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Assessment of Pipe Fill Heights

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16. Abstract

The design of buried pipes, in terms of the allowable minimum and maximum cover heights, requires the use of both geotechnical and structural design procedures. The geotechnical procedure focuses on estimating the load on the pipe and the compressibility of the foundation soil. The focus of the structural design is choosing the correct cross-section details of the pipe under consideration. The uncertainties of the input parameters and installation procedures are significant. Because of that, the Load Resistance Factor Design (LRFD) method is considered to be suitable for the design of buried pipes. Furthermore, the interaction between the pipe structure and surrounding soil is better captured by implementing soil-structure interaction in a finite element numerical solution technique. The minimum cover height is highly dependent on the anticipated traffic load, whereas the maximum cover height is controlled by the section properties of the pipe and the installation type. The project focuses on the determination of the maximum cover heights for lock-seam CSP, HDPE, PVC, polypropylene, spiral bound steel, aluminum alloy, steel pipe lock seam and riveted, steel pipe and aluminum arch lock seam and riveted, non-reinforced concrete, ribbed and smooth wall polyethylene, smooth wall PVC, vitrified clay, structural plate steel or aluminum alloy pipe, and structural plate pipe arch steel, or aluminum alloy pipes. The calculations are done with the software CANDE, a 2D plane strain FEM code that is well-accepted for designing and analyzing buried pipes, that employs the LRFD method. Plane strain and beam elements are used for the soil and pipe, respectively, while interface elements are placed at the contact between the pipe and the surrounding soil. The Duncan-Selig model is employed for the soil, while the pipe is assumed to be elastic. Results of the numerical simulations for the maximum fill for each type and size of pipe are included in the form of tables and figures.

17. Key Words
buried pipes, maximum fill height, CANDE, 2D analysis

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EXECUTIVE SUMMARY

Introduction

Recently in Indiana, buried pipes have been increasingly used for drainage culverts and other highway applications. One of the major concerns for pipe design is determining the maximum and minimum burial depths that the pipe can sustain. Such determination is based on the short-term and long-term strength capacities of the pipe, its maximum deflection, and serviceability. Key factors that strongly affect pipe performance are the type of pipe (e.g., PVC, HDPE, steel, concrete, etc.), cross section of the pipe, plain or corrugated surfaces, the soil around and above the pipe, soil placement and compaction, and live loads that may occur during construction or during the life of the pipe.

At the request of the pipe committee of INDOT, this research was established to review the maximum and minimum heights of the pipes in the INDOT catalog, as well as new ones requested by industry. Two fill soils were targeted—SW85 and SW90 soil. The scope of the work changed when it was found that SW85 soils required, for stability, unrealistic soil heights above the pipes, and because of the decision of the pipe committee to use a minimum fill height of 2 ft. for construction purposes. The studies were carried out using the finite element method CANDE (Culvert Analysis and Design), which was the result of a project sponsored by the Federal Highway Administration (FHWA). The calculations were done using a 2D plane strain analysis and included the LRFD method. Plane strain and beam elements were used for the soil and pipe, respectively, while interface elements were placed at the contact between the pipe and the surrounding soil. The Duncan-Selig model was employed for the soil and the pipe was assumed to be elastic. The following types of pipes are included in the report: lock-seam CSP, HDPE, PVC, polypropylene, spiral bound steel, aluminum alloy, steel pipe lock seam and riveted, steel pipe and aluminum arch lock seam and riveted, non-reinforced concrete, ribbed and smooth wall polyethylene, smooth wall PVC, vitrified clay, structural plate steel or aluminum alloy pipe, and structural plate pipe arch steel or aluminum alloy pipes. Results of the numerical simulations for the maximum fill for each type and size of pipe are included in the report in the form of tables and figures.

Findings

The following is a list of the major findings obtained from the research.

- The optimum pipe design in CANDE required a large number of trial-and-error cases until the largest demand/capacity ratio for all strength criteria was exactly one, while simultaneously the performance limit criteria was satisfied. It was found that relatively small differences in the demand to capacity ratio were associated with 1–3 ft. differences in maximum fill height. These differences seemed to depend on the diameter of the pipe and on the type of pipe.
- A comparison of the different maximum heights on similar pipes across different DOTs suggested that different assumptions regarding materials and material properties, pipe bedding, construction, failure criteria, and service limits had a dramatic effect on fill heights.
- A limited analysis on the effect of soil type, more specifically soils SW85 and SW90, showed that differences between fill heights for SW85 and SW90 soils ranged from 12 ft. to 36 ft. This indicated an extremely large sensitivity of the results to a relatively small change in the density of the soil. It was noted that the soil that contributed the most to the pipe performance was the soil adjacent to the pipe, which was the most difficult to compact and test for density quality.
- A comparison between results from CANDE and those from existing INDOT requirements suggested that INDOT's values were obtained under the assumption that buckling was the dominant mode of failure. In CANDE, however, other modes of failure are possible, which seems to explain the discrepancies found.
- The maximum fill heights for all the pipe types and sizes requested by INDOT are provided in the report in the form of tables and figures. The maximum fill height is measured from the center of the pipe to the ground surface.

Implementation

This report presents recommendations for maximum fill height that can be sustained safely by the pipes investigated. The results are based on calculations performed by CANDE with the assumption that the fill is SW90. This report does not discuss minimum fill heights.

The results and recommendations strongly depend on the assumptions made regarding the properties of the materials and on the installation process. It was noted that the results are particularly sensitive to the type of soil, and so care should be taken in the field to assure that the quality of materials and construction is consistent with the assumptions made in the calculations. When the soil quality cannot be achieved in the field, the maximum field height can be estimated using the results provided in the report, which were obtained following ASTM calculations considering the corner pressure (P_c) as the limiting factor. It is suggested, for pipe arches, to take the maximum fill height obtained following the ASTM standards, as discussed in the report, where the bearing capacity of the soil around the pipe has a limiting value.

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1. BACKGROUND

This report covers the extension of the ongoing project: SPR-3857 *Assessment of Pipe Fill Heights*. The project started on February 15, 2014, at the request of INDOT, to review the maximum and minimum cover heights of pipes calculated by Dr. Jung in 2009 and 2010. The scope of the project increased when cover height calculations for additional pipe types were requested and when the pipe committee expressed interest in the calculations of fill heights for two different soils. This changed the scope of the project to determine the maximum and minimum fill heights for the types of pipes listed in Table 1.1. The soil model used was the Duncan-Selig Model with (a) gravely sand at relative compaction of 90% (SW90) and (b) gravely sand at relative compaction of 85% (SW85).

However, several issues appeared during the extension phase of the project, which changed the project scope. Most importantly, it was found that the fill height computation using SW85 soil caused severe convergence problems using the software chosen for the analysis, and the results were questionable. So, the pipe committee decided to discontinue the fill height calculations with SW85 soil and use SW90 soil. Another significant change affected the minimum fill height calculations. The pipe committee decided to use a minimum fill height of 2 ft. for all the pipes. In addition, significant issues were encountered when modeling pipe arches, including the inability of the standard Culvert Analysis and Design software (CANDE), using the Level 2 mesh solution, to model pipe-arches (e.g., generate mesh for arch shapes, discretize the model), and the lack of convergence that led to performing small deformation analysis and to verifying the buckling failure using the finite element software Abaqus. Furthermore, fill cover results were higher than expected, and for assuring the reliability of the results, Load and Resistant Factor Design (LRFD) calculations, based on ASTM standard practices, were performed. Details of the issues are discussed in Chapters 2 and 3.

The outline of the report is as follows. In Section 2, the Finite Element Method CANDE is discussed, as well as the assumptions and justifications behind those assumptions. The challenges that appeared during the project are discussed in Section 3. Section 4 contains the

TABLE 1.1
Pipe Types

Task No.	Tasks	No. of Cases
1.1a	Lock Seam CSP for 27-in. diameters	1
1.1b	Lock Seam CSP for 33-in. diameters	1
1.2	HDPE Pipe	18
1.3	PVC Pipe	18
1.4	Polypropylene Pipe (PP)[1]	18
1.5	Spiral Bound Steel Pipe[1]	1
2.1a	1 1/2 × 1/4 Aluminum Alloy Pipe	14
2.1b	2 2/3 × 1/2 Aluminum Alloy Pipe	42
2.1c	3 × 1 Aluminum Alloy Pipe	59
2.1d	6 × 1 Aluminum Alloy Pipe	40
2.2	2 2/3 × 1/2 Steel Pipe Riveted	53
2.3a	3 × 1 Steel Pipe Lock Seam	68
2.3b	3 × 1 Steel Pipe Riveted	68
2.4	5 × 1 Steel Pipe Lock Seam	64
2.5a	2 2/3 × 1/2 Steel Pipe Arch Lock Seam	35
2.5b	2 2/3 × 1/2 Steel Pipe Arch Riveted	35
2.5c	2 2/3 × 1/2 Aluminum Pipe Arch Lock Seam	28
2.5d	2 2/3 × 1/2 Aluminum Pipe Arch Riveted	28
2.6a	3 × 1 Steel Pipe Arch Lock Seam	38
2.6b	3 × 1 Steel Pipe Arch Riveted	38
2.6c	3 × 1 Aluminum Pipe Arch Lock Seam	23
2.6d	3 × 1 Aluminum Pipe Arch Riveted	23
2.7	5 × 1 Steel Pipe Arch Lock Seam	29
2.8	Non-Reinforced Concrete Pipe, Class III	9
2.9	Ribbed Polyethylene Pipe[2]	14
2.10	Smooth Wall Polyethylene Pipe[2]	23
2.11	Smooth Wall PVC Pipe	6
2.12	Vitrified Clay Pipe, extra strength	9
2.13a	6 × 2 Structural Plate Pipe Steel (Bolted)	209
2.13b	9 × 2 1/2 Structural Plate Pipe AL Alloy (stl Bolted)	155
2.13c	6 × 2 Structural Plate Pipe Arch Steel (Bolted)	88
2.13d	9 × 2 1/2 Structural Plate Pipe Arch AL Alloy (stl Bolted)	259

[1] Results submitted to INDOT in 2016.

[2] Results submitted to INDOT in 2010.

calculated maximum fill heights for different types of pipes and the mechanical and geometrical properties used for the analyses. A comparison of the finite element results, the fill heights from INDOT, and the results obtained using ASTM standards for pipe-arches is also included. The recommendations from the findings are discussed in Section 5. All the pipe inputs used for the calculations are included in Section 4 and were submitted to INDOT in the SAC meeting on 10/17/2016.

In Table 1.1, results for tasks numbered 1.4 and 1.5, for polypropylene and spiral bound pipes, were submitted to INDOT in 2016. Results for tasks numbered 2.9 and 2.10, for polyethylene pipes, where provided to INDOT in 2010.

2. METHODOLOGY

2.1 Introduction

To determine the maximum fill heights correctly, it is essential to model the pipe/soil system as realistically as possible. To do so, specific parameters such as live load, soil type, soil properties, pipe type, pipe-soil interface, pipe properties, pipe geometry, analysis methodology, and design criteria are needed. Careful consideration is required while selecting these parameters as each parameter can lead to significant changes in fill heights. Buried pipes need to withstand loading from both the soil overburden and the traffic load. The maximum cover height is controlled by the section properties of the pipe and installation. The pipes analyses, as discussed, are listed in Table 1.1. The studies were carried out using the finite element method CANDE. Katona et al. (1976) pioneered the application of the finite element method for the solution of buried pipe problems. Their Federal Highway Administration (FHWA) sponsored project produced the well-known public domain computer Program CANDE, which has been used for the project.

2.2 Finite Element Code CANDE

Figure 2.1 is a two-dimensional idealization of the actual soil-pipe system. Given that the length of the pipe is much larger than its diameter, it can be assumed that plane strain conditions apply to any cross-section perpendicular to the pipe axis. Thus, the soil is represented by plane strain elements, while the pipe itself is modeled using beam elements. Interface elements are used between the pipe and the soil that allow separation of the soil from the pipe and frictional slip at the contact. Also, note that Figure 2.1 includes only half of the soil-pipe system, due to the symmetry of the problem. As for the boundary conditions, fixed support is placed at the bottom of the soil domain and rollers are placed at the sides of the model.

The Level 2 mesh in CANDE provides 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

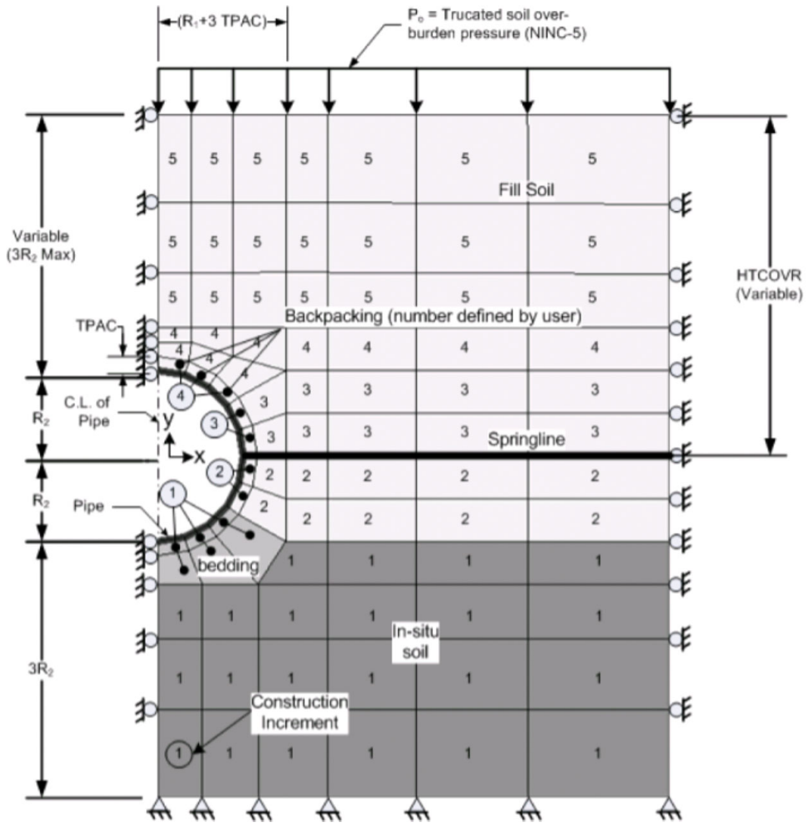


Figure 2.1 Soil-pipe mesh.

different shapes of pipes, round, or elliptical, rectangular, and arch culverts, 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 analyses on a typical culvert, this is usually the most convenient option (Musser, 2015).

The Level 2 mesh worked well with all pipes except pipe-arches, where severe limitations were found, such as the following.

- 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) 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.

Calculations for the maximum fill for pipe-arches were performed using the Level 3 solution instead of Level 2. Level 3 is based on a user-defined mesh and the same finite element solution methodology as Level 2. With Level 3, one can model any structural shape, soil systems and loading conditions. The process for creating and running the model requires the discretization of the mesh using another FEM software (Abaqus), a custom-made software created in MATLAB to have the Abaqus output in a format that can be read by CANDE; finally, the CANDE code created using Level 3 solution is run. Figure 2.2 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 with boundary conditions is shown in Figure 2.3 and the conceptual mesh used with soil layers, dimension of the soil and boundary conditions is shown in Figure 2.4.

Only half the domain is modeled, because of symmetry. To be able to obtain the mesh information (nodes coordinates and element connectivity), the file created in Abaqus is 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 the data in CANDE format.

For circular pipes, the analyses have been carried out using large deformation theory. For pipe-arches, due to convergence problems, small deformation theory was used.

The input properties of the pipes can be found in Chapter 4. For the soil, the Duncan-Selig soil model was used. The parameters for the Duncan-Selig Model were obtained from the CANDE user manual, which provides typical values for different soils, as listed in Table 2.1. Initially, two types of soil were requested by INDOT—gravelly sand with 90% relative compaction, per AASHTO T-99, (SW90); and gravelly sand with 85% relative compaction, per AASHTO T-99, (SW85), but the calculations, as mentioned, were done for SW90.

Execution of the FEM code CANDE requires the user to provide data that includes geometry, material properties and loading conditions. For circular and elliptical shape pipes, CANDE has the functionality to automatically generate the mesh; however, for pipe arches, nodal coordinates, element connectivity data and boundary conditions need to be entered manually. Information for each material type (pipe, soil, and interface) is required. The properties for the pipe include cross-sectional area, modulus of elasticity, moment of inertia, shear area, Poisson's ratio, and weight per unit length. These properties can be found in Chapter 4. The Duncan-Selig soil model assumes that the stress strain properties of the soil can be represented using a hyperbolic function. The input parameters for the model were obtained from the CANDE user manual, which provides typical values for different soils, as listed in Table 2.1.

For embankment-type installation, which is the case considered, CANDE uses interface segments between the pipe and the soil. The user is required to input properties in the form of a coefficient of friction and tensile strength at the contact, for each interface segment. The coefficient of friction assumed for the calculations was 0.5, and the tensile strength, 20 lb/in for circular pipes and 10 lb/in for pipe-arches, a force small enough to represent an unbonded contact, but large enough to facilitate convergence of the simulations.

2.3 Design Criteria and CANDE Output

CANDE-2015 uses the probabilistic-based load and resistance factor design (LRFD) methodology, based on the 2014 *AASHTO LRFD Bridge Design Specifications*. For strength limit states, such as the yield strength, ultimate strain, or global buckling capacity of the soil-structure system, the LRFD method assigns net multiplying factors to the service loads. The resulting structural response is higher than the service load response. Concurrently, resistance factors, typically 1.0 or less, are applied to the strength values. The factored capacities need to be greater or equal than the corresponding factored demands for all the strength-state design criteria. Table 2.2 lists the load factors for buried structures according to AASHTO LRFD specifications, as stated in the CANDE user manual.

AASHTO LRFD has specific design criteria for different materials. Corrugated metal pipes have four design criteria and one performance limit criterion, whereas plastic pipes have three design criteria and two performance limit criteria. The design criteria for

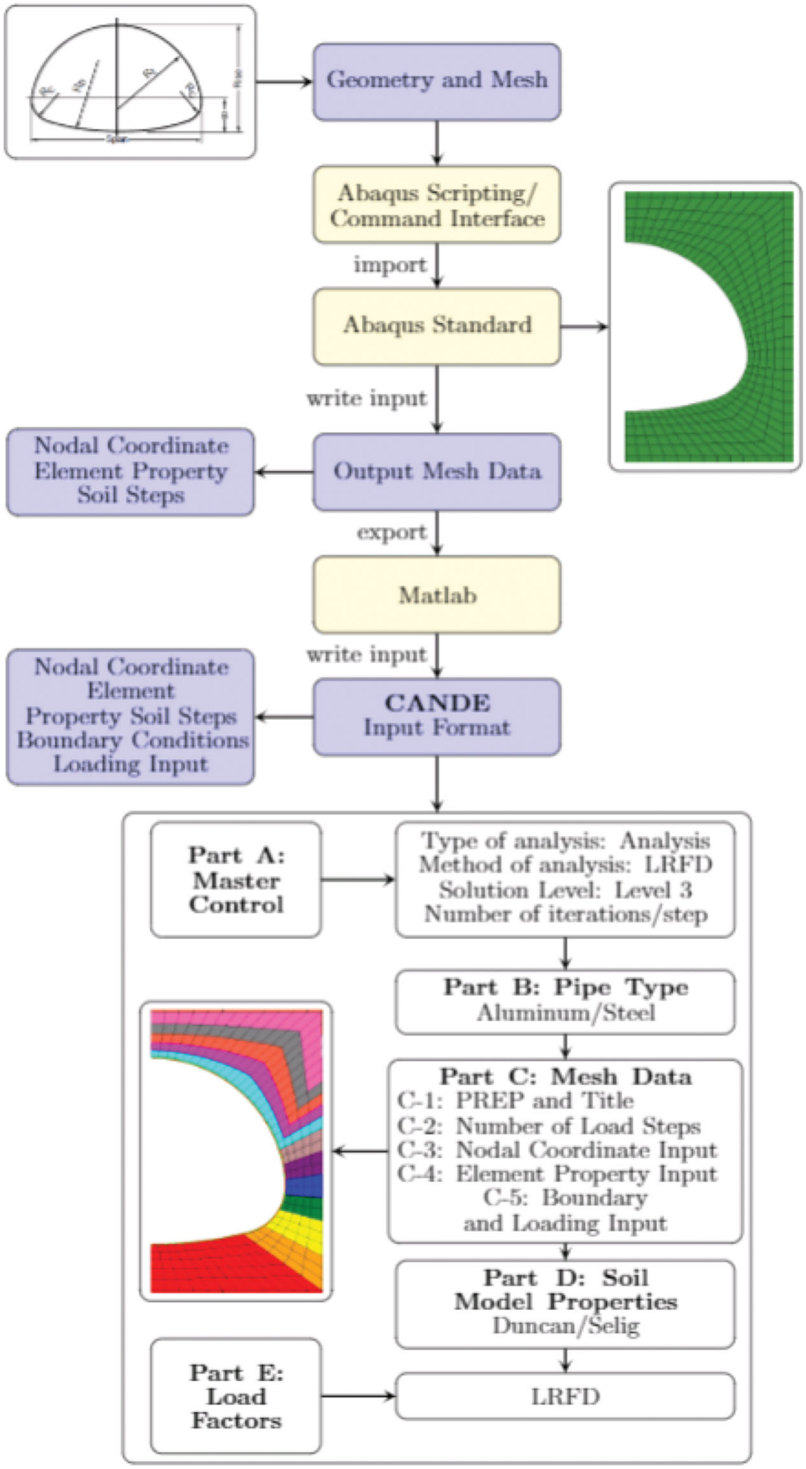


Figure 2.2 CANDE level three input data flow chart.

corrugated metal pipes are (1) thrust stress; (2) global buckling; (3) seam strength; and (4) plastic penetration. The performance limit criterion is the allowable deflection. For plastic pipes the design criteria are (1) thrust failure; (2) global buckling; and (3) combined strain. The performance limit criteria are (1) allowable displacement; and (2) allowable tensile strain. The resistance factors for each of these design criteria are also incorporated in CANDE and are based on the AASHTO LRFD specifications.

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 and that the performance limit criteria are met (e.g., the maximum deflection is below 5%).

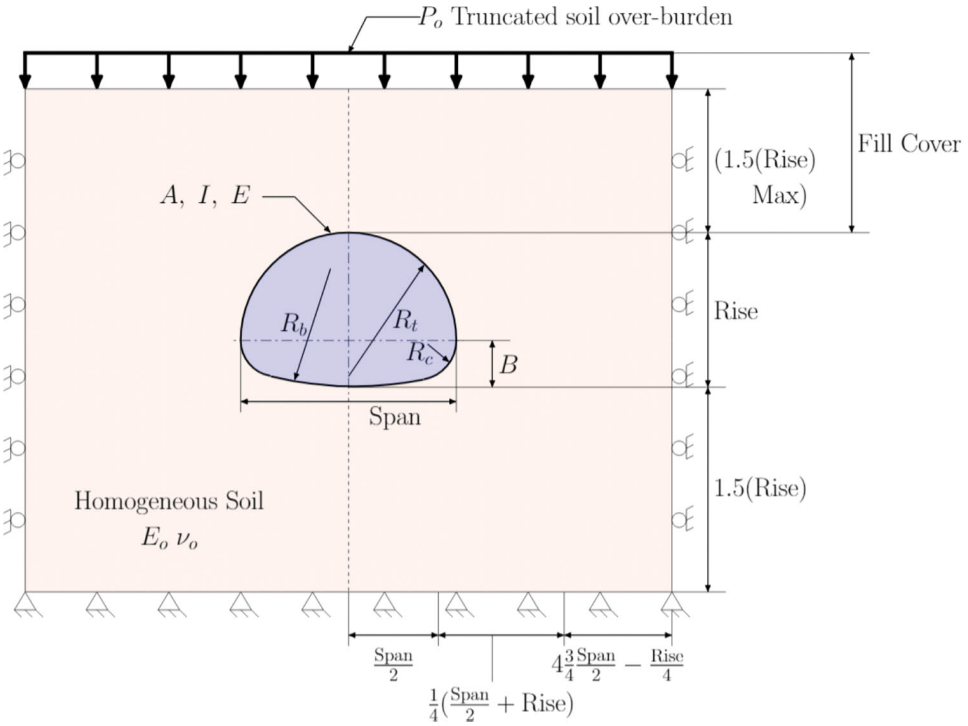


Figure 2.3 Conceptual soil-structure model with finite boundaries.

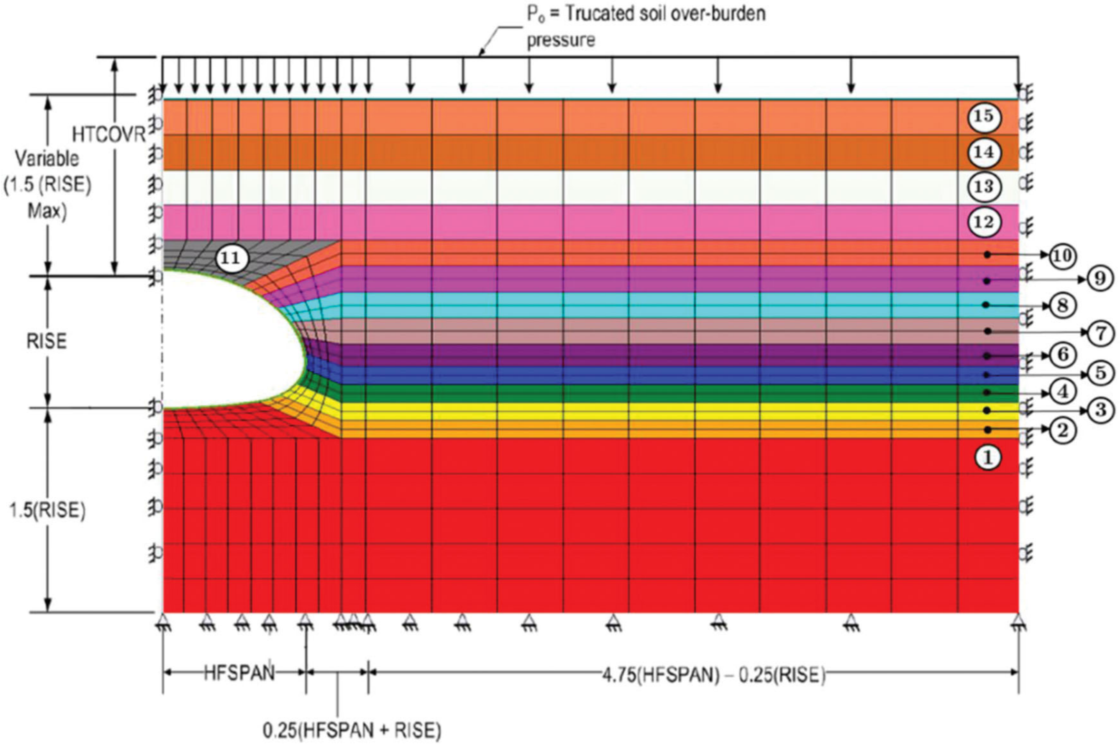


Figure 2.4 Conceptual mesh used for Level 3 mesh calculations. The different colors represent the soil steps; HTCOVR is the height of the soil cover above the top of the arch and HFSPAN is one-half of the arch span.

TABLE 2.1
Soil Parameters for the Duncan-Selig Model (Musser, 2015)

	Stiffness and Strength						Bulk Modulus		
Soil Type	K	n	C (*psi*)	φ_0 (*deg*)	$\Delta\varphi$ (*deg*)	R_f	B_i/P_a	ε_u	**Density** (lb/ft^3)
SW90	640	0.43	0	42	4	0.75	40.8	0.05	140
SW85	450	0.35	0	38	2	0.8	12.7	0.08	130

TABLE 2.2
Load Factors and Modifiers Used in the Analysis (Musser, 2015)

	Dead Load Culvert DC			Earth Fill Loading EB			Live Load LL	
Culvert Type	γ_{max}	γ_{min}	η_{DC}	γ_{max}	γ_{min}	η_{EB}	γ_{max}	η_{LL}
Corrugated Metal Pipe or Arch	1.25	0.9	1.05	1.95	0.9	1.05	1.75	1
Plastic Pipe (HDPE or PVC)	1.25	0.9	1.05	1.95	0.9	1.05	1.75	1

3. CHALLENGES

While determining the maximum fill height for the pipes, several issues appeared, and a significant amount of time was devoted to investigating them. These issues are discussed in the following sections.

