LONG-TERM MONITORING AND ANALYSIS OF FULL SCALE CONCRETE PIPE TEST BEDS

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ABSTRACT:

Current design standards for concrete pipe bedding in Canada utilize the Indirect Design Method for the design of backfill and bedding. This approach does not fully account for the strength of the pipe and does not take into account the nature of the native soil, as every installation is considered to be the same. Consequently, the Indirect Design Method is overly conservative in many cases where the pipe is installed in competent ground and the anticipated level of live loads is minimal. The Standard Installation Direct Design (SIDD) system for design and installation of concrete pipes was developed through the American Concrete Pipe Association's (ACPA) long-term research program. The method takes into account the inherent strength of the concrete pipe as well as insitu soil conditions. The SIDD design minimizes the use of imported material while making maximum use of native soils.

This paper describes the design, installation, long-term monitoring and Finite Element Modeling of full-scale SIDD Type 4 installations. Type 4 installations do not use any imported material and require minimal backfill compaction. Pipe diameter is selected to be 600mm with a burial depth of 1.8m. The test sections are located in heavy traffic areas and simulate the worse case scenario for pipe installation. The results from a 16-month monitoring period are reported and compared with predictions from the ASCE 15-93 specification, Marston-Spangler theory and two finite element analyses. It was concluded based on nearly 40,000 data points that the SIDD method illustrates well the stress envelope around a buried rigid pipe installed using the cut-and-cover construction method.

Introduction

This paper investigates the long-term behaviour of buried concrete pipes installed according to the Standard Installation Direct Design (SIDD) Type-4 specification (ASCE 93-15). Data collected over a period of 16 months from four full scale test beds located across the province of Ontario, Canada, were compared to two design approaches: the classical indirect design method (Marston Method) and the direct design method (SIDD) as well as and predictions from two finite element models: SPIDA and AFENA. Based on the findings, conclusions are drawn on the adequacy of the various prediction methods. The data collected also assist in determining the practicality of using the SIDD Type 4 design specifications for shallow cover installations in heavily travelled areas.

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Background

Bedding material is placed in open trench construction of rigid pipes to uniformly support the weight of the pipe segment as well as the overburden earth load and any applicable live loads. In the early 1970s, the American Concrete Pipe Association (ACPA) developed SIDD through its long-term research program. In SIDD, the use of native soils during installation is maximized, thus reducing the need for imported materials. The utilization of native bedding materials can result in a 15% cost savings in terms of installation costs. It is believed that 40% of the installations that take place annually in Ontario can utilize native material to some degree. Additional benefits include the conservation of non-renewable granular material deposits and conservation of landfill space. Recently, SIDD has been adopted in the United States and parts of Western Canada including the city of Calgary and the province of Manitoba. In 2000, the Ontario Concrete Pipe Association (OCPA) worked with the National Research Council (NRC), Ministry of Transportation of Ontario (MTO), the Regional Municipality of Ottawa-Carleton and the University of Western Ontario (UWO) to study the possibility of using SIDD as an alternative design approach to the current Ontario Provincial Standards (OPS). The UWO research team is responsible for the performance of four Type 4 installations and the monitoring of in-situ stresses around the pipe segments for a period of three years. This paper represents one such installation that took place in Barrie, Ontario in the summer of 2000. For a description of the remaining three sites refer to “OCPA SIDD Bedding Study – Final Report” (Allouche and Wong, 2002).

Literature Review

Concrete pipe design starts in the determination of the overburden earth load and live load to establish the required strength of the pipe. In this context, installation parameters such as bedding type and compaction effort are important factors to be considered by the designer. Two design philosophies were developed for this purpose, namely: the indirect and direct design approaches. Marston pioneered buried pipe design when he developed the indirect design method in the 1920s and 1930s. His work was continued by Spangler in the 1950s and 1960s. As for the indirect design method, while initial theoretical developments were reported back as far as the 1920s, it did not come of age until the early 1970s when computer technology and finite element modeling provided the ability to simulate relatively accurately the stress distribution around the pipe during various stages of the construction process.

