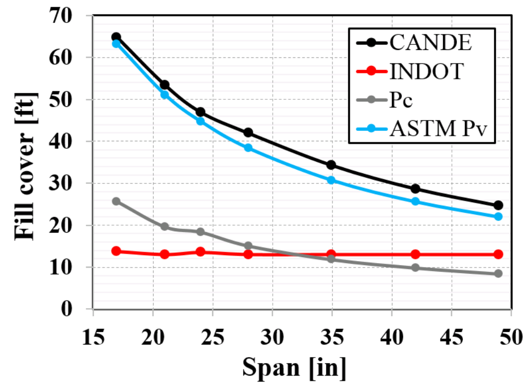
Rc (in)	SPAN (in)	RISE (in)	AREA (sft)	Thickness (in) 0.064						0.079					0.109					0.138				0.168			
				INDOT	ASTM	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
3 1/2	17	13	1.1	13.70	13.73	35.04	86.36	87.70	90.05	13.70	38.19	94.12	107.90	108.00	13.70	49.10	121.01	134.90	134.33								
4 1/8	21	15	1.6	13.00	13.10	26.83	69.91	73.93	73.18	13.00	29.24	76.19	82.70	81.44	13.00	37.59	97.96	110.90	101.44								
4 7/8	24	18	2.2	13.50	13.55	25.11	61.17	68.62	62.35	13.50	27.37	66.67	76.53	68.13	13.50	35.19	85.71	97.75	84.95								
5 1/2	28	20	2.9	13.00	13.10	20.60	52.43	46.00	50.34	13.00	22.45	57.14	50.50	55.45	13.00	28.86	73.47	67.00	69.21								
6 7/8	35	24	4.5	13.00	13.10	16.13	41.95	34.40	36.01	13.00	17.58	45.71	36.10	41.16	13.00	22.61	58.78	40.28	51.45	13.00	23.67	61.54	44.50				
8 1/4	42	29	6.5	13.00	13.10	13.41	34.96	31.25	30.21	13.00	14.62	38.10	32.35	32.26	13.00	18.79	48.98	34.90	40.38	13.00	19.68	51.28	37.30	13.00	20.56	53.58	40.25
9 5/8	49	33	8.9							13.00	12.51	32.65	28.70	26.25	13.00	16.08	41.98	30.40	32.90	13.00	16.84	43.96	32.00	13.00	17.59	45.93	33.80
11	57	38	11.6												12.80	13.87	36.09	28.95	26.91	12.80	14.52	37.79	30.17	12.80	15.17	39.48	31.30
12 3/8	64	43	14.7												12.80	12.33	32.14	27.75	23.07	12.80	12.91	33.65	28.60	12.80	13.49	35.16	29.50
13 3/4	71	47	18.1																	12.90	11.67	30.34	27.00	12.90	12.19	31.70	27.50
15 1/8	77	52	21.9																					13.00	11.23	29.23	26.92
16 1/2	83	57	26																					13.20	10.40	27.12	26.15

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

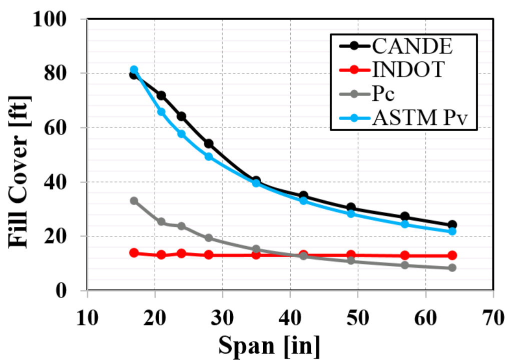
$2^2/3" \times 1/2"$ Corrugated Steel Pipe-Arch Riveted



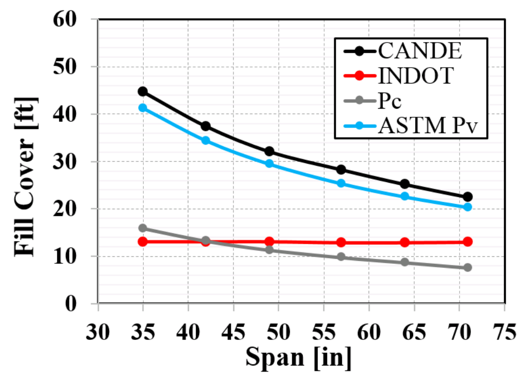
(a) Thickness 0.064 in.



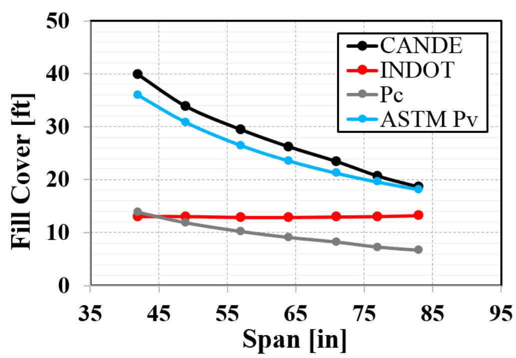
(b) Thickness 0.079 in.



(c) Thickness 0.109 in.



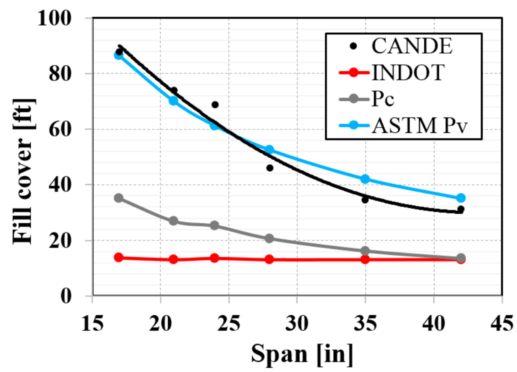
(d) Thickness 0.138 in.



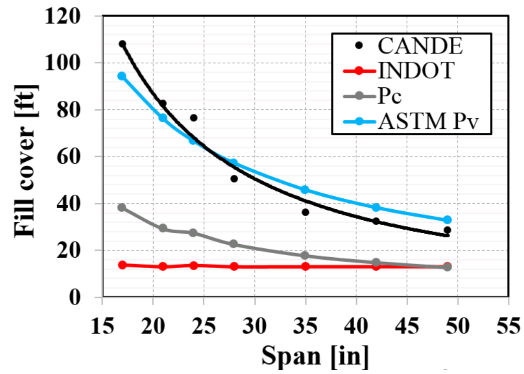
(e) Thickness 0.168 in.

Fig. 4.3. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for $2^2/3" \times 1/2"$ Corrugated Steel Pipe-Arch Riveted with Thicknesses of 0.064in (4.3(a)), 0.079 in (4.3(b)), 0.109 in (4.3(c)), 0.138 in (4.3(d)) and 0.168in (4.3(e)).

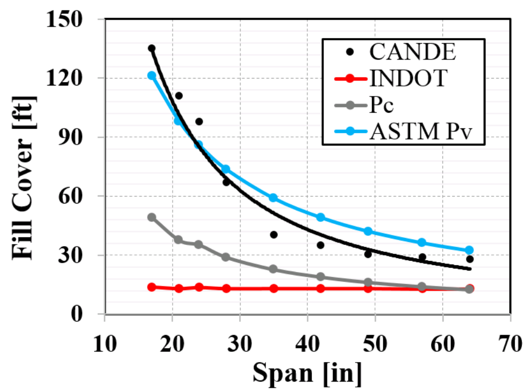
$2^2/_3$” × $^1/_2$” **Corrugated Steel Pipe-Arch Lock Seam**



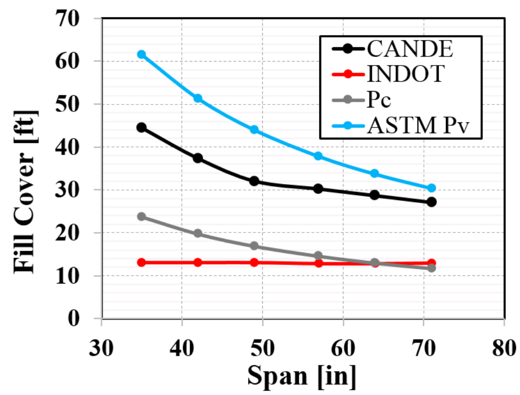
(a) Thickness 0.064 in.



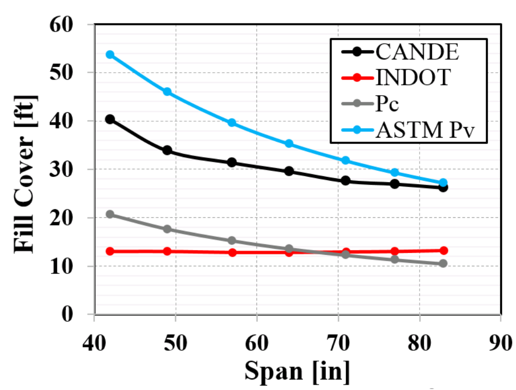
(b) Thickness 0.079 in.



(c) Thickness 0.109 in.



(d) Thickness 0.138 in.



(e) Thickness 0.168 in.

Fig. 4.4. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for $2^2/_3$” × $^1/_2$” Corrugated Steel Pipe-Arch Lock Seam with Thicknesses of 0.064in (4.4(a)), 0.079 in (4.4(b)), 0.109 in (4.4(c)), 0.138 in (4.4(d)) and 0.168in (4.4(e)).

4.2.2 3” × 1” Corrugated Steel Pipe-Arch

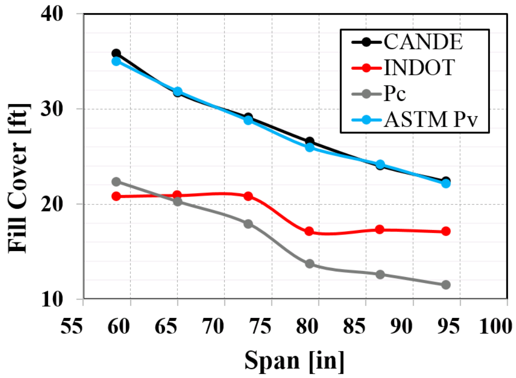
Table 4.3.
Maximum Soil Cover for 3” × 1” Corrugated Steel Pipe-Arch Riveted and Lock Seam.

3'' x 1'' Corrugated Steel Pipe-Arch Riveted - Cover Limit (ft)																				
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.079				0.109				0.138				0.168			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 1/2	48 1/2	15.6	20.80	22.37	35.05	35.83	20.80	34.06	53.36	55.00	20.80	40.94	64.14	66.60	20.80	45.44	71.18	74.00
20 3/4	66 x 51	65	54	19.3	20.90	20.26	31.86	31.72	20.90	30.55	48.03	48.28	20.90	36.71	57.72	58.81	20.90	40.75	64.07	65.25
22 7/8	73 x 55	72 1/2	58 1/4	23.2	20.80	17.93	28.81	29.10	20.80	26.80	43.06	44.05	20.80	32.21	51.75	53.50	20.80	35.75	57.44	59.15
20 7/8	81 x 59	79	62 1/2	27.4	17.10	13.72	25.96	26.58	17.10	20.88	39.52	39.90	17.10	25.10	47.49	48.30	17.10	27.86	52.71	53.00
22 5/8	87 x 63	86 1/2	67 1/4	32.1	17.30	12.61	24.17	24.03	17.30	18.82	36.09	36.07	17.30	22.63	43.38	43.71	17.30	25.11	48.14	47.15
24 3/8	95 x 67	93 1/2	71 3/4	37	17.10	11.48	22.13	22.40	17.10	17.32	33.39	33.62	17.10	20.81	40.13	40.70	17.10	23.10	44.54	43.25
26 1/8	103 x 71	101 1/2	76	42.4					16.90	15.68	30.76	31.00	16.90	18.84	36.97	37.00	16.90	20.91	41.03	38.00
27 3/4	112 x 75	108 1/2	80 1/2	48					16.50	14.55	28.77	28.48	16.50	17.49	34.58	34.38	16.50	19.41	38.38	38.07
29 1/2	117 x 79	116 1/2	84 3/4	54.2					16.80	13.31	26.80	26.65	16.80	16.00	32.21	32.30	16.80	17.76	35.75	36.00
31 1/4	128 x 83	123 1/2	89 1/4	60.5									16.20	15.01	30.38	30.14	16.20	16.66	33.72	33.40
33	137 x 87	131	93 3/4	67.4									16.00	14.03	28.64	27.89	16.00	15.57	31.79	30.91
34 3/4	142 x 91	138 1/2	98	74.5													16.30	14.59	30.07	29.40

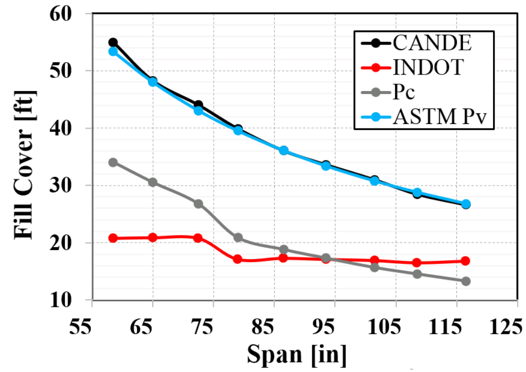
3'' x 1'' Corrugated Steel Pipe-Arch Lock Seam - Cover Limit (ft)																				
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.079				0.109				0.138				0.168			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 1/2	48 1/2	15.6	20.80	34.24	53.65	56.00	20.80	49.38	77.36	78.00	20.80	61.10	95.73	88.00	20.80	67.82	106.25	94.50
20 3/4	66 x 51	65	54	19.3	20.90	30.71	48.28	48.77	20.90	44.28	69.63	65.85	20.90	54.80	86.15	76.00	20.90	60.82	95.62	82.14
22 7/8	73 x 55	72 1/2	58 1/4	23.2	20.80	26.95	43.29	44.60	20.80	38.86	62.42	55.60	20.80	48.08	77.24	60.20	20.80	53.36	85.73	63.80
20 7/8	81 x 59	79	62 1/2	27.4	17.10	21.00	39.73	40.30	17.10	30.28	57.29	46.50	17.10	37.46	70.89	49.60	17.10	41.58	78.68	53.00
22 5/8	87 x 63	86 1/2	67 1/4	32.1	17.30	18.93	36.28	36.56	17.30	27.29	52.32	42.22	17.30	33.77	64.74	44.67	17.30	37.48	71.85	47.10
24 3/8	95 x 67	93 1/2	71 3/4	37	17.10	17.41	33.57	34.05	17.10	25.10	48.40	39.75	17.10	31.06	59.89	41.60	17.10	34.47	66.47	43.25
26 1/8	103 x 71	101 1/2	76	42.4					16.90	22.73	44.59	35.70	16.90	28.12	55.17	37.00	16.90	31.22	61.24	38.00
27 3/4	112 x 75	108 1/2	80 1/2	48					16.50	21.09	41.71	36.31	16.50	26.10	51.61	37.50	16.50	28.97	57.28	38.09
29 1/2	117 x 79	116 1/2	84 3/4	54.2					16.80	19.30	38.85	36.10	16.80	23.88	48.07	36.75	16.80	26.51	53.35	37.70
31 1/4	128 x 83	123 1/2	89 1/4	60.5									16.20	22.40	45.34	34.80	16.20	24.87	50.33	35.60
33	137 x 87	131	93 3/4	67.4									16.00	20.94	42.75	30.49	16.00	23.24	47.45	34.25
34 3/4	142 x 91	138 1/2	98	74.5													16.30	21.77	44.88	32.20

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

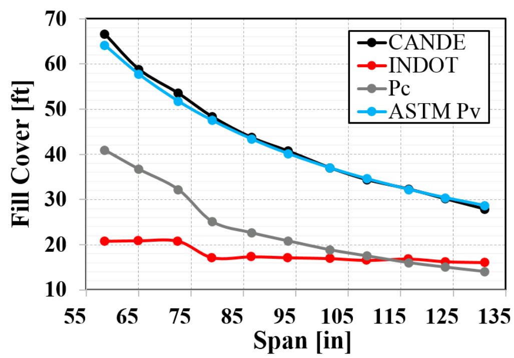
3” × 1” **Corrugated Steel Pipe-Arch Riveted**



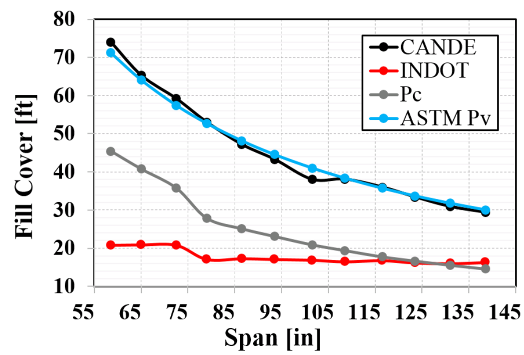
(a) Thickness 0.079 in.