3.1 Demand-Capacity Ratio

The optimum pipe design, following the LRFD methodology, requires that the ratio between the factored demands and the corresponding factored capacities, for all strength criteria, is equal to 1.0. In CANDE, this involves a (large) number of trial-and-error cases until the largest demand/capacity ratio for all strength criteria is exactly one, while the case still satisfies the performance limit criteria. Table 3.1 shows the fill heights for three different diameters of aluminum alloy pipe (3 × 1, t = 0.105) obtained when the maximum demand-capacity ratio, for all strength criteria, is 0.98 or 1.0. The table shows that relatively small differences in the demand to capacity ratio are associated with 1–3 ft. differences in maximum fill height. These differences seem to depend on the diameter of the pipe and are expected to be a function of the type of pipe.

Given the issues described previously regarding the convergence problems with CANDE, some of them associated with the interface and mesh, discretization, the dependence of the results on the target strength ratio, and the ability of CANDE to reach the ratio, they increase the uncertainty of the results.

3.2 Assumptions for Soil-Pipe Model and Interaction

There are other assumptions, in addition to those described regarding the type of soil, pipe-soil interface, and convergence of the solution. Those include the actual properties of the soil used in the analyses, the pipe bedding, installation, etc. The number of variables is very large; however, a sense of how different assumptions affect the results can be accomplished by comparing INDOT's recommendations with those from other States. To that end, the maximum fill heights for corrugated steel pipe (lock seam) prescribed by INDOT are compared with those from neighboring States in Table 3.2.

Figure 3.1 plots the data shown in the table. INDOT's fill heights are larger than those from other States. The differences suggest that different assumptions do have a dramatic effect on fill heights, which brings uncertainty to recommendations reached, as somewhat small differences in assumptions, materials, construction, etc. may carry a large impact on the maximum safe fill height.

3.3 SW90 vs. SW85 Soil

The simulations showed that a reduction of the maximum soil cover of the order of tens of feet occurred when changing the soil, from SW90 to SW85. In Figure 3.2, fill heights for different diameters of aluminum alloy pipes (t = 0.105) are plotted for both SW85 (red) and SW90 (blue) soil.

It can be seen in Figure 3.2 that the difference between fill heights for SW85 and SW90 soil ranges from 12 ft. to 36 ft. This indicates an extremely large sensitivity of the results to a relatively small change of the density of the soil. It has to be noted that the soil that contributes the most to the pipe behavior is the soil adjacent to the pipe, which is the most difficult to compact and test for compaction quality.

3.4 Fill Height Comparison with INDOT Tables for Circular Pipes

Once the maximum fill heights were calculated for a specific pipe, the results were compared with INDOT's

TABLE 3.1
Fill Cover for Different Demand-Capacity Ratios

	Fill Cover (ft.)	
Diameter (in)	**Max. Demand-Capacity Ratio = 0.98**	**Max. Demand-Capacity Ratio = 1.00**
36	92	95
42	78	80
48	69	70

TABLE 3.2
Maximum Fill Heights from Neighboring States

	t = 0.064				t = 0.079			
D (in)	**INDOT**	**MNDOT**	**WIDOT**	**ILDOT**	**INDOT**	**MNDOT**	**WIDOT**	**ILDOT**
36	82	N/A	N/A	N/A	–	–	–	–
42	70	N/A	N/A	N/A	87	N/A	N/A	N/A
48	61	N/A	N/A	N/A	77	N/A	N/A	N/A
54	54	48	N/A	N/A	68	60	N/A	15
60	49	43	24	N/A	61	54	30	10
66	45	39	22	N/A	56	49	27	10
72	41	36	20	N/A	51	45	25	10
78	38	33	18	N/A	47	41	23	N/A
84	35	31	17	N/A	44	38	22	N/A
90	33	29	16	N/A	41	36	20	N/A
96	–	–	–	–	38	34	19	N/A
102	–	–	–	–	36	32	17	N/A

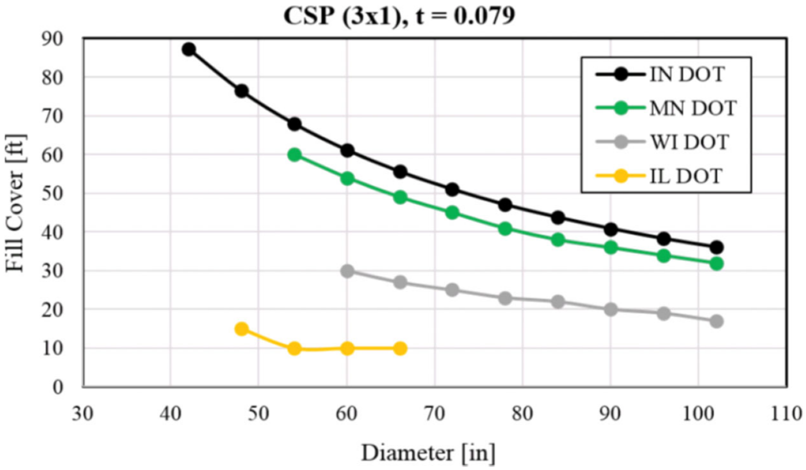


Figure 3.1 Maximum fill cover. Comparison between INDOT results and other state DOT results for corrugated steel pipe (3 × 1) with t = 0.079.

published tables. It was found that the differences varied with the type of pipe and diameter. As an example, Figure 3.3 shows the fill heights for aluminum alloy pipe (3 × 1, t = 0.135). The blue line represents the results from CANDE and the black line from INDOT.

It can be seen from Figure 3.3 that, for those cases where buckling is the dominant mode of failure in CANDE, which is the case for large diameter pipes, the results match. This seems to indicate that INDOT's values were obtained under the assumption that buckling was the dominant mode of failure. In CANDE, however, other modes of failure are possible. For smaller pipe diameters, Figure 3.3 shows that the critical failure in CANDE was thrust stress, which results in maximum fill heights smaller than those from INDOT.

Figure 3.4 is a plot similar to that of Figure 3.3 but for t = 0.105. The results from CANDE are obtained with the assumption of failure only through buckling. The close comparison between CANDE and INDOT results (small differences are thought to be caused by soil differences) seem to support the notion that INDOT's values for maximum fill height were calculated for buckling.

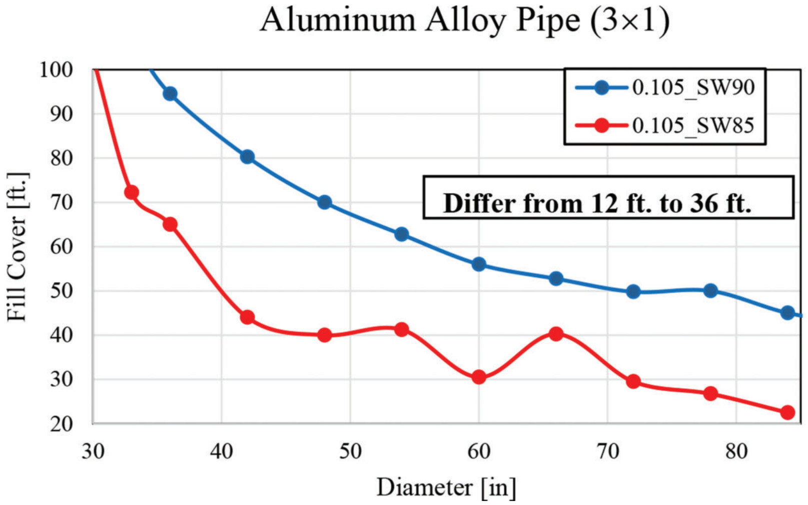


Figure 3.2 Fill height vs. diameter for aluminum alloy pipe (3 × 1).

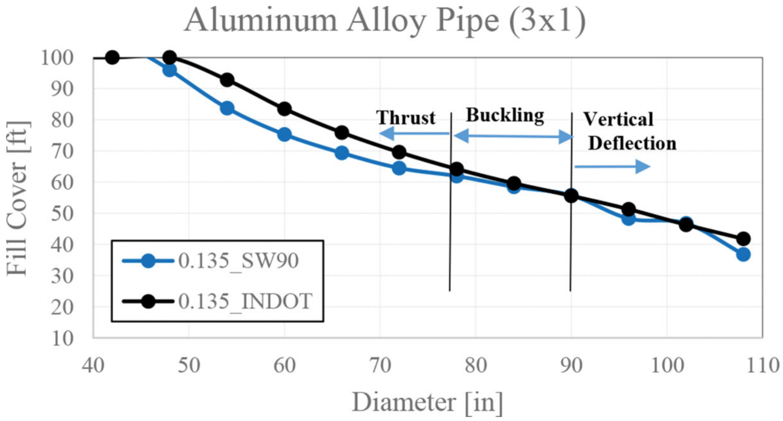


Figure 3.3 Maximum fill cover. Comparison between CANDE and INDOT results for aluminum alloy pipe (3 × 1) with t = 0.135.

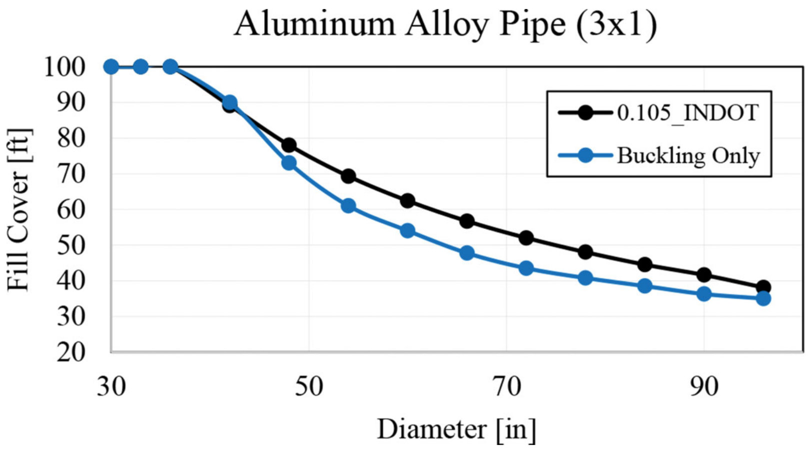


Figure 3.4 Maximum fill cover. Comparison between CANDE and INDOT results for aluminum alloy pipe (3 × 1) with t = 0.105, under the assumption of failure through buckling only.

3.5 Challenges Related to Pipe-Arches

3.5.1 ASTM LRFD Design Methodology

As will be shown later with the results, the maximum fill heights computed with CANDE were very different than those from INDOT, and generally much larger. To check that the results obtained with CANDE and that the assumptions made were reasonable, two additional calculations were done to (1) check that buckling was not a mode of failure missed in CANDE; and (2) understand the differences between the CANDE results and INDOT specifications.

The first series of calculations were done using ABAQUS, where buckling was specifically included and where it was assumed large-deformation analyses (in CANDE Level 3, it was assumed small-deformation analysis, and buckling was computed based on the thrust on the pipe). Calculations were done for the 6 × 2 Structural Plate Steel Pipe-Arch (Bolted) with 18 Rc (in.) and 7-8 Span (ft.-in.), with the maximum fill obtained in CANDE. The results in ABAQUS showed that buckling, in agreement with CANDE, was not the limiting failure mode, and also showed a large concentration of stresses in the soil immediately adjacent to the small radius of the pipe-arch (see discussion later regarding the effects of the small radius on the maximum fill height).

For the second series, analytical calculations were performed following the ASTM standards ASTM A796/A796M (ASTM, 2017b) for steel and ASTM B790/B790M (ASTM, 2017a) for aluminum. Figure 3.5 summarizes the process for finding the maximum fill cover. First, the design pressure (P_f) was calculated using Equation 3.2 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 inversely proportional to the radius of curvature of the top (R_t) and corner (R_c) radii, as shown in Figure 3.6. Next, the factored load (FP_f) was computed using the first part of Equation 3.3 (FP_f= $1.95(P_f)$), multiplying the dead load (DL) by the load factor (calculated using the factors in Table 2.2). The second part of this equation considers the Live (LL) and Impact (IL) loads and was only used when the maximum fill cover was less than 8 ft. Then, the Factored thrust (T_f) was computed with Equation 3.5 and the factored resistances (R_f) with Equation 3.6. This analysis included calculations for Wall Resistance (R_n) in Equation 3.7, Resistance to buckling (f_c) in Equation 3.4 and Seam Resistance; the resistances values were factored using Equation 3.4. Finally, the minimum value of the factored resistances calculated was compared to the factored thrust such that the factored resistance should be equal or exceed the factored thrust, $R_f \geq T_f$, and the required height was back-calculated.

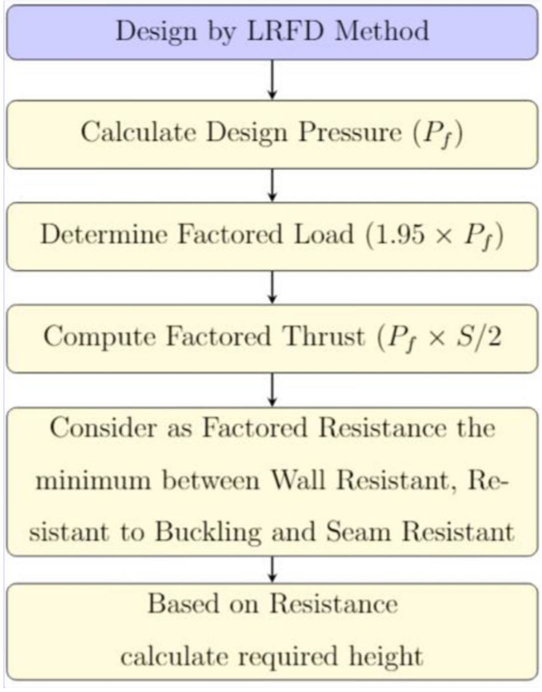


Figure 3.5 Steps for performing an ASTM LRFD analysis according to ASTM 2017 a and b.

$$DL = Hw \qquad \text{(Eq. 3.1)}$$

$$P_f = \begin{cases} P_v = DL, & A.\ \textit{Considering the radial pressure} \\ P_c = DL \times R_t/R_c, & B.\ \textit{Considering the pressure at the corners} \end{cases} \qquad \text{(Eq. 3.2)}$$

$$FP_f = 1.95(P_f) + 1.75(LL + IL) \qquad \text{(Eq. 3.3)}$$

$$f_c = \begin{cases} f_u - \dfrac{f_u^2}{48E}\left(\dfrac{ks}{r}\right)^2 & \textit{if } s < \dfrac{r}{k}\sqrt{\dfrac{24E}{f_u}} \\ \dfrac{12E}{\left(\dfrac{ks}{r}\right)^2} & \textit{if } s > \dfrac{r}{k}\sqrt{\dfrac{24E}{f_u}} \end{cases} \qquad \text{(Eq. 3.4)}$$

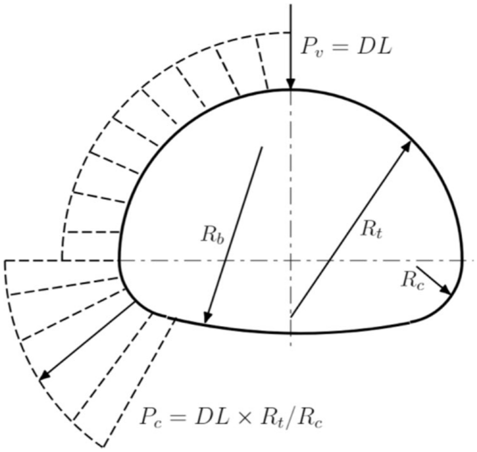


Figure 3.6 Pressure on a pipe-arch.

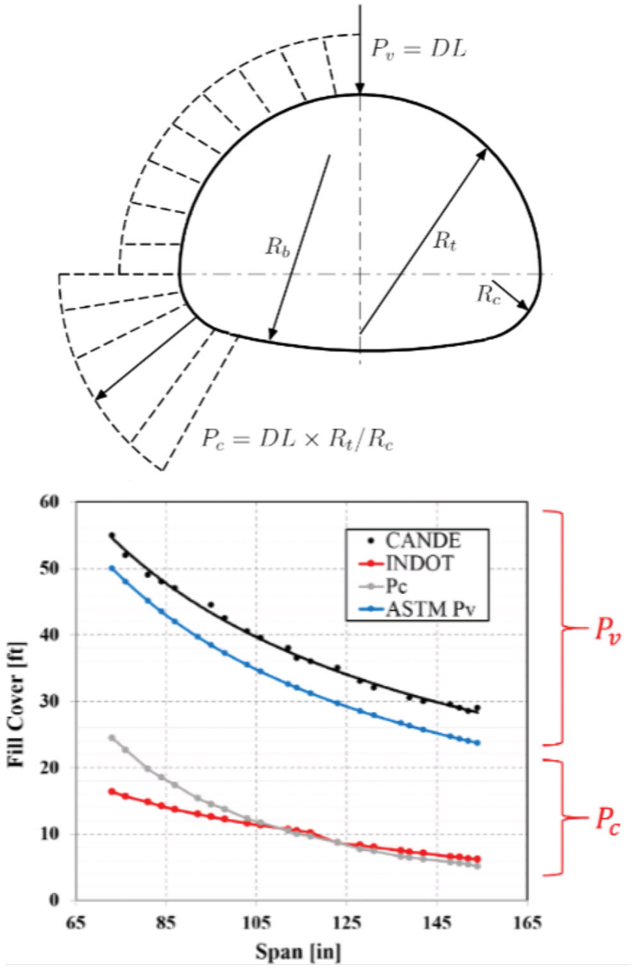


Figure 3.7 Differences between CANDE and INDOT results due to different assumptions on pipe loading. Case example for 6″ × 2″ SPSPA t = 0.140 in.

$$T_f = P_f S/2 \qquad \text{(Eq. 3.5)}$$

$$R_f = \varphi R_n \qquad \text{(Eq. 3.6)}$$

$$R_n = f_y A \qquad \text{(Eq. 3.7)}$$

3.6 Fill Height Comparison with INDOT

The results from INDOT on corrugated steel and aluminum pipe-arches with riveted and lock seam are all the same and are unchanged for all corrugation thicknesses. Even though it was not specified where these results came from, it seems that the heights were calculated using Equation 3.8 from ASTM B790/B790M (ASTM, 2017a). Since Equation 3.8 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). However, Equation 3.8 is only specified for aluminum pipes. Moreover, for structural plate pipe-arches, INDOT calculations seem to be obtained for the worst-case scenario, i.e., for the smallest thickness, and repeated for the other corrugations. All this makes comparisons between INDOT specifications and CANDE's results challenging, since CANDE results depend on all mechanical and geometrical properties of the pipe-arches. As the thickness corrugation increases, INDOT results become less comparable to CANDE. In fact, CANDE results are similar to the results calculated using Equation 3.2 for the radial pressure, and INDOT results compare with the results computed using Equation 3.2 for the corner pressure, as shown in Figure 3.7.

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

(Eq. 3.8)

4. RESULTS

This section includes the maximum fill heights of lock-seam CSP, HDPE pipe, smooth wall, and profile wall PVC pipe, aluminum alloy pipes, non-reinforced concrete pipe (Class III), vitrified clay pipe (extra strength), corrugated pipes and pipe-arches, structural plate pipes and pipe-arches obtained with CANDE. The mechanical and geometrical properties used to perform the calculations are also included. The type of soil used for the analysis is the gravelly sand with 90% compaction (SW90) unless specified otherwise. Each fill height listed in the tables is color-coded according to the critical failure criterion. The results are plotted in Figures 4.1 to 4.57.

4.1 2 2/3″ × 1/2″ Corrugated Steel Pipe Lock Seam (27- and 33-in. diameters)

The mechanical and geometrical properties of the corrugated steel pipes were selected based on CANDE user manual-2015, and are summarized in Tables 4.1, 4.2, and 4.3. The results are shown in Table 4.4.

4.2 Plastic Pipe HDPE (High-Density Polyethylene)

The mechanical and geometrical properties for the HDPE pipes were selected based on Jung (2010) report and are summarized in Tables 4.5 and 4.6.

Table 4.7 lists the maximum fill cover for HDPE pipes, for SW90 and SW85 soil, along with the fill height previously published by INDOT. The fill heights are color-coded per the failure criteria.

TABLE 4.1
Mechanical Properties of Corrugated Steel Pipe

Young's Modulus (psi)	29,000,000
Yield Stress (psi)	33,000
Poisson's Ratio	0.3
Density (pci)	0.284

TABLE 4.2
Seam Strength of Corrugated Steel Pipe

2 2/3″ × 1/2″ Steel	
Thickness (in)	**Seam Strength Double (lb/ft)**
0.064	16,700
0.079	18,200
0.109	23,400
0.138	24,500
0.168	25,600

TABLE 4.3
Geometrical Properties of Corrugated Steel Pipe 2 2/3″ × 1/2″

	Corrugation Pile (in)		
	2 2/3 × 1/2		
Corrugation Thickness (in)	**PA (in^2/in)**	**PI (in^4/in)**	**PS (in^3/in)**
0.064	0.0646	0.00189	0.0067
0.079	0.0807	0.00239	0.00826
0.109	0.113	0.00342	0.01123
0.138	0.1453	0.00453	0.0142
0.168	0.1778	0.00573	0.01716

Figure 4.1 is a plot of the data in Table 4.7. The blue line represents the values for SW90 soil, the red line for SW85 soil, and the black line for INDOT's tabulated results.

4.3 Profile Wall PVC Pipe

The mechanical and geometrical properties for Profile Wall PVC Pipe were selected based on the literature and are summarized in Tables 4.8 and 4.9. Table 4.10 lists the results of the simulations and Figure 4.2 plots the results listed in Table 4.10.

4.4 Aluminum Alloy Pipe

The mechanical and geometrical properties for the aluminum alloy pipes were selected based on CANDE user manual-2015 and are summarized in Tables 4.11 and 4.12.

The next sections list the maximum fill heights for aluminum alloy pipes for different corrugation profiles and soil compaction, i.e., SW90 and SW85. Figures 4.3 through 4.12 plot the results and compare CANDE's predictions with INDOT's current values. The blue line represents current calculations for SW90 soil, the red

TABLE 4.4
Maximum Soil Cover for 2 2/3″ × 1/2″ Corrugated Steel Pipes (Lock Seam)

	2 2/3″ × 1/2″ Corrugated Steel Pipe-Arch Lock Seam–Cover Limit (ft)									
	Thickness (in)									
D (in)	**INDOT**	**CANDE**	**INDOT**	**CANDE**	**INDOT**	**CANDE**	**CANDE**	**INDOT**	**INDOT**	**CANDE**
27	94.70	54.70	100.00	58.50	100.00	74.95	–	81.49	–	81.25
33	71.00	45.21	48.93	48.93	100.00	61.74	100.00	64.95	–	67.17

Note: Failure modes: blue text = INDOT and red text = seam and material thrust.

TABLE 4.5
Mechanical Properties for HDPE Pipes

Young's Modulus for Short-Term Loading (ksi)	110.0
Ultimate Strength for Short-Term Loading (ksi)	3.0
Young's Modulus for Long-Term Loading (ksi)	22.0
Ultimate Strength for Long-Term Loading (ksi)	0.9
Poisson's Ratio	0.4
Density (pci)	0.034

TABLE 4.6
Geometrical Properties for HDPE Pipes

D. Inner (in)	12	15	18	24	30	36	42	48	60
D. Average (in)	12.88	16.08	19.15	25.43	31.78	38.14	44.3	50.51	63.05
Profile Length (in)	1.92	2.59	2.68	3.15	4.12	5.25	5.19	5.25	6
Total Height (in)	1.14	1.33	1.54	1.79	2.53	2.54	3.16	3.04	3.44
Web Angle (deg)	82	80	80.5	74.5	75	78	82.5	77.5	77
Web Thickness (in)	0.11	0.16	0.14	0.17	0.17	0.25	0.23	0.24	0.33
Web "k" value	4	4	4	4	4	4	4	4	4

line for SW85 soil, and the black line for INDOT's. Section 4.4.1 shows results for the 1 1/2″ × 1/4″ aluminum alloy pipes, Section 4.4.2 for the 2 2/3″ × 1/2″ aluminum alloy pipes, Section 4.4.3 for the 3″ × 1″ aluminum alloy pipes and Section 4.4.4 for the 6″ × 1″ aluminum alloy pipes. The results for maximum soil cover for the 1 1/2″ × 1/4″ Aluminum Alloy Pipe are listed in Table 4.13. The results include SW90 and SW85 soils, but the later only for pipes with 12″ diameter.

TABLE 4.7
Maximum Soil Cover for HDPE Pipes

	HDPE		
D (in)	**SW90**	**SW85**	**INDOT**
12	22	13	22
15	22	12	22
18	19	11	20
24	19	10	19
30	17	9	17
36	18	9	17
42	15	7	17
48	15	8	15
60	15	8	15

Note: Failure modes: red = INDOT, green = seam and material thrust, and blue = vertical deflection.

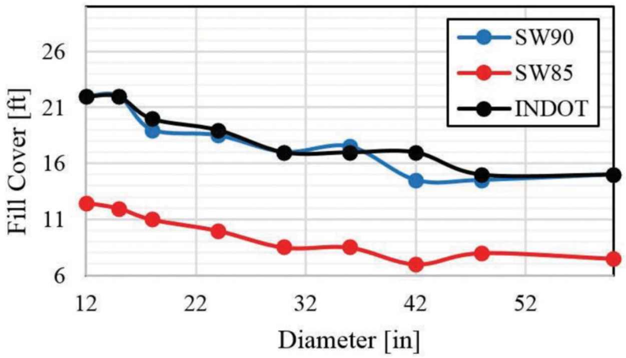


Figure 4.1 Maximum fill cover. Comparison between CANDE and INDOT results for HDPE pipe.

TABLE 4.8
Mechanical Properties for Profile Wall PVC Pipe

Young's Modulus for Short-Term Loading (ksi)	400
Ultimate Strength for Long-Term Loading (ksi)	6.0
Young's Modulus for Long-Term Loading (ksi)	140
Ultimate Strength for Long-Term Loading (ksi)	2.6
Poisson's Ratio	0.4
Density (pci)	0.05

TABLE 4.9
Geometrical Properties for Profile Wall PVC Pipe

D_{inner} (in.)	12	15	18	24	30	36
D_{ig} (in.)	12.26	15.31	18.35	24.35	30.81	37.11
Profile Length (in)	1.03	1.38	1.38	1.90	2.32	2.61
Total Height (in)	0.54	0.66	0.80	1.06	1.34	1.63
Web Angle (deg)	75.1	76.6	75.6	75.9	76.9	77.1
Web Thickness (in)	0.05	0.06	0.07	0.09	0.11	0.13
Web "k" value	4	4	4	4	4	4

TABLE 4.10
Maximum Soil Cover for Profile Wall PVC Pipe

D (in)	**SW90**	**INDOT**
12	20.5	35.3
15	18.4	34.2
18	20.3	34.0
24	19.0	31.0
30	19.8	29.0
36	19.5	27.0

Note: Green text = seam and material thrust, and blue = vertical deflection.

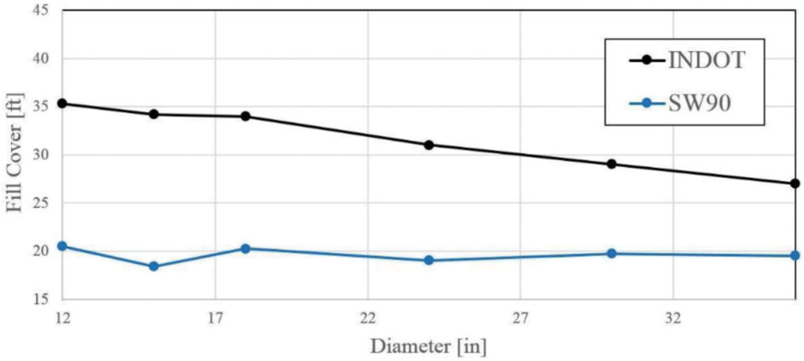


Figure 4.2 Maximum fill cover. Comparison between CANDE and INDOT results for profile wall PVC pipe.

TABLE 4.11
Mechanical Properties of Aluminum Alloy Pipes

Young's Modulus (psi)	10,000,000
Yield Stress (psi)	24,000
Yield Stress of Pipe Seam (psi)	24,000
Poisson's Ratio	0.33
Density (pci)	0.0975

TABLE 4.12
Geometrical Properties of Aluminum Alloy Pipes

Corrugation Profile	Section Properties	Corrugation Thickness – in					
		0.048	**0.060**	**0.075**	**0.105**	**0.135**	**0.164**
1-1/2 × 1/4	PA in^2/in	0.05070	0.06324	0	0	0	0
	PI in^4/in	0.00034	0.00035	0	0	0	0
	PS in^3/in	0.00228	0.00226	0	0	0	0
2-2/3 × 1/2	PA in^2/in	0	0.06458	0.08067	0.11300	0.14533	0.17775
	PI in^4/in	0	0.00189	0.00239	0.00342	0.00453	0.00573
	PS in^3/in	0	0.00675	0.00831	0.01131	0.01427	0.01726
3 × 1	PA in^2/in	0	0.07416	0.09317	0.1300	0.17400	0.20483
	PI in^4/in	0	0.00866	0.01088	0.01545	0.02017	0.02508
	PS in^3/in	0	0.01634	0.02024	0.02796	0.03554	0.04309
6 × 1	PA in^2/in	0	0.0646	0.08067	0.11300	0.14533	0.17775
	PI in^4/in	0	0.00850	0.01060	0.01490	0.01910	0.02340
	PS in^3/in	0	0.01604	0.01972	0.02697	0.03366	0.04021

PA = area of pipe wall section per unit length, PI = moment of inertia of pipe wall section per unit length, and PS = section modulus of pipe wall per unit length.