The Indirect Design Approach

The indirect design approach is based on empirical methods for determining the total earth and surface loads acting on a buried pipe (Moser, 1990). The assumption made is that the pipe supports the entire weight of soil in the trench above the crown elevation of the pipe. Eq. 1 gives the weight of the soil, W_E, known as earth load, to be supported by the pipe.

$$W_E = C_d \gamma B_d^{\,2} \qquad \text{(Eq. 1)}$$

where C_d is the load coefficient for trench installation; γ is unit weight of the soil in kN/m^3; and B_d is the width of the trench at the top of the pipe in metres. The earth load is then converted to equivalent three edge bearing (3EB) load through the bedding factor, B_f, and the factor of safety

F.S. as given in Eq. 2. The surface load, W_L, such as the vehicle weight, should be taken into account if it is available. In this research, live load considerations were ignored.

$$3EB = \left[\frac{W_L + W_E}{B_f}\right] F.S. \qquad \text{(Eq. 2)}$$

A series of 'bedding factors' were established to account for specific levels of compaction effort and bedding materials in order to estimate the earth pressure distributions of installations with various bedding materials. The bedding factor, B_f, is defined as the ratio of the supporting strength of the buried pipe to the strength of the pipe as determined by the 3EB test.

The bedding factor depends on numerous factors including: the width of the bedding area; the quality of the contact between the bedding soil and the pipe; the density of the bedding materials particularly under the haunch; the magnitude of the lateral supporting pressure on the pipe and the area over which the lateral pressure acts. The bedding factor is always greater than unity, thus providing that the concentrated loading condition from the 3EB test is always more severe than the actual in-ground loading. As the quality of the bedding improves, and the pipe is supported in a more uniform manner, the magnitude of the bedding factor increases. In Ontario Provincial Standard OPSS421.05.02, the bedding factors for Classes A, B, C and D beddings are 2.8, 1.9, 1.5 and 1.1, respectively, where Class A bedding is either a concrete cradle or arch that provides a perfect support for the pipe; Class B is either a shaped subgrade with granular foundation or a granular foundation to the springline; Class C is either a shaped subgrade or a granular foundation extending to one sixth of the outside diameter; and Class D is a flat bottom with no placement of imported bedding material. In this case, the pipe directly bears on native soil, and consequently experiences a higher bending moment than other classes as the contact surface area between the pipe's invert and the soil is relatively small. The loading condition for Class D most closely resembles the loads experienced by the pipe during the 3EB test.

The indirect design approach mainly adopts the 3EB load as a representative value in concrete pipe design. In fact, this estimate is conservative compared to the in-ground condition that the pipe actually experiences. This approach does not consider the actual stress distribution around the pipe. Also, the indirect design approach neglects any contribution due to soil support, and assumes that the pipe carries the entire load. In this paper, the limitations of the indirect design approach will be illustrated through a full scale concrete pipe test bed instrumented using 12 earth pressure cells.

The Direct Design Approach (SIDD)

In contrast to the indirect design methods that rely on the computation of equivalent field loads based on the results of a simple loading test, the direct design of concrete pipes is based on an assumed pressure distribution developed around the pipe due to the applied vertical load. Examples of such pressure distributions are those developed by Paris (1921) and Olander (1950). However, these methods still require the use of the Marston-Spangler method to determine the total load on the pipe.

Research initiated to determine the effect of soil structure interaction using a finite element analysis program named SPIDA (Heger et al., 1985) lead to the development of a new pressure distribution called 'the Heger Earth Pressure Distribution' (ASCE 93-15, 1993). This distribution deviates from previous practices by: 1) proposing a new approach for computing the earth load on the pipe, and 2) accounting separately for the support provided by the invert and lower haunch region.

The major feature of the Heger pressure distribution is the use of bedding reaction with three separate pressure bulbs. This accounts for the fact that it is unlikely that the backfill can be properly compacted in the lower haunch region (Allouche et al, 2001). Thus a trough is introduced into the supporting pressure in this region. The pressure bulb directly under the invert models the pipe bedding condition and the two side bulbs model the soil support offered in the upper haunch region as a result of backfill compaction. Good installation practices result in relatively large pressure bulbs in the upper haunch region. No soil support is offered in the upper haunches when the backfill is not compacted.

SPIDA presents four standard variations of the Heger pressure distribution that together represent a wide range of qualities of installations. These are described in Table 1. The vertical arching factor, VAF, and the horizontal arching factor, HAF, are respectively the ratio of the total vertical and lateral earth loads on the pipe to the weight of the prism of earth above the top of the pipe, PL. PL is computed using the following expression:

$$PL = \left(\frac{wD_0}{1000}\right)\left[H + \left(\frac{0.107D_0}{1000}\right)\right] \qquad \text{(Eq. 3)}$$

where w is the unit weight of the soil (N/m^3), D_0 is the outside diameter of the pipe (mm), and H is the height of earth above the top of the pipe (m). A more complete description of SIDD and its applications can be found in the ASCE 15-93 specification.