(b) Thickness 0.109 in.



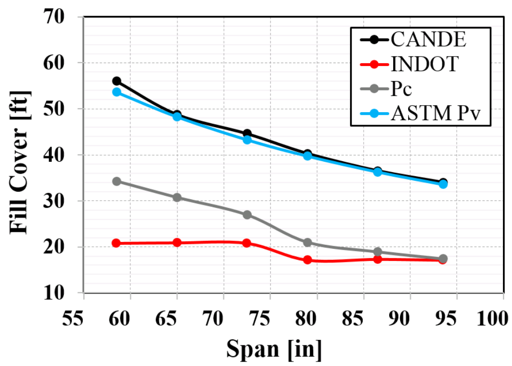
(c) Thickness 0.138 in.



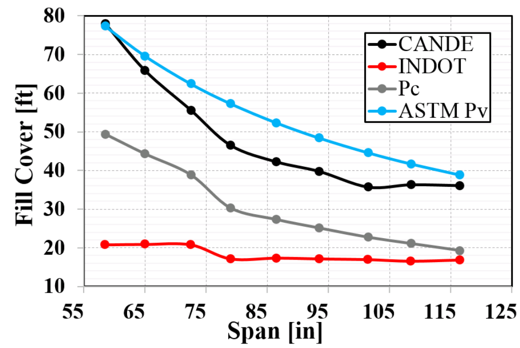
(d) Thickness 0.168 in.

Fig. 4.5. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 3 × 1” Corrugated Steel Pipe-Arch Riveted with Thicknesses of 0.079 in (4.5(a)), 0.109 in (4.5(b)), 0.138 in (4.5(c)) and 0.168in (4.3(e)).

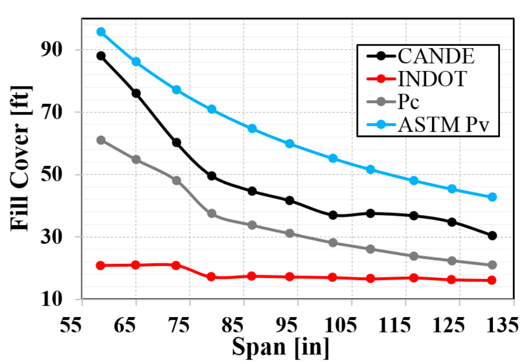
3” × 1” **Corrugated Steel Pipe-Arch Lock Seam**



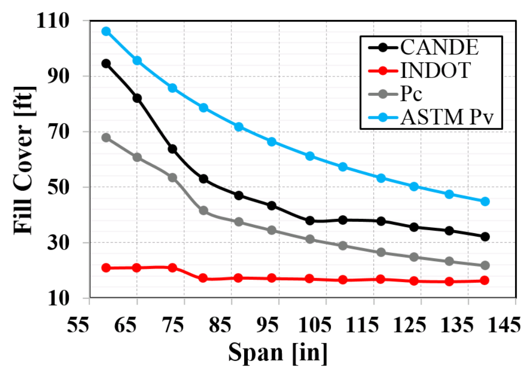
(a) Thickness 0.079 in.



(b) Thickness 0.109 in.



(c) Thickness 0.138 in.



(d) Thickness 0.168 in.

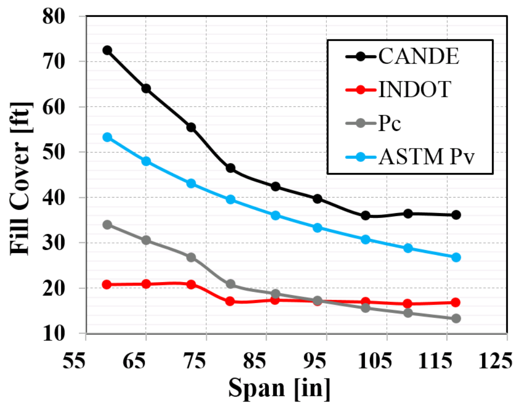
Fig. 4.6. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 3” × 1” Corrugated Steel Pipe-Arch Lock Seam with Thicknesses of 0.079 in (4.6(a)), 0.109 in (4.6(b)), 0.138 in (4.6(c)) and 0.168in (4.6(d)).

4.2.3 5” × 1” Corrugated Steel Pipe-Arch Lock Seam

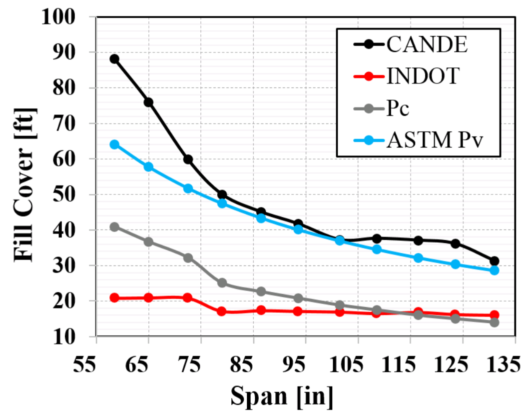
Table 4.4.
Maximum Soil Cover for 5” × 1” Corrugated Steel Pipe-Arch Lock Seam.

5'' x 1'' Corrugated Steel Pipe-Arch Lock Seam - Cover Limit (ft)																
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.109				0.138				0.168			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 1/2	48 1/2	15.6	20.80	34.06	53.36	72.50	20.80	40.94	64.14	88.10				
20 3/4	66 x 51	65	54	19.3	20.90	30.55	48.03	64.07	20.90	36.71	57.72	76.00				
22 7/8	73 x 55	72 1/2	58 1/4	23.2	20.80	26.80	43.06	55.50	20.80	32.21	51.75	59.80				
20 7/8	81 x 59	79	62 1/2	27.4	17.10	20.88	39.52	46.50	17.10	25.10	47.49	50.00	17.10	27.86	52.71	53.00
22 5/8	87 x 63	86 1/2	67 1/4	32.1	17.30	18.82	36.09	42.45	17.30	22.63	43.38	45.05	17.30	25.11	48.14	47.12
24 3/8	95 x 67	93 1/2	71 3/4	37	17.10	17.32	33.39	39.75	17.10	20.81	40.13	41.75	17.10	23.10	44.54	43.20
26 1/8	103 x 71	101 1/2	76	42.4	16.90	15.68	30.76	36.00	16.90	18.84	36.97	37.25	16.90	20.91	41.03	38.30
27 3/4	112 x 75	108 1/2	80 1/2	48	16.50	14.55	28.77	36.44	16.50	17.49	34.58	37.62	16.50	19.41	38.38	38.68
29 1/2	117 x 79	116 1/2	84 3/4	54.2	16.80	13.31	26.80	36.15	16.80	16.00	32.21	37.10	16.80	17.76	35.75	37.80
31 1/4	128 x 83	123 1/2	89 1/4	60.5					16.20	15.01	30.38	36.14	16.20	16.66	33.72	35.80
33	137 x 87	131	93 3/4	67.4					16.00	14.03	28.64	31.28	16.00	15.57	31.79	32.02
34 3/4	142 x 91	138 1/2	98	74.5									16.30	14.59	30.07	32.40

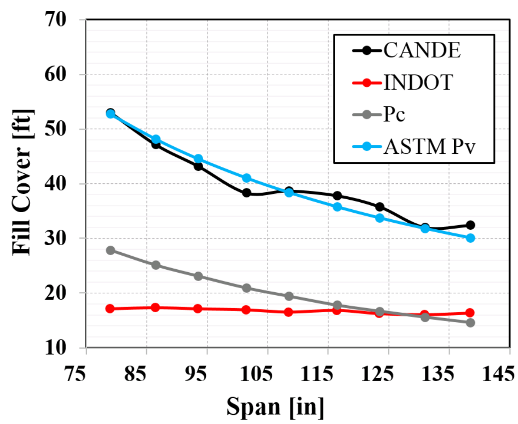
	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged



(a) Thickness 0.109 in.



(b) Thickness 0.138 in.



(c) Thickness 0.168 in.

Fig. 4.7. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 5" × 1" Corrugated Steel Pipe-Arch Lock Seam with Thicknesses of 0.109 in (4.7(a)), 0.138 in (4.7(b)) and 0.168in (4.7(c)).

4.2.4 $2^2/_3$” × $^1/_2$” Corrugated Aluminum Pipe-Arch

Table 4.5.
Maximum Soil Cover for $2^2/_3$” × $^1/_2$” Corrugated Aluminum Pipe-Arch Riveted and Lock Seam.

2 2/3'' x 1/2'' Corrugated Aluminum Pipe-Arch Riveted - Cover Limit (ft)

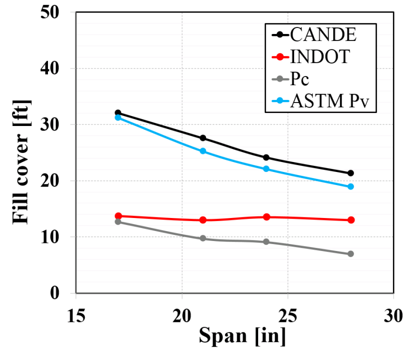
Rc (in)	SPAN (in)	RISE (in)	AREA (sft)	Thickness (in) 0.060				0.075				0.105				0.135				0.164			
				INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
3 1/2	17	13	1.1	13.70	12.65	31.18	32.00	13.70	12.65	31.18	31.50	13.70	21.93	54.05	54.85								
4 1/8	21	15	1.6	13.00	9.69	25.24	27.52	13.00	9.69	25.24	27.12	13.00	16.79	43.76	47.60								
4 7/8	24	18	2.2	13.50	9.07	22.09	24.10	13.50	9.07	22.09	23.80	13.50	15.72	38.29	41.60								
5 1/2	28	20	2.9	13.00	6.93	18.93	21.26	13.00	6.90	18.93	21.13	13.00	12.89	32.82	36.40	13.00	13.39	34.08	37.30				
6 7/8	35	24	4.5					13.00	5.25	15.15	16.96	13.00	10.10	26.25	29.70	13.00	10.49	27.26	30.64				
8 1/4	42	29	6.5					13.00	3.90	12.62	13.90	13.00	8.39	21.88	24.75	13.00	8.72	22.72	25.60				
9 5/8	49	33	8.9					13.00	3.00	10.82	11.56	13.00	6.76	18.75	21.23	13.00	7.10	19.47	21.87				
11	57	38	11.6									12.80	5.75	16.12	18.10	12.80	6.00	16.74	18.73	12.80	6.26	17.36	19.41
12 3/8	64	43	14.7													12.80	5.26	14.91	16.40	12.80	5.50	15.46	17.10
13 3/4	71	47	18.1																	12.90	4.88	13.94	15.05

2 2/3'' x 1/2'' Corrugated Aluminum Pipe-Arch Lock Seam - Cover Limit (ft)

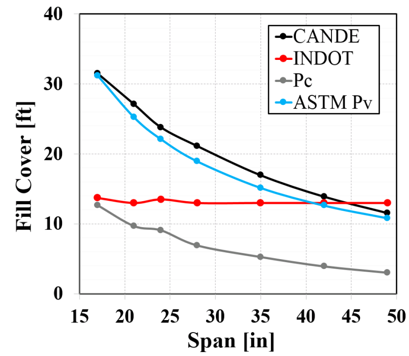
Rc (in)	SPAN (in)	RISE (in)	AREA (sft)	Thickness (in) 0.060				0.075				0.105					0.135					0.164			
				INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE
3 1/2	17	13	1.1	13.70	18.89	46.54	49.50	13.70	18.89	46.54	48.55	13.70	32.74	80.67	86.54	70.39									
4 1/8	21	15	1.6	13.00	14.46	37.68	40.55	13.00	14.46	37.68	41.30	13.00	25.06	65.31	51.50	57.85									
4 7/8	24	18	2.2	13.50	13.53	32.97	36.35	13.50	13.53	32.97	36.00	13.50	23.46	57.14	52.10	51.10									
5 1/2	28	20	2.9	13.00	11.10	28.26	32.00	13.00	11.10	28.26	31.77	13.00	19.24	48.98	39.80	44.28	13.00	19.98	50.86	43.70	40.52				
6 7/8	35	24	4.5					13.00	8.69	22.61	25.77	13.00	15.07	39.18	31.55	35.99	13.00	15.65	40.69	33.09	35.31				
8 1/4	42	29	6.5					13.00	6.80	18.84	21.45	13.00	12.53	32.65	29.35	30.38	13.00	13.01	33.91	30.30	31.55				
9 5/8	49	33	8.9					13.00	5.72	16.15	18.25	13.00	10.72	27.99	26.87	26.33	13.00	11.13	29.06	27.50	28.69				
11	57	38	11.6									12.80	9.25	24.06	26.54	22.88	12.80	9.60	24.99	27.03	26.13	12.80	9.96	25.91	27.56
12 3/8	64	43	14.7														12.80	8.54	22.25	25.20	24.33	12.80	8.86	23.08	26.10
13 3/4	71	47	18.1																			12.90	8.00	20.80	23.24

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

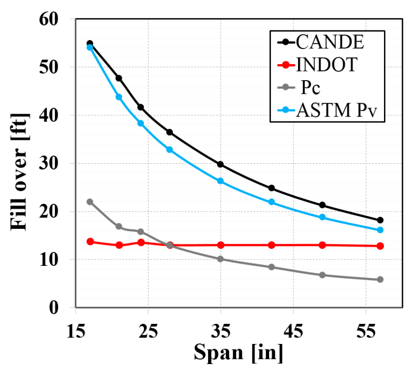
$2^2/_3$" $\times$ $^1/_2$" Corrugated Aluminum Pipe-Arch Riveted



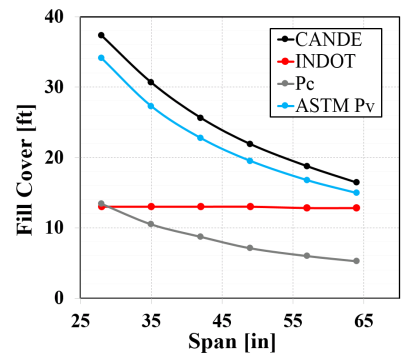
(a) Thickness 0.060 in.