4.4.1 1 1/2″ × 1/4″ Aluminum Alloy Pipe

TABLE 4.13
Maximum Soil Cover for the 1 1/2″ × 1/4″ Aluminum Alloy Pipe

	Aluminum Alloy (1-1/2 × 1/4)			
	0.048		**0.06**	
D (in)	**SW90**	**SW85**	**SW90**	**SW85**
12	114	112.0	136	124.5
15	94	NC	113	NC
18	74	N/A	94	N/A
21	63	N/A	68	N/A
24	53	N/A	58	N/A
27	42	N/A	47	N/A
30	33	N/A	35	N/A

Note: NC = not converged, blue text = seam and material thrust, yellow text = buckling, and red text = vertical deflection.

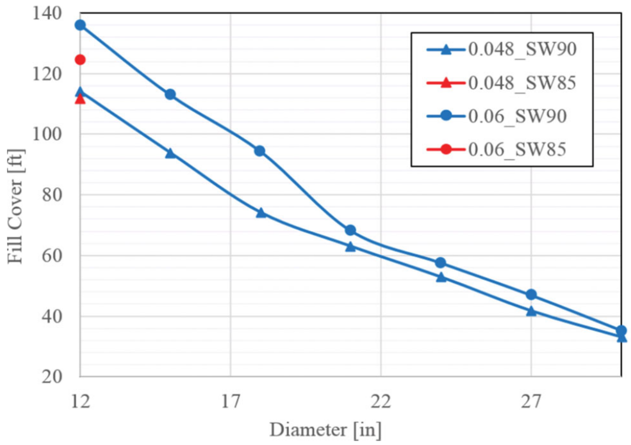
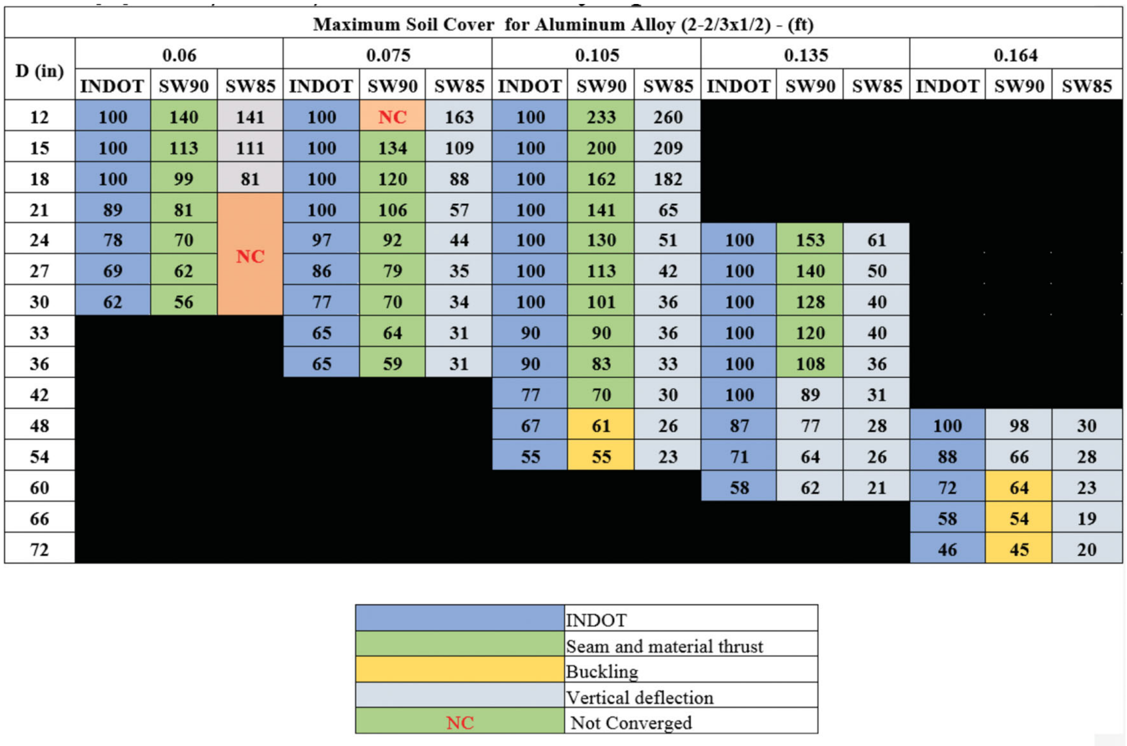


Figure 4.3 Maximum fill cover. CANDE results for the 1 1/2″ × 1/4″ aluminum alloy pipes with t = 0.048 and 0.06.

4.4.2 2 2/3″ × 1/2″ Aluminum Alloy Pipe



Maximum Soil Cover for Aluminum Alloy (2-2/3x1/2) - (ft)															
D (in)	0.06			0.075			0.105			0.135			0.164		
	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85
12	100	140	141	100	NC	163	100	233	260						
15	100	113	111	100	134	109	100	200	209						
18	100	99	81	100	120	88	100	162	182						
21	89	81	NC	100	106	57	100	141	65						
24	78	70		97	92	44	100	130	51	100	153	61			
27	69	62		86	79	35	100	113	42	100	140	50			
30	62	56		77	70	34	100	101	36	100	128	40			
33				65	64	31	90	90	36	100	120	40			
36				65	59	31	90	83	33	100	108	36			
42							77	70	30	100	89	31			
48							67	61	26	87	77	28	100	98	30
54							55	55	23	71	64	26	88	66	28
60										58	62	21	72	64	23
66													58	54	19
72													46	45	20

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.4 Maximum soil cover for the 2 2/3″ × 1/2″ aluminum alloy pipe.

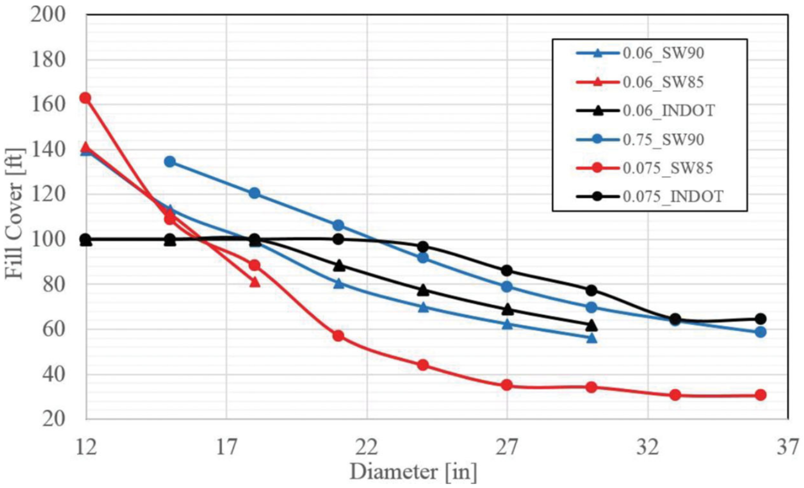


Figure 4.5 Maximum fill cover. Comparison between CANDE and INDOT results for 2 2/3″ × 1/2″ aluminum alloy pipes with t = 0.06, 0.075.

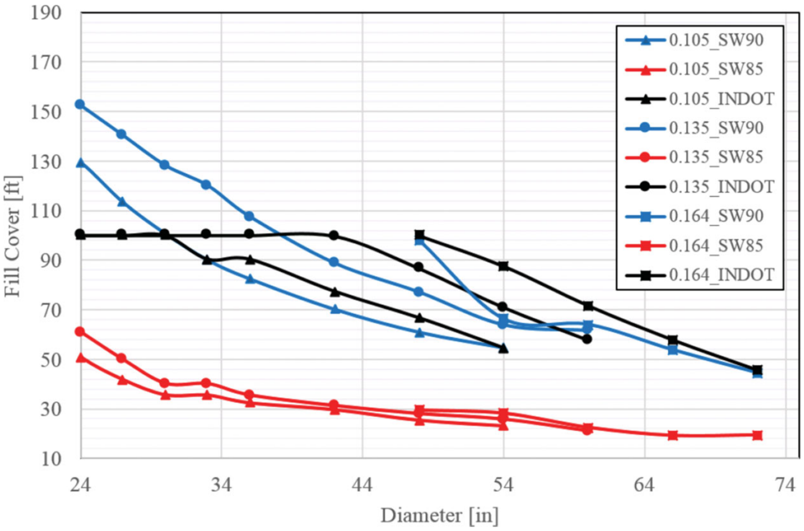
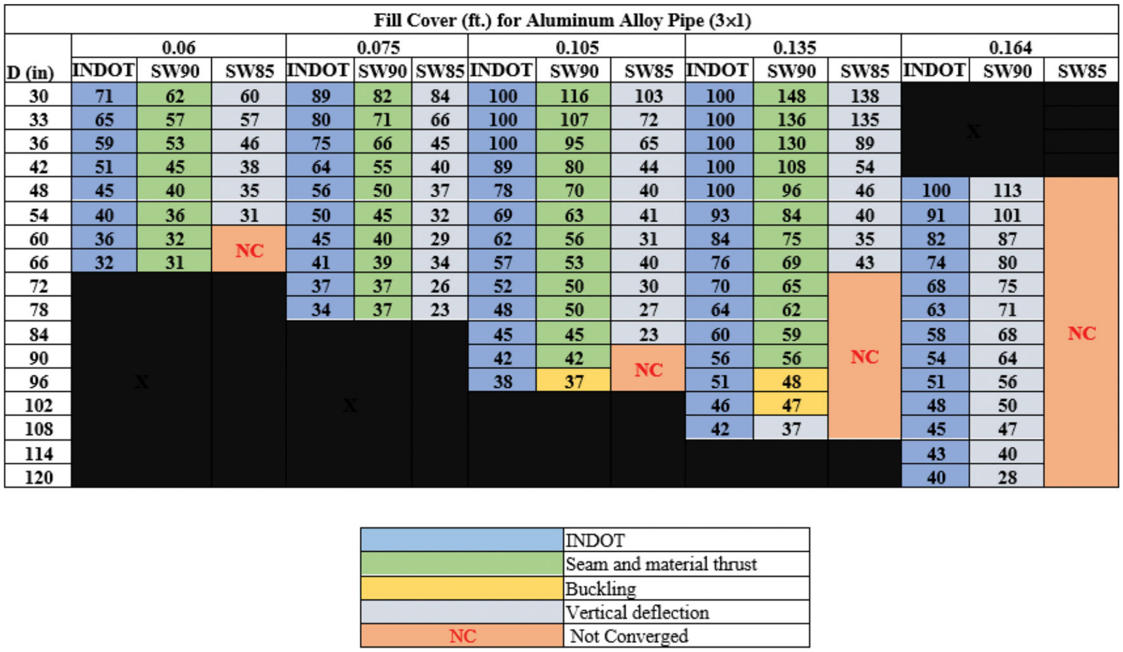


Figure 4.6 Maximum fill cover. Comparison between CANDE and INDOT results for 2 2/3″ × 1/2″ aluminum alloy pipes with t = 0.105, 0.135, 0.164.

4.4.3 3″ × 1″ Aluminum Alloy Pipe



Fill Cover (ft.) for Aluminum Alloy Pipe (3×1)															
	0.06			0.075			0.105			0.135			0.164		
D (in)	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85
30	71	62	60	89	82	84	100	116	103	100	148	138	X		
33	65	57	57	80	71	66	100	107	72	100	136	135			
36	59	53	46	75	66	45	100	95	65	100	130	89			
42	51	45	38	64	55	40	89	80	44	100	108	54			
48	45	40	35	56	50	37	78	70	40	100	96	46	100	113	NC
54	40	36	31	50	45	32	69	63	41	93	84	40	91	101	
60	36	32	NC	45	40	29	62	56	31	84	75	35	82	87	
66	32	31		41	39	34	57	53	40	76	69	43	74	80	
72	X			37	37	26	52	50	30	70	65	NC	68	75	
78				34	37	23	48	50	27	64	62		63	71	
84				X			45	45	23	60	59		58	68	
90							42	42	NC	56	56		54	64	
96							38	37		51	48		51	56	
102										46	47		48	50	
108										42	37		45	47	
114													43	40	
120													40	28	

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.7 Maximum soil cover for the 3″ × 1″ aluminum alloy pipe.

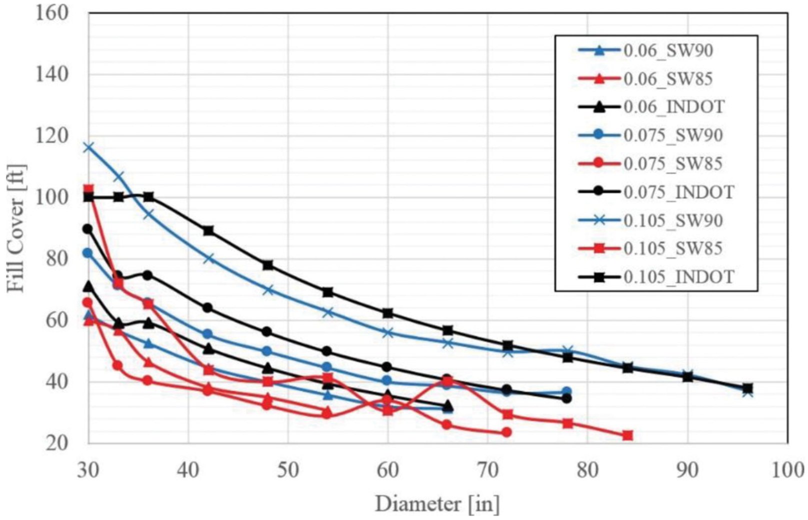


Figure 4.8 Maximum fill cover. Comparison between CANDE and INDOT results for 3″ × 1″ aluminum alloy pipes with t = 0.06, 0.075, 0.105.

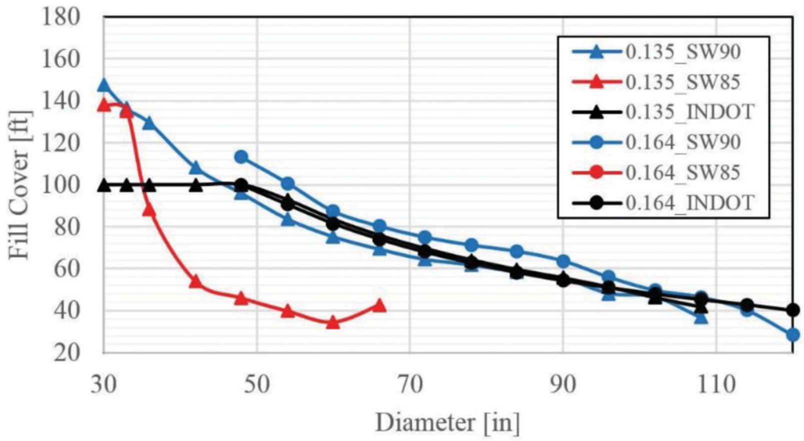
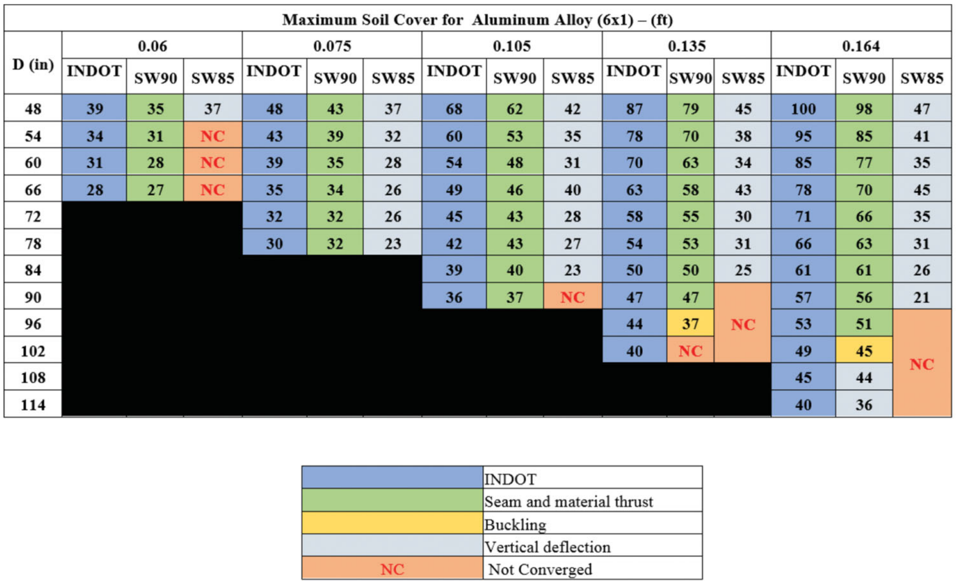


Figure 4.9 Maximum fill cover. Comparison between CANDE and INDOT results for 3″ × 1″ aluminum alloy pipes with t = 0.135, 0.164.

4.4.4 6″ × 1″ Aluminum Alloy Pipe



Maximum Soil Cover for Aluminum Alloy (6x1) – (ft)

D (in)	0.06			0.075			0.105			0.135			0.164		
	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85	INDOT	SW90	SW85
48	39	35	37	48	43	37	68	62	42	87	79	45	100	98	47
54	34	31	NC	43	39	32	60	53	35	78	70	38	95	85	41
60	31	28	NC	39	35	28	54	48	31	70	63	34	85	77	35
66	28	27	NC	35	34	26	49	46	40	63	58	43	78	70	45
72				32	32	26	45	43	28	58	55	30	71	66	35
78				30	32	23	42	43	27	54	53	31	66	63	31
84							39	40	23	50	50	25	61	61	26
90							36	37	NC	47	47	NC	57	56	21
96										44	37		53	51	NC
102										40	NC		49	45	
108													45	44	
114													40	36	

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.10 Maximum soil cover for the 6″ × 1″ aluminum alloy pipe.

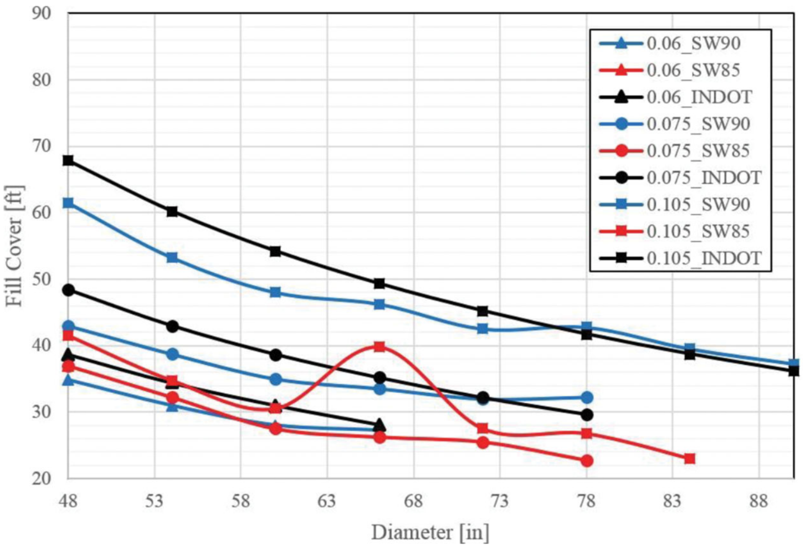


Figure 4.11 Maximum fill cover. Comparison between CANDE and INDOT results for 6″ × 1″ aluminum alloy pipes with t = 0.06, 0.075, 0.105.

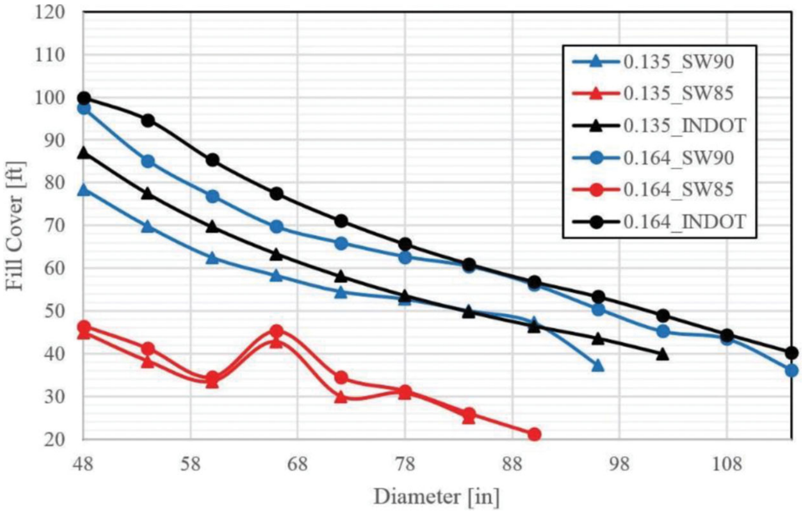


Figure 4.12 Maximum fill cover. Comparison between CANDE and INDOT results for 6″ × 1″ aluminum alloy pipes with t = 0.134, 0.164.

4.5 Corrugated Steel Pipes

The mechanical and geometrical properties of the corrugated steel pipes were selected based on CANDE user manual-2015 and are summarized in Tables 4.14 and 4.15.

The next sections list the maximum fill heights for corrugated steel pipe (lock seam) for different corrugation profiles and soil compaction, i.e., SW90 and SW85. Figures 4.14 to 4.22 plot the results and compare CANDE's predictions with INDOT's current values. In the figures, the blue line represents current calculations for SW90 soil, the red line for SW85 soil, and the black for INDOT's recommendations. Results with SW85 soil may not be complete because, for some diameters, CANDE was not able to calculate a fill height (listed as not converged in Figures 4.13, 4.16, 4.19, and 4.21). For riveted joints, a resistance factor of 0.67 was used for seam strength, as prescribed by the *AASHTO LRFD Bridge Design Specification.* Section 4.5.1 shows results for the 2 2/3″ × 1/2″ corrugated steel pipes (riveted), Section 4.5.2 for the 3″ × 1″ corrugated steel pipes (lock seam), Section 4.5.3 for the 3″ × 1″ corrugated steel pipes (riveted), and Section 4.5.4 for the 5″ × 1″ corrugated steel pipes (lock seam).

TABLE 4.14
Mechanical Properties of Corrugated Steel Pipe

Young's Modulus (psi)	29,000,000
Yield Stress (psi)	33,000
Poisson's Ratio	0.3
Density (pci)	0.284

TABLE 4.15
Geometrical Properties of Corrugated Steel Pipe 2 2/3″ × 1/2″, 3″ × 1″, 5″ × 1″

Corrugation Profile	Section Properties	Corrugation Thickness–in						
		0.04	**0.052**	**0.064**	**0.079**	**0.109**	**0.138**	**0.168**
2-2/3 × 1/2	PA in^{2}/in	0.03880	0.05160	0.06460	0.08070	0.11300	0.14530	0.17780
	PI in^{4}/in	0.00112	0.00150	0.00189	0.00239	0.00342	0.00453	0.00573
	PS in^{3}/in	0.00415	0.00543	0.00670	0.00826	0.01123	0.01420	0.01716
3 × 1	PA in^{2}/in	0.04450	0.05930	0.07420	0.09280	0.13000	0.16730	0.20480
	PI in^{4}/in	0.00515	0.00689	0.00866	0.01088	0.01546	0.02018	0.02509
	PS in^{3}/in	0.00990	0.01310	0.01628	0.02017	0.02788	0.03547	0.04296
5 × 1	PA in^{2}/in	0.0000	0.0000	0.06620	0.82670	0.11580	0.14900	0.18220
	PI in^{4}/in	0.00000	0.00000	0.00885	0.01109	0.01565	0.02032	0.02509
	PS in^{3}/in	0.00000	0.00000	0.01664	0.02056	0.02822	0.03571	0.04296

PA = area of pipe wall section per unit length, PI = moment of inertia of pipe wall section per unit length, and PS = section modulus of pipe wall per unit length.

4.5.1 2 2/3″ × 1/2″ Corrugated Steel Pipes (Riveted)

Maximum Soil Cover for 2 2/3 x ½ Corrugated Steel Pipes (Riveted) – (ft)										
D (in)	Thickness									
	0.064		0.079		0.109		0.138		0.168	
	SW90	INDOT	SW90	INDOT	SW90	INDOT	SW90	INDOT	SW90	INDOT
12	118	93	130	100						
15	97	74	112	81	140	100				
18	84	62	98	67	125	87				
21	69	53	84	58	110	74				
24	61	46	73	51	100	65				
27	56	41	66	45	91	58				
30	49	37	61	40	85	52	113	54		
33	45	31	55	34	79	43	107	45		
36	43	31	51	34	73	43	99	45	109	47
42	36	34	42	47	60	74	81	78	98	81
48	31	30	38	41	54	65	70	68	88	71
54			36	37	49	58	62	60	76	63
60					47	52	57	54	68	57
66							52	49	65	52
72							49	45	59	48
78									57	44
84									53	41

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.13 Maximum soil cover for the 2 2/3″ × 1/2″ corrugated steel pipes (riveted).

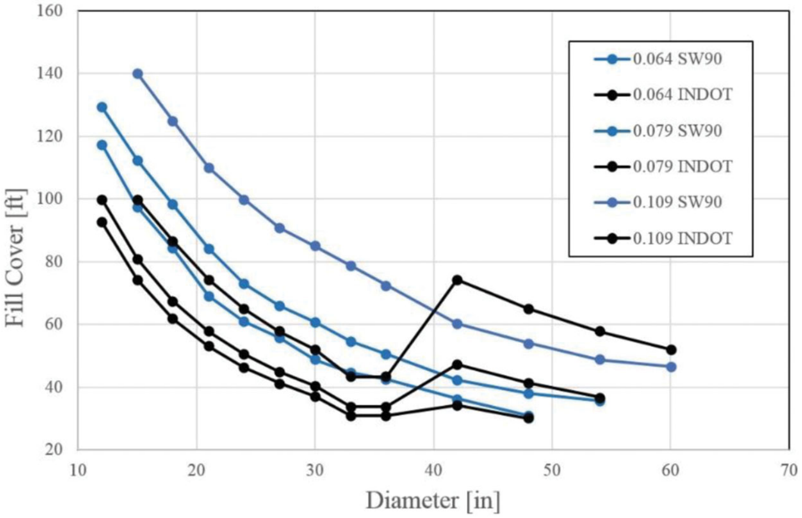


Figure 4.14 Maximum fill cover. Comparison between CANDE and INDOT results 2 2/3″ × 1/2″ corrugated steel pipes (riveted) with t = 0.064, 0.079, 0.109.