Table 1: Standard Trench Installation Types (CAN/CSA-S6-00)

	Minimum Bedding Thickness		Minimum Standard Proctor Compaction	
Installation Type	Soil Foundations	Rock Foundations	Haunch and Outer Bedding	Lower Sidefill
1	D_o/24, not less than 75mm	D_o/12, not less than 150mm	95%*	90%-100%
2	D_o/24, not less than 75mm	D_o/12, not less than 150mm	90% - 95%**	85%-95%
3	D_o/24, not less than 75mm	D_o/12, not less than 150mm	85%-95%	85%-95%
4	No bedding needed	D_o/12, not less than 150mm	Not Needed***	Not Needed***

Note: * Only applicable to sand and gravel; ** Not applicable for Clay; *** 85% Compaction for Clay

Current Standards

The ASCE Standard for SIDD was approved in 1993 and was given the designation ASCE 15-93. The main innovation in this standard is the adoption of the Heger Earth Pressure Distribution. Thus it analytically takes the pipe-soil interaction into account, resulting in a less conservative estimate of the load carried by the pipe in comparison with the conventional indirect design method. In Canada, the Canadian Highway Bridge Design Code (CAN/CSA-S6-00, 2000) includes the SIDD under a new section called buried structures. In addition, SIDD was adopted by the Manitoba Department of Transportation in 1993 and by the city of Calgary in 1999. However the indirect design is still widely practiced in Ontario.

Test Site Configuration and Instrumentation

The test site described in the following section is located just outside the city of Barrie, in Southern Ontario, Canada (approximately 150km north of Toronto). The test bed included the installation of a 600mm diameter, Class 4 reinforced concrete storm drain. Five 2.44m (lay length) pipe segments were installed at a depth of 1.8m under a new weigh scale approach ramp. Trench geometry consisted of a trapezoid shape approximately 2.6m wide at the base, 2.7m wide at grade and 1.8m deep (relative to native grade). The soil conditions at the Barrie site can be classified as uniform silty sand (SW) and in-situ moisture content that varied between 2% and 5% across the profile of the excavation. The maximum Standard Proctor density of the in-situ material was found to be 1725 kg/m^3 with an optimum moisture content of 10%. The three central pipe segments were instrumented to collect the desired data. Access to the pipe segments was secured by installing a 1.5m O.D. manhole at the south end of the installation. Figure 1 and Table 2 provide information regarding the location and orientation of the 12 earth pressure cells installed around the test and control pipe sections. The pressure cells have a capacity of 25psi for the vertical cells and 100psi for the horizontal cells with ±0.25% accuracy. The cells were 274mm in diameter vibrating wire earth pressure cells manufactured by Geokon. The data acquisition system included a CR10X Campbell Scientific datalogger connected to a multiplexer. The datalogger was programmed to read and store the data six times daily. The data are downloaded on a monthly basis.