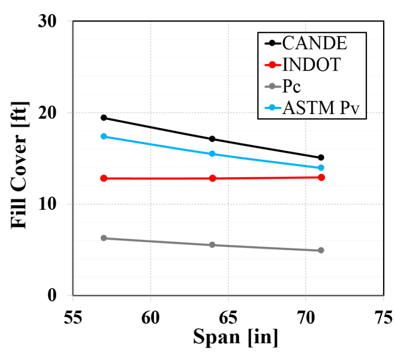
(b) Thickness 0.075 in.



(c) Thickness 0.105 in.



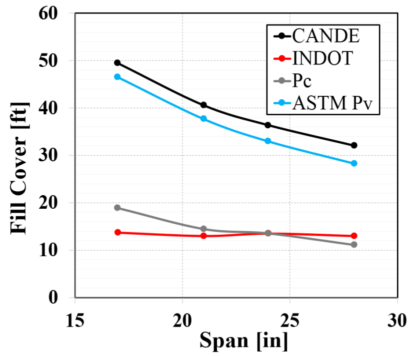
(d) Thickness 0.135 in.



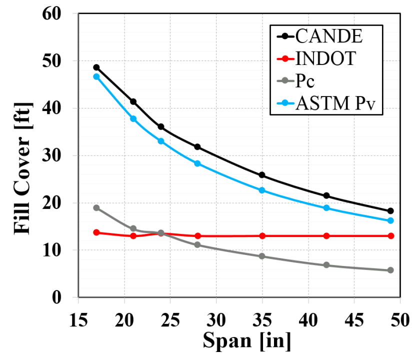
(e) Thickness 0.164 in.

Fig. 4.8. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for $2^2/_3$" $\times$ $^1/_2$" Corrugated Aluminum Pipe-Arch Riveted with Thicknesses of 0.060in (4.8(a)), 0.075 in (4.8(b)), 0.105 in (4.8(c)), 0.135 in (4.8(d)) and 0.164in (4.8(e)).

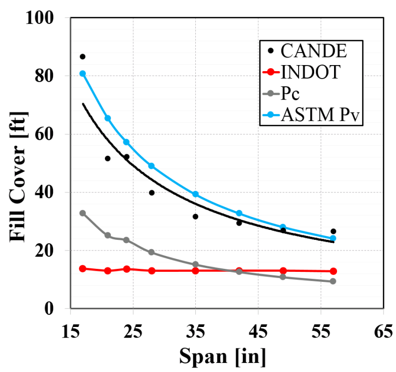
$2^{2}/_{3}$" × $^{1}/_{2}$" Corrugated Aluminum Pipe-Arch Lock Seam



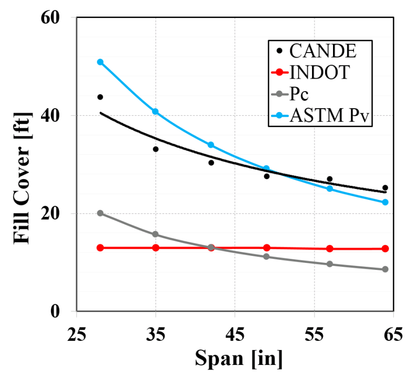
(a) Thickness 0.060 in.



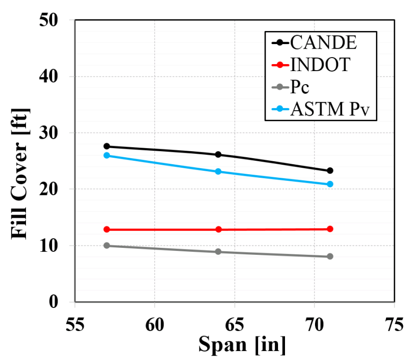
(b) Thickness 0.075 in.



(c) Thickness 0.105 in.



(d) Thickness 0.135 in.



(e) Thickness 0.164 in.

Fig. 4.9. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for $2^{2}/_{3}$" × $^{1}/_{2}$" Corrugated Aluminum Pipe-Arch Lock Seam with Thicknesses of 0.060in (4.9(a)), 0.075 in (4.9(b)), 0.105 in (4.9(c)), 0.135 in (4.9(d)) and 0.164in (4.9(e)).

4.2.5 3” × 1” Corrugated Aluminum Pipe-Arch

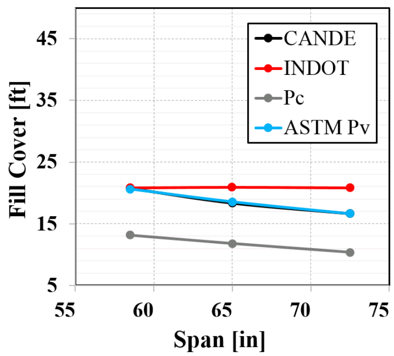
Table 4.6.
Maximum Soil Cover for 3” × 1” Corrugated Aluminum Pipe-Arch Riveted and Lock Seam.

3'' x 1'' Corrugated Aluminum Pipe-Arch Riveted - Cover Limit (ft)																				
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.075				0.105				0.135				0.164			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 1/2	48 1/2	15.6	20.80	13.17	20.64	20.74	20.80	17.99	28.19	28.38	20.80	26.99	42.29	44.45	20.80	35.03	54.87	58.00
20 3/4	66 x 51	65	54	19.3	20.90	11.81	18.58	18.36	20.90	16.14	25.37	25.17	20.90	24.21	38.06	39.58	20.90	31.41	49.39	50.38
22 7/8	73 x 55	72 1/2	58 1/4	23.2	20.80	10.37	16.65	16.65	20.80	14.16	22.75	23.00	20.80	21.24	34.12	36.15	20.80	27.56	44.28	46.05
20 7/8	81 x 59	79	62 1/2	27.4					17.10	11.03	20.88	20.90	17.10	16.55	31.31	33.10	17.10	21.47	40.63	41.60
22 5/8	87 x 63	86 1/2	67 1/4	32.1					17.30	9.95	19.07	18.84	17.30	14.92	28.60	30.05	17.30	19.36	37.11	37.62
24 3/8	95 x 67	93 1/2	71 3/4	37									17.10	13.72	26.46	27.87	17.10	17.81	34.33	35.05
26 1/8	103 x 71	101 1/2	76	42.4									16.90	12.42	24.37	25.60	16.90	16.12	31.63	32.16
27 3/4	112 x 75	108 1/2	80 1/2	48													16.50	14.96	29.59	29.76

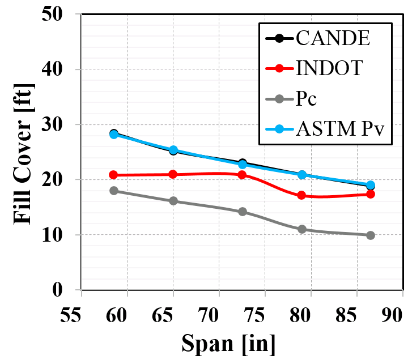
3'' x 1'' Corrugated Aluminum Pipe-Arch Lock Seam - Cover Limit (ft)																				
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.075				0.105				0.135				0.164			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 1/2	48 1/2	15.6	20.80	19.66	30.81	31.44	20.80	26.86	42.08	43.00	20.80	40.29	63.12	60.40	20.80	52.28	81.90	63.08
20 3/4	66 x 51	65	54	19.3	20.90	17.63	27.73	28.03	20.90	24.09	37.87	38.34	20.90	36.13	56.80	54.24	20.90	46.88	73.71	58.00
22 7/8	73 x 55	72 1/2	58 1/4	23.2	20.80	15.47	24.86	25.50	20.80	21.13	33.95	34.80	20.80	31.70	50.93	46.10	20.80	41.13	66.09	48.50
20 7/8	81 x 59	79	62 1/2	27.4					17.10	16.47	31.16	31.80	17.10	24.70	46.74	40.50	17.10	32.05	60.65	42.00
22 5/8	87 x 63	86 1/2	67 1/4	32.1					17.30	14.84	28.46	28.90	17.30	22.27	42.69	37.82	17.30	28.89	55.39	38.88
24 3/8	95 x 67	93 1/2	71 3/4	37									17.10	20.48	39.49	36.50	17.10	26.58	51.24	37.20
26 1/8	103 x 71	101 1/2	76	42.4									16.90	18.54	36.38	33.00	16.90	24.06	47.20	33.70
27 3/4	112 x 75	108 1/2	80 1/2	48													16.50	21.84	43.18	34.48

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

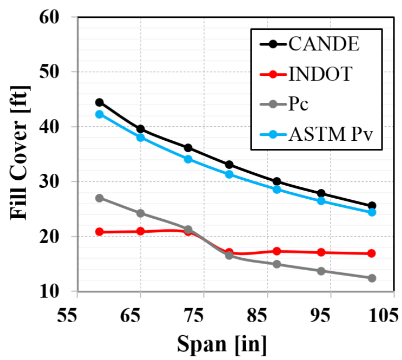
3” × 1” **Corrugated Aluminum Pipe-Arch Riveted**



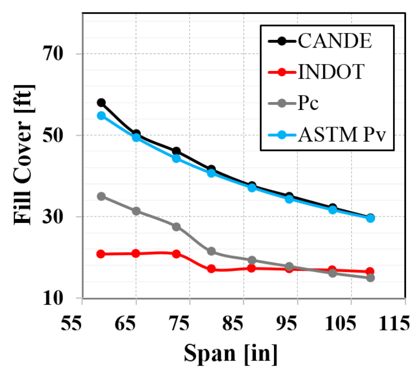
(a) Thickness 0.075 in.



(b) Thickness 0.105 in.



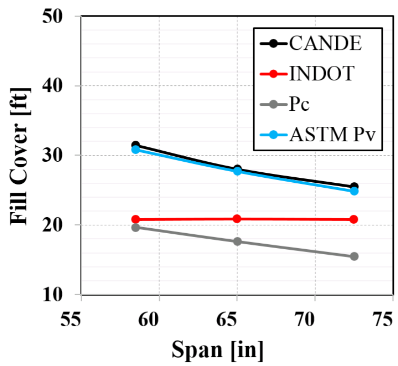
(c) Thickness 0.135 in.



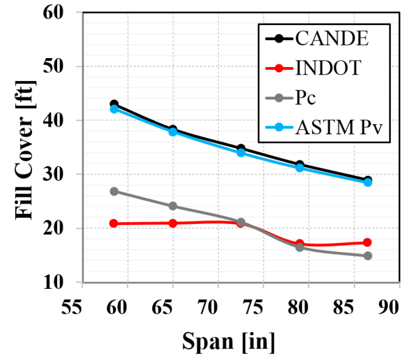
(d) Thickness 0.164 in.

Fig. 4.10. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 3” × 1” Corrugated Aluminum Pipe-Arch Riveted with Thicknesses of 0.075 in (4.10(a)), 0.105 in (4.10(b)), 0.135 in (4.10(c)) and 0.164in (4.10(d)).

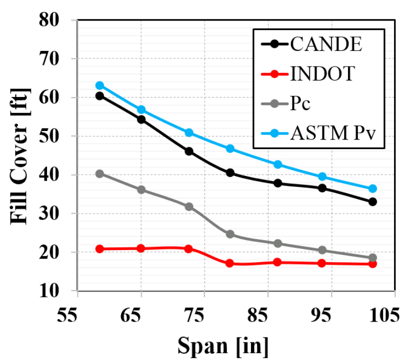
3” × 1” **Corrugated Aluminum Pipe-Arch Lock Seam**



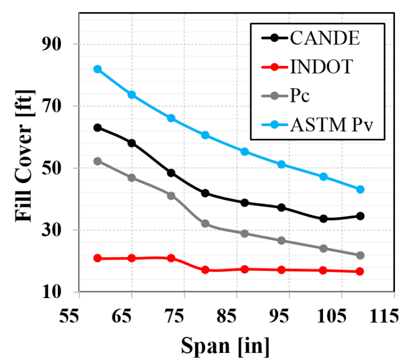
(a) Thickness 0.075 in.



(b) Thickness 0.105 in.



(c) Thickness 0.135 in.



(d) Thickness 0.164 in.

Fig. 4.11. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 3” × 1” Corrugated Aluminum Pipe-Arch Lock Seam with Thicknesses of 0.075 in (4.11(a)), 0.105 in (4.11(b)), 0.135 in (4.11(c)) and 0.164in (4.11(d)).

4.3 Structural Plate Pipe-Arches

The mechanical and geometrical properties for Structural Plate Steel Pipe-Arch and Structural Plate Aluminum Pipe-Arch are summarized in Table 2.1 and, and Section A.0.2.

INDOT maximum fill cover results for 6” × 2” Structural Plate Steel Pipe-Arch (Bolted) shown in Tables 4.7 and 4.8, remain constant when increasing the corrugation thicknesses. No background was given for INDOT calculations. Similarly, for 9" × 2½" Structural Plate Aluminum Pipe-Arch (shown in Tables 4.9 to 4.14), the maximum cover results remain equal regardless the thickness of corrugation. In these tables some cases did not converge (shown with red in the tables), making it impossible to calculate the maximum fill height. Non-convergence may be due to the magnitude of load increments, mesh changes for every pipe-arch case, number of elements in the mesh, coefficient of friction and tensile force used. Every mesh change to be made in CANDE is a laborious task, and thus the missing values were interpolated according to the maximum fill cover obtained for the surrounding cases. Also, all the cases failed because of seam strength failure mode or vertical deflection. Other failure modes did not determine the maximum depth of pipe-arches.

Figures 4.12 and 4.13, show the results for 6" × 2" Structural Plate Steel Pipe-Arches, and Figures 4.14 and 4.15 show the covers for 9" × 2½" Structural Plate Aluminum Pipe-Arches. In these figures, the red curve represents INDOT results, the grey curve the ASTM P_c results, the blue curve ASTM P_v results, and the black curve CANDE. These Figures show that for the first corrugation (o.111 in and 0.150 in), INDOT results are comparable to CANDE results. This is because INDOT calculations seem to be estimated for the worst case scenario which is the smallest thickness, and used identically for the other corrugations.

As the thickness corrugation increased, INDOT results became less comparable to CANDE. In fact, CANDE results are more comparable to the results calculated using Equation 3.11 for the radial pressure, and INDOT results can be compared to the results computed using Equation 3.11 for the corner pressure. Additionally, fill covers decreases when increasing span, and increases when increasing corrugation thickness.

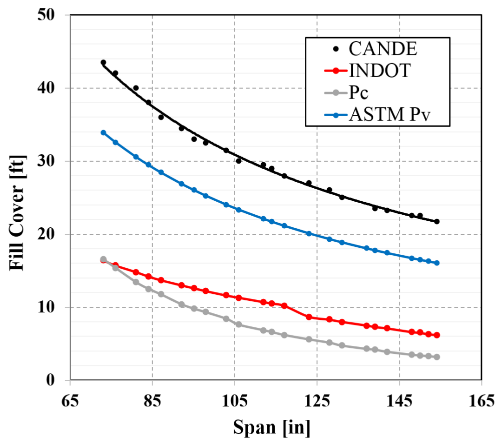
Since some of the curves are not smooth, mainly because of the variation in geometry of the pipe-arches, changes in the failure mode from seam strength to vertical deflection, and differences in the element size in every pipe-arch case, smooth best-fit estimates were calculated from smoothed approximations of the results, and these values also appear in the tables.