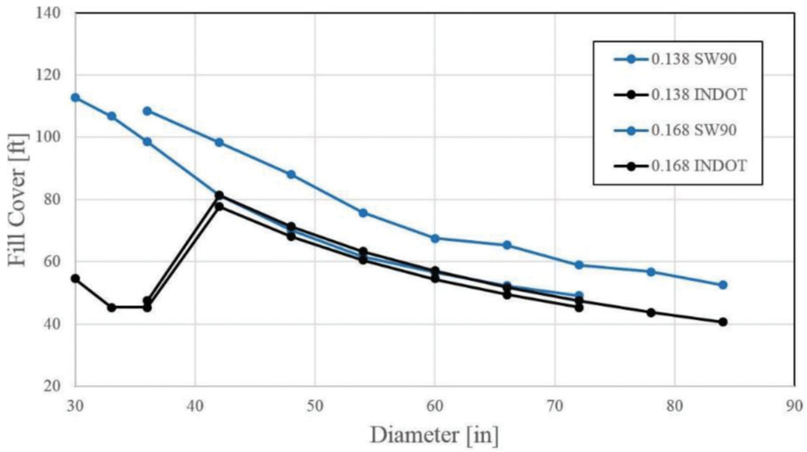
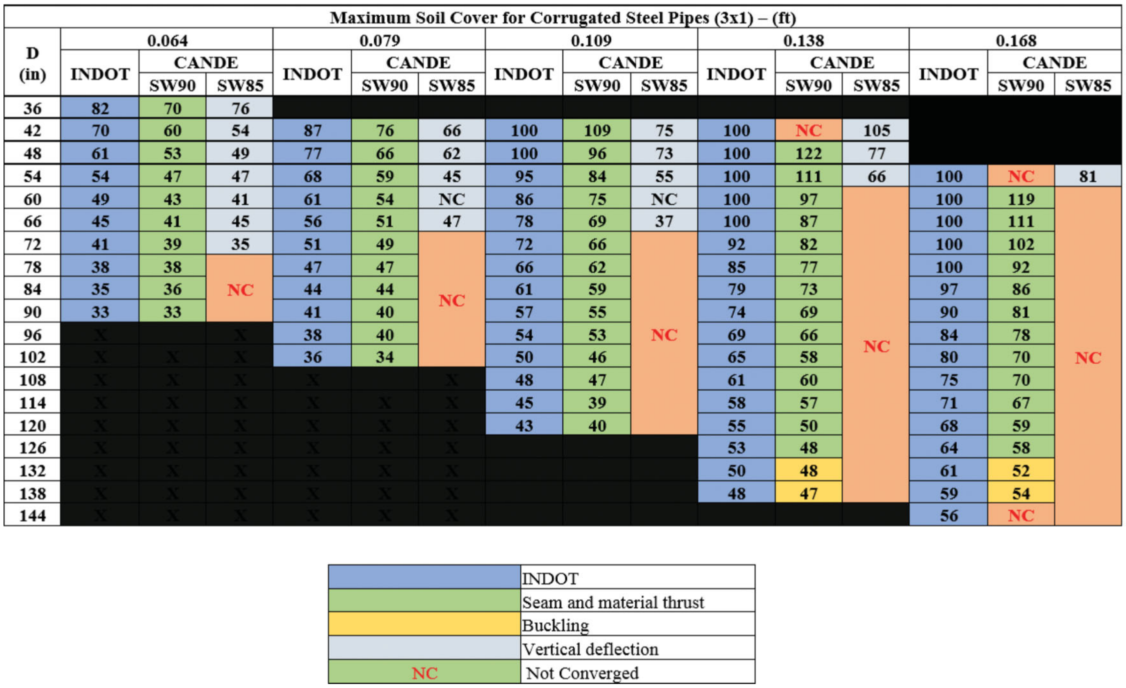


Figure 4.15 Maximum fill cover. Comparison between CANDE and INDOT results 2 2/3″ × 1/2″ corrugated steel pipes (riveted) with t = 0.138 and 0.168.

4.5.2 3″ × 1″ Corrugated Steel Pipes (Lock Seam)



Maximum Soil Cover for Corrugated Steel Pipes (3x1) – (ft)															
D (in)	0.064			0.079			0.109			0.138			0.168		
	INDOT	CANDE		INDOT	CANDE		INDOT	CANDE		INDOT	CANDE		INDOT	CANDE	
		SW90	SW85		SW90	SW85		SW90	SW85		SW90	SW85		SW90	SW85
36	82	70	76												
42	70	60	54	87	76	66	100	109	75	100	NC	105			
48	61	53	49	77	66	62	100	96	73	100	122	77			
54	54	47	47	68	59	45	95	84	55	100	111	66	100	NC	81
60	49	43	41	61	54	NC	86	75	NC	100	97	NC	100	119	NC
66	45	41	45	56	51	47	78	69	37	100	87		100	111	
72	41	39	35	51	49	NC	72	66	NC	92	82		100	102	
78	38	38	NC	47	47		66	62		85	77		100	92	
84	35	36		44	44		61	59		79	73		97	86	
90	33	33		41	40		57	55		74	69		90	81	
96	X		X	38	40		54	53		69	66		84	78	
102	X	X	X	36	34		50	46		65	58		80	70	
108	X	X	X	X		X	48	47		61	60		75	70	
114	X	X	X	X	X	X	45	39		58	57		71	67	
120	X	X	X	X	X	X	43	40		55	50		68	59	
126	X	X	X	X	X	X				53	48		64	58	
132	X	X	X	X	X	X				50	48		61	52	
138	X	X	X	X	X	X				48	47		59	54	
144	X	X	X	X	X	X							56	NC	

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.16 Maximum soil cover for the 3″ × 1″ corrugated steel pipes (lock seam).

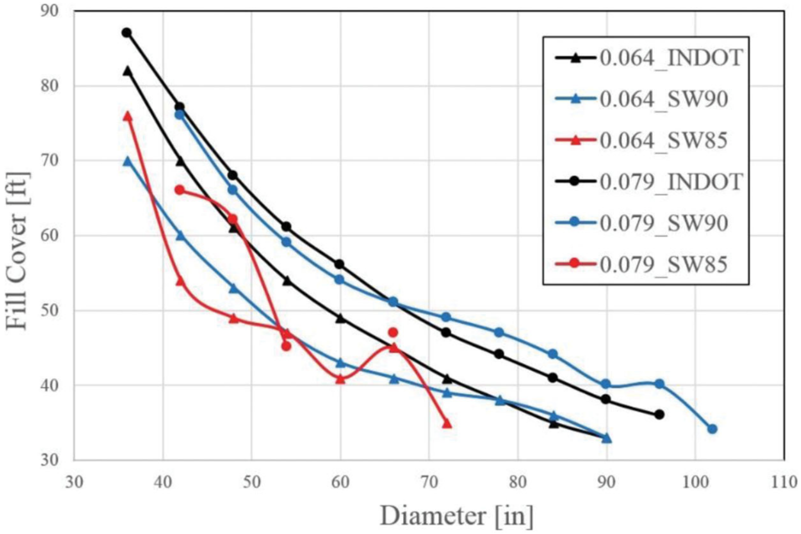


Figure 4.17 Maximum fill cover. Comparison between CANDE and INDOT results for 3″ × 1″ corrugated steel pipes (lock seam) with t = 0.064, 0.079.

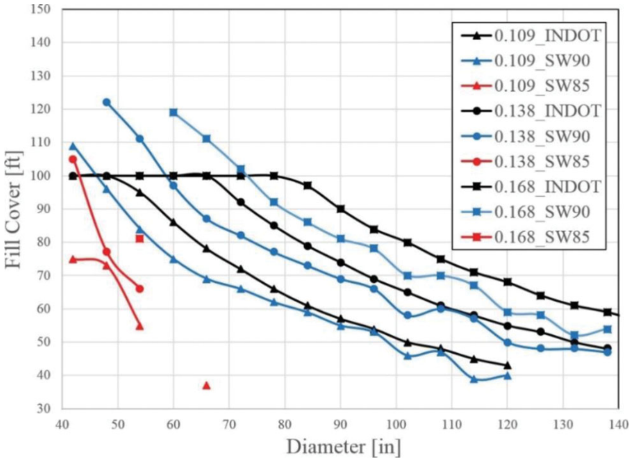
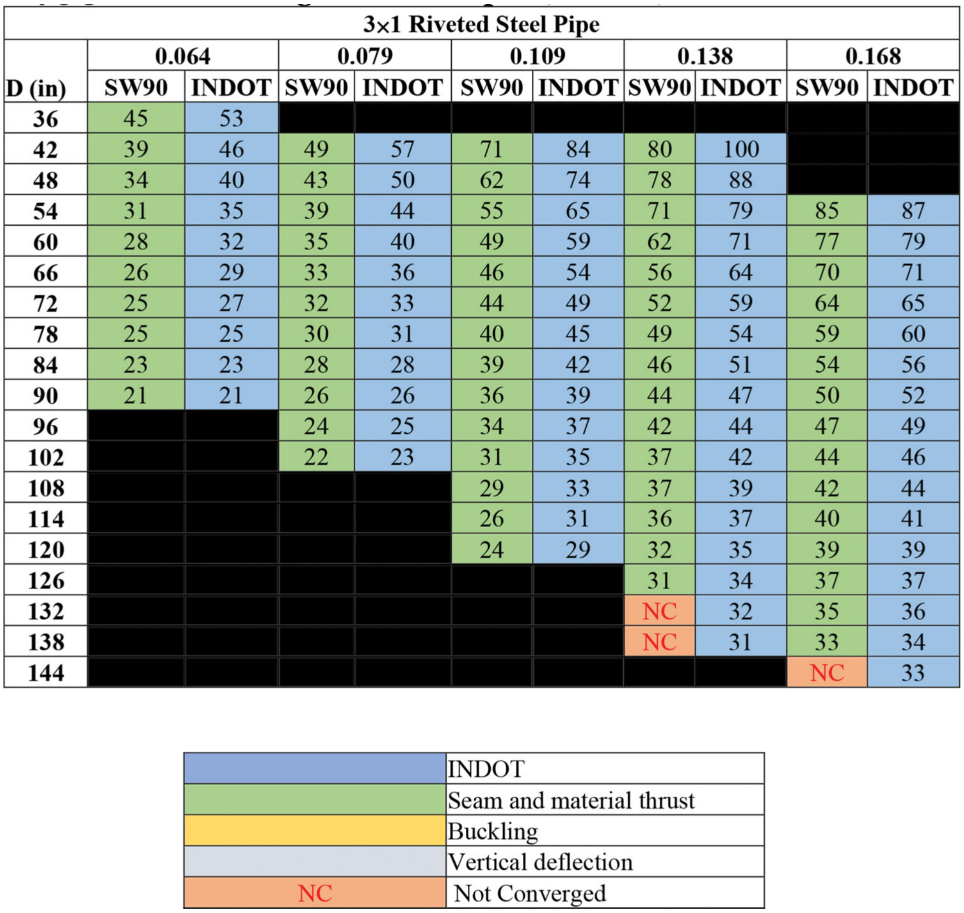


Figure 4.18 Maximum fill cover. Comparison between CANDE and INDOT results for 3″ × 1″ corrugated steel pipes (lock seam) with t = 0.109, 0.138, 0.168.

4.5.3 3″ × 1″ Corrugated Steel Pipes (Riveted)



3×1 Riveted Steel Pipe										
	0.064		0.079		0.109		0.138		0.168	
D (in)	SW90	INDOT	SW90	INDOT	SW90	INDOT	SW90	INDOT	SW90	INDOT
36	45	53								
42	39	46	49	57	71	84	80	100		
48	34	40	43	50	62	74	78	88		
54	31	35	39	44	55	65	71	79	85	87
60	28	32	35	40	49	59	62	71	77	79
66	26	29	33	36	46	54	56	64	70	71
72	25	27	32	33	44	49	52	59	64	65
78	25	25	30	31	40	45	49	54	59	60
84	23	23	28	28	39	42	46	51	54	56
90	21	21	26	26	36	39	44	47	50	52
96			24	25	34	37	42	44	47	49
102			22	23	31	35	37	42	44	46
108					29	33	37	39	42	44
114					26	31	36	37	40	41
120					24	29	32	35	39	39
126							31	34	37	37
132							NC	32	35	36
138							NC	31	33	34
144									NC	33

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.19 Maximum soil cover for the 3″ × 1″ corrugated steel pipes (riveted).

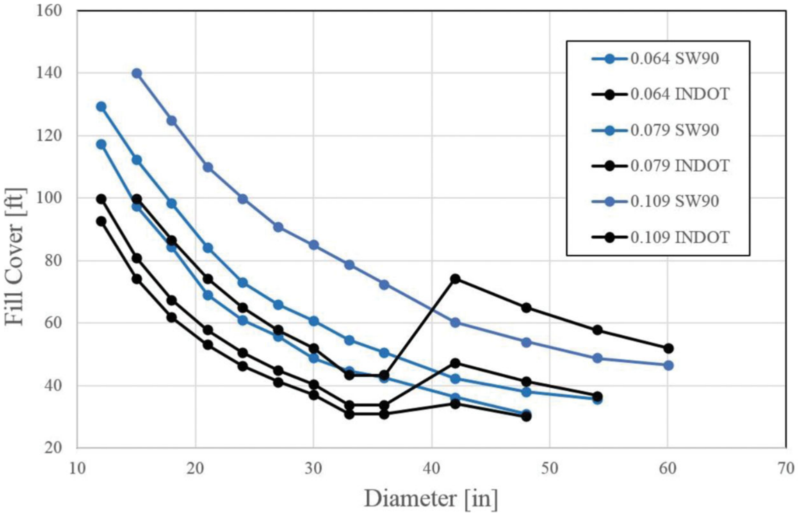
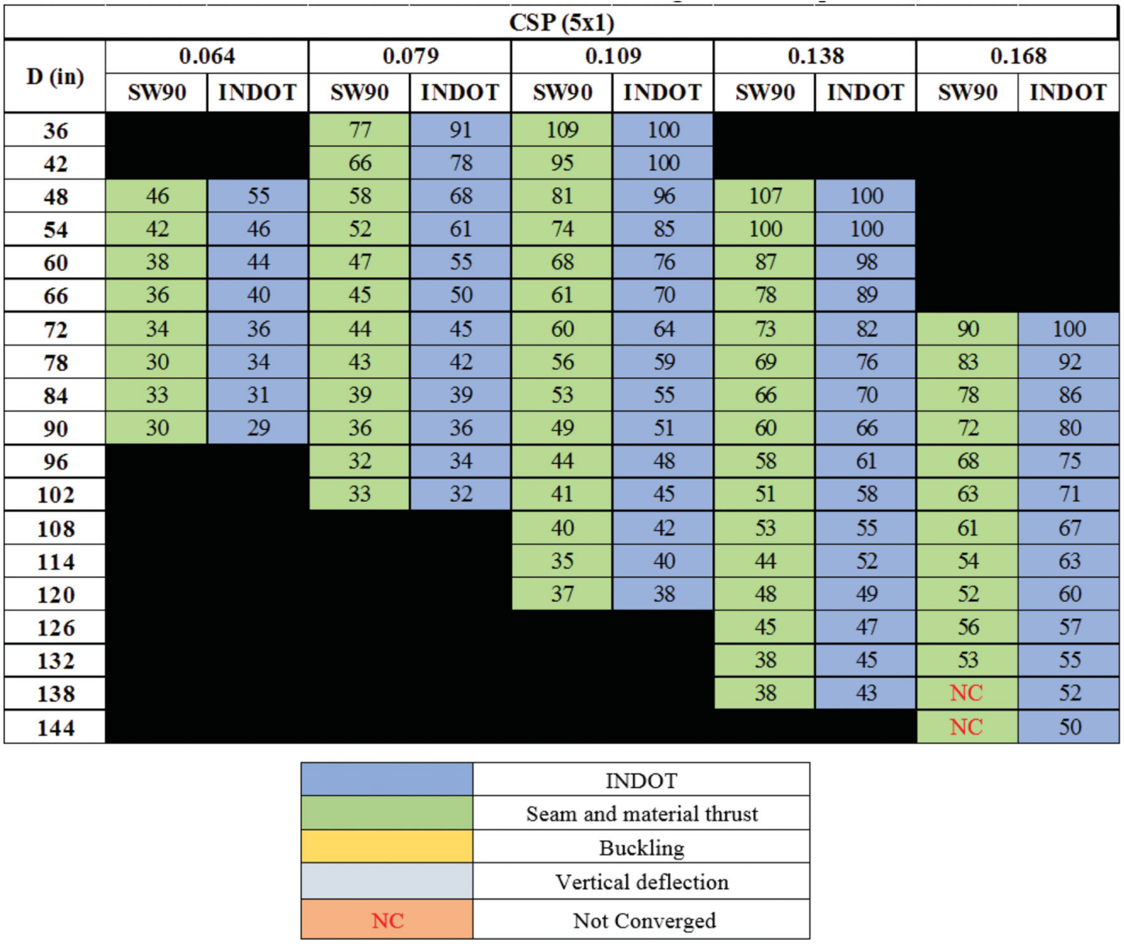


Figure 4.20 Maximum fill cover. Comparison between CANDE and INDOT results for 3″ × 1″ corrugated steel pipes (riveted) with t = 0.064, 0.079, 0.109, 0.138, 0.168.

4.5.4 5″ × 1″ Corrugated Steel Pipes (Lock Seam)



CSP (5x1)										
D (in)	0.064		0.079		0.109		0.138		0.168	
	SW90	INDOT	SW90	INDOT	SW90	INDOT	SW90	INDOT	SW90	INDOT
36			77	91	109	100				
42			66	78	95	100				
48	46	55	58	68	81	96	107	100		
54	42	46	52	61	74	85	100	100		
60	38	44	47	55	68	76	87	98		
66	36	40	45	50	61	70	78	89		
72	34	36	44	45	60	64	73	82	90	100
78	30	34	43	42	56	59	69	76	83	92
84	33	31	39	39	53	55	66	70	78	86
90	30	29	36	36	49	51	60	66	72	80
96			32	34	44	48	58	61	68	75
102			33	32	41	45	51	58	63	71
108					40	42	53	55	61	67
114					35	40	44	52	54	63
120					37	38	48	49	52	60
126							45	47	56	57
132							38	45	53	55
138							38	43	NC	52
144									NC	50

🟦	INDOT
🟩	Seam and material thrust
🟨	Buckling
⬜	Vertical deflection
NC	Not Converged

Figure 4.21 Maximum soil cover for 5″ × 1″ corrugated steel pipes (lock seam).

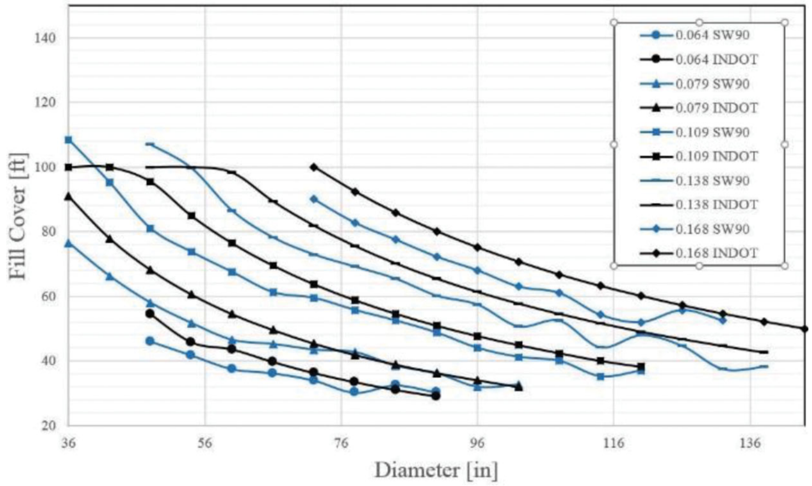


Figure 4.22 Maximum fill cover. Comparison between CANDE and INDOT results for 5″× 1″ corrugated steel pipes (lock seam) with t = 0.064, 0.079, 0.109, 0.138, 0.168.

4.6 Corrugated Pipe-Arches

The mechanical properties for corrugated steel pipe arches (CSPA) and corrugated aluminum pipe arches (CAPA) can be found in Tables 4.16 and 4.17.

The size and layout details for CSPA and CAPA with 22/3″ × 1/2″ corrugation is found in Table 4.18, and for CSPA and CAPA with 3 × 1″ and 5 × 1″ corrugations, in Table 4.19. A description of the parameters can be found in Figure 4.23.

The section properties details for CSPA with 2 2/3″ × 1/2″, 3 × 1″ and 5 × 1″ corrugations are listed in Table 4.20, and for CAPA with 2 2/3″ × 1/2″ and 3 × 1″ corrugations, in Table 4.21.

The maximum fill height tables in the next sections include results previously published by INDOT, results obtained with CANDE, ASTM calculations computed using the pressure in the corners (P_c) and the overall pressure (P_v). Tables are color-coded according to the critical failure criterion, and results are plotted for better comparison. In the figures, the red curve represents INDOT results, the grey curve shows the ASTM P_c results, the blue curve, the ASTM P_v results, and the black curve represents CANDE results. Figures 4.24 to 4.37 provide the results for corrugated steel and aluminum pipe-arch, Figure 4.38 for reinforced concrete pipe Class III, Figure 4.39 for smooth wall PVC pipe, Figure 4.40 for vitrified clay pipe, Figures 4.41 to 4.44 for structural plate steel and aluminum alloy pipe, and Figures 4.46 to 4.57 for structural plate steel and aluminum pipe arch. The plots in the figures may correspond to best-fit results when the calculations output was not smooth; the best fit values also appear in the tables.

TABLE 4.16
Mechanical Properties of Corrugated Pipe-Arches

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

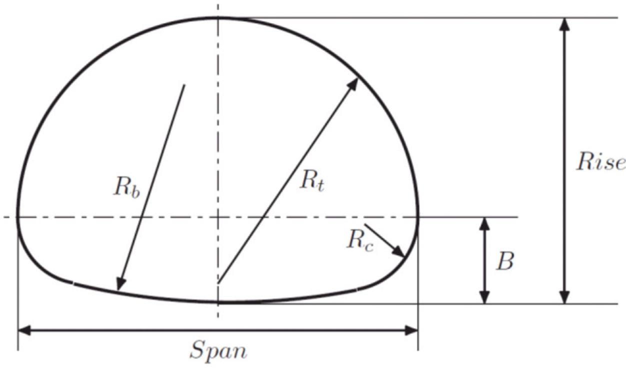


Figure 4.23 Geometrical representation of pipe-arches.

TABLE 4.17
Ultimate Longitudinal Seam Strength of Corrugated Pipes

	Steel	
Corrugation Profile (in)	**3 × 1**	**5 × 1**
Thickness (in)	**Seam Strength Double (lb/ft)**	**Seam Strength Double (lb/ft)**
0.064	28,700	28,700
0.079	35,700	35,700
0.109	53,000	53,000
0.138	63,700	63,700
0.168	70,700	70,700
	Aluminum	
Corrugation Profile (in)	**2 2/3 × 1/2**	**3 × 1**
Thickness (in)	**Seam Strength Double (lb/ft)**	**Seam Strength Double (lb/ft)**
0.060	14,000	16,500
0.075	18,000	20,500
0.105	31,500	28,000
0.135	33,000	42,000
0.164	34,000	54,500

TABLE 4.18
CSPA and CAPA Size and Layout Details for 2 2/3″ × 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 4.19
CSPA and CAPA Size and Layout Details for 3″ × 1″ and 5″ × 1″ Corrugations

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

TABLE 4.20
CSPA Section Properties Details for 2 2/3″ × 1/2″, 3″ × 1″ and 5″ × 1″ Corrugation

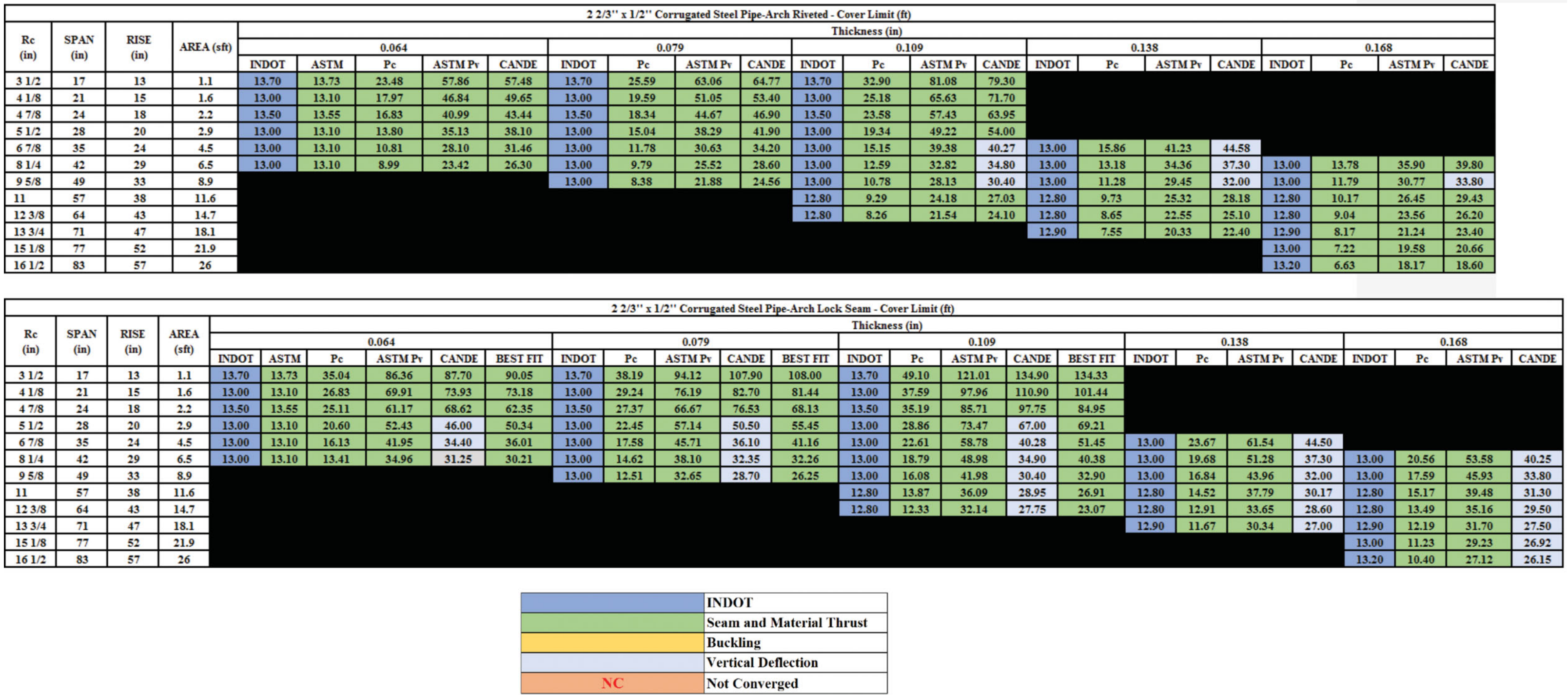
	Corrugation Profile (in)								
Corrugation	2 2/3 × 1/2			3 × 1			5 × 1		
Thickness (in)	PA (in^2/in)	PA (in^4/in)	PA (in^3/in)	PA (in^2/in)	PA (in^4/in)	PA (in^3/in)	PA (in^2/in)	PA (in^4/in)	PA (in^3/in)
0.064	0.0646	0.00189	0.0067	0.0742	0.00866	0.01628	0.0662	0.00885	0.01664
0.079	0.0807	0.00239	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 4.21
CAPA Section Properties Details for 2 2/3″ × 1/2″ and 3″ × 1″ Corrugation

	Corrugation Profile (in)					
Corrugation	2 2/3 × 1/2			3 × 1		
Thickness (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)
0.060	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

4.6.1 2 2/3″ × 1/2″ Corrugated Steel Pipe-Arch

The results of the maximum fill heights are tabulated in Figure 4.24 and plotted in Figures 4.25 and 4.26.



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

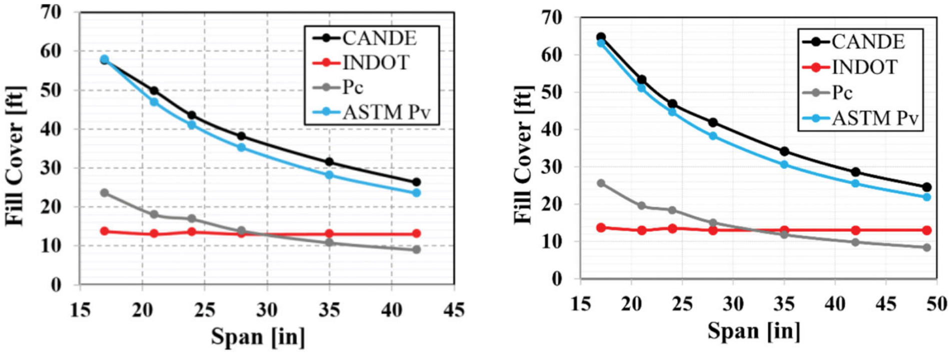
Rc (in)	SPAN (in)	RISE (in)	AREA (sft)	Thickness (in)																				
				0.064					0.079				0.109				0.138				0.168			
				INDOT	ASTM	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
3 1/2	17	13	1.1	13.70	13.73	23.48	57.86	57.48	13.70	25.59	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

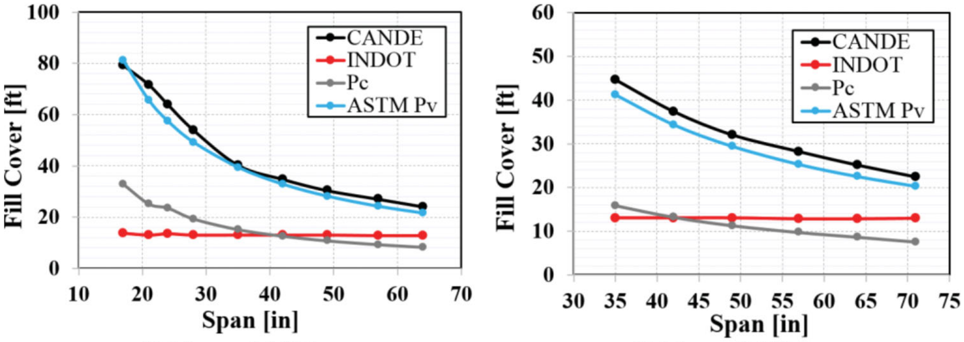
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.24 Maximum soil cover for 2 2/3″ × 1/2″ corrugated steel pipe-arch riveted and lock seam.