Figure 1. Configuration of Monitoring System at Barrie Site

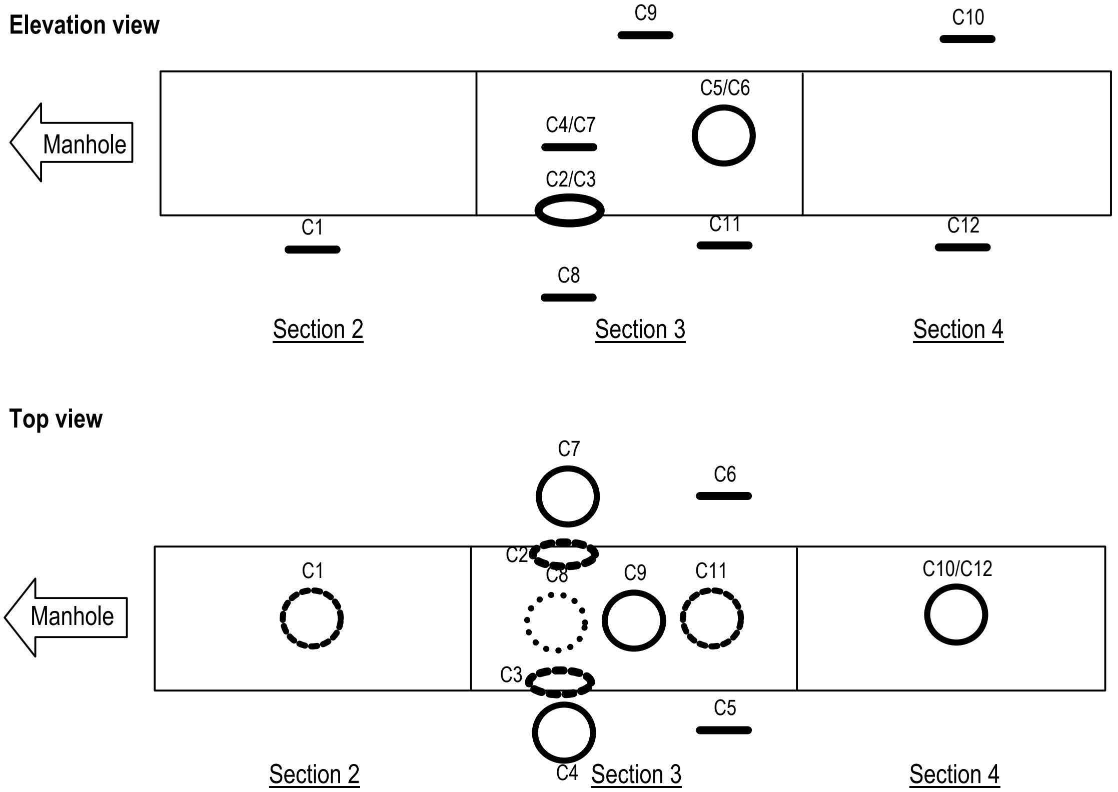


Table 2. Load Cell Designation and Location for the Barrie Site

Cell	Stress Rating (psi)	Location	Orientation
1	50	100 mm below invert	Horizontal
2	50	Offset 22° from vertical between invert and springline	Oblique
3	50	Offset 22° from vertical between invert and springline	Oblique
4	50	At springline	Horizontal
5	25	At springline	Vertical
6	25	At springline	Vertical
7	50	At springline	Horizontal
8	50	250 mm below invert	Horizontal
9	50	150 mm above crown	Horizontal
10	50	150 mm above crown	Horizontal
11	100	100 mm below invert	Horizontal
12	100	100 mm below invert	Horizontal

Field Measurements

The data presented in this paper were collected between the completion time of the installation in July of 2000 and November of 2001. Nearly 160,000 data points were collected for the four sites, 40,000 of which were for the site discussed in this paper. The measurement consisted of five groups of data: invert, oblique, springline vertical and horizontal, and crown cells. The annual performance of the earth pressure cells shows excellent agreement among the cell groups. Table 3 shows the overall performance of each cell group including the baseline, minimum, mean and maximum monthly values. The invert cell readings from July 2000 to November 2001 are plotted in Figure 2.

Figure 2. Actual Response of the Invert Cells at the Barrie Site

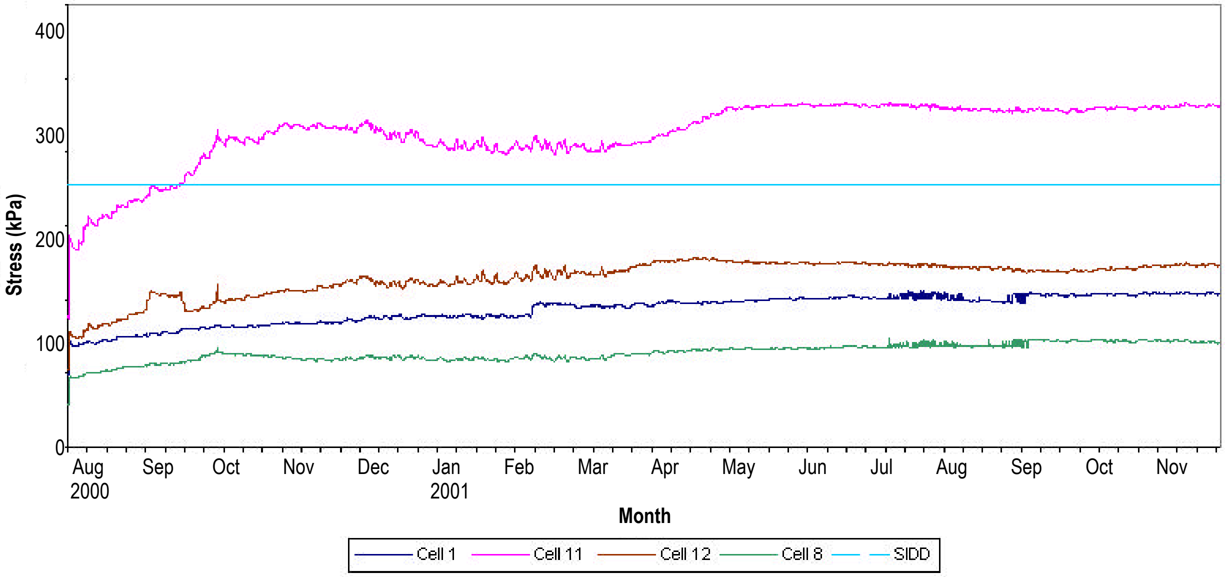


Table 3. Overall Performance of Pressure Cells at Barrie Site