4.3.1 6" × 2" Structural Plate Steel Pipe-Arch (Bolted)

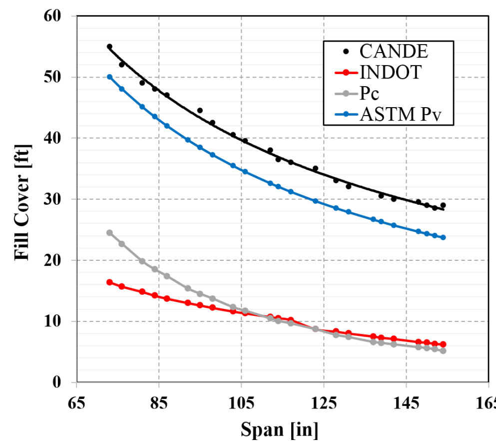
Table 4.7.
Maximum Soil Cover for 6" × 2" Structural Plate Steel Pipe-Arch for a Corner Radius of 18 in.

6" x 2" Structural Plate Steel Pipe-Arch - Cover Limit (ft)																		
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)														
				0.111					0.140					0.280				
				INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT
18	6-1	4-7	22	16.4	16.6	33.9	43.5	43.2	16.4	24.4	50.0	55.0	54.1	16.4	56.8	116.2	106.8	111.5
18	6-4	4-9	24	15.7	15.4	32.6	42.0	41.6	15.7	22.7	48.1	52.0	52.6	15.7	52.6	111.6	103.0	105.3
18	6-9	4-11	26	14.8	13.4	30.5	40.0	39.3	14.8	19.8	45.1	49.0	50.1	14.8	45.9	104.7	101.0	95.6
18	7-0	5-1	28	14.2	12.5	29.5	38.0	38.0	14.2	18.5	43.5	48.0	48.7	14.2	42.9	101.0	98.0	90.1
18	7-3	5-3	31	13.7	11.8	28.4	36.0	36.8	13.7	17.3	42.0	47.0	47.4	13.7	40.3	97.5	91.0	84.9
18	7-8	5-5	33	13.0	10.4	26.9	34.5	34.9	13.0	15.3	39.7	NC	45.2	13.0	35.6	92.2	75.0	76.8
18	7-11	5-7	35	12.6	9.8	26.0	33.0	33.9	12.6	14.5	38.4	44.5	44.0	12.6	33.6	89.3	70.0	72.2
18	8-2	5-9	38	12.2	9.3	25.2	32.5	32.9	12.2	13.7	37.3	42.5	42.8	12.2	31.8	86.5	66.0	67.9
18	8-7	5-11	40	11.6	8.4	24.0	31.5	31.5	11.6	12.3	35.5	40.5	41.0	11.6	28.5	82.3	58.0	61.3
18	8-10	6-1	43	11.3	7.6	23.3	30.0	30.7	11.3	11.7	34.5	39.5	39.9	11.3	27.2	80.0	55.0	57.7
18	9-4	6-3	46	10.7	6.9	22.1	29.5	29.1	10.7	10.5	32.6	38.0	37.9	10.7	24.3	75.7	49.0	51.3
18	9-6	6-5	49	10.5	6.6	21.7	29.0	28.7	10.5	10.1	32.0	36.5	37.3	10.5	23.3	74.4	48.0	49.4
18	9-9	6-7	52	10.2	6.2	21.1	28.0	28.0	10.2	9.6	31.2	36.0	36.4	10.2	22.4	72.5	47.0	46.7
18	10-3	6-9	55	8.7	5.6	20.1	27.0	26.7	8.7	8.7	29.7	35.0	34.8	8.7	20.2	69.0	43.0	42.1
18	10-8	6-11	58	8.3	5.2	19.3	26.0	25.8	8.3	7.8	28.5	33.0	33.6	8.3	18.4	66.3	41.0	39.1
18	10-11	7-1	61	8.0	4.8	18.9	25.0	25.2	8.0	7.4	27.9	32.0	32.9	8.0	17.7	64.7	42.0	37.6
18	11-5	7-3	64	7.5	4.3	18.1	NC	24.2	7.5	6.6	26.7	NC	31.8	7.5	16.1	61.9	39.0	35.4
18	11-7	7-5	67	7.3	4.2	17.8	23.5	23.9	7.3	6.5	26.3	30.5	31.4	7.3	15.6	61.0	38.0	34.9
18	11-10	7-7	71	7.1	3.9	17.4	23.3	23.4	7.1	6.2	25.7	30.0	30.9	7.1	15.1	59.7	37.0	34.4
18	12-4	7-9	74	6.6	3.5	16.7	22.5	22.5	6.6	5.8	24.7	29.5	30.1	6.6	13.8	57.3	33.5	34.1
18	12-6	7-11	78	6.5	3.4	16.5	22.5	22.3	6.5	5.6	24.3	29.0	29.8	6.5	13.5	56.5	33.5	34.2
18	12-8	8-1	81	6.3	3.3	16.3	NC	22.0	6.3	5.4	24.0	28.5	29.6	6.3	13.1	55.8	33.5	34.4
18	12-10	8-4	85	6.2	3.2	16.1	21.8	21.7	6.2	5.1	23.7	29.0	29.4	6.2	12.8	55.1	34.5	34.8

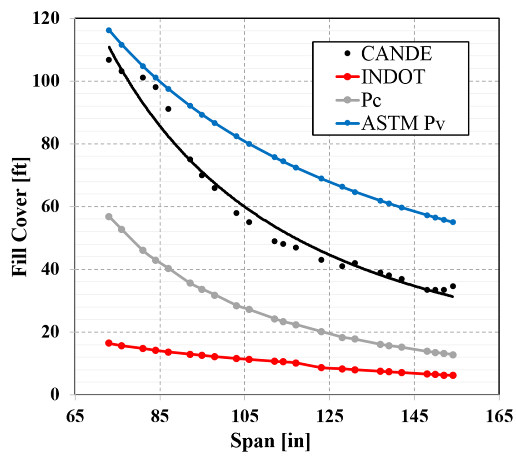
	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged



(a) Thickness 0.111 in.



(b) Thickness 0.140 in.



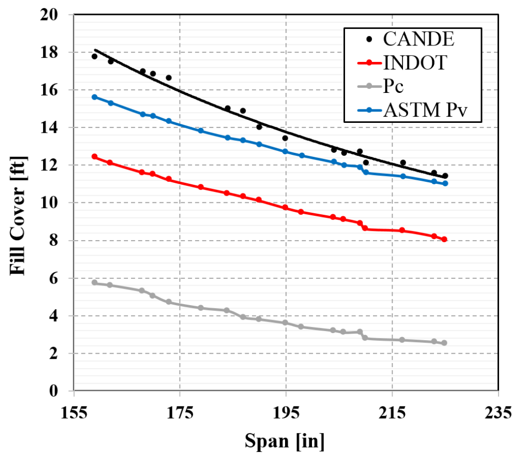
(c) Thickness 0.280 in.

Fig. 4.12. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 6” $\times$2” Structural Plate Steel Pipe-Arch with Corner Radius of 18 in and thicknesses of 0.111 in (4.12(a)), 0.140 in (4.12(b)) and 0.280 in (4.12(c)).

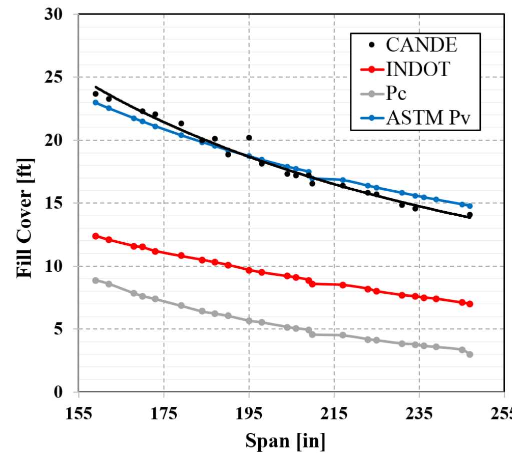
Table 4.8.
Maximum Soil Cover for 6” × 2” Structural Plate Steel Pipe-Arch for a Corner Radius of 31 in.

6" x 2" Structural Plate Steel Pipe-Arch - Cover Limit (ft)																		
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)														
				0.111					0.140					0.280				
				INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT
31	13-3	9-4	97	12.40	5.70	15.60	17.75	18.13	12.40	8.88	22.97	23.66	24.16	12.40	20.63	53.34	41.00	40.02
31	13-6	9-6	102	12.10	5.60	15.30	17.50	17.67	12.10	8.60	22.54	23.25	23.60	12.10	19.95	52.36	39.00	39.21
31	14-0	9-8	105	11.60	5.30	14.70	17.00	16.82	11.60	7.84	21.74	NC	22.53	11.60	18.55	50.49	37.00	37.66
31	14-2	9-10	109	11.50	5.05	14.60	16.85	16.55	11.50	7.62	21.48	22.30	22.20	11.50	18.08	49.89	36.40	37.17
31	14-5	10-0	114	11.20	4.70	14.30	16.60	16.16	11.20	7.38	21.11	22.10	21.71	11.20	17.54	49.03	36.20	36.46
31	14-11	10-2	118	10.80	4.40	13.80	NC	15.43	10.80	6.85	20.40	21.30	20.79	10.80	16.36	47.38	34.50	35.11
31	15-4	10-4	123	10.50	4.25	13.45	15.00	14.86	10.50	6.40	19.85	20.00	20.08	10.50	15.35	46.10	34.00	34.05
31	15-7	10-6	127	10.30	3.90	13.30	14.86	14.54	10.30	6.23	19.53	20.14	19.67	10.30	14.95	45.36	33.00	33.45
31	15-10	10-8	132	10.10	3.80	13.10	14.00	14.23	10.10	6.05	19.22	18.88	19.28	10.10	14.54	44.64	35.00	32.87
31	16-3	10-10	137	9.70	3.60	12.70	13.40	13.73	9.70	5.67	18.73	20.20	18.65	9.70	13.69	43.50	37.00	31.94
31	16-6	11-0	142	9.50	3.40	12.50	NC	13.45	9.50	5.53	18.44	18.10	18.30	9.50	13.35	42.84	31.25	31.40
31	17-0	11-2	146	9.20	3.20	12.15	12.80	12.92	9.20	5.17	17.90	17.30	17.62	9.20	12.52	41.58	30.65	30.38
31	17-2	11-4	151	9.10	3.10	12.00	12.63	12.75	9.10	5.06	17.73	17.20	17.40	9.10	12.30	41.17	30.00	30.06
31	17-5	11-6	157	8.90	3.10	11.90	12.70	12.50	8.90	4.93	17.47	17.18	17.08	8.90	12.01	40.58	NC	29.58
31	17-6	11-8	161	8.60	2.80	11.60	12.13	12.42	8.60	4.58	16.99	16.56	16.98	8.60	11.30	39.45	27.80	29.42
31	18-1	11-10	167	8.50	2.70	11.40	12.10	11.88	8.50	4.50	16.83	16.40	16.29	8.50	11.11	39.09	27.00	28.38
31	18-7	12-0	172	8.20	2.60	11.10	11.55	11.44	8.20	4.20	16.38	15.80	15.74	8.20	10.48	38.03	26.00	27.53
31	18-9	12-2	177	8.00	2.50	11.00	11.45	11.31	8.00	4.11	16.23	15.70	15.56	8.00	10.29	37.70	26.00	27.26
31	19-3	12-4	182						7.70	3.85	15.81	14.85	15.05	7.70	9.73	36.72	28.00	26.48
31	19-6	12-6	188						7.60	3.80	15.61	14.55	14.80	7.60	9.53	36.25	25.80	26.10
31	19-8	12-8	194						7.50	3.67	15.47	NC	14.64	7.50	9.38	35.94	26.00	25.86
31	19-11	12-10	200						7.40	3.58	15.28	NC	14.41	7.40	9.19	35.49	25.45	25.50
31	20-5	13-0	205						7.10	3.36	14.91	NC	13.97	7.10	8.71	34.62	25.50	24.81
31	20-7	13-2	211						7.00	2.96	14.78	14.10	13.82	7.00	7.64	34.34	25.50	24.59

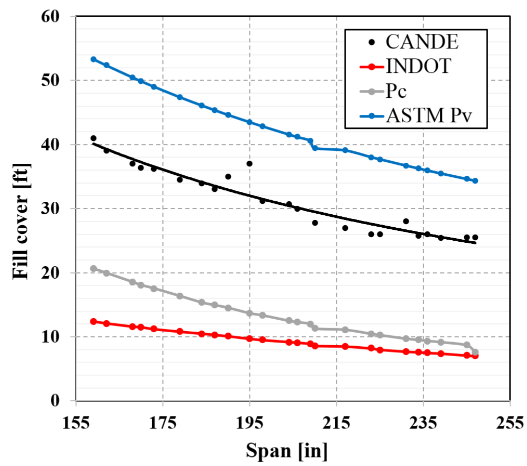
	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged



(a) Thickness 0.111 in.



(b) Thickness 0.140 in.



(c) Thickness 0.280 in.

Fig. 4.13. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 6" $\times$ 2" Structural Plate Steel Pipe-Arch with Corner Radius of 31 in and thicknesses of 0.111 in (4.13(a)), 0.140 in (4.13(b)) and 0.280 in (4.13(c)).

4.3.2 9" × 2^1/$_2$" Structural Plate Aluminum Pipe-Arch (Steel Bolted)

Table 4.9.
Maximum Soil Cover for 9" × 2^1/$_2$" Structural Plate Aluminum Pipe-Arch for a Corner Radius of 31.75 in, and Thickness of 0.100in and 0.125in.