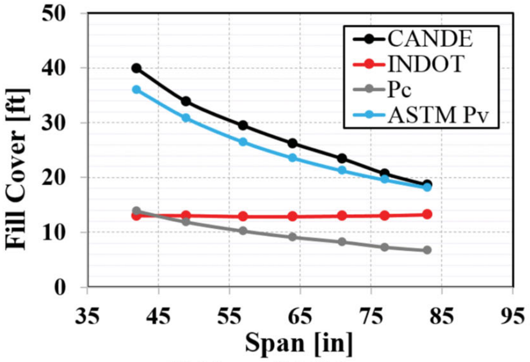
Thickness 0.064 in.

Thickness 0.079 in.



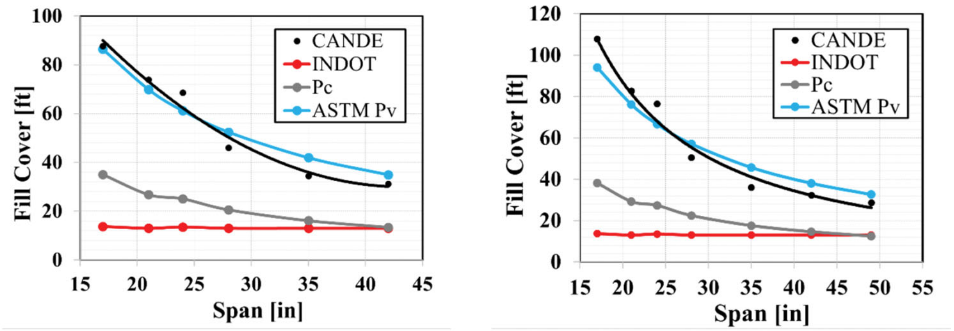
Thickness 0.109 in.

Thickness 0.138 in.



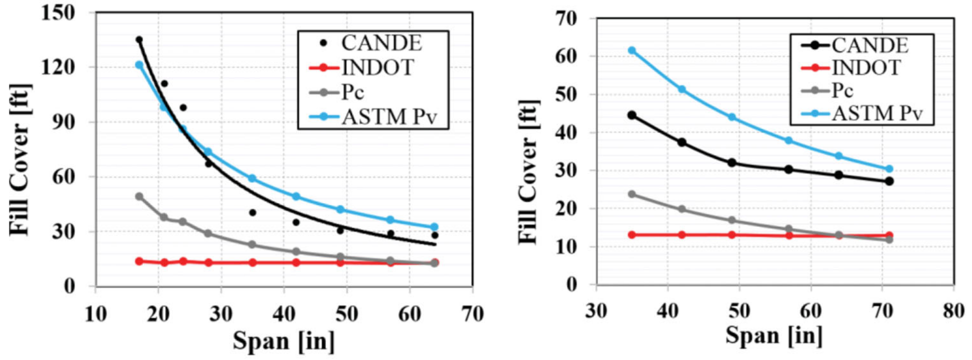
Thickness 0.168 in.

Figure 4.25 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 2 2/3″ × 1/2″ corrugated steel pipe-arch riveted with thicknesses of (a) 0.064 in., (b) 0.079 in., (c) 0.109 in., (d) 0.138 in., and (e) 0.168 in.



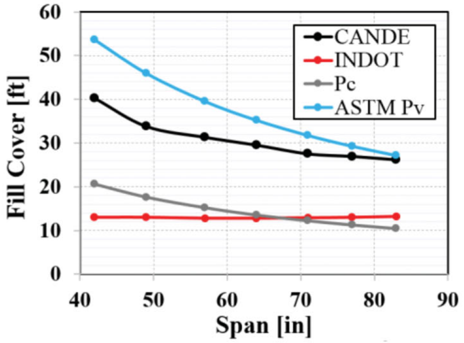
(a) Thickness 0.064 in.

(b) Thickness 0.079 in.



(c) Thickness 0.109 in.

(d) Thickness 0.138 in.

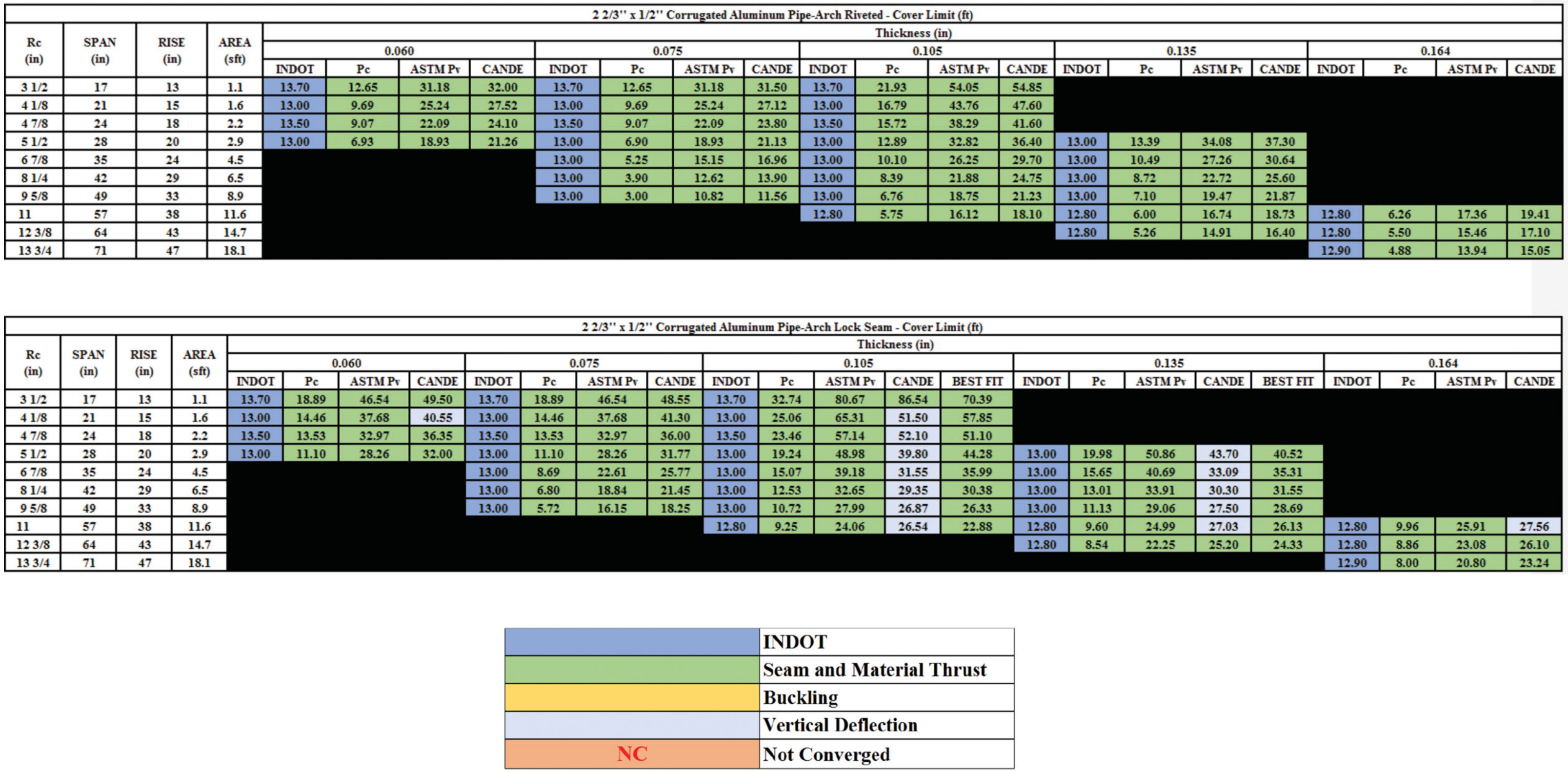


(e) Thickness 0.168 in.

Figure 4.26 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 2 2/3″ × 1/2″ corrugated steel pipe-arch lock seam with thicknesses of (a) 0.064 in., (b) 0.079 in., (c) 0.109 in., (d) 0.138 in., and (e) 0.168 in.

4.6.2 2 2/3″ × 1/2″ Corrugated Aluminum Pipe-Arch

Figure 4.27 lists the maximum fill for the different pipe sizes and thicknesses. The results are plotted in Figures 4.28 and 4.29.

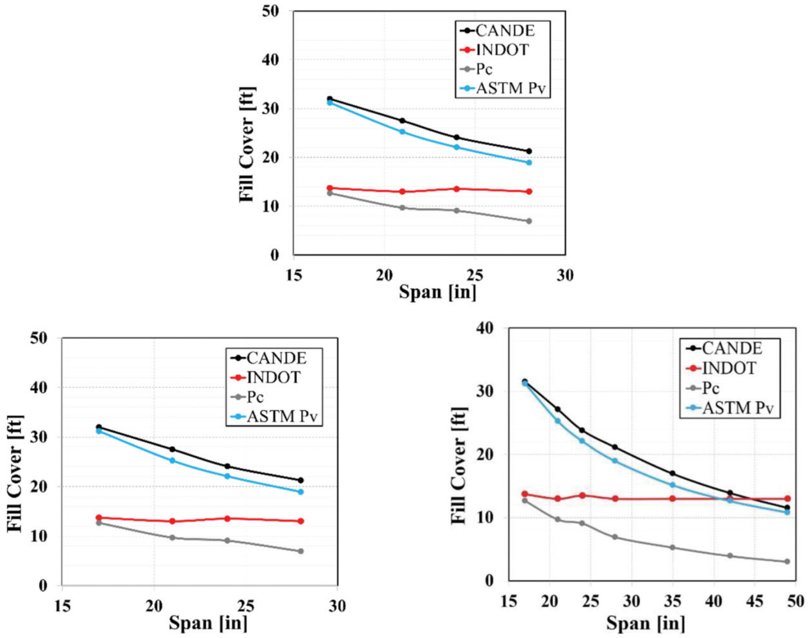


2 2/3'' x 1/2'' Corrugated Aluminum Pipe-Arch Riveted - Cover Limit (ft)																							
Rc (in)	SPAN (in)	RISE (in)	AREA (sft)	Thickness (in)																			
				0.060				0.075				0.105				0.135				0.164			
				INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM 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

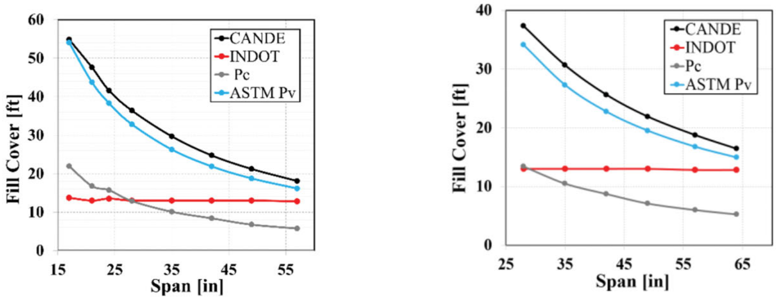
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.27 Maximum soil cover for 2 2/3″ × 1/2″ corrugated aluminum pipe-arch riveted and lock seam.



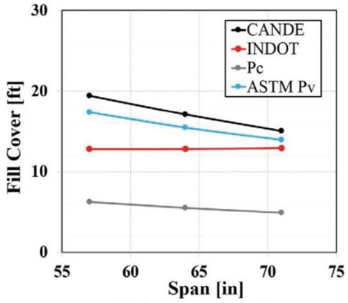
(a) Thickness 0.060 in.

(b) Thickness 0.075 in.



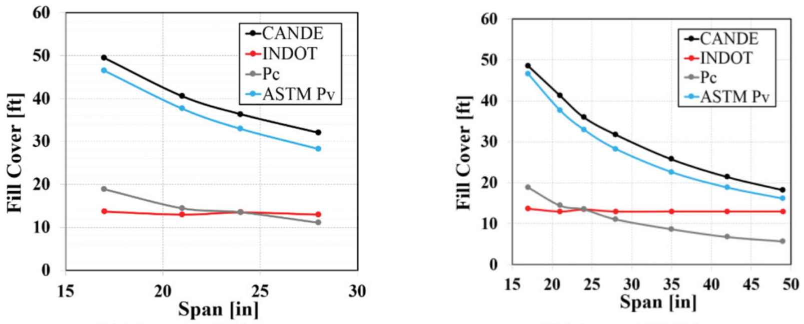
(c) Thickness 0.105 in.

(d) Thickness 0.135 in.



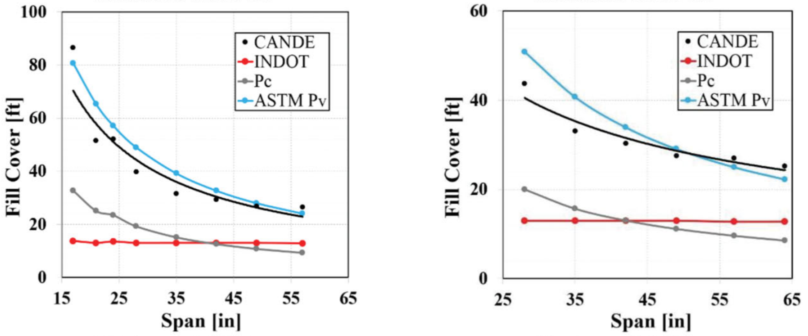
(e) Thickness 0.164 in.

Figure 4.28 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 2 2/3″ × 1/2″ corrugated aluminum pipe-arch riveted with thicknesses of (a) 0.060 in., (b) 0.075 in., (c) 0.105 in., (d) 0.135 in., and (e) 0.164 in.



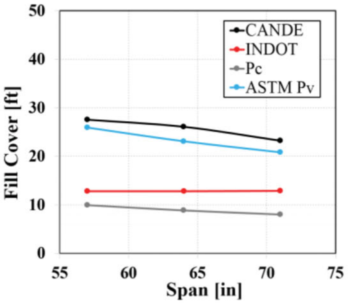
Thickness 0.060 in.

Thickness 0.075 in.



Thickness 0.105 in.

Thickness 0.135 in.

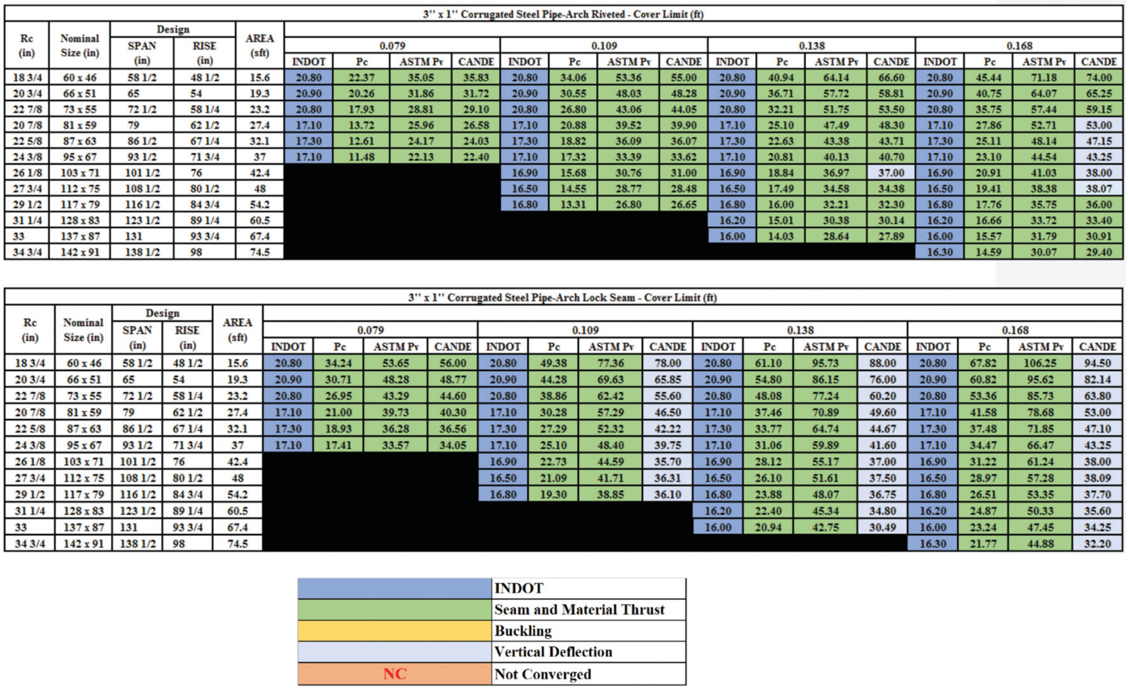


Thickness 0.164 in.

Figure 4.29 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 2 2/3″ × 1/2″ corrugated aluminum pipe-arch lock seam with thicknesses of (a) 0.060 in., (b) 0.075 in., (c) 0.105 in., (d) 0.135 in., and (e) 0.164 in.

4.6.3 *3″ × 1″ Corrugated Steel Pipe-Arch*

The numerical results from the calculations with CANDE are provided in Figure 4.30, and are plotted in Figures 4.31 and 4.32.



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

Figure 4.30 Maximum soil cover for 3″ × 1″ corrugated steel pipe-arch riveted and lock seam.

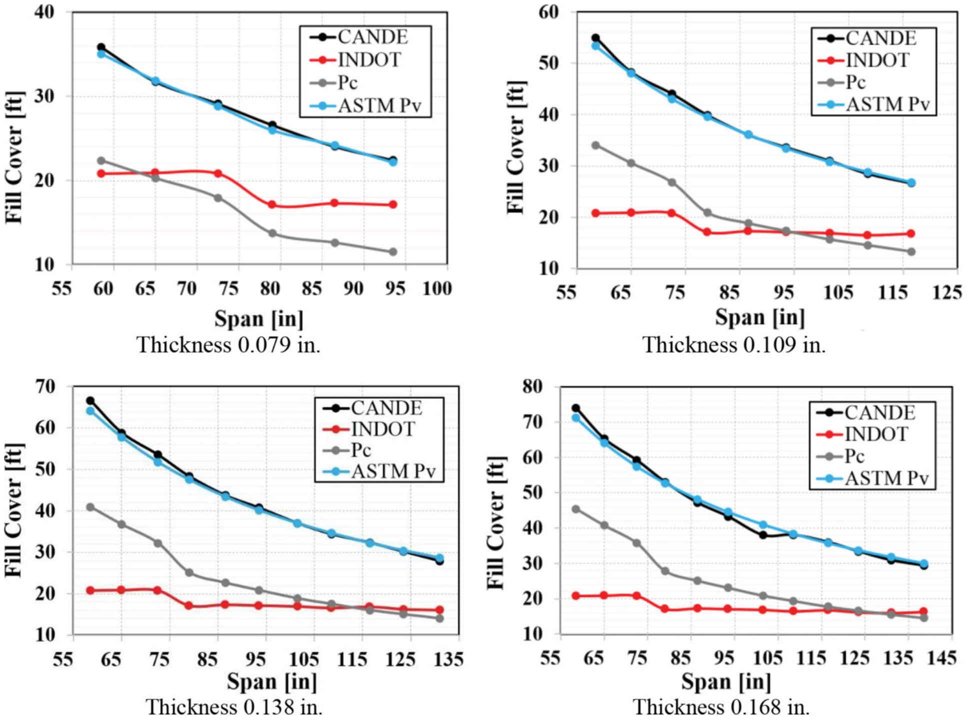
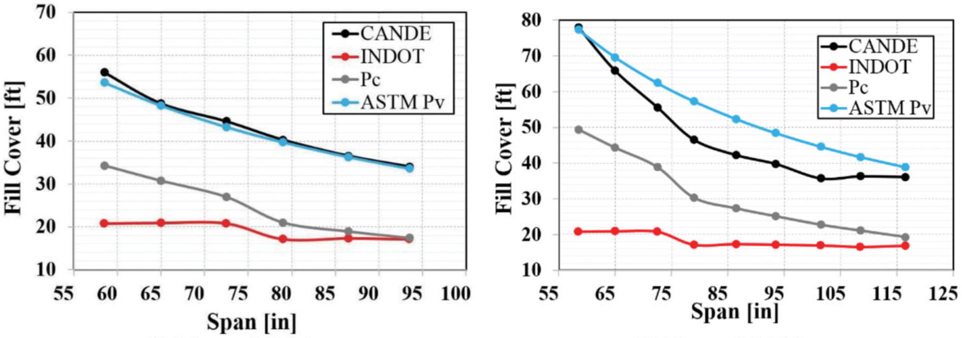
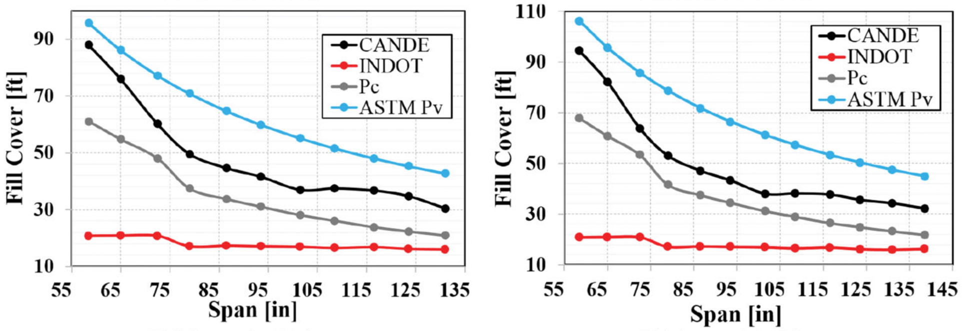


Figure 4.31 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 3″ × 1″ corrugated steel pipe-arch riveted with thicknesses of (a) 0.079 in., (b) 0.109 in., (c) 0.138 in., and (d) 0.168 in.



Thickness 0.079 in.

Thickness 0.109 in.



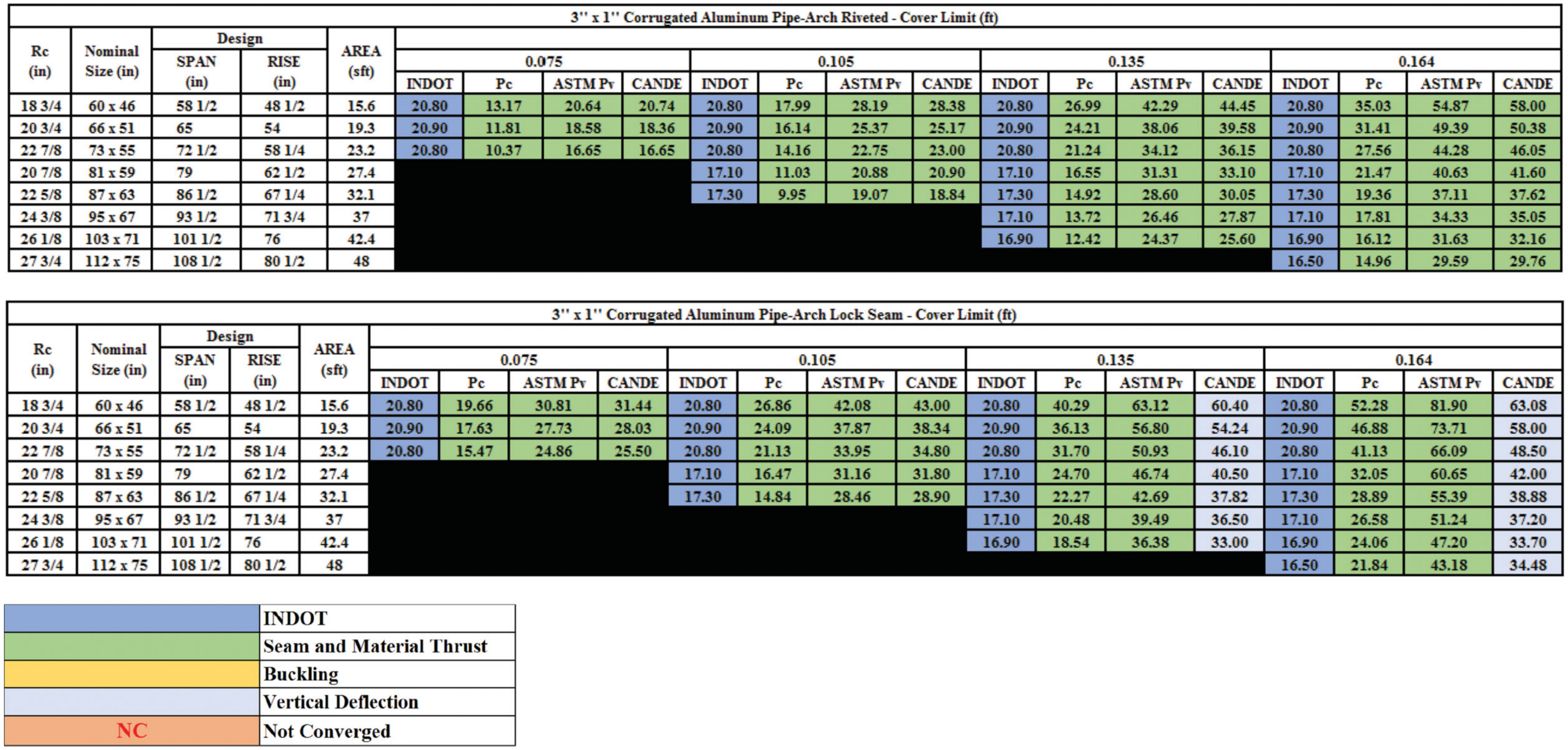
Thickness 0.138 in.

Thickness 0.168 in.

Figure 4.32 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 3″ × 1″ corrugated steel pipe-arch lock seam with thicknesses of (a) 0.079 in., (b) 0.109 in., (c) 0.138 in., and (d) 0.168 in.

4.6.4 3″ × 1″ Corrugated Aluminum Pipe-Arch

Figure 4.33 tabulates the maximum fill heights, and Figures 4.34 and 4.35 plot the results.

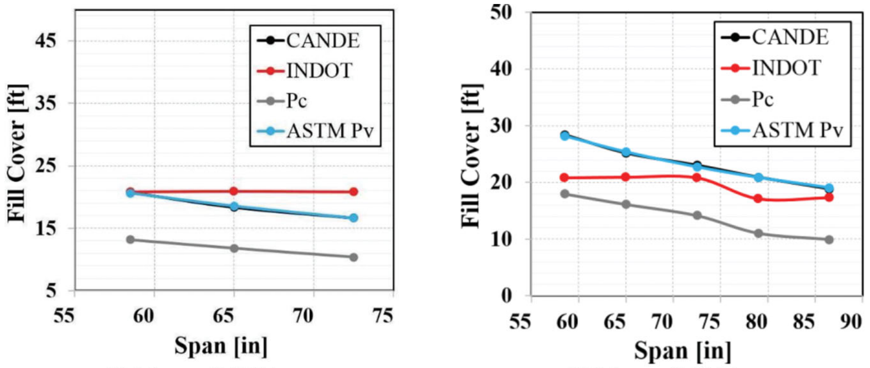


3'' x 1'' Corrugated Aluminum Pipe-Arch Riveted - Cover Limit (ft)																				
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.075				0.105				0.135				0.164			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 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

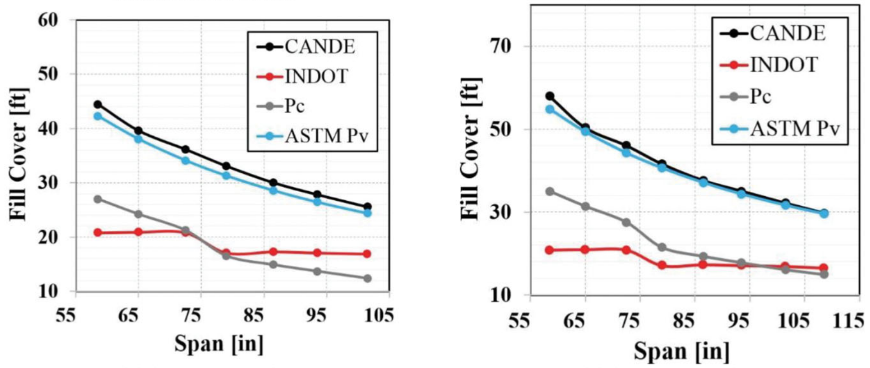
3'' x 1'' Corrugated Aluminum Pipe-Arch Lock Seam - Cover Limit (ft)																				
Rc (in)	Nominal Size (in)	Design		AREA (sft)	0.075				0.105				0.135				0.164			
		SPAN (in)	RISE (in)		INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE	INDOT	Pc	ASTM Pv	CANDE
18 3/4	60 x 46	58 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

Figure 4.33 Maximum soil cover for 3″ × 1″ corrugated aluminum pipe-arch riveted and lock seam.

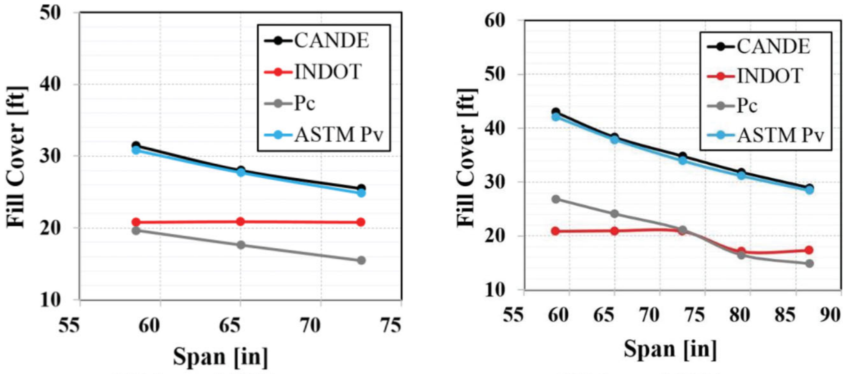


Thickness 0.075 in. Thickness 0.105 in.

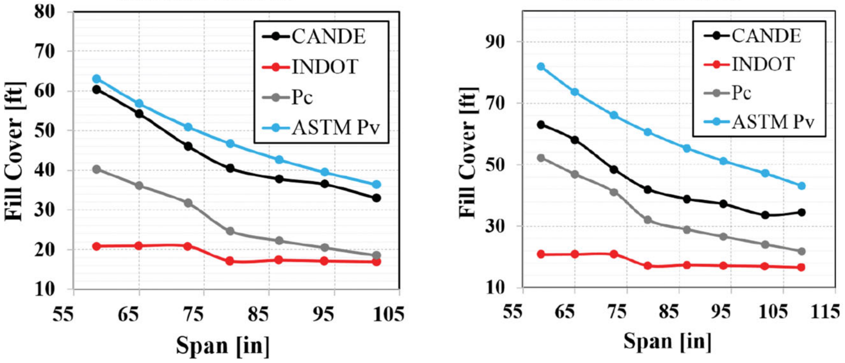


Thickness 0.135 in. Thickness 0.164 in.

Figure 4.34 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 3″ × 1″ corrugated aluminum pipe-arch riveted with thicknesses of (a) 0.075 in., (b) 0.105 in., (c) 0.135 in., and (d) 0.164 in.



Thickness 0.075 in. Thickness 0.105 in.

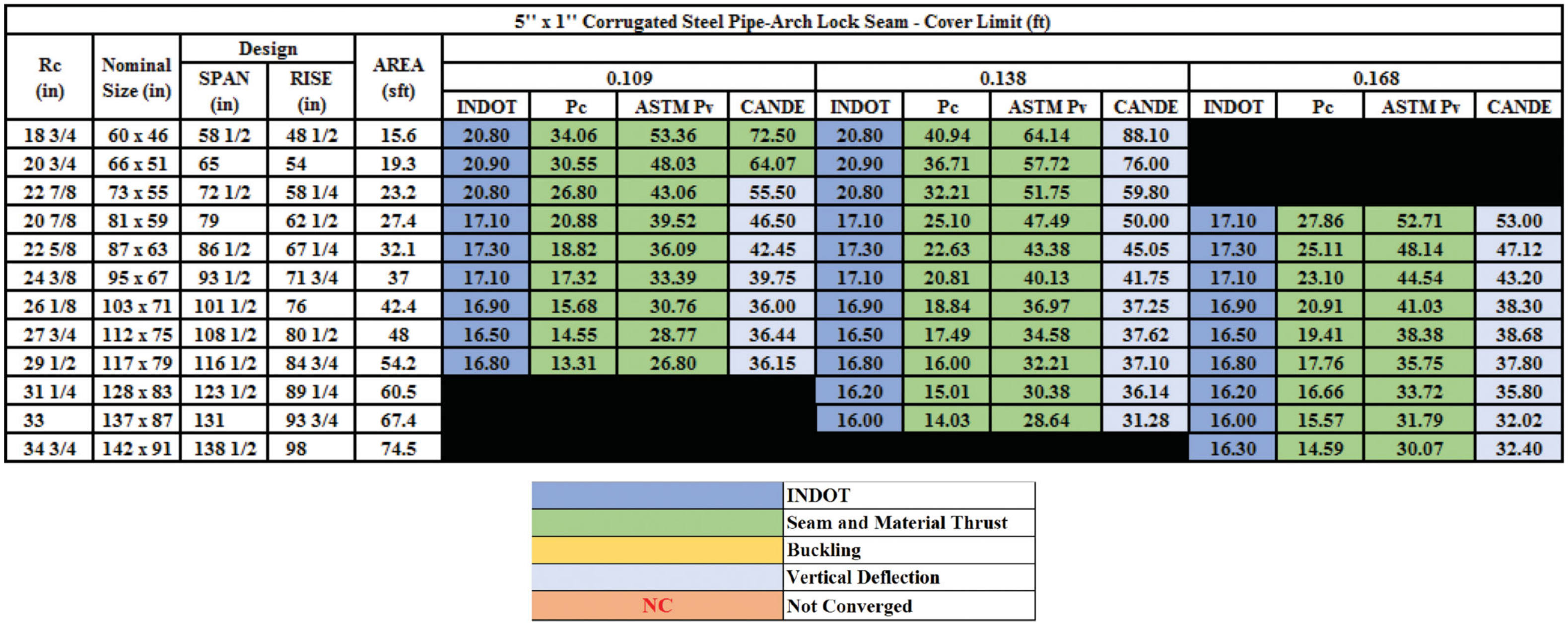


Thickness 0.135 in. Thickness 0.164 in.

Figure 4.35 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 3″ × 1″ corrugated aluminum pipe-arch lock seam with thicknesses of (a) 0.075 in., (b) 0.105 in., (c) 0.135 in., and (d) 0.164 in.

4.6.5 5″ × 1″ Corrugated Steel Pipe-Arch Lock Seam

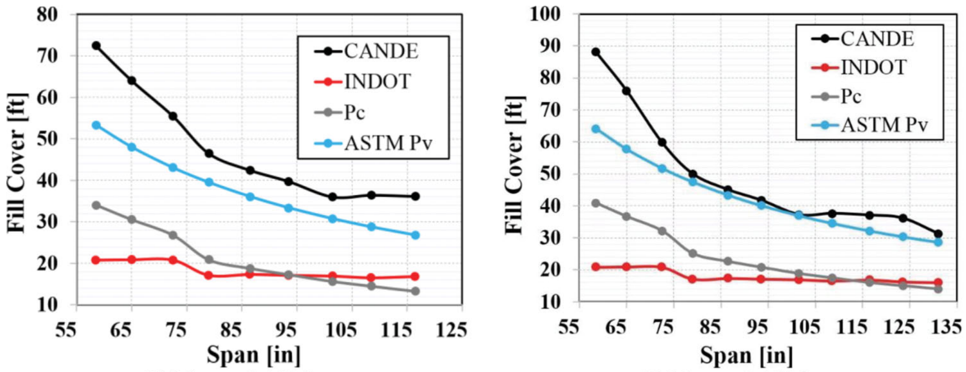
The results are included in Figure 4.36 and displayed in Figure 4.37.



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

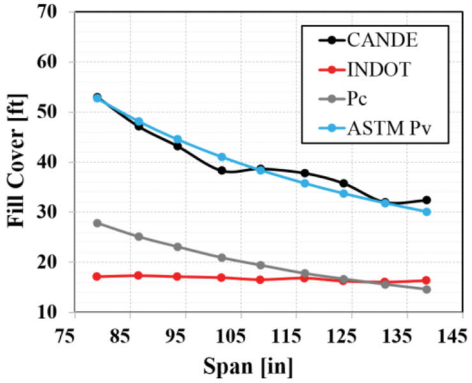
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.36 Maximum soil cover for 5″ × 1″ corrugated steel pipe-arch lock seam.



Thickness 0.109 in.

Thickness 0.138 in.



Thickness 0.168 in.

Figure 4.37 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 5″ × 1″ corrugated steel pipe-arch lock seam with thicknesses of (a) 0.109 in., (b) 0.138 in., and (c) 0.168 in.

4.7 Non-Reinforced Concrete Pipe, Class III

The mechanical and geometrical properties for the non-reinforced concrete, Class III, pipes were selected based on the literature and are summarized in Tables 4.22 and 4.23. Table 4.24 lists the results of the simulations and Figure 4.38 plots the results.

4.8 Smooth Wall PVC Pipe

The mechanical and geometrical properties for Smooth Wall PVC Pipe were selected based on the literature and are summarized in Tables 4.25 and 4.26. Table 4.27 lists the results of the simulations and Figure 4.39 plots the results.

4.9 Vitrified Clay Pipe, Extra Strength

The mechanical and geometrical properties for vitrified clay pipe (extra strength) were selected based on the literature and are summarized in Tables 4.28 and 4.29. Table 4.30 lists the results of the simulation and Figure 4.40 plots the results.

4.10 Structural Plate Pipes

The mechanical properties of the aluminum and steel structural plate pipes can be found in Table 4.31. The geometrical properties for the 6″ × 2″ structural plate steel pipes and for the 9″ × 2 1/2″ structural plate aluminum pipes can be found in Tables 4.32 and 4.33, respectively. Section 4.10.1 contains the table with maximum fill covers for the 6″ × 2″ structural plate steel pipes, and a plot of the results. Section 4.10.2 contains the maximum fill cover for the 9″ × 2 1/2″ structural plate aluminum alloy pipes.

TABLE 4.22
Mechanical Properties for Non-Reinforced Concrete Pipe, Class III

Young's Modulus (psi)	3.05E+06
Poisson's Ratio	0.12
Density (pci)	0.06
Compressive Strength of Concrete (psi)	4,000

TABLE 4.23
Geometrical Properties for Non-Reinforced Concrete Pipe, Class III

Internal Designated Diameter (in.)	Minimum Wall Thickness (in)
12	1.75
15	1.88
18	2.25
21	2.75
24	3.38
27	3.75
30	4.25
33	4.50
36	4.75

TABLE 4.24
Maximum Soil Cover for Non-Reinforced Concrete Pipe, Class III

D (in)	SW90	INDOT
12	12.5	14.10
15	11.4	13.10
18	11.3	12.80
21	12.6	13.40
24	12.5	13.50
27	10.9	12.10
30	9.8	10.70
33	8.6	9.80
36	7.5	9.00

Note: Red text = crack width, green text = shear, and blue text = INDOT.

TABLE 4.25
Mechanical Properties for Smooth Wall PVC Pipe

Young's Modulus for Short-Term Loading (ksi)	400
Compressive Strength for Short-Term Loading (ksi)	6.0
Young's Modulus for Long-Term Loading (ksi)	140
Ultimate Strength for Long-Term Loading (ksi)	2.6
Poisson's Ratio	0.4
Density (pci)	0.05

TABLE 4.26
Geometrical Properties for Smooth Wall PVC Pipe

Inner Vertical Diameter (in)	Minimum Thickness (in)
12	0.305
15	0.375
18	0.499
21	0.588
24	0.661
27	0.745

TABLE 4.27
Maximum Soil Cover for Smooth Wall PVC Pipe

D (in)	SW90	INDOT
12	47	64
15	48	64
18	53	61
21	53	61
24	53	61
27	53	61

Note: Red text = vertical deflection, green text = buckling, and blue text = INDOT.

The tables with the maximum fill height in the next sections include results previously published by INDOT, and the results obtained with CANDE. The tables are color-coded according to the critical failure criterion, and the results are plotted for better comparison. In the figures, the red (or orange) curve represents INDOT results, and the black (or blue) curve represents CANDE results. The CANDE results were best fitted where the data were not smooth or for cases where convergence was not achieved.

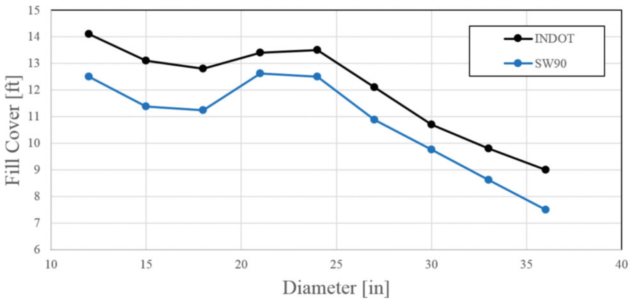


Figure 4.38 Maximum fill cover. Comparison between CANDE and INDOT results for non-reinforced concrete pipe Class III.

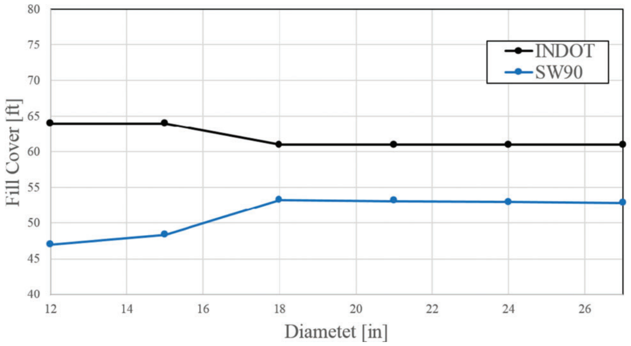


Figure 4.39 Maximum fill cover. Comparison between CANDE and INDOT results for smooth wall PVC pipe.

TABLE 4.28
Mechanical Properties for Vitrified Clay Pipe, Extra Strength

Young's Modulus (psi)	7,251,886
Poisson's Ratio	0.25
Density (pci)	0.035
Compressive Strength (psi)	9,000

TABLE 4.29
Geometrical Properties for Vitrified Clay Pipe, Extra Strength

D Inner (in)	Thickness (in)
12.00	1.26
15.00	1.71
18.00	2.03
21.00	2.36
24.00	2.47
27.00	2.99
30.00	3.13
33.00	3.23
36.00	3.68

4.10.1 6″ × 2″ Structural Plate Steel Pipe

The results are tabulated in Figure 4.41 and plotted in Figure 4.42.

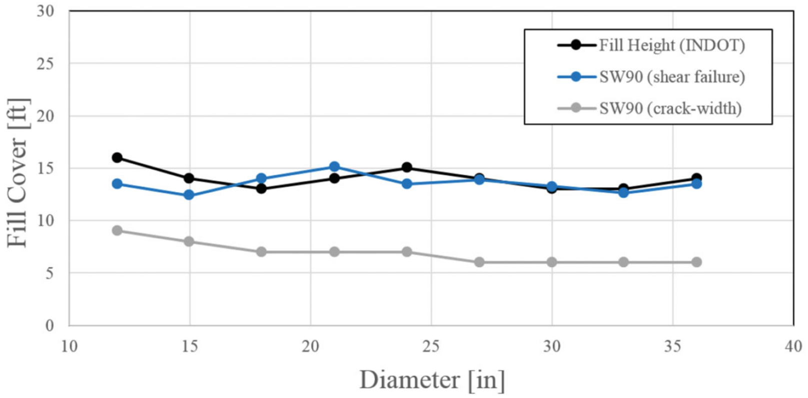


Figure 4.40 Maximum fill cover. Comparison between CANDE and INDOT results for vitrified clay pipe, extra strength.

TABLE 4.30
Maximum Soil Cover for Vitrified Clay Pipe, Extra Strength

D (in)	SW90	SW90	INDOT
12	13.5	9.00	16.0
15	12.4	8.00	14.0
18	14.0	7.00	13.0
21	15.1	7.00	14.0
24	13.5	7.00	15.0
27	13.9	6.00	14.0
30	13.3	6.00	13.0
33	12.6	6.00	13.0
36	13.5	6.00	14.0

Note: Red text = crack width, green text = shear, and blue text = INDOT.

TABLE 4.31
Mechanical Properties of Structural Plate Pipes

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

4.10.2 9″ × 2 1/2″ Structural Plate Aluminum Alloy Pipe

Results from the calculations are listed in Figure 4.43 and plotted in Figure 4.44.

4.11 Structural Plate Pipe-Arches

The mechanical properties of the structural plate steel pipe-arches (SPSPA) and of the structural plate aluminum pipe-arches (SPAPA) can be found in Table 4.34.

The size and layout details for the SPSPA with 3″ × 2″ corrugation are found in Tables 4.35 and 4.36, and for SPAPA with 9″ × 2 1/2″, in Tables 4.37 and 4.38. Details of the geometry of the arches can be found in Figure 4.45.

TABLE 4.32
Geometrical Properties of the 6″ × 2″ Structural Plate Steel Pipes

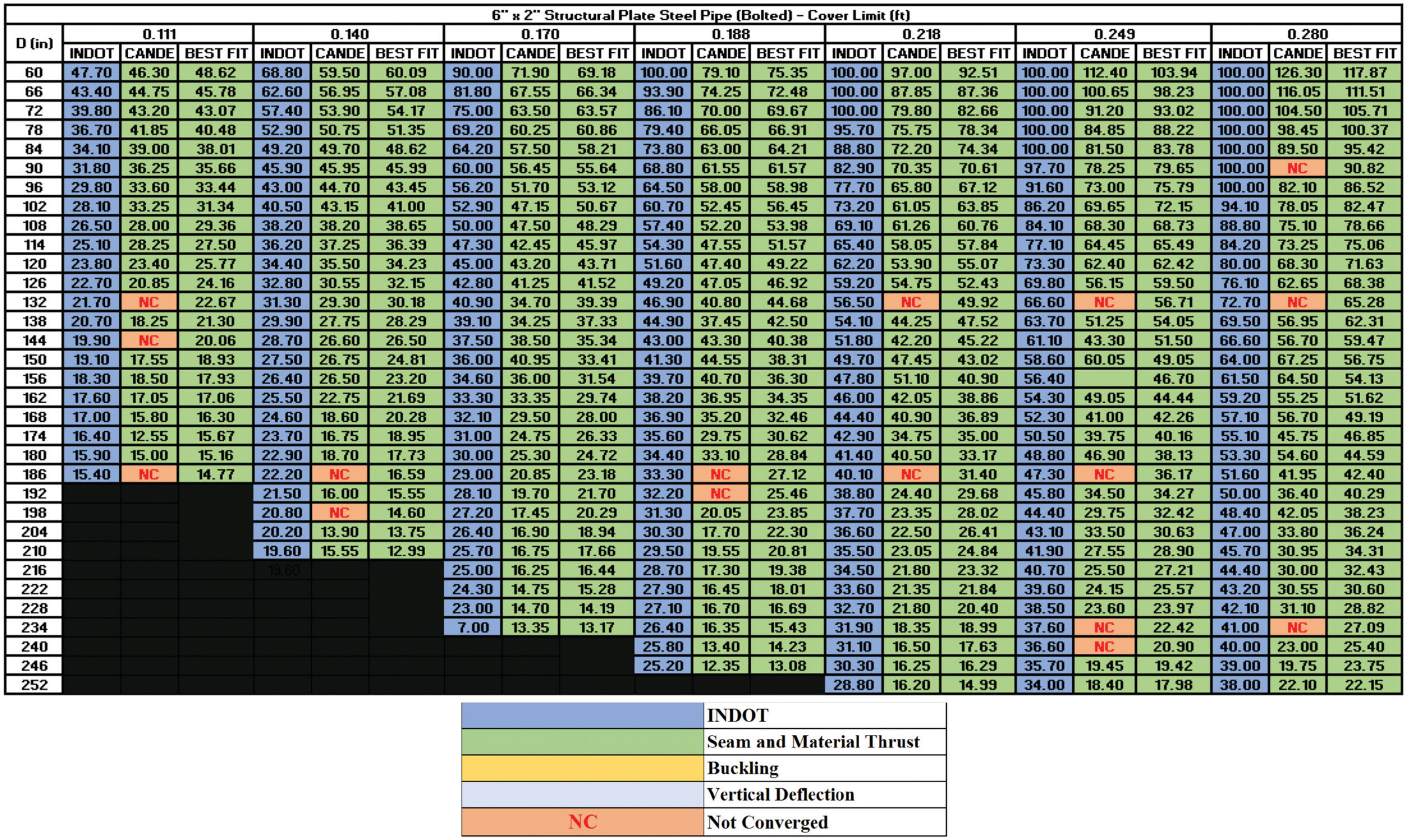
Corrugation Thickness (in.)	PA (in^2/in.)	PA (in^4/in.)	PS (in^3/in.)
0.11	0.12970	0.06041	0.05726
0.14	0.16690	0.07816	0.07305
0.17	0.20410	0.09616	0.08863
0.188	0.22830	0.10800	0.09872
0.218	0.26660	0.12691	0.11444
0.249	0.30420	0.14616	0.12900
0.28	0.34330	0.16583	0.14546
0.318	0.38930	0.16393	0.16393
0.38	0.46780	0.23200	0.19496

TABLE 4.33
Geometrical Properties for the 9″× 2 1/2″ Structural Plate Aluminum Alloy Pipes

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

The section properties for the SPSPA with 6″ × 2″ corrugation are listed in Table 4.39, and for the SPAPA with 9″ × 2 1/2″ corrugation, in Table 4.40.

The maximum fill height tables in the next sections include results previously published by INDOT, results obtained with CANDE, ASTM calculations considering the pressure at the corners (P_c) and the overall pressure (P_v). Tables are color-coded according to the critical failure criterion, and results are plotted for better comparison. In the figures, the red curve

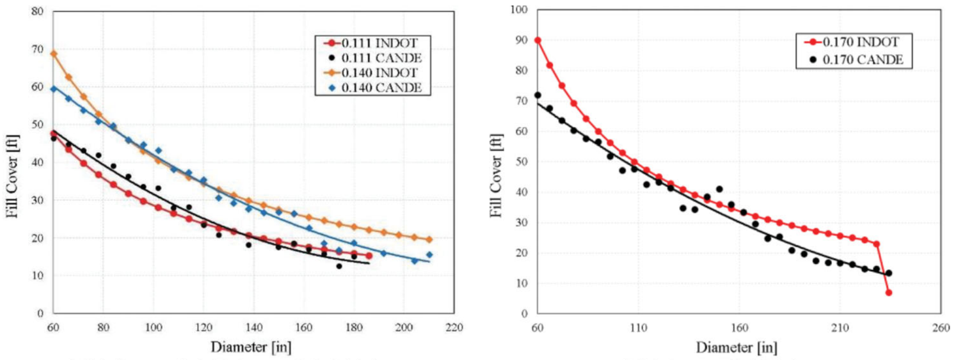


6" x 2" Structural Plate Steel Pipe (Bolted) – Cover Limit (ft)

D (in)	0.111			0.140			0.170			0.188			0.218			0.249			0.280		
	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT
60	47.70	46.30	48.62	68.80	59.50	60.09	90.00	71.90	69.18	100.00	79.10	75.35	100.00	97.00	92.51	100.00	112.40	103.94	100.00	126.30	117.87
66	43.40	44.75	45.78	62.60	56.95	57.08	81.80	67.55	66.34	93.90	74.25	72.48	100.00	87.85	87.36	100.00	100.65	98.23	100.00	116.05	111.51
72	39.80	43.20	43.07	57.40	53.90	54.17	75.00	63.50	63.57	86.10	70.00	69.67	100.00	79.80	82.66	100.00	91.20	93.02	100.00	104.50	105.71
78	36.70	41.85	40.48	52.90	50.75	51.35	69.20	60.25	60.86	79.40	66.05	66.91	95.70	75.75	78.34	100.00	84.85	88.22	100.00	98.45	100.37
84	34.10	39.00	38.01	49.20	49.70	48.62	64.20	57.50	58.21	73.80	63.00	64.21	88.80	72.20	74.34	100.00	81.50	83.78	100.00	89.50	95.42
90	31.80	36.25	35.66	45.90	45.95	45.99	60.00	56.45	55.64	68.80	61.55	61.57	82.90	70.35	70.61	97.70	78.25	79.65	100.00	NC	90.82
96	29.80	33.60	33.44	43.00	44.70	43.45	56.20	51.70	53.12	64.50	58.00	58.98	77.70	65.80	67.12	91.60	73.00	75.79	100.00	82.10	86.52
102	28.10	33.25	31.34	40.50	43.15	41.00	52.90	47.15	50.67	60.70	52.45	56.45	73.20	61.05	63.85	86.20	69.65	72.15	94.10	78.05	82.47
108	26.50	28.00	29.36	38.20	38.20	38.65	50.00	47.50	48.29	57.40	52.20	53.98	69.10	61.26	60.76	84.10	68.30	68.73	88.80	75.10	78.66
114	25.10	28.25	27.50	36.20	37.25	36.39	47.30	42.45	45.97	54.30	47.55	51.57	65.40	58.05	57.84	77.10	64.45	65.49	84.20	73.25	75.06
120	23.80	23.40	25.77	34.40	35.50	34.23	45.00	43.20	43.71	51.60	47.40	49.22	62.20	53.90	55.07	73.30	62.40	62.42	80.00	68.30	71.63
126	22.70	20.85	24.16	32.80	30.55	32.15	42.80	41.25	41.52	49.20	47.05	46.92	59.20	54.75	52.43	69.80	56.15	59.50	76.10	62.65	68.38
132	21.70	NC	22.67	31.30	29.30	30.18	40.90	34.70	39.39	46.90	40.80	44.68	56.50	NC	49.92	66.60	NC	56.71	72.70	NC	65.28
138	20.70	18.25	21.30	29.90	27.75	28.29	39.10	34.25	37.33	44.90	37.45	42.50	54.10	44.25	47.52	63.70	51.25	54.05	69.50	56.95	62.31
144	19.90	NC	20.06	28.70	26.60	26.50	37.50	38.50	35.34	43.00	43.30	40.38	51.80	42.20	45.22	61.10	43.30	51.50	66.60	56.70	59.47
150	19.10	17.55	18.93	27.50	26.75	24.81	36.00	40.95	33.41	41.30	44.55	38.31	49.70	47.45	43.02	58.60	60.05	49.05	64.00	67.25	56.75
156	18.30	18.50	17.93	26.40	26.50	23.20	34.60	36.00	31.54	39.70	40.70	36.30	47.80	51.10	40.90	56.40		46.70	61.50	64.50	54.13
162	17.60	17.05	17.06	25.50	22.75	21.69	33.30	33.35	29.74	38.20	36.95	34.35	46.00	42.05	38.86	54.30	49.05	44.44	59.20	55.25	51.62
168	17.00	15.80	16.30	24.60	18.60	20.28	32.10	29.50	28.00	36.90	35.20	32.46	44.40	40.90	36.89	52.30	41.00	42.26	57.10	56.70	49.19
174	16.40	12.55	15.67	23.70	16.75	18.95	31.00	24.75	26.33	35.60	29.75	30.62	42.90	34.75	35.00	50.50	39.75	40.16	55.10	45.75	46.85
180	15.90	15.00	15.16	22.90	18.70	17.73	30.00	25.30	24.72	34.40	33.10	28.84	41.40	40.50	33.17	48.80	46.90	38.13	53.30	54.60	44.59
186	15.40	NC	14.77	22.20	NC	16.59	29.00	20.85	23.18	33.30	NC	27.12	40.10	NC	31.40	47.30	NC	36.17	51.60	41.95	42.40
192				21.50	16.00	15.55	28.10	19.70	21.70	32.20	NC	25.46	38.80	24.40	29.68	45.80	34.50	34.27	50.00	36.40	40.29
198				20.80	NC	14.60	27.20	17.45	20.29	31.30	20.05	23.85	37.70	23.35	28.02	44.40	29.75	32.42	48.40	42.05	38.23
204				20.20	13.90	13.75	26.40	16.90	18.94	30.30	17.70	22.30	36.60	22.50	26.41	43.10	33.50	30.63	47.00	33.80	36.24
210				19.60	15.55	12.99	25.70	16.75	17.66	29.50	19.55	20.81	35.50	23.05	24.84	41.90	27.55	28.90	45.70	30.95	34.31
216				19.60			25.00	16.25	16.44	28.70	17.30	19.38	34.50	21.80	23.32	40.70	25.50	27.21	44.40	30.00	32.43
222							24.30	14.75	15.28	27.90	16.45	18.01	33.60	21.35	21.84	39.60	24.15	25.57	43.20	30.55	30.60
228							23.00	14.70	14.19	27.10	16.70	16.69	32.70	21.80	20.40	38.50	23.60	23.97	42.10	31.10	28.82
234							7.00	13.35	13.17	26.40	16.35	15.43	31.90	18.35	18.99	37.60	NC	22.42	41.00	NC	27.09
240										25.80	13.40	14.23	31.10	16.50	17.63	36.60	NC	20.90	40.00	23.00	25.40
246										25.20	12.35	13.08	30.30	16.25	16.29	35.70	19.45	19.42	39.00	19.75	23.75
252													28.80	16.20	14.99	34.00	18.40	17.98	38.00	22.10	22.15

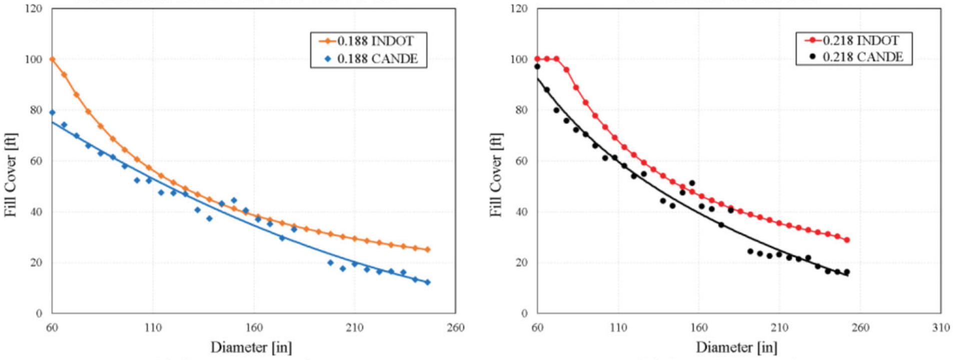
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.41 Maximum fill cover for the 6″ × 2″ structural plate steel pipe.