9" x 2 1/2" Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)															
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)											
				0.100						0.125					
				INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv	INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv
31.75	6-7	5-8	29.6	23.60	23.80	23.69	15.97	16.18	20.88	26.70	29.80	29.49	23.39	22.51	30.57
31.75	6-11	5-9	31.9	22.40	23.00	22.93	14.44	14.39	19.87	25.40	28.85	28.55	21.14	20.30	29.10
31.75	7-3	5-11	34.3	21.40	21.95	22.18	13.20	12.87	18.96	24.20	27.50	27.62	19.33	18.39	27.76
31.75	7-9	6-0	36.8	20.00	21.10	21.08	10.91	10.98	17.73	22.70	26.40	26.26	15.98	16.00	25.97
31.75	8-1	6-1	39.3	19.20	20.44	20.37	10.13	9.94	17.00	21.70	25.70	25.38	14.83	14.65	24.90
31.75	8-5	6-3	41.9	18.40	19.20	19.67	9.44	9.03	16.33	20.90	24.20	24.51	13.83	13.46	23.91
31.75	8-10	6-4	44.5	17.60	18.75	18.83	7.58	8.05	15.56	19.90	23.65	23.46	11.43	12.17	22.78
31.75	9-3	6-5	47.1	16.80	18.21	18.01	7.05	7.22	14.86	19.00	23.10	22.44	10.73	11.05	21.76
31.75	9-7	6-6	49.9	16.20	17.00	17.37	6.68	6.64	14.34	18.30	21.67	21.65	10.19	10.26	21.00
31.75	9-11	6-8	52.7	15.60	16.45	16.75	6.35	6.12	13.86	17.70	20.95	20.87	9.70	9.55	20.29
31.75	10-3	6-9	55.5	15.10	16.10	16.14	5.53	5.66	13.41	17.10	20.50	20.11	9.25	8.91	19.63
31.75	10-9	6-10	58.4	14.40	15.00	15.26	4.90	5.05	12.78	16.30	19.15	19.01	7.46	8.07	18.72
31.75	11-1	7-0	61.4	14.00	14.30	14.69	4.70	4.70	12.40	15.80	18.35	18.31	7.20	7.57	18.16
31.75	11-5	7-1	64.4	13.60	14.38	14.14	4.50	4.38	12.04	15.40	18.35	17.62	6.91	7.11	17.63
31.75	11-9	7-2	67.5	13.20	13.42	13.61	4.30	4.09	11.70	14.90	17.26	16.95	6.80	6.70	17.13
31.75	12-3	7-3	70.5	12.60	12.90	12.83	3.36	3.70	11.22	14.30	16.76	15.98	5.47	6.14	16.43
31.75	12-7	7-5	73.7	11.70	12.15	12.34	3.30	3.48	10.92	13.90	16.05	15.35	5.33	5.80	15.99
31.75	12-11	7-6	77	11.30	11.80	11.86	3.20	3.27	10.64	13.60	15.23	14.75	5.20	5.49	15.58
31.75	13-1	8-2	83	11.20	11.60	11.63	3.20	3.17	10.50	13.40	15.00	14.46	5.22	5.35	15.38
31.75	13-1	8-4	86.8	11.20	11.85	11.63	3.48	3.17	10.50	13.40	15.15	14.46	5.72	5.35	15.38
31.75	13-11	8-5	90.3	10.40	10.25	10.52	2.47	2.74	9.88	12.00	13.40	13.06	4.20	4.70	14.46
31.75	14-0	8-7	94.2	10.30	10.48	10.42	2.85	2.70	9.82	11.90	13.74	12.92	4.75	4.64	14.37
31.75	13-11	9-5	101.5	10.40	9.90	10.52	3.03	2.74	9.76	12.00	12.90	13.06	5.00	4.70	14.29
31.75	14-3	9-7	105.7	10.10	9.62	10.11	2.50	2.59	9.64	11.70	12.85	12.53	4.85	4.47	14.12
31.75	14-8	9-8	109.9							11.30	12.43	11.90	4.45	4.21	13.72
31.75	14-11	9-10	114.2							11.10	11.94	11.53	4.30	4.07	13.49
31.75	15-4	10-0	118.6							10.70	11.85	10.95	4.00	3.84	13.12
31.75	15-7	10-2	123.1							10.50	11.29	10.62	3.85	3.71	12.91
31.75	16-1	10-4	127.6							10.10	10.72	9.98	3.52	3.47	12.51

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

Table 4.11.
Maximum Soil Cover for 9” × 2$^{1}/_{2}$” Structural Plate Aluminum Pipe-Arch for a Corner Radius of 31.75 in, and Thickness of 0.200in.

9" x 2 1/2" Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)									
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)					
				0.200					
				INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv
31.75	6-7	5-8	29.6	26.70	48.00	49.16	41.87	39.36	54.73
31.75	6-11	5-9	31.9	25.40	46.40	47.07	37.84	35.71	52.09
31.75	7-3	5-11	34.3	24.20	44.40	45.05	34.60	32.54	49.69
31.75	7-9	6-0	36.8	22.70	42.80	42.16	28.60	28.53	46.49
31.75	8-1	6-1	39.3	21.70	41.80	40.33	26.55	26.25	44.57
31.75	8-5	6-3	41.9	20.90	39.20	38.57	24.76	24.24	42.81
31.75	8-10	6-4	44.5	19.90	37.20	36.47	20.46	22.04	40.79
31.75	9-3	6-5	47.1	19.00	34.50	34.49	19.20	20.12	38.95
31.75	9-7	6-6	49.9	18.30	31.60	32.99	18.25	18.76	37.59
31.75	9-11	6-8	52.7	17.70	31.30	31.56	17.37	17.54	36.33
31.75	10-3	6-9	55.5	17.10	31.20	30.20	16.56	16.43	35.15
31.75	10-9	6-10	58.4	16.30	27.00	28.31	13.73	14.96	33.51
31.75	11-1	7-0	61.4	15.80	26.90	27.14	13.27	14.08	32.51
31.75	11-5	7-1	64.4	15.40	25.70	26.04	12.81	13.28	31.56
31.75	11-9	7-2	67.5	14.90	23.00	25.01	12.37	12.55	30.66
31.75	12-3	7-3	70.5	14.30	21.95	23.62	10.28	11.56	29.41
31.75	12-7	7-5	73.7	13.90	21.60	22.78	10.04	10.96	28.63
31.75	12-11	7-6	77	13.60	21.20	22.01	9.80	10.41	27.89
31.75	13-1	8-2	83	13.40	24.48	25.38	9.85	10.15	27.54
31.75	13-1	8-4	86.8	13.40	25.80	25.38	10.70	10.15	27.54
31.75	13-11	8-5	90.3	12.00	22.40	23.61	8.19	8.99	25.89
31.75	14-0	8-7	94.2	11.90	23.73	23.44	9.05	8.88	25.73
31.75	13-11	9-5	101.5	12.00	22.23	23.61	9.42	8.99	25.58
31.75	14-3	9-7	105.7	11.70	22.80	22.95	9.21	8.58	25.28
31.75	14-8	9-8	109.9	11.30	21.50	22.15	8.58	8.10	24.56
31.75	14-11	9-10	114.2	11.10	20.66	21.70	8.35	7.84	24.15
31.75	15-4	10-0	118.6	10.70	20.56	20.97	7.66	7.42	23.50
31.75	15-7	10-2	123.1	10.50	19.63	20.55	7.45	7.19	23.12
31.75	16-1	10-4	127.6	10.10	18.92	19.76	6.90	6.76	22.40
31.75	16-4	10-6	132.3	9.90	19.10	19.38	6.74	6.55	22.06
31.75	16-9	10-8	136.9	9.60	17.54	18.79	6.30	6.24	21.51
31.75	17-0	10-10	141.8	9.50	17.80	18.45	6.17	6.06	21.19
31.75	17-3	11-0	146.7	9.30	17.70	18.13	6.10	5.88	20.89
31.75	17-9	11-2	151.6	8.90	16.54	17.53	5.60	5.56	20.30
31.75	18-0	11-4	156.7	8.80	16.54	17.25	5.50	5.41	20.02
31.75	18-5	11-6	161.7	8.50	15.95	16.82	5.14	5.17	19.56
31.75	18-8	11-8	167	8.40	15.38	16.58	5.07	5.04	19.30
31.75	19-2	11-9	172.2	8.00	NC	16.14	4.73	4.78	18.80
31.75	19-5	11-11	177.6	7.90	15.40	15.94	4.60	4.66	18.56
31.75	19-10	12-1	182.9	7.70	14.25	15.64	4.30	4.47	18.17
31.75	20-1	12-3	188.5	7.50	14.25	15.48	4.26	4.36	17.94

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

Table 4.10.
Maximum Soil Cover for 9" × $2^1/_2$" Structural Plate Aluminum Pipe-Arch for a Corner Radius of 31.75 in, and Thickness of 0.150in and 0.175in.

9" x 2 1/2" Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)															
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)											
				0.150						0.175					
				INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv	INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv
31.75	6-7	5-8	29.6	26.70	35.90	35.78	30.86	29.15	40.34	26.70	42.10	42.08	36.34	34.18	47.49
31.75	6-11	5-9	31.9	25.40	34.80	34.67	27.89	26.40	38.39	25.40	40.70	40.72	32.84	30.98	45.20
31.75	7-3	5-11	34.3	24.20	33.10	33.57	25.50	24.02	36.63	24.20	38.80	39.41	30.03	28.22	43.13
31.75	7-9	6-0	36.8	22.70	31.80	31.98	21.08	21.01	34.26	22.70	37.20	37.50	24.82	24.71	40.34
31.75	8-1	6-1	39.3	21.70	31.00	30.95	19.57	19.31	32.85	21.70	36.30	36.27	23.04	22.73	38.68
31.75	8-5	6-3	41.9	20.90	29.20	29.95	18.25	17.81	31.55	20.90	34.25	35.07	21.48	20.97	37.15
31.75	8-10	6-4	44.5	19.90	28.60	28.73	15.08	16.16	30.06	19.90	33.50	33.63	17.75	19.05	35.40
31.75	9-3	6-5	47.1	19.00	27.85	27.55	14.15	14.73	28.71	19.00	32.60	32.24	16.66	17.38	33.80
31.75	9-7	6-6	49.9	18.30	26.34	26.64	13.45	13.72	27.71	18.30	30.20	31.17	15.84	16.20	32.63
31.75	9-11	6-8	52.7	17.70	25.50	25.75	12.80	12.81	26.78	17.70	29.98	30.13	15.08	15.14	31.53
31.75	10-3	6-9	55.5	17.10	24.90	24.89	12.20	11.99	25.91	17.10	29.20	29.13	14.37	14.18	30.50
31.75	10-9	6-10	58.4	16.30	23.42	23.64	10.12	10.90	24.70	16.30	26.30	27.69	11.92	12.89	29.09
31.75	11-1	7-0	61.4	15.80	22.55	22.85	9.78	10.25	23.96	15.80	26.25	26.78	11.51	12.14	28.21
31.75	11-5	7-1	64.4	15.40	22.40	22.07	9.44	9.66	23.26	15.40	25.80	25.90	11.12	11.44	27.39
31.75	11-9	7-2	67.5	14.90	21.16	21.33	9.12	9.11	22.60	14.90	22.40	25.06	10.74	10.80	26.61
31.75	12-3	7-3	70.5	14.30	20.50	20.25	7.40	8.38	21.68	14.30	21.57	23.86	8.92	9.95	25.52
31.75	12-7	7-5	73.7	13.90	19.75	19.57	7.20	7.94	21.10	13.90	21.30	23.11	8.72	9.43	24.85
31.75	12-11	7-6	77	13.60	18.59	18.91	7.00	7.54	20.56	13.60	20.70	22.39	8.50	8.95	24.21
31.75	13-1	8-2	83	13.40	18.47	18.59	7.05	7.35	20.30	13.40	21.92	22.04	8.54	8.73	23.90
31.75	13-1	8-4	86.8	13.40	18.65	18.59	7.73	7.35	20.30	13.40	22.20	22.04	9.29	8.73	23.90
31.75	13-11	8-5	90.3	12.00	16.60	17.09	5.80	6.49	19.08	12.00	19.85	20.44	6.90	7.72	22.47
31.75	14-0	8-7	94.2	11.90	17.03	16.95	6.44	6.41	18.97	11.90	20.35	20.29	7.70	7.63	22.33
31.75	13-11	9-5	101.5	12.00	16.00	17.09	6.73	6.49	18.86	12.00	19.05	20.44	8.18	7.72	22.20
31.75	14-3	9-7	105.7	11.70	15.90	16.54	6.56	6.19	18.63	11.70	19.70	19.86	7.99	7.36	21.94
31.75	14-8	9-8	109.9	11.30	15.25	15.88	6.10	5.84	18.11	11.30	18.21	19.19	7.26	6.95	21.32
31.75	14-11	9-10	114.2	11.10	14.46	15.50	5.93	5.65	17.80	11.10	17.74	18.81	7.05	6.72	20.96
31.75	15-4	10-0	118.6	10.70	14.75	14.91	5.52	5.34	17.32	10.70	17.65	18.22	6.57	6.37	20.39
31.75	15-7	10-2	123.1	10.50	14.07	14.57	5.37	5.17	17.04	10.50	16.54	17.90	6.40	6.16	20.06
31.75	16-1	10-4	127.6	10.10	13.40	13.94	5.00	4.85	16.51	10.10	16.13	17.31	5.60	5.79	19.44
31.75	16-4	10-6	132.3	9.90	13.65	13.65	5.04	4.71	16.26	9.90	16.35	17.04	5.80	5.61	19.14
31.75	16-9	10-8	136.9	9.60	12.52	13.19	4.50	4.47	15.85	9.60	15.00	16.64	5.42	5.34	18.67
31.75	17-0	10-10	141.8	9.50	12.64	12.93	4.38	4.34	15.62	9.50	15.20	16.43	5.30	5.18	18.39
31.75	17-3	11-0	146.7	9.30	12.70	12.69	4.27	4.22	15.39	9.30	15.20	16.23	5.20	5.04	18.13
31.75	17-9	11-2	151.6							8.90	13.83	15.91	4.80	4.76	17.62
31.75	18-0	11-4	156.7							8.80	14.12	15.77	4.70	4.63	17.37
31.75	18-5	11-6	161.7							8.50	13.73	15.59	4.36	4.42	16.98
31.75	18-8	11-8	167							8.40	13.11	15.51	4.30	4.31	16.75

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

Table 4.12.
Maximum Soil Cover for 9" × 2 1/2" Structural Plate Aluminum Pipe-Arch for a Corner Radius of 31.75 in, and Thickness of 0.225in.