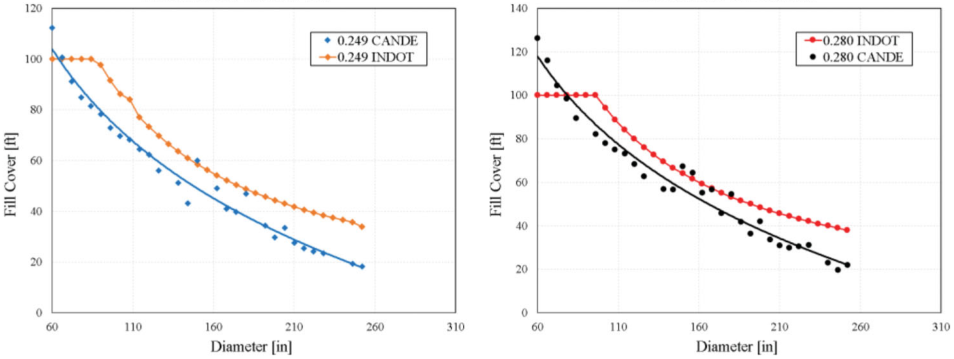
Thickness 0.111 in. and 0.140 in.

Thickness 0.170 in.



Thickness 0.188 in.

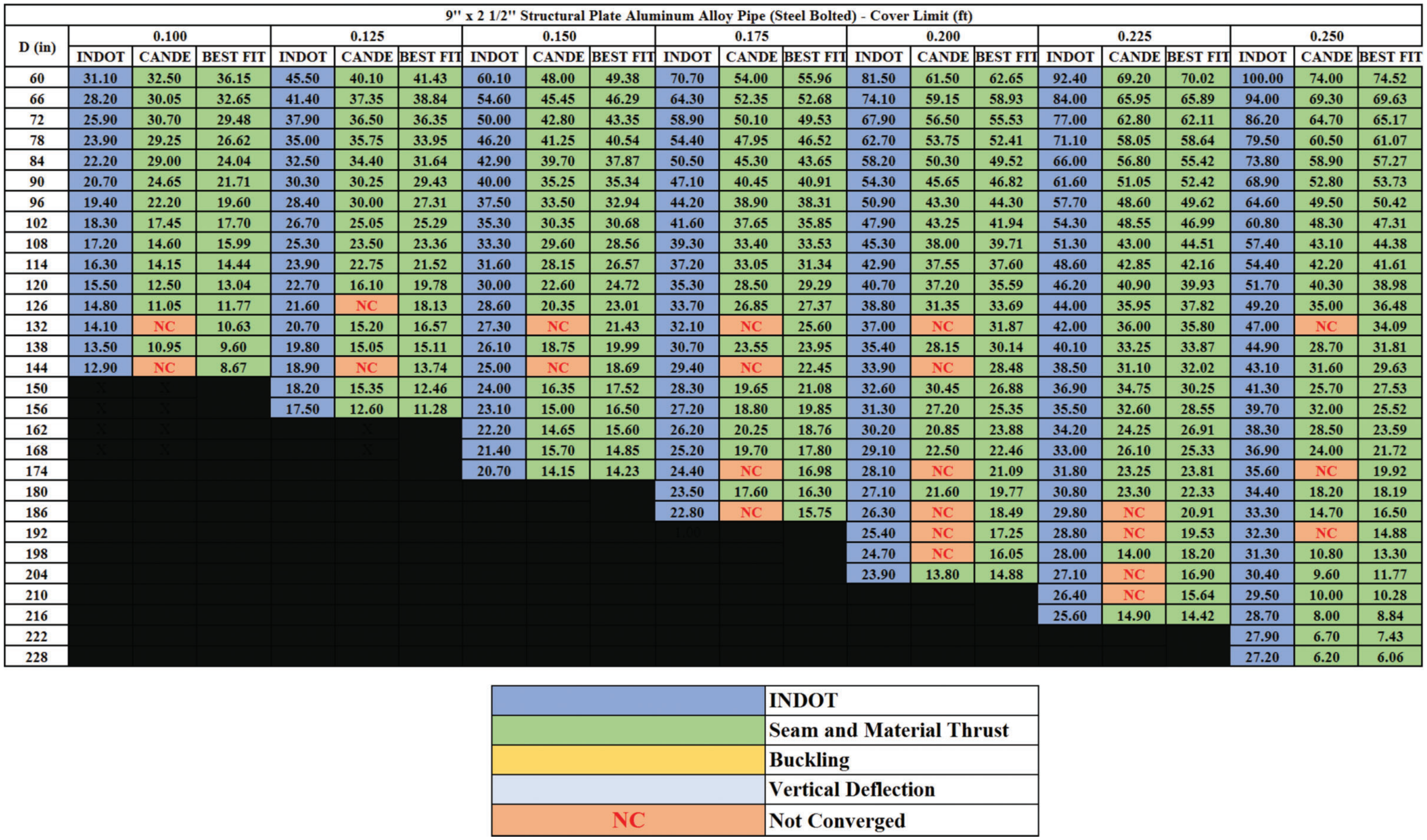
Thickness 0.218 in.



Thickness 0.249 in.

Thickness 0.280 in.

Figure 4.42 Maximum fill cover. Comparison between CANDE and INDOT for 6″ × 2″ structural plate steel pipe with thicknesses of (a) 0.111 in. and 0.140 in., (b) 0.170 in., (c) 0.188 in., (d) 0.218 in., (e) 0.249 in., and (f) 0.280 in.

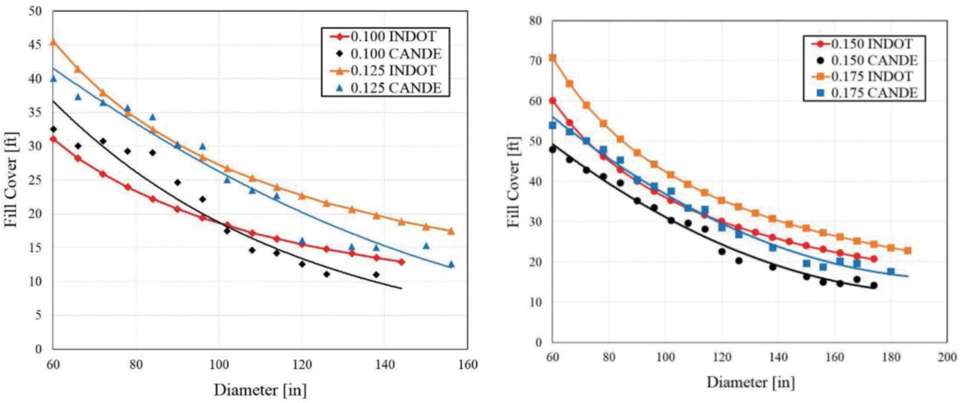


9" x 2 1/2" Structural Plate Aluminum Alloy Pipe (Steel Bolted) - Cover Limit (ft)

D (in)	0.100			0.125			0.150			0.175			0.200			0.225			0.250		
	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT	INDOT	CANDE	BEST FIT
60	31.10	32.50	36.15	45.50	40.10	41.43	60.10	48.00	49.38	70.70	54.00	55.96	81.50	61.50	62.65	92.40	69.20	70.02	100.00	74.00	74.52
66	28.20	30.05	32.65	41.40	37.35	38.84	54.60	45.45	46.29	64.30	52.35	52.68	74.10	59.15	58.93	84.00	65.95	65.89	94.00	69.30	69.63
72	25.90	30.70	29.48	37.90	36.50	36.35	50.00	42.80	43.35	58.90	50.10	49.53	67.90	56.50	55.53	77.00	62.80	62.11	86.20	64.70	65.17
78	23.90	29.25	26.62	35.00	35.75	33.95	46.20	41.25	40.54	54.40	47.95	46.52	62.70	53.75	52.41	71.10	58.05	58.64	79.50	60.50	61.07
84	22.20	29.00	24.04	32.50	34.40	31.64	42.90	39.70	37.87	50.50	45.30	43.65	58.20	50.30	49.52	66.00	56.80	55.42	73.80	58.90	57.27
90	20.70	24.65	21.71	30.30	30.25	29.43	40.00	35.25	35.34	47.10	40.45	40.91	54.30	45.65	46.82	61.60	51.05	52.42	68.90	52.80	53.73
96	19.40	22.20	19.60	28.40	30.00	27.31	37.50	33.50	32.94	44.20	38.90	38.31	50.90	43.30	44.30	57.70	48.60	49.62	64.60	49.50	50.42
102	18.30	17.45	17.70	26.70	25.05	25.29	35.30	30.35	30.68	41.60	37.65	35.85	47.90	43.25	41.94	54.30	48.55	46.99	60.80	48.30	47.31
108	17.20	14.60	15.99	25.30	23.50	23.36	33.30	29.60	28.56	39.30	33.40	33.53	45.30	38.00	39.71	51.30	43.00	44.51	57.40	43.10	44.38
114	16.30	14.15	14.44	23.90	22.75	21.52	31.60	28.15	26.57	37.20	33.05	31.34	42.90	37.55	37.60	48.60	42.85	42.16	54.40	42.20	41.61
120	15.50	12.50	13.04	22.70	16.10	19.78	30.00	22.60	24.72	35.30	28.50	29.29	40.70	37.20	35.59	46.20	40.90	39.93	51.70	40.30	38.98
126	14.80	11.05	11.77	21.60	NC	18.13	28.60	20.35	23.01	33.70	26.85	27.37	38.80	31.35	33.69	44.00	35.95	37.82	49.20	35.00	36.48
132	14.10	NC	10.63	20.70	15.20	16.57	27.30	NC	21.43	32.10	NC	25.60	37.00	NC	31.87	42.00	36.00	35.80	47.00	NC	34.09
138	13.50	10.95	9.60	19.80	15.05	15.11	26.10	18.75	19.99	30.70	23.55	23.95	35.40	28.15	30.14	40.10	33.25	33.87	44.90	28.70	31.81
144	12.90	NC	8.67	18.90	NC	13.74	25.00	NC	18.69	29.40	NC	22.45	33.90	NC	28.48	38.50	31.10	32.02	43.10	31.60	29.63
150				18.20	15.35	12.46	24.00	16.35	17.52	28.30	19.65	21.08	32.60	30.45	26.88	36.90	34.75	30.25	41.30	25.70	27.53
156				17.50	12.60	11.28	23.10	15.00	16.50	27.20	18.80	19.85	31.30	27.20	25.35	35.50	32.60	28.55	39.70	32.00	25.52
162							22.20	14.65	15.60	26.20	20.25	18.76	30.20	20.85	23.88	34.20	24.25	26.91	38.30	28.50	23.59
168							21.40	15.70	14.85	25.20	19.70	17.80	29.10	22.50	22.46	33.00	26.10	25.33	36.90	24.00	21.72
174							20.70	14.15	14.23	24.40	NC	16.98	28.10	NC	21.09	31.80	23.25	23.81	35.60	NC	19.92
180										23.50	17.60	16.30	27.10	21.60	19.77	30.80	23.30	22.33	34.40	18.20	18.19
186										22.80	NC	15.75	26.30	NC	18.49	29.80	NC	20.91	33.30	14.70	16.50
192													25.40	NC	17.25	28.80	NC	19.53	32.30	NC	14.88
198													24.70	NC	16.05	28.00	14.00	18.20	31.30	10.80	13.30
204													23.90	13.80	14.88	27.10	NC	16.90	30.40	9.60	11.77
210																26.40	NC	15.64	29.50	10.00	10.28
216																25.60	14.90	14.42	28.70	8.00	8.84
222																			27.90	6.70	7.43
228																			27.20	6.20	6.06

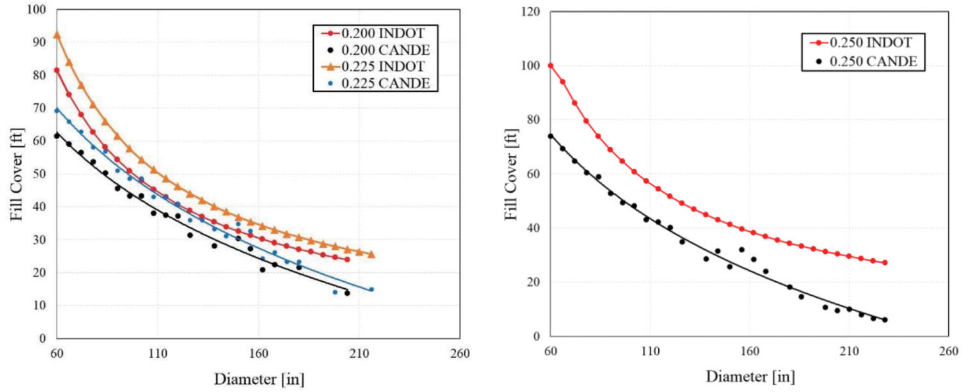
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.43 Maximum fill cover for 9″ × 2 1/2″ structural plate aluminum alloy pipe.



Thickness 0.100 in. and 0.125 in.

Thickness 0.150 in. and 0.175 in.



Thickness 0.200 in. and 0.225.

Thickness 0.250 in.

Figure 4.44 Maximum fill cover. Comparison between CANDE and INDOT for 9″ × 2 1/2″ structural plate aluminum pipe with thicknesses of (a) 0.100 in. and 0.125 in., (b) 0.150 in. and 0.175 in., (c) 0.200 in. and 0.225 in., and (d) 0.250 in.

TABLE 4.34
Mechanical Properties of the Structural Plate Pipe-Arches

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

TABLE 4.35
SPSPA Size and Layout Details for the 6″ × 2″ Corrugation, 18-in. Corner Radius R_c

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 4.36
SPSPA Size and Layout Details for the 6″ × 2″ Corrugation, 31-in. Corner Radius R_c

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 4.37
SPAPA Details for the 9″ × 2 1/2″ Corrugation, 31.75-in. Corner Radius, R_c

SPAN (ft-in.)	RISE (ft-in.)	A (sft)	Rt (ft)	Rb (ft)
88.86-7	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
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 4.38
SPAPA Details for the 9″ × 2 1/2″ Corrugation, 47-in. Corner Radius, R_c

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 4.39
SPSPA Section Properties for 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

TABLE 4.40
SPAPA Section Properties for 9″ × 2 1/2″ Corrugation

Corrugation Thickness (in.)	PA ($in^2/in.$)	PI ($in^4/in.$)	PS ($in^3/in.$)
0.100	0.1170	0.8031	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

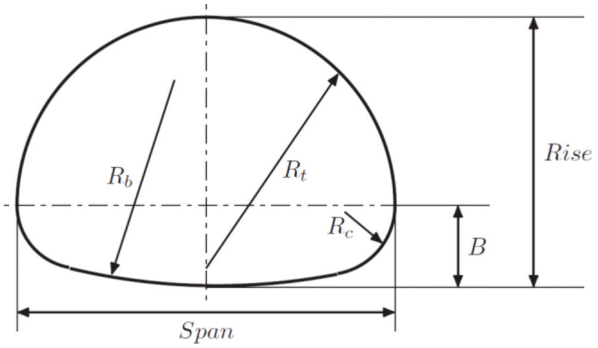


Figure 4.45 Geometrical representation of pipe-arches.

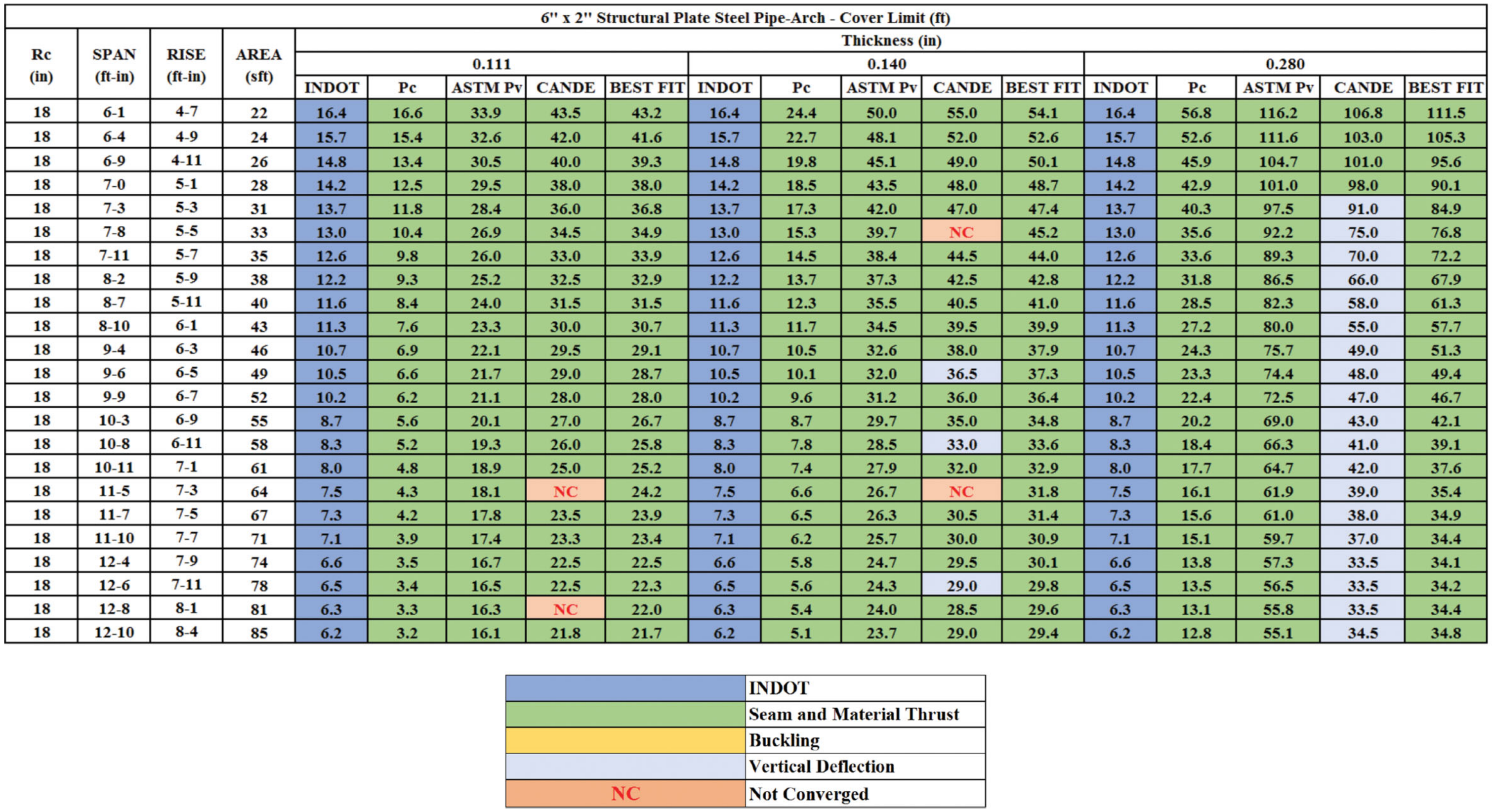
represents INDOT results, the grey curve shows the ASTM P_c results, the blue curve, the ASTM P_v results, and the black curve, CANDE results. The CANDE results were best fitted where the data were not smooth or for cases where convergence was not achieved.

4.11.1 6″ × 2″ Structural Plate Steel Pipe-Arch (Bolted)

The numerical results from the calculations with CANDE are listed in Figures 4.46 and 4.48. Figures 4.47 to 4.49 display the results and compare the values obtained from the different methods: CANDE, INDOT, P_c and ASTM P_v.

4.11.2 9″ × 2 1/2″ Structural Plate Aluminum Pipe-Arch (Steel Bolted)

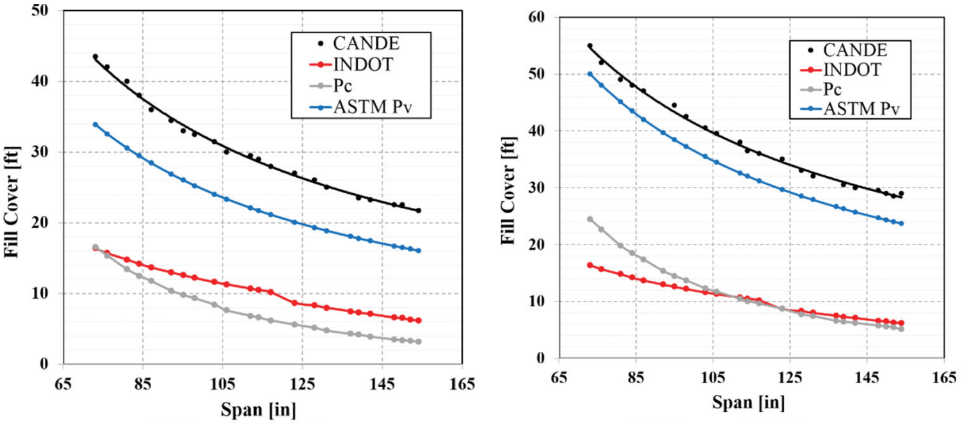
Similar to what is done in Section 4.11.1, Figures 4.50 to 4.55 tabulate the numerical results, while Figures 4.56 and 4.57 plot the results. Also included in the figures are comparisons between the values obtained with CANDE, INDOT, and with the P_c and ASTM P_v methods.



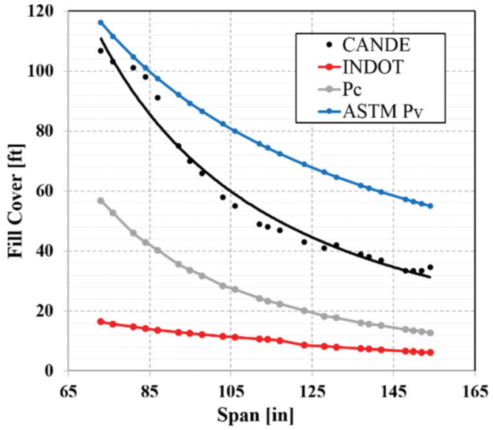
6" x 2" Structural Plate Steel Pipe-Arch - Cover Limit (ft)																		
Rc (in)	SPAN (ft-in)	RISE (ft-in)	AREA (sft)	Thickness (in)														
				0.111					0.140					0.280				
				INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT	INDOT	Pc	ASTM Pv	CANDE	BEST FIT
18	6-1	4-7	22	16.4	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

Figure 4.46 Maximum soil cover for the 6″ × 2″ structural plate steel pipe-arch for a corner radius of 18 in.

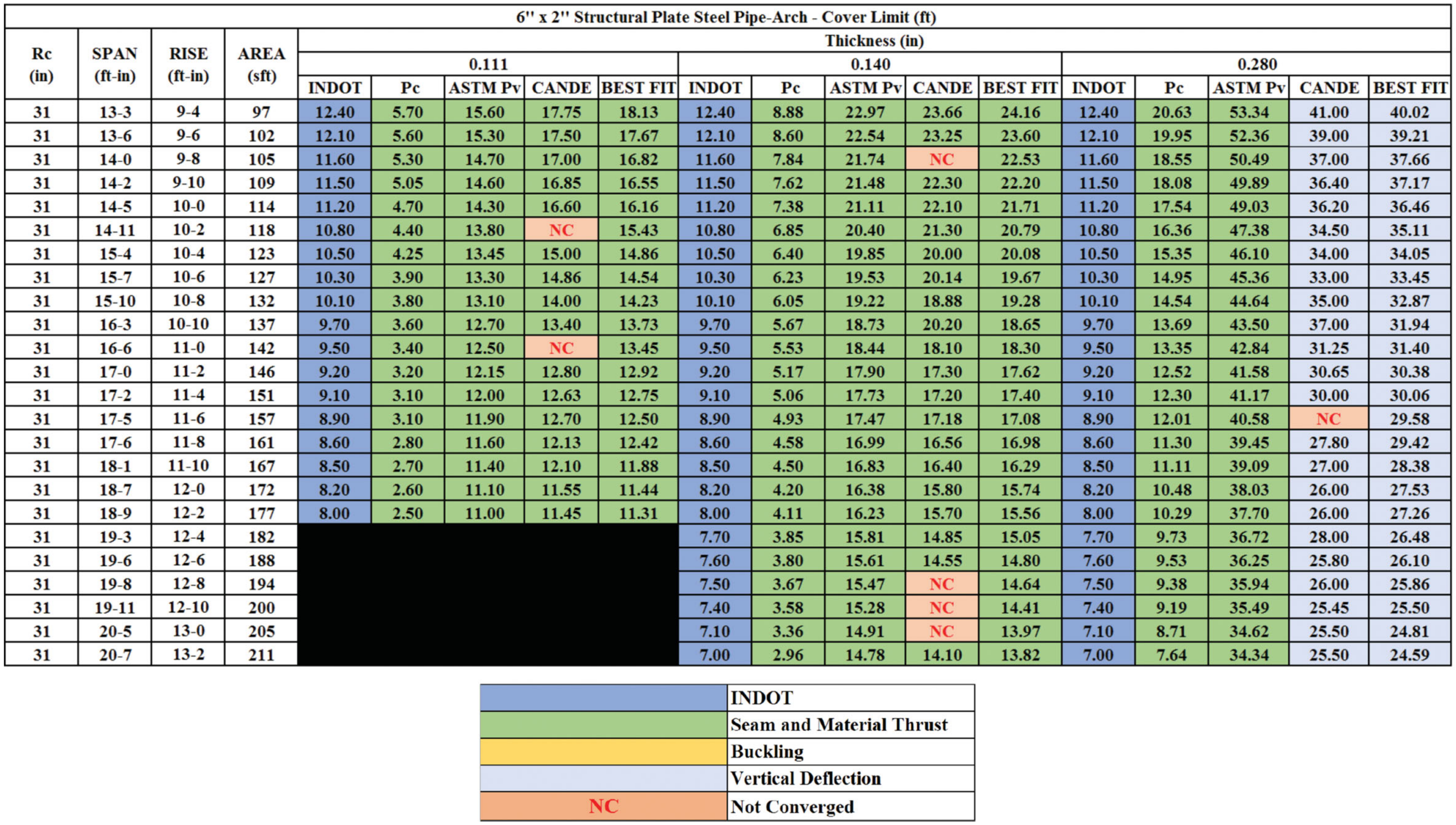


Thickness 0.111 in. Thickness 0.140 in.



Thickness 0.280 in.

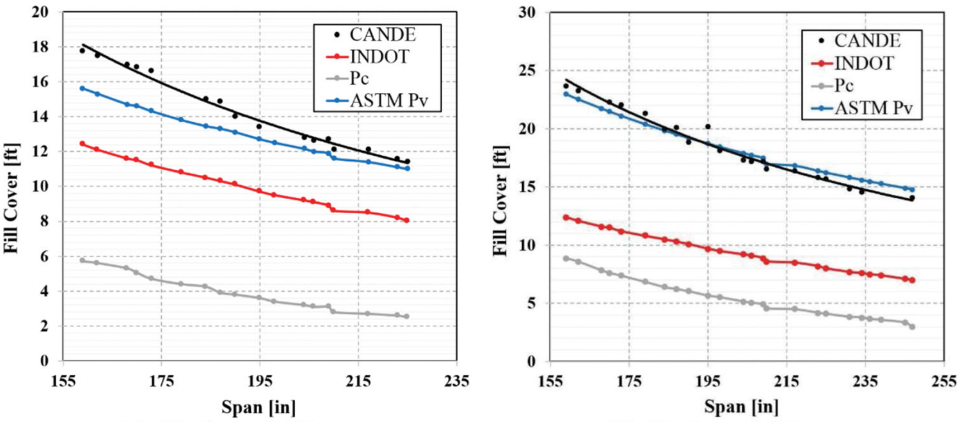
Figure 4.47 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 6" × 2" structural plate steel pipe-arch with a corner radius of 18 in. and thicknesses of (a) 0.111 in., (b) 0.140 in., and (c) 0.280 in.



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

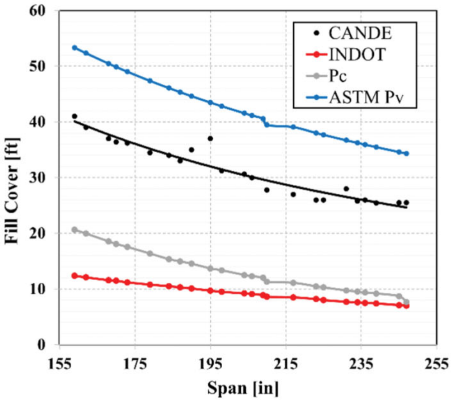
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.48 Maximum soil cover for the 6″× 2″ structural plate steel pipe-arch for a corner radius of 31 in.



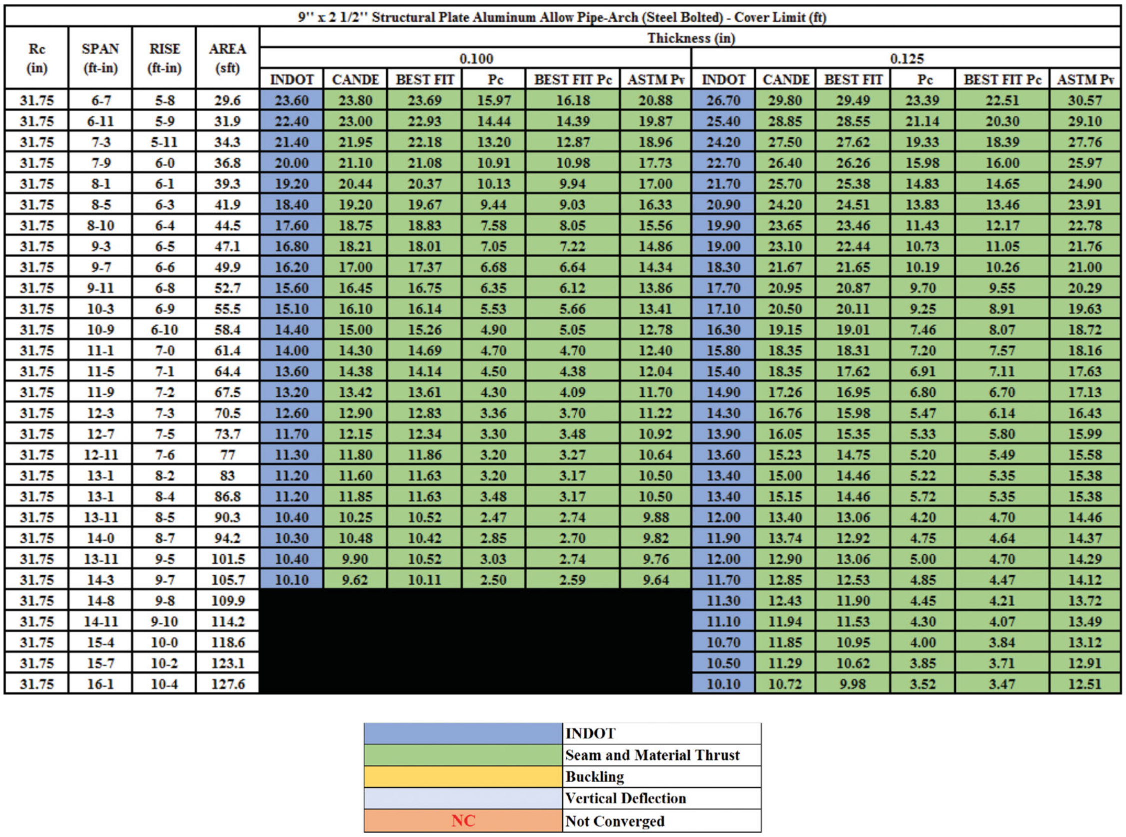
(a) Thickness 0.111 in.

(b) Thickness 0.140 in.



(c) Thickness 0.280 in.

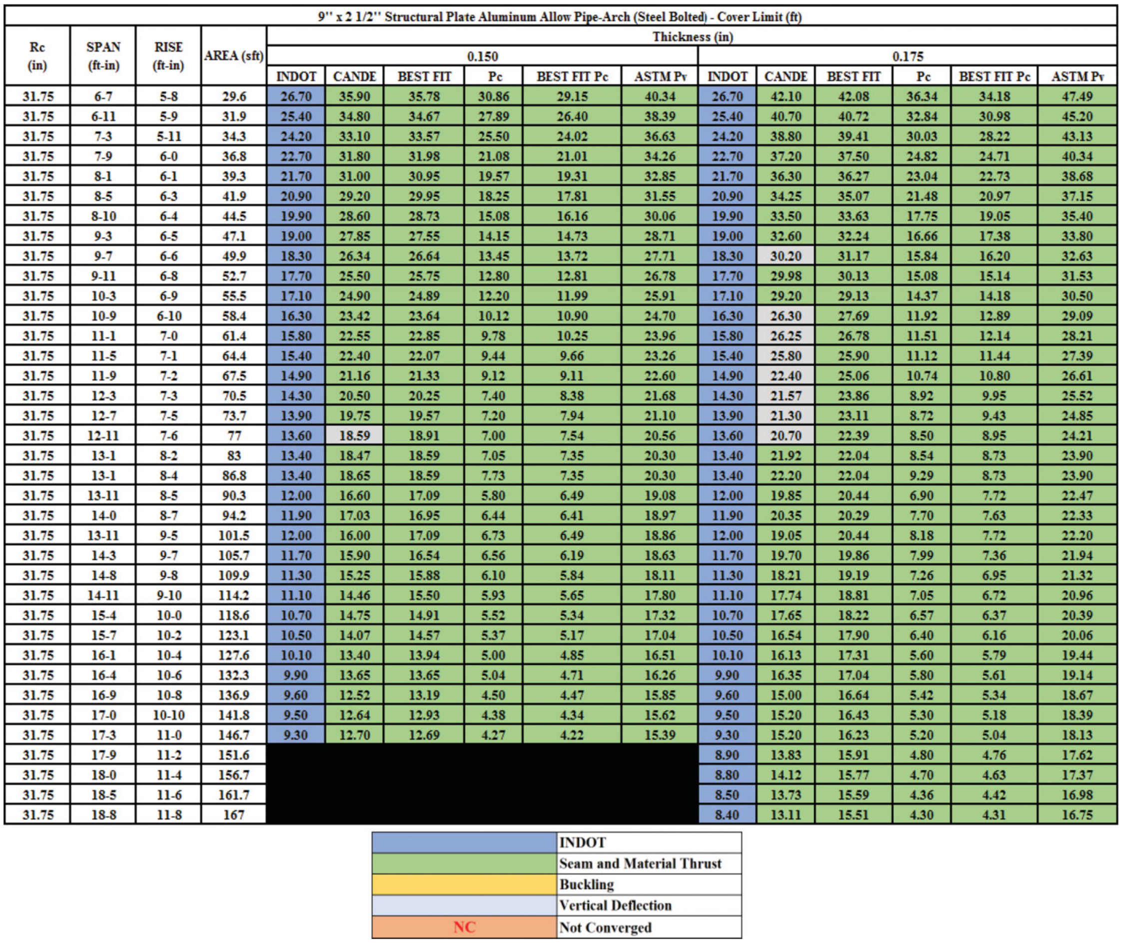
Figure 4.49 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 6″ × 2″ structural plate steel pipe-arch with a corner radius of 31 in. and thicknesses of (a) 0.111 in., (b) 0.140 in., and (c) 0.280 in.



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

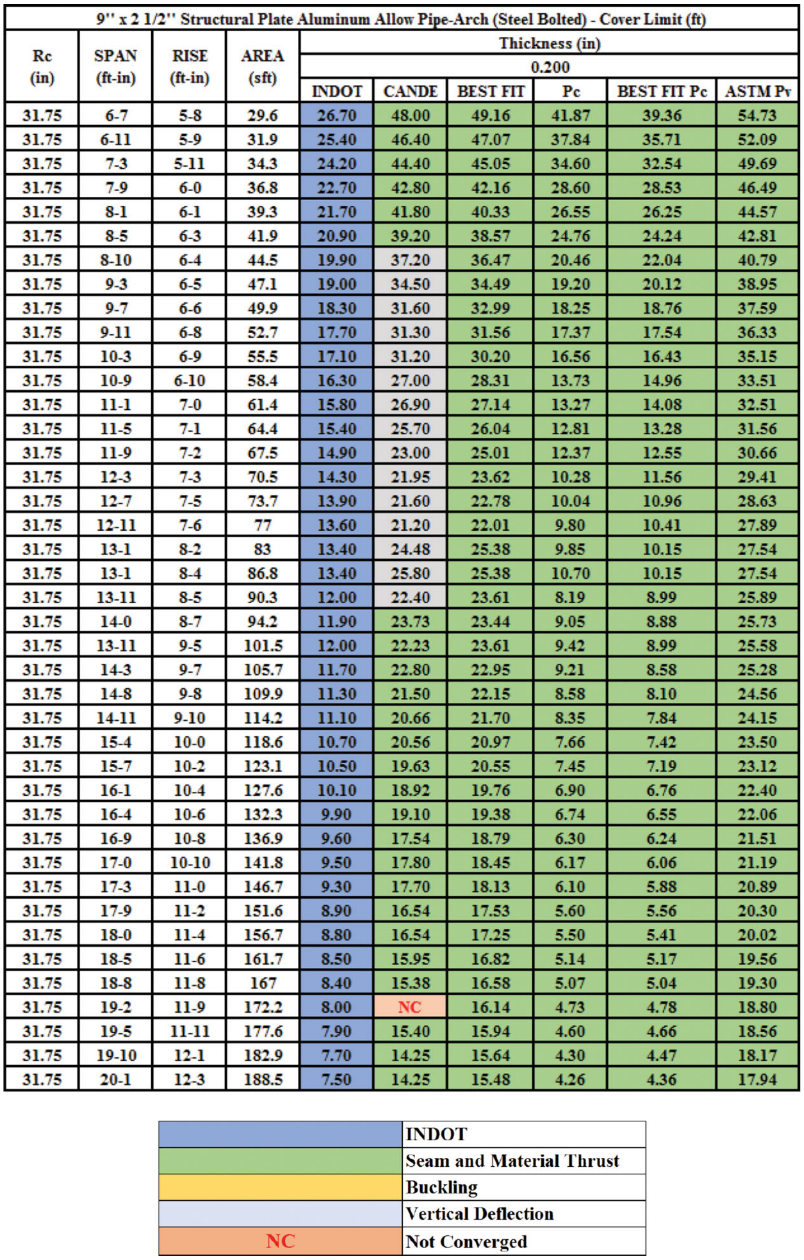
Figure 4.50 Maximum soil cover for the 9″ × 2 1/2″ structural plate aluminum pipe-arch for a corner radius of 31.75 in. and thickness of 0.100 in. and 0.125 in.



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

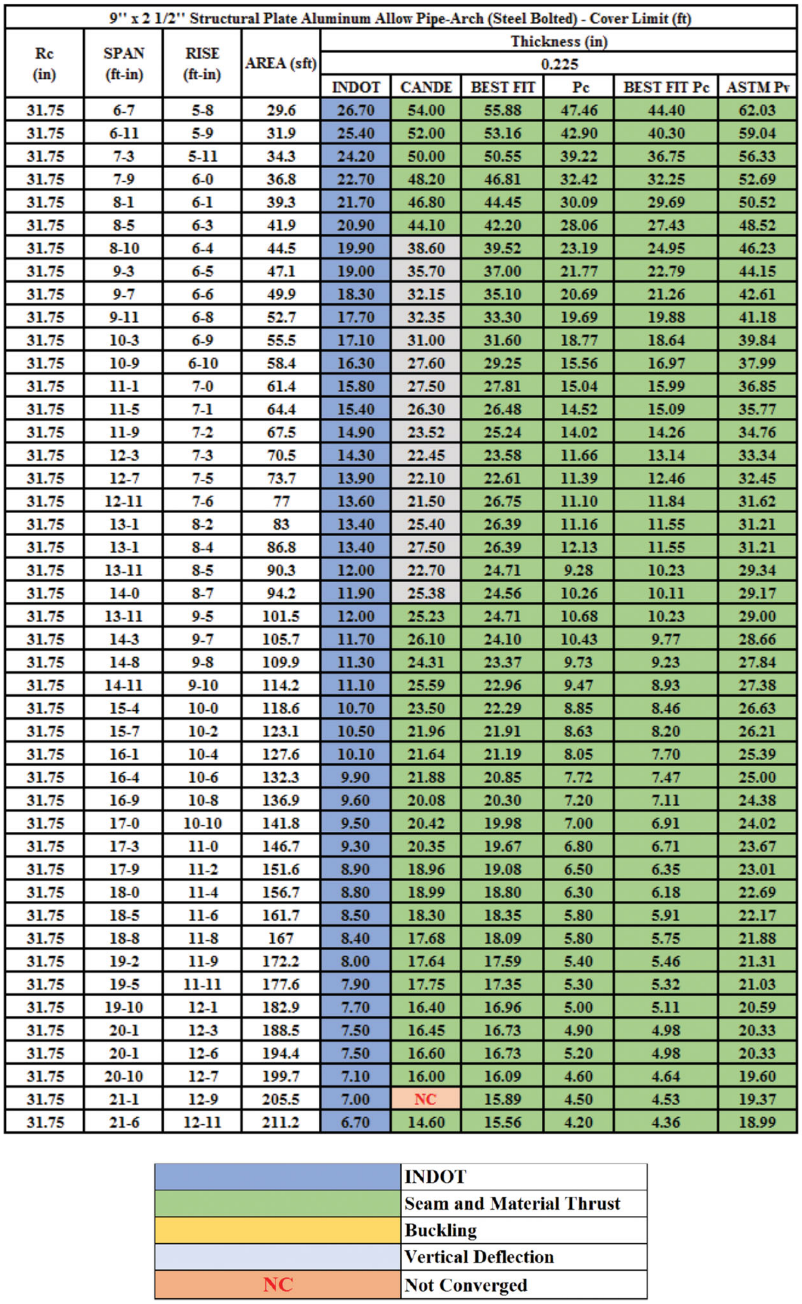
Figure 4.51 Maximum soil cover for 9″ × 2 1/2″ structural plate aluminum pipe-arch for a corner radius of 31.75 in. and thickness of 0.150 in. and 0.175 in.



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

Figure 4.52 Maximum soil cover for 9″ × 2 1/2″ structural plate aluminum pipe-arch for a corner radius of 31.75 in. and thickness of 0.200 in.

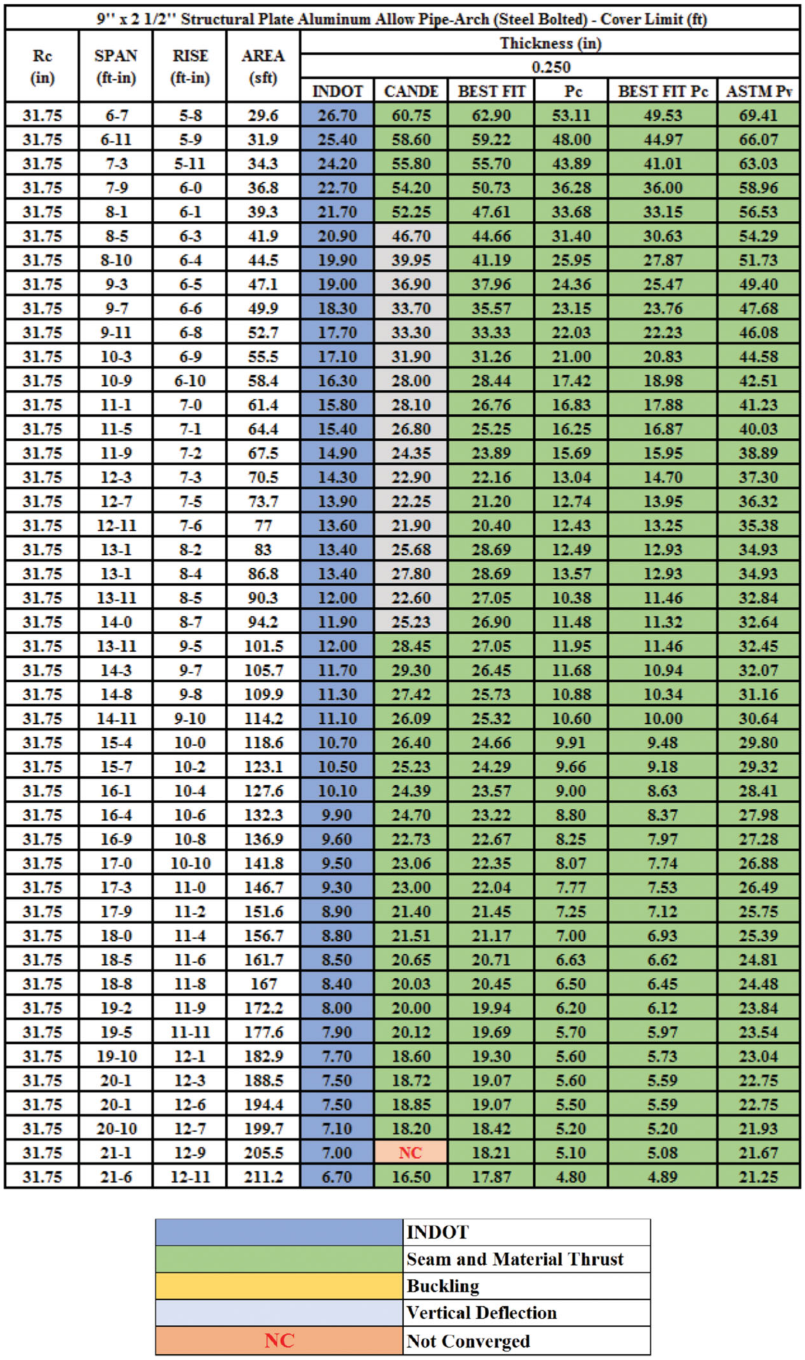


9'' x 2 1/2'' Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)

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

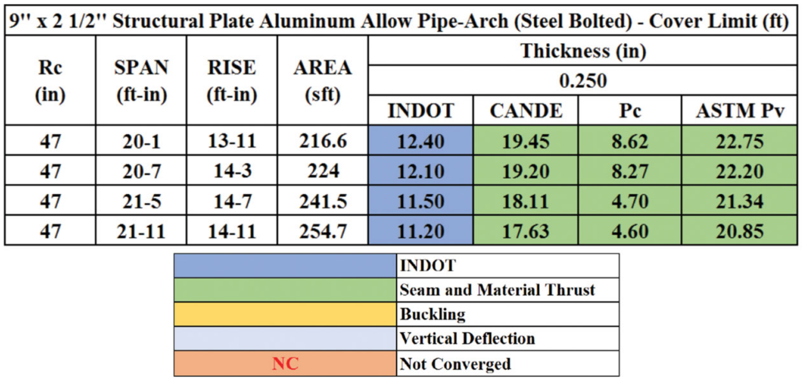
Figure 4.53 Maximum soil cover for the 9″ × 2 1/2″ structural plate aluminum pipe-arch for a corner radius of 31.75 in. and thickness of 0.225 in.



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

Figure 4.54 Maximum soil cover for the 9″ × 2 1/2″ structural plate aluminum pipe-arch for a corner radius of 31.75 in. and thickness of 0.250 in.

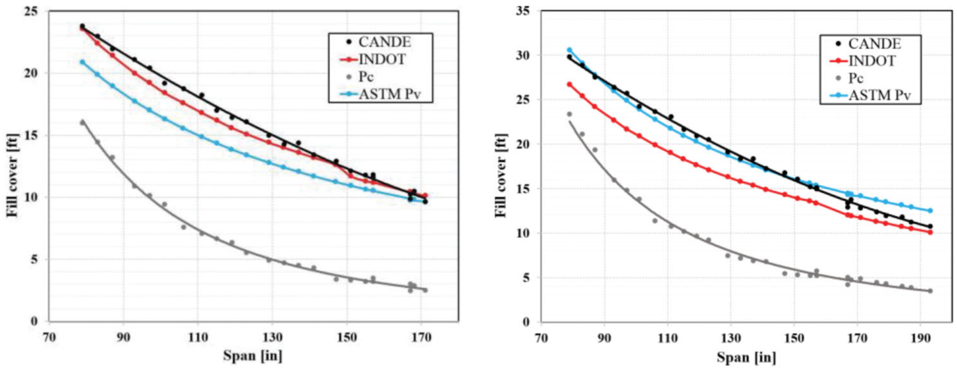


9'' x 2 1/2'' Structural Plate Aluminum Allow Pipe-Arch (Steel Bolted) - Cover Limit (ft)

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

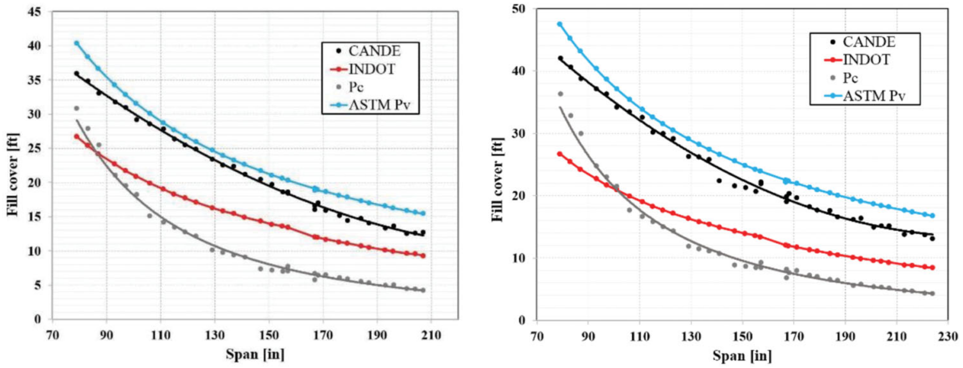
🟦	INDOT
🟩	Seam and Material Thrust
🟨	Buckling
⬜	Vertical Deflection
NC	Not Converged

Figure 4.55 Maximum soil cover for the 9″ × 2 1/2″ structural plate aluminum pipe-arch for a corner radius of 47 in. and thickness of 0.250 in.



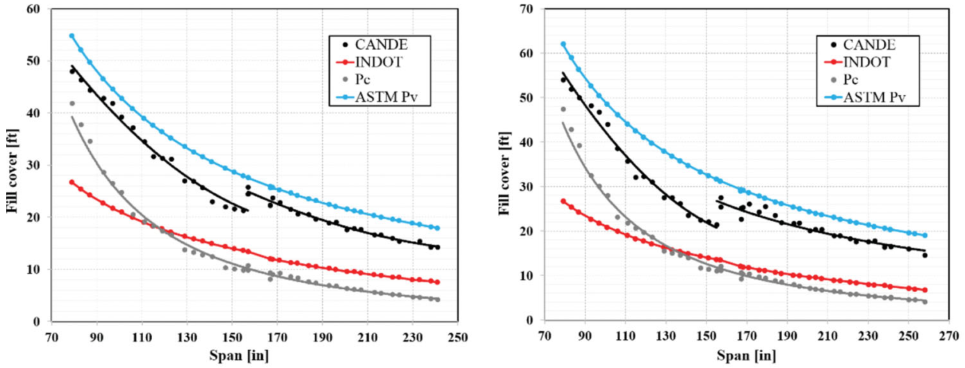
Thickness 0.100 in.

Thickness 0.125 in.



Thickness 0.150 in.

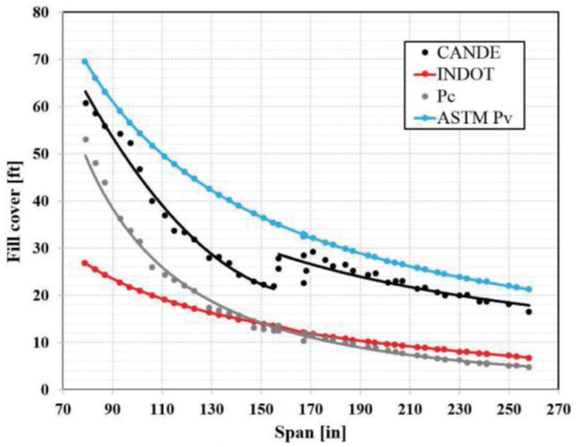
Thickness 0.175 in.



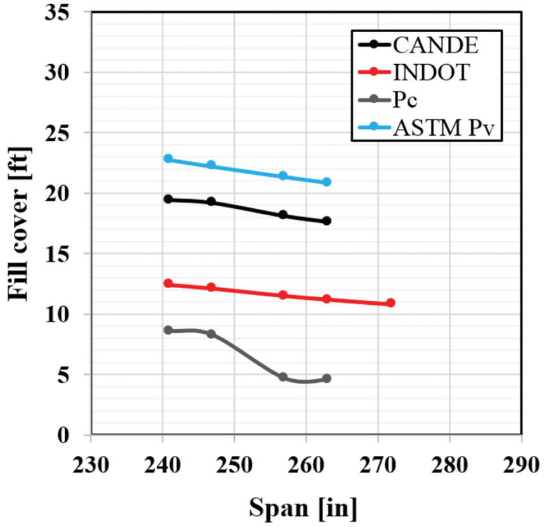
Thickness 0.200 in.

Thickness 0.225 in.

Figure 4.56 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 9″ × 2 1/2″ structural plate aluminum pipe-arch with a corner radius of 31.75 in. and thicknesses of (a) 0.100 in., (b) 0.125 in., (c) 0.150 in., (d) 0.175 in., (e) 0.200 in., and (f) 0.225 in.



Thickness 0.250 in.



Thickness 0.250 in.

Figure 4.57 Maximum fill cover. Comparison between CANDE, INDOT, P_c and ASTM P_v for 9″ × 2 1/2″ structural plate aluminum pipe-arch with a thickness of (a) 0.250 in. with a corner radius of 31.75 in., and (b) thickness of 0.250 in. with a corner radius of 47 in.

5. SUMMARY AND RECOMMENDATIONS

The report presents recommendations for maximum fill height that can be sustained safely by the pipes investigated. The results are based on calculations performed by CANDE with the assumption that the fill is SW90. The report does not discuss minimum fill heights.

It is important to mention that the recommendations strongly depend on the assumptions made on the properties of the materials and on the installation process. The results are particularly sensitive to the type of soil. A limited number of calculations show very large differences in maximum fill height between SW85 and SW90 soils, and so care should be taken in the field to assure that the quality of materials and construction is consistent with the assumptions made in the calculations. This issue is of concern for flexible pipes (flexible pipes are those that need to deform to engage, for support, the soil surrounding the pipe, as opposed to rigid pipes, e.g., concrete pipes, where the deformations are small and thus their response is less sensitive to the surrounding ground), and particularly to pipe arches due to their shape and large dimensions. The behavior of pipe arches strongly depends on their interaction, and thus on the quality, of the soil placed at their haunches. At this location, proper compaction of the soil may be challenging and so it is imperative that the soil quality assumed for the calculations is met. When this is not the case, the maximum fill height obtained with CANDE is incorrect and will likely induce failure of the pipe. When the soil quality cannot be achieved in the field, the maximum field height can be estimated using the results provided in the report and obtained following ASTM calculations considering the corner pressure (*Pc*) as the limiting factor. *Because of the issues discussed regarding sensitivity to construction and the large economic impact that failure of a pipe arch has, it is suggested to take as the maximum fill height of pipe arches that obtained following the ASTM standards, where the bearing capacity of the soil around the pipe is limited.*

REFERENCES

AASHTO. (2014). *LRFD bridge design specifications* (7th ed.). American Association of Highway and Transportation Officials.

ASTM. (2017a). *Structural design of corrugated aluminum pipe, pipe-arches, and arches for culverts, storm sewers, and other buried conduits* (ASTM B790/B790M). ASTM International.

ASTM. (2017b). *Structural design of corrugated steel pipe, pipe-arches, and arches for storm and sanitary sewers and other buried applications* (ASTM A796/A796M). ASTM International.

Jung, C. (2010). *Allowable cover heights for buried corrugated steel pipe* (Unpublished manuscript). Indiana Department of Transportation.

Katona, M. G. (1976). *CANDE: A modern approach for the structural design and analysis of buried culverts*. Federal Highway Administration Offices of Research and Development.

Musser, S. (2015). *CANDE-2015 culvert analysis and design user manual and guideline* (NCHRP Research Project 15-28). National Cooperative Highway Research Program.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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