9" x 2 1/2" Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)									
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)					
				0.225					
				INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv
31.75	6-7	5-8	29.6	26.70	54.00	55.88	47.46	44.40	62.03
31.75	6-11	5-9	31.9	25.40	52.00	53.16	42.90	40.30	59.04
31.75	7-3	5-11	34.3	24.20	50.00	50.55	39.22	36.75	56.33
31.75	7-9	6-0	36.8	22.70	48.20	46.81	32.42	32.25	52.69
31.75	8-1	6-1	39.3	21.70	46.80	44.45	30.09	29.69	50.52
31.75	8-5	6-3	41.9	20.90	44.10	42.20	28.06	27.43	48.52
31.75	8-10	6-4	44.5	19.90	38.60	39.52	23.19	24.95	46.23
31.75	9-3	6-5	47.1	19.00	35.70	37.00	21.77	22.79	44.15
31.75	9-7	6-6	49.9	18.30	32.15	35.10	20.69	21.26	42.61
31.75	9-11	6-8	52.7	17.70	32.35	33.30	19.69	19.88	41.18
31.75	10-3	6-9	55.5	17.10	31.00	31.60	18.77	18.64	39.84
31.75	10-9	6-10	58.4	16.30	27.60	29.25	15.56	16.97	37.99
31.75	11-1	7-0	61.4	15.80	27.50	27.81	15.04	15.99	36.85
31.75	11-5	7-1	64.4	15.40	26.30	26.48	14.52	15.09	35.77
31.75	11-9	7-2	67.5	14.90	23.52	25.24	14.02	14.26	34.76
31.75	12-3	7-3	70.5	14.30	22.45	23.58	11.66	13.14	33.34
31.75	12-7	7-5	73.7	13.90	22.10	22.61	11.39	12.46	32.45
31.75	12-11	7-6	77	13.60	21.50	26.75	11.10	11.84	31.62
31.75	13-1	8-2	83	13.40	25.40	26.39	11.16	11.55	31.21
31.75	13-1	8-4	86.8	13.40	27.50	26.39	12.13	11.55	31.21
31.75	13-11	8-5	90.3	12.00	22.70	24.71	9.28	10.23	29.34
31.75	14-0	8-7	94.2	11.90	25.38	24.56	10.26	10.11	29.17
31.75	13-11	9-5	101.5	12.00	25.23	24.71	10.68	10.23	29.00
31.75	14-3	9-7	105.7	11.70	26.10	24.10	10.43	9.77	28.66
31.75	14-8	9-8	109.9	11.30	24.31	23.37	9.73	9.23	27.84
31.75	14-11	9-10	114.2	11.10	25.59	22.96	9.47	8.93	27.38
31.75	15-4	10-0	118.6	10.70	23.50	22.29	8.85	8.46	26.63
31.75	15-7	10-2	123.1	10.50	21.96	21.91	8.63	8.20	26.21
31.75	16-1	10-4	127.6	10.10	21.64	21.19	8.05	7.70	25.39
31.75	16-4	10-6	132.3	9.90	21.88	20.85	7.72	7.47	25.00
31.75	16-9	10-8	136.9	9.60	20.08	20.30	7.20	7.11	24.38
31.75	17-0	10-10	141.8	9.50	20.42	19.98	7.00	6.91	24.02
31.75	17-3	11-0	146.7	9.30	20.35	19.67	6.80	6.71	23.67
31.75	17-9	11-2	151.6	8.90	18.96	19.08	6.50	6.35	23.01
31.75	18-0	11-4	156.7	8.80	18.99	18.80	6.30	6.18	22.69
31.75	18-5	11-6	161.7	8.50	18.30	18.35	5.80	5.91	22.17
31.75	18-8	11-8	167	8.40	17.68	18.09	5.80	5.75	21.88
31.75	19-2	11-9	172.2	8.00	17.64	17.59	5.40	5.46	21.31
31.75	19-5	11-11	177.6	7.90	17.75	17.35	5.30	5.32	21.03
31.75	19-10	12-1	182.9	7.70	16.40	16.96	5.00	5.11	20.59
31.75	20-1	12-3	188.5	7.50	16.45	16.73	4.90	4.98	20.33
31.75	20-1	12-6	194.4	7.50	16.60	16.73	5.20	4.98	20.33
31.75	20-10	12-7	199.7	7.10	16.00	16.09	4.60	4.64	19.60
31.75	21-1	12-9	205.5	7.00	NC	15.89	4.50	4.53	19.37
31.75	21-6	12-11	211.2	6.70	14.60	15.56	4.20	4.36	18.99

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

Table 4.13.
Maximum Soil Cover for 9” × 2½” Structural Plate Aluminum Pipe-Arch for a Corner Radius of 31.75 in, and Thickness of 0.250in.

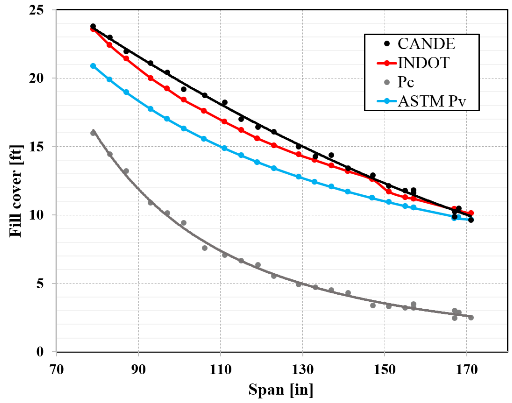
9'' x 2 1/2'' Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)									
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)					
				0.250					
				INDOT	CANDE	BEST FIT	Pc	BEST FIT Pc	ASTM Pv
31.75	6-7	5-8	29.6	26.70	60.75	62.90	53.11	49.53	69.41
31.75	6-11	5-9	31.9	25.40	58.60	59.22	48.00	44.97	66.07
31.75	7-3	5-11	34.3	24.20	55.80	55.70	43.89	41.01	63.03
31.75	7-9	6-0	36.8	22.70	54.20	50.73	36.28	36.00	58.96
31.75	8-1	6-1	39.3	21.70	52.25	47.61	33.68	33.15	56.53
31.75	8-5	6-3	41.9	20.90	46.70	44.66	31.40	30.63	54.29
31.75	8-10	6-4	44.5	19.90	39.95	41.19	25.95	27.87	51.73
31.75	9-3	6-5	47.1	19.00	36.90	37.96	24.36	25.47	49.40
31.75	9-7	6-6	49.9	18.30	33.70	35.57	23.15	23.76	47.68
31.75	9-11	6-8	52.7	17.70	33.30	33.33	22.03	22.23	46.08
31.75	10-3	6-9	55.5	17.10	31.90	31.26	21.00	20.83	44.58
31.75	10-9	6-10	58.4	16.30	28.00	28.44	17.42	18.98	42.51
31.75	11-1	7-0	61.4	15.80	28.10	26.76	16.83	17.88	41.23
31.75	11-5	7-1	64.4	15.40	26.80	25.25	16.25	16.87	40.03
31.75	11-9	7-2	67.5	14.90	24.35	23.89	15.69	15.95	38.89
31.75	12-3	7-3	70.5	14.30	22.90	22.16	13.04	14.70	37.30
31.75	12-7	7-5	73.7	13.90	22.25	21.20	12.74	13.95	36.32
31.75	12-11	7-6	77	13.60	21.90	20.40	12.43	13.25	35.38
31.75	13-1	8-2	83	13.40	25.68	28.69	12.49	12.93	34.93
31.75	13-1	8-4	86.8	13.40	27.80	28.69	13.57	12.93	34.93
31.75	13-11	8-5	90.3	12.00	22.60	27.05	10.38	11.46	32.84
31.75	14-0	8-7	94.2	11.90	25.23	26.90	11.48	11.32	32.64
31.75	13-11	9-5	101.5	12.00	28.45	27.05	11.95	11.46	32.45
31.75	14-3	9-7	105.7	11.70	29.30	26.45	11.68	10.94	32.07
31.75	14-8	9-8	109.9	11.30	27.42	25.73	10.88	10.34	31.16
31.75	14-11	9-10	114.2	11.10	26.09	25.32	10.60	10.00	30.64
31.75	15-4	10-0	118.6	10.70	26.40	24.66	9.91	9.48	29.80
31.75	15-7	10-2	123.1	10.50	25.23	24.29	9.66	9.18	29.32
31.75	16-1	10-4	127.6	10.10	24.39	23.57	9.00	8.63	28.41
31.75	16-4	10-6	132.3	9.90	24.70	23.22	8.80	8.37	27.98
31.75	16-9	10-8	136.9	9.60	22.73	22.67	8.25	7.97	27.28
31.75	17-0	10-10	141.8	9.50	23.06	22.35	8.07	7.74	26.88
31.75	17-3	11-0	146.7	9.30	23.00	22.04	7.77	7.53	26.49
31.75	17-9	11-2	151.6	8.90	21.40	21.45	7.25	7.12	25.75
31.75	18-0	11-4	156.7	8.80	21.51	21.17	7.00	6.93	25.39
31.75	18-5	11-6	161.7	8.50	20.65	20.71	6.63	6.62	24.81
31.75	18-8	11-8	167	8.40	20.03	20.45	6.50	6.45	24.48
31.75	19-2	11-9	172.2	8.00	20.00	19.94	6.20	6.12	23.84
31.75	19-5	11-11	177.6	7.90	20.12	19.69	5.70	5.97	23.54
31.75	19-10	12-1	182.9	7.70	18.60	19.30	5.60	5.73	23.04
31.75	20-1	12-3	188.5	7.50	18.72	19.07	5.60	5.59	22.75
31.75	20-1	12-6	194.4	7.50	18.85	19.07	5.50	5.59	22.75
31.75	20-10	12-7	199.7	7.10	18.20	18.42	5.20	5.20	21.93
31.75	21-1	12-9	205.5	7.00	NC	18.21	5.10	5.08	21.67
31.75	21-6	12-11	211.2	6.70	16.50	17.87	4.80	4.89	21.25

	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged

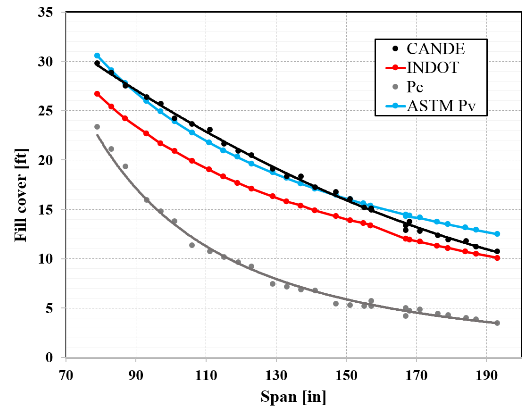
Table 4.14.
Maximum Soil Cover for 9” × 2½” Structural Plate Aluminum Pipe-Arch for a Corner Radius of 47 in, and Thickness of 0.250in.

9" x 2 1/2" Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)							
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)			
				0.250			
				INDOT	CANDE	Pc	ASTM Pv
47	20-1	13-11	216.6	12.40	19.45	8.62	22.75
47	20-7	14-3	224	12.10	19.20	8.27	22.20
47	21-5	14-7	241.5	11.50	18.11	4.70	21.34
47	21-11	14-11	254.7	11.20	17.63	4.60	20.85

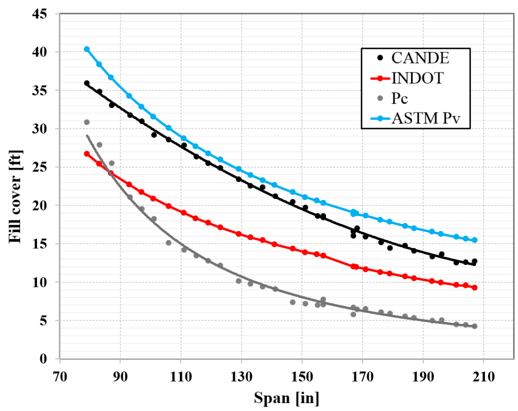
	INDOT
	Seam and Material Thrust
	Buckling
	Vertical Deflection
NC	Not Converged



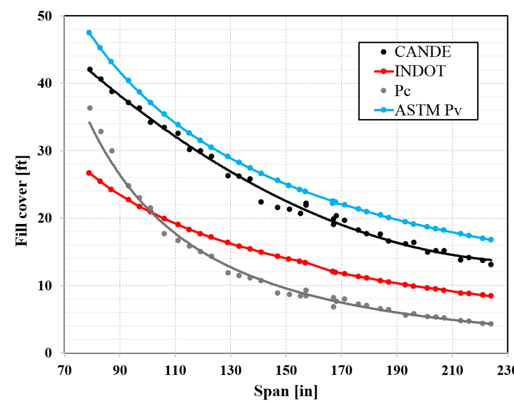
(a) Thickness 0.100 in.



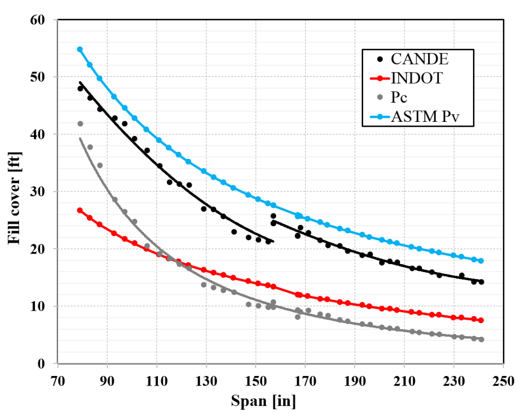
(b) Thickness 0.125 in.



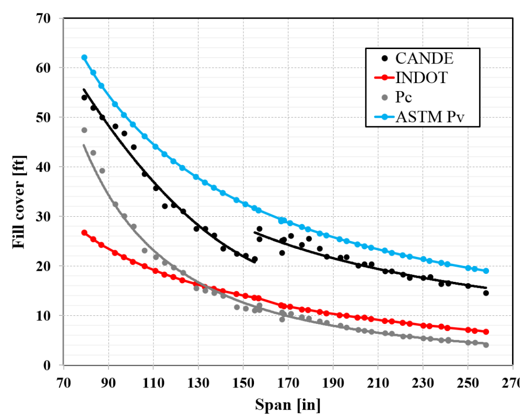
(c) Thickness 0.150 in.



(d) Thickness 0.175 in.

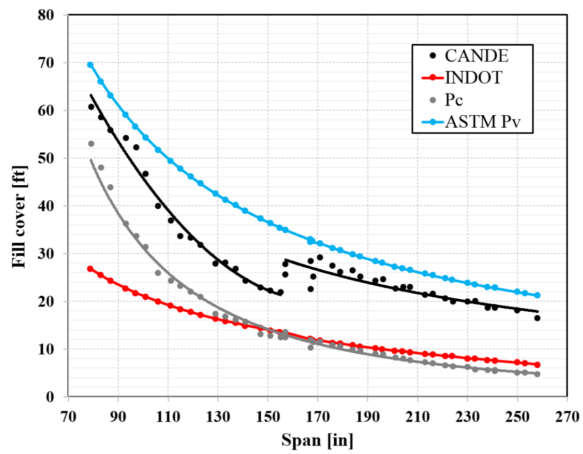


(e) Thickness 0.200 in.

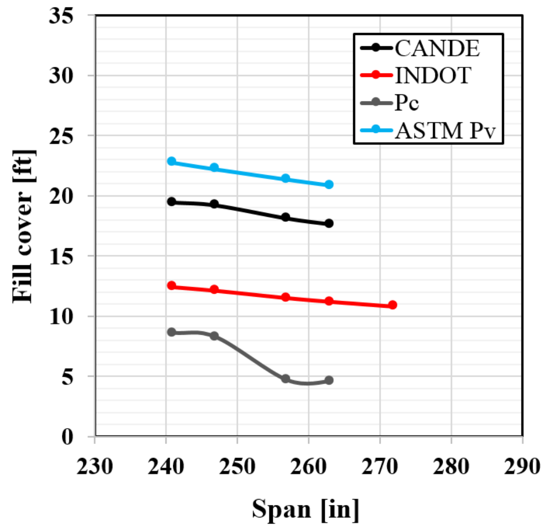


(f) Thickness 0.225 in.

Fig. 4.14. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 9" × 2½" Structural Plate Aluminum Pipe-Arch with Corner Radius of 31.75 in, and Thicknesses of 0.100 in (4.14(a)), 0.125 in (4.14(b)), 0.150 in (4.14(c)), 0.175 in (4.14(d)), 0.200 in (4.14(e)) and 0.225 in (4.14(f)).



(a) Thickness 0.250 - Rc 31.75 in in.



(b) Thickness 0.250 - Rc 47 in in.

Fig. 4.15. Maximum Fill Cover. Comparison between CANDE, INDOT, Pc and ASTM Pv for 9” × 2½” Structural Plate Aluminum Pipe-Arch with Corner Radius of 31.75 in, and Thicknesses of 0.250 in (4.15(a)); and a Corner Radius of 47 in, and a of 0.250 in (4.15(b)).

5. CONCLUSIONS

Six hundred twenty-four pipe-arches fill heights were calculated using the finite element method at the software CANDE, 624 fill heights for pipe-arches were analytically calculated using ASTM standards assuming two different design pressures, radial (P_v) and corner (P_c) pressure, and 9 cases were verified using the finite element method at Abaqus for the buckling failure mode. Overall, fill covers decreased when increasing span, and increased when increasing the corrugation thickness.

The CANDE finite element results and INDOT calculations, differ significantly due to different assumptions on pipe loading: the maximum height of the fill cover is defined by the failure of the pipe due to radial soil pressure, or is defined the by the maximum pressure that the pipe can exert on the soil surrounding it, where the critical point is at the location of the corner radius of the pipe (R_c). When assuming the model will fail because of the pipe (determined by the critical mode of failure), the results obtained with the analytical solution using ASTM calculations and considering the radial pressure (P_v) are in general agreement with those obtained using the finite element solution in CANDE. If assuming the bearing capacity of the soil around the corner radius will determine the maximum fill cover, the results obtained with the analytical solution using ASTM calculations and considering the corner pressure (P_c) will be smaller than those obtained considering the first approach, but aligned with the INDOT tables.

Some of the analyses performed in CANDE assuming small deformations did not converge. This nonconvergence may be caused because of the magnitude of load increments, change in mesh for every pipe-arch case (same number of elements, but different element sizes), or because the coefficient of friction and tensile force used.

The more reliable solutions for solving nonconvergence issues were: using more load steps to define thinner soil layers for gravity loads or smaller force increments for boundary conditions, and refining the mesh (i.e., using Mesh 3 instead of Mesh 2 in Table 3.1). These solutions considered the fact that the coefficient of friction and tensile force remain constant for all the analysis for ensuring the comparability of the results and that varying the number of elements in the mesh for a Level 3 solution in CANDE (use a different mesh from those shown in Table 3.1) is a difficult task.

After analyzing the results obtained in Abaqus for the global buckling failure mode, it can be concluded that, for both approaches (pipe failing or bearing capacity of the soil), buckling is not the failure mode governing the analysis and that the small deformation approximation was adequate for evaluating maximum fill covers over pipe-arches. When considering only the pipe failure, the seam strength due to thrust stress and vertical deflection govern the analysis. Moreover, none of the cases failed because of the wall yielding failure mode or the plastic penetration limit criterion.

The calculations performed are very sensitive to the assumption. Carefully consideration should be made when selecting the type of installation to be used, gravelly sand compaction, coefficient of friction, and tensile force for the soil-pipe interaction, soil and pipe properties, analysis methodology and design criteria. Each parameter can lead to significant changes in the maximum fill heights calculated in CANDE.

Specific considerations should be made if the soil to be used differs from gravelly sand with 90% compaction. Furthermore, pipe-arches should be handled according to to ASTM standards [11], [12]. The critical zone for the plastic strain of the soil is the one surrounding the corner radius, an area where the soil compaction and quality control are difficult, increasing the risk of failing because of soil bearing capacity.

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REFERENCES

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APPENDICES

A. INPUTS

A.0.1 Geometrical properties of Corrugated Steel and Aluminum Pipe-Arches

Table A.1.
CSPA and CAPA size and layout details 2²/₃” × ¹/₂” corrugation.

Rc (in)	**SPAN (in)**	**RISE (in)**	**A (sft)**	**B (in)**	**Rt (in)**	**Rb (in)**
3 1/2	17	13	1.1	4 1/8	8 5/8	25 5/8
4 1/8	21	15	1.6	4 7/8	10 3/4	33 1/8
4 7/8	24	18	2.2	5 5/8	11 7/8	34 5/8
5 1/2	28	20	2.9	6 1/2	14	42 1/4
6 7/8	35	24	4.5	8 1/8	17 7/8	55 1/8
8 1/4	42	29	6.5	9 3/4	21 1/2	66 1/8
9 5/8	49	33	8.9	11 3/8	25 1/8	77 1/4
11	57	38	11.6	13	28 5/8	88 1/4
12 3/8	64	43	14.7	14 5/8	32 1/4	99 1/4
13 3/4	71	47	18.1	16 1/4	35 3/4	110 1/4
15 1/8	77	52	21.9	17 7/8	39 3/8	121 1/4
16 1/2	83	57	26	19 1/2	43	132 1/4

Table A.2.
CSPA and CAPA size and layout details 3 × 1" and 5 × 1" corrugation.

Nominal Size(in)	Rc (in)	Design SPAN (in)	Design RISE (in)	A (sft)	B(in)	Rt (in)	Rb (in)
60 x 46	18 3/4	58 1/2	48 1/2	15.6	20 1/2	29 3/8	51 1/8
66 x 51	20 3/4	65	54	19.3	22 3/4	32 5/8	56 1/4
73 x 55	22 7/8	72 1/2	58 1/4	23.2	25 1/8	36 3/4	63 3/4
81 x 59	20 7/8	79	62 1/2	27.4	23 3/4	39 1/2	82 5/8
87 x 63	22 5/8	86 1/2	67 1/4	32.1	25 3/4	43 3/8	92 1/4
95 x 67	24 3/8	93 1/2	71 3/4	37	27 3/4	47	100 1/4
103 x 71	26 1/8	101 1/2	76	42.4	29 3/4	51 1/4	111 5/8
112 x 75	27 3/4	108 1/2	80 1/2	48	31 5/8	54 7/8	120 1/4
117 x 79	29 1/2	116 1/2	84 3/4	54.2	33 5/8	59 3/8	131 3/4
128 x 83	31 1/4	123 1/2	89 1/4	60.5	35 5/8	63 1/4	139 3/4
137 x 87	33	131	93 3/4	67.4	37 5/8	67 3/8	149 1/2
142 x 91	34 3/4	138 1/2	98	74.5	39 1/2	71 5/8	162 3/8

Table A.3.
CSPA section properties details $2^2/_3$" × $^1/_2$", 3 × 1" and 5 × 1" corrugation.

Corrugation Thickness (in)	Corrugation Profile (in)								
	2 2/3 x 1/2			3 x 1			5 x 1		
	PA (in^2/in)	PI (in^4/in)	PS (in^3/in)	PA (in^2/in)	PI (in^4/in)	PS (in^3/in)	PA (in^2/in)	PI (in^4/in)	PS (in^3/in)
0.064	0.0646	0.00189	0.0067	0.0742	0.00866	0.01628	0.0662	0.00885	0.01664
0.079	0.0807	0.00239	0.00826	0.0928	0.01088	0.02017	0.8267	0.01109	0.02056
0.109	0.113	0.00342	0.01123	0.13	0.01546	0.02788	0.1158	0.01565	0.02822
0.138	0.1453	0.00453	0.0142	0.1673	0.02018	0.03547	0.149	0.02032	0.03571
0.168	0.1778	0.00573	0.01716	0.2048	0.02509	0.04296	0.1822	0.02509	0.04296

Table A.4.
CAPA section properties details $2^2/_3$" × $^1/_2$" and 3 × 1" corrugation.

Corrugation Thickness (in)	Corrugation Profile (in)					
	2 2/3 x 1/2			3 x 1		
	PA (in^2/in)	PI (in^4/in)	PS (in^3/in)	PA (in^2/in)	PI (in^4/in)	PS (in^3/in)
0.060	0.06458	0.00189	0.00675	0.07416	0.00866	0.01634
0.075	0.08067	0.00239	0.00831	0.09317	0.01088	0.02024
0.105	0.11300	0.00342	0.01131	0.13000	0.01545	0.02796
0.135	0.14533	0.00453	0.01427	0.17400	0.02017	0.03554
0.164	0.17775	0.00573	0.01726	0.20483	0.02508	0.04309

A.0.2 Geometrical properties of Structural Plate Steel Pipe-Arches

Table A.5.
SPSPA size and layout details 6” × 2” corrugation - 18 in Corner Radius, Rc.

SPAN (ft-in)	RISE (ft-in)	A (ft^2)	B (in)	Rt (ft)	Rb (ft)
6-1	4-7	22	21	3.07	6.36
6-4	4-9	24	20.5	3.18	8.22
6-9	4-11	26	22	3.42	6.96
7-0	5-1	28	21.4	3.53	8.68
7-3	5-3	31	20.8	3.63	11.35
7-8	5-5	33	22.4	3.88	9.15
7-11	5-7	35	21.7	3.98	11.49
8-2	5-9	38	20.9	4.08	15.24
8-7	5-11	40	22.7	4.33	11.75
8-10	6-1	43	21.8	4.42	14.89
9-4	6-3	46	23.8	4.68	12.05
9-6	6-5	49	22.9	4.78	14.79
9-9	6-7	52	21.9	4.86	18.98
10-3	6-9	55	23.9	5.13	14.86
10-8	6-11	58	26.1	5.41	12.77
10-11	7-1	61	25.1	5.49	15.03
11-5	7-3	64	27.4	5.78	13.16
11-7	7-5	67	26.3	5.85	15.27
11-10	7-7	71	25.2	5.93	18.03
12-4	7-9	74	27.5	6.23	15.54
12-6	7-11	78	26.4	6.29	18.07
12-8	8-1	81	25.2	6.37	21.45
12-10	8-4	85	24	6.44	26.23

Table A.6.
SPSPA size and layout details 6” × 2” corrugation - 31 in corner radius, Rc.

SPAN (ft-in)	**RISE (ft-in)**	**A (ft^2)**	**B (in)**	**Rt (ft)**	**Rb (ft)**
13-3	9-4	97	38.5	6.68	16.05
13-6	9-6	102	37.7	6.78	18.33
168	9-8	105	39.6	7.03	16.49
14-2	9-10	109	38.8	7.13	18.55
14-5	10-0	114	37.9	7.22	21.38
14-11	10-2	118	39.8	7.48	18.98
15-4	10-4	123	41.8	7.76	17.38
15-7	10-6	127	40.9	7.84	19.34
15-10	10-8	132	40	7.93	21.72
16-3	10-10	137	42.1	8.21	19.67
16-6	11-0	142	41.1	8.29	21.93
17-0	11-2	146	43.3	8.58	20.08
17-2	11-4	151	42.3	8.65	22.23
17-5	11-6	157	41.3	8.73	24.83
17-6	11-8	161	43.5	9.02	22.55
18-1	11-10	167	42.4	9.09	24.98
18-7	12-0	172	44.7	9.38	22.88
18-9	12-2	177	43.6	9.46	25.19
19-3	12-4	182	45.9	9.75	23.22
19-6	12-6	188	44.8	9.83	25.43
19-8	12-8	194	43.7	9.9	28.04
19-11	12-10	200	42.5	9.98	31.19
20-5	13-0	205	44.9	10.27	28.18
20-7	13-2	211	43.7	10.33	31.13

Table A.7.
SPSPA section properties details 6” × 2” corrugation.

Corrugation Thickness (in)	**PA (in^2/in)**	**PI (in^4/in)**	**PS (in^3/in)**
0.111	0.1297	0.06041	0.05726
0.140	0.1669	0.07816	0.07305
0.280	0.3433	0.16583	0.14546

A.0.3 Geometrical properties of Structural Plate Aluminum Pipe-Arches

Table A.8.
SPAPA size and layout details 9" × 2½" Corrugation - 31.75 in corner radius, Rc.

SPAN (ft-in)	RISE (ft-in)	A (sft)	Rt (in)	Rb (in)
6-7	5-8	29.6	41.5	69.9
6-11	5-9	31.9	43.7	102.9
7-3	5-11	34.3	45.6	188.3
7-9	6-0	36.8	51.6	83.8
8-1	6-1	39.3	53.3	108.1
8-5	6-3	41.9	54.9	150.1
8-10	6-4	44.5	63.3	93
9-3	6-5	47.1	64.4	112.6
9-7	6-6	49.9	65.4	141.6
9-11	6-8	52.7	66.4	188.7
10-3	6-9	55.5	67.4	278.8
10-9	6-10	58.4	77.5	139.6
11-1	7-0	61.4	77.8	172
11-5	7-1	64.4	78.2	222
11-9	7-2	67.5	78.7	309.5
12-3	7-3	70.5	90.8	165.2
12-7	7-5	73.7	90.5	200
12-11	7-6	77	90.4	251.7
13-1	8-2	83	88.8	143.6
13-1	8-4	86.8	81.7	300.8
13-11	8-5	90.3	100.4	132
14-0	8-7	94.2	90.3	215.7
13-11	9-5	101.5	86.2	159.3

SPAN (ft-in)	RISE (ft-in)	A (sft)	Rt (in)	Rb (in)
14-3	9-7	105.7	87.2	176.3
14-8	9-8	109.9	90.9	166.2
14-11	9-10	114.2	91.8	183
15-4	10-0	118.6	95.5	173
15-7	10-2	123.1	96.4	189.6
16-1	10-4	127.6	100.2	179.7
16-4	10-6	132.3	101	196.1
16-9	10-8	136.9	105	186.5
17-0	10-10	141.8	105.7	202.5
17-3	11-0	146.7	106.5	221.7
17-9	11-2	151.6	110.4	208.9
18-0	11-4	156.7	111.1	227.3
18-5	11-6	161.7	115.8	215.3
18-8	11-8	167	115.8	233.7
19-2	11-9	172.2	119.9	221.5
19-5	11-11	177.6	120.5	239.7
19-10	12-1	182.9	124.7	227.7
20-1	12-3	188.5	125.2	245.3
20-1	12-6	194.4	122.5	310.8
20-10	12-7	199.7	130	251.2
21-1	12-9	205.5	130.5	270.9
21-6	12-11	211.2	134.8	257.3

Table A.9.
SPAPA size and layout details 9” × 2½” in Corrugation - 47 in corner radius, Rc.

SPAN (ft-in)	RISE (ft-in)	A (sft)	Rt (in)	Rb (in)
20-1	13-11	216.6	124	225.4
20-7	14-3	224	126.2	257.6
21-5	14-7	241.5	133	238.6
21-11	14-11	254.7	135	270

Table A.10.
SPAPA section properties details 9” × 2½” in corrugation.

Corrugation Thickness (in)	PA (in^2/in)	PI (in^4/in)	PS (in^3/in)
0.100	0.1170	0.0831	0.0639
0.125	0.1458	0.1040	0.0793
0.150	0.1750	0.1249	0.0943
0.175	0.2041	0.1459	0.1091
0.200	0.2333	0.1670	0.1237
0.225	0.2624	0.1882	0.1381
0.250	0.2918	0.2094	0.1523

B. CANDE INPUT FILE (.CID) EXAMPLE

rows — columns → `123456789   (Every dot counts as a column. The first column starts after the caracter "!")`

```
0001                A-1!!ANALYS   3 1  1New Input file title                                        1000    0    0    0
0002             A-2.L3!!STEEL       48
0003          B-1.Steel!!  29000000      0.3     33000     32336     0.284         0    0    1    0
0004        B-2.Steel.A!!   0.18220   0.02509   0.04296
0005  B-3.Steel.AD.LRFD!!         1         1         1       0.9         5
0006             C-1.L3!!PREP
0007             C-2.L3!!   30    3    0    3    1 1185  831  589    4    2    1
0008             C-3.L3!!    1  000    0.0000  -44.6250    1         1.0000    0.0000
0009             C-3.L3!!    2  000    3.5328  -44.5803    1         1.0000    0.0000
0010             C-3.L3!!    3  000    7.0634  -44.4464    1         1.0000    0.0000
```

```
0912             C-3.L3!! 1183  000    7.0517   44.2307    0         0.0000    0.0000
0913             C-3.L3!! 1184  000    3.5313   44.5263    0         0.0000    0.0000
0914             C-3.L3!!L1185  000    0.0000   44.6250    0         0.0000    0.0000
0915             C-4.L3!!    1    1   50   51    2    1    1    0
0916             C-4.L3!!    2    2   51   52    3    1    1    0
0917             C-4.L3!!    3    3   52   53    4    1    1    0
```

```
1743             C-4.L3!!  829 1134   47 1183    0   47    8    1
1744             C-4.L3!!  830 1135   48 1184    0   48    8    1
1745             C-4.L3!!L 831 1136   49 1185    0   49    8    1
1746             C-5.L3!!  544    0              0   -7.3605             20
1747             C-5.L3!!  543    0              0   -7.3605             20
```

```
1790             C-5.L3!! 1037    0              0  -29.8652             20
1791             C-5.L3!! 1087    0              0  -29.8652             20
1792             C-5.L3!!  544    0              0   -7.3605             21
1793             C-5.L3!!  543    0              0   -7.3605             21
```

```
1836             C-5.L3!! 1037    0              0  -29.8652             21
1837             C-5.L3!! 1087    0              0  -29.8652             21
1838             C-5.L3!!  544    0              0   -7.3605             22
```


Fig. B.1. Example Input file CANDE (.cid) Level 3 Mesh. Part A, B, C-1 to C-5. *continued on next page*

rows

columns

```
123456789   (Every dot counts as a column. The first column starts after the caracter "!")
```

```
2250             C-5.L3!! 1037    0              0  -29.8652             30
2251             C-5.L3!! 1087    0              0  -29.8652             30
2252             C-5.L3!!  446    1              0                        0
2253             C-5.L3!!  396    1              0                        0
```

```
2305             C-5.L3!! 1086    1              0                        0
2306             C-5.L3!! 1087    1              0                        0
2307             C-5.L3!!  496    1              1                        0
2308             C-5.L3!!  497    1              1                        0
```

```
2330             C-5.L3!! 1053    1              1                        0
2331             C-5.L3!! 1088    1              0                        0
2331             C-5.L3!! 1136    1              0                        0
2333             C-5.L3!! 1137    0              1                        0
2334             C-5.L3!!L1185    0              1                        0
2335                D-1!!    1    3       140SW90                0
2336         D-2.Duncan!!    0       0.5    1
2337                D-1!!    2    3       140SW90                0
2338         D-2.Duncan!!    0       0.5    1
2339                D-1!!    3    3       140SW90                0
2340         D-2.Duncan!!    0       0.5    1
2341                D-1!!    4    3       140SW90                0
2342         D-2.Duncan!!    0       0.5    1
2343                D-1!!    1    6         0                    0
2344      D-2.Interface!!       -90       0.5        10         0
2345                D-1!!L  49    6         0                    0
2346      D-2.Interface!!        90       0.5        10         0
2347                E-1!!    1    1      2.05Factor for load step #1
2348                E-1!!    2    2      2.05Factor for load step #2
```

```
2375                E-1!!   29   29      2.05Factor for load step #29
2376                E-1!!   30   30      2.05Factor for load step #30
2377   STOP
```

Fig. B.2. Example Input file CANDE (.cid) Level 3 Mesh. Part C-5, D and E.

Table B.1.: Detailed CANDE input for Pipe-Arches.

Parameter (rows) (columns) (units)	**Input Options and Description**
A-1 Master Control Input Data	
Design/Analysis Parameter (1) (01-08) (character)	Controls the decision of design or analysis mode. **Analysis** mode is selected on the analysis.
Solution Level (1) (09-10) (integer)	Defines between Level 1, 2 or 3, as Solution Level to be used. For the analysis is used the Solution **Level 3** user define mesh.
Method of Analysis/ Design (LRFD) (1) (11-12) (integer)	Choice of Working Stress or LRFD methodology for analysis and design. **LRFD** design methodology is used.
Number of Pipe Element Groups (1) (13-15) (integer)	Defines the number of pipe element groups evaluated in the same analysis. For pipe-arches every pipe is evaluated separated, and **option (=1)** is selected representing one pipe group.
Heading for Output Files (1) (16-75) (character)	Heading of the problem defined by the user.
Maximum Number of Iterations per Step (1) (76-80) (integer)	Defines the maximum number of iterations per load step. Typically **1000** iterations per step.
Process ID (1) (86-90) (integer)	Process identifier number for CANDE 2007 version. Default=0.

continued on next page

Table B.1.: *continued*

Parameter **(rows) (columns) (units)**	**Input Options and Description**
A-2.L3 Master Control Input Data	
Pipe Type **(2) (01-10) (word)**	Word defining type of pipe material. Either **ALUMINUM** or **STEEL** is selected depending on the pipe to be analyzed.
N° of Beam Elements **(2) (11-15) (word)**	Number of connected beam elements. Typically 48 for pipe-arches.
B-1.ALUMINUM or B-1.STEEL Aluminum or Steel Material and Control Parameters	
Youngs Modulus **(3) (01-10)** (lb/in^2)	Elastic Youngs Modulus of pipe material. See Table 2.1 for specific values.
Poissons Ratio **(3) (11-20) (–)**	Poissons ratio of pipe material. See Table 2.1 for specific values.
Yield Stress of Pipe **(3) (21-30)** (lb/in^2)	Yield stress of pipe. See Table 2.1 for specific values.
Yield Strength of Seam **(3) (31-40)** (lb/in^2)	Yield strength of pipe seam. See Table 2.2 for specific values.
Density of Material **(3) (41-50)** (lb/in^3)	Density of material. See Table 2.1 for specific values.
Linear Material Behavior **(3) (61-65) (integer)**	Code to select material behavior. **Code (=1)** is used and represents a linear stress-strain analysis.
Buckling Indicator **(3) (66-70) (integer)**	**Code (=0)** is used and represents a small deformation analysis.

continued on next page

Table B.1.: *continued*

Parameter (rows) (columns) (units)	Input Options and Description
B-2.ALUMINUM.A or B-2.STEEL.A Aluminum or Steel analysis section properties	
Area of pipe wall (4) (01-10) (in^2/in^2)	Area of pipe wall section per unit length (PA). See Annex A for specific values.
Moment of inertia (4) 11-20) (in^4/in^2)	Moment of inertia of pipe wall section per unit length (PI). See Annex A for specific values.
Section modulus (4) 21-30) (in^4/in^2)	Section modulus of pipe wall per unit length (PS). See Annex A for specific values.
B-3.ALUMINUM.AD.LRFD or B-3.StEEL.AD.LRFD Resistance factors for LRFD limit states	
Wall area yielding (5) (01-10) (–)	Resistance factor for wall area yielding due to thrust stress. See Table 2.4 for specific values.
Global buckling (5) (11-20) (–)	Resistance factor for global buckling due to thrust stress. See Table 2.4 for specific values.
Seam strength (5) (21-30) (–)	Resistance factor for seam strength due to thrust stress. See Table 2.4 for specific values.
Plastic-penetration (5) (31-40) (–)	Resistance factor for cross-section capacity for plastic-penetration. Defined as 0.9 for steel and 0.85 for aluminum .
Allowable deflection (5) (41-50) (–)	Allowable deflection at service load. For steel and aluminum is equal to 5%.
C-1.L3 Preparation (WORD), =PREP	
(6) (01-04) (word)	Required to continue inputting mesh data.

continued on next page

Table B.1.: *continued*

Parameter (rows) (columns) (units)	Input Options and Description
C-2.L3 Element number and property array	
Number of load steps (7) (01-05) (integer)	The number of load steps to be executed, Default=1. **Typically 30 load steps for pipe-arches.**
Mesh output (7) (06-10) (integer)	It controls the amount of mesh data to be written at CANDE output file. Default=3 prints the control information plus the created data, other options are printing only the control information (1), option (1) plus printing node and element input is (2) and option (1) plus Laplace generated nodes is (4). **For pipe-arches is equal to 3.**
Data check control (7) (11-15) (integer)	Check the validity of the input data. Choices include only to check the data and stop (1) or run the solution (0), Default=0. **For pipe-arches is equal to 0.**
Plot file control (7) (16-20) (integer)	Controls the plot files units 10 and 30. Default=3 creates units 10 and 30, where unit 10 contains all the finite element mesh and the structural responses and unit 30 the pipe responses or each load step. **For pipe-arches is equal to 3.**
Response data output (7) (21-25) (integer)	**The "standard" option (=1) is used**, where pipe plus the soil-system responses are printed.

continued on next page

Table B.1.: *continued*

Parameter (rows) (columns) (units)	**Input Options and Description**
Total number of nodes (7) (26-30) (integer)	The mumber of nodes used to create the mesh. If the numbering of nodes is not sequential, the higher node number correspond to the number of nodes. **Typically 1185 for pipe-arches.**
Total number of elements (7) (31-35) (integer)	The number of elements used to create the mesh, including the beam, continuum, and interface elements for the pipe, soil, and interface, respectively. **Typically 831 for biggest pipe-arches.**
Total number of boundary conditions (7) (36-40) (integer)	The total number of boundary conditions for this problem. **For pipe-arches typically is equal to 589.**
Total number of soil materials (7) (41-45) (integer)	The total number of soil materials used, where the minimum is four. **For pipe-arches one soil materials is defined for four different zones.**
Total number of interface materials (7) (46-50) (integer)	The total number of interface materials used. **For pipe-arches, this number is defined as 2**; since the automatic generation of interface materials is defined, only the first and last element at $-90°$ and $90°$, respectively is needed.
Code to minimize bandwidth (7) (51-55) (integer)	This feature on CANDE internally rearranges the defined node numbering scheme to minimize the bandwidth of the stiffness matrix. If it is set to 0,

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Table B.1.: *continued*

Parameter **(rows) (columns) (units)**	**Input Options and Description**
	no action is performed, set to 1 minimize the stiffness matrix and set to 2 minimize and print. **Typically is set to 1.**
C-3.L3 Level 3 node input	
Node **(8-914) (02-05) (integer)**	The node number to be defined.
Special reference code **(8-914) (06-08) (integer)**	It allows defining the coordinates based on previous coordinates. **Set to 0**, (standard input without nodal reference) for pipe-arches.
Special generation code **(8-914) (09-09) (integer)**	It allows defining nodal generation options. **Set to 0**, (no special generation modes are activated) for pipe-arches.
Basic generation code **(8-914) (10-10) (integer)**	It controls the basic options for the nodal generation of coordinates. **Set to 0**, (basic input, x and y coordinates will be specified).
X-coordinate **(8-914) (11-20) (inches)**	X-coordinate value.
Y-coordinate **(8-914) (21-30) (inches)**	Y-coordinate value.
Increment **(8-914) (31-35) (integer)**	Increment added to generate nodes when numbering is not sequential. **Default = 1.**

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Table B.1.: *continued*

Parameter (rows) (columns) (units)	**Input Options and Description**
Spacing (8-914) (41-50) (ratio)	Spacing ratio for generated node lengths. **Default** = **1**, all nodes generated will be evenly spaced.
Radius (8-914) (51-60) (inches)	Controls the path for the generation of nodes. **Default** = **0**, the path is a straight line.
Limit (914) (01-01) (letter)	Signal to indicate last node to be input, ***L***.
C-4.L3 Level 3 element input	
Element Number (915-1745) (02-05) (int.)	Element number to be defined.
Node I (915-1745) (06-10) (int.)	The first node in the element connectivity array.
Node J (915-1745) (11-15) (int.)	The second node in the element connectivity array.
Node K (915-1745) (16-20) (int.)	The third node in the element connectivity array, for interface and quadrilateral elements.
Node L (915-1745) (21-25) (int.)	The fourth node in the element connectivity array, only for quadrilateral elements For all other element types set Node L=0 .
Material Number (915-1745) (26-30) (int.)	It identifies the element type. The quadrilateral elements for the soil use one as the material

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Table B.1.: *continued*

Parameter (rows) (columns) (units)	Input Options and Description
	identification number, beam elements for the pipe use also 1. Every interface element uses a different identification number, ranging between 1 and 99 since only the interface elements that share the same friction coefficient, tension resistance and angle of the interface can have the same material number.
Load Step (915-1745) (31-35) (int.)	Load step number where the element is introduced into the system. When an element enters the system, it stays there for the next steps until the end of the analysis.
Interface (915-1745) (36-40) (int.)	When it is set to 1, it distinguishes the interface elements form the triangular elements. Non-interface elements are set to 0.
Node increment added (915-1745) (41-45) (int.)	Element increment added to compute node connectivity when the numbering of elements is not sequential. **Default=1**.
Node rows added (915-1745) (46-50) (int.)	The number of element rows to be generated for the computed node connectivity when the numbering is not sequential. **Default=1**.
Node increment between rows	It refers to the increment of node number between element rows, typically is the number of

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Table B.1.: *continued*

Parameter (rows) (columns) (units)	**Input Options and Description**
(915-1745) (51-55) (int.)	elements in the row plus 1.
Limit (1745) (01-01) (letter)	Signal to indicate last element to be input, ***L***.
C-5.L3 Boundary Condition Input	
Node (1746-2334) (02-05) (int.)	Node number where the boundary condition is going to be applied.
X-code (1746-2334) (06-10) (int.)	The boundary condition for the coordinate X. Defined as 0 specified a force input with rotation free. Defined as 1 specified a displacement input with fix rotation.
Y-code (1746-2334) (21-25) (int.)	The boundary condition for the coordinate Y. Defined as 0 specified a force input with rotation free. Defined as 1 specified a displacement input with fix rotation.
Y-value (1746-2334) (26-35) (int.)	Value of force for the specific node over the Y coordinate.
Load Step (1746-2334) (46-50) (int.)	Number of load step where the boundary condition is applied.
D-1 Material control parameters	
Material ID number (2335) (02-05) (integer)	Material Zone ID. The soil is divided into 4 zones, all of them with the same soil properties.

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Table B.1.: *continued*

Parameter (rows) (columns) (units)	**Input Options and Description**
Model Type (2335) (06-10) (integer)	Select material model to be associated with material zone. Defined as (=3) for the **Duncan/Selig** model.
Density (2335) (11-20) (lb/ft^3)	Density of material in zone. For gravelly sand with 90% compaction (SW90) is 140 lb/ft^3.
Material name (2335) (21-40) (words)	Name to characterize the selection of model parameters. For the analysis is **SW90**.
D-2.Duncan - Duncan fundamental controls	
LRFD stiffness control (2336) (01-05) (integer)	The LRFD control for material stiffness is set to cero for adjusting the soil model to its stiffness based on service-load stresses, not the higher factored stresses.
Moduli averaging ratio (2336) (06-15) (–)	Average of the tangent stiffness at the start and at the end of the load step. Set as **0.5** for an evenly balanced average.
Soil Model (2336) (16-20) (integer)	Is set to 1 for selecting the Duncan/Selig formulation
D-2.Interface Interface angle, friction, and tensile breaking force	
Angle from x-axis to normal of interface (2344) (01-10) (degrees)	For the first interface node (starting from the bottom of the pipe) is defined as $-90°$, for the last one is $-90°$.

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Table B.1.: *continued*

Parameter (rows) (columns) (units)	**Input Options and Description**
Coefficient of friction between nodes I and J **(2344) (11-20) (–)**	Coefficient of friction between nodes I and J. For all pipe types defined as 0.5.
Tensile breaking force of contact nodes **(2344) (21-30)** (lb/in)	Force per unit length required to break the bond between nodes I and J. For all pipe types defined as 10 lb/in.
E-1 LRFD net load factor per load step	
Starting load step **(2347) (01-05) (integer)**	Starting load step number to apply the same load factor.
Last load step **(2347) (06-10) (integer)**	Last load step number to apply the same load factor.
Load factor **(2347) (11-20) (–)**	LRFD load factor applied to the load steps. Usually 2.05 for metal pipes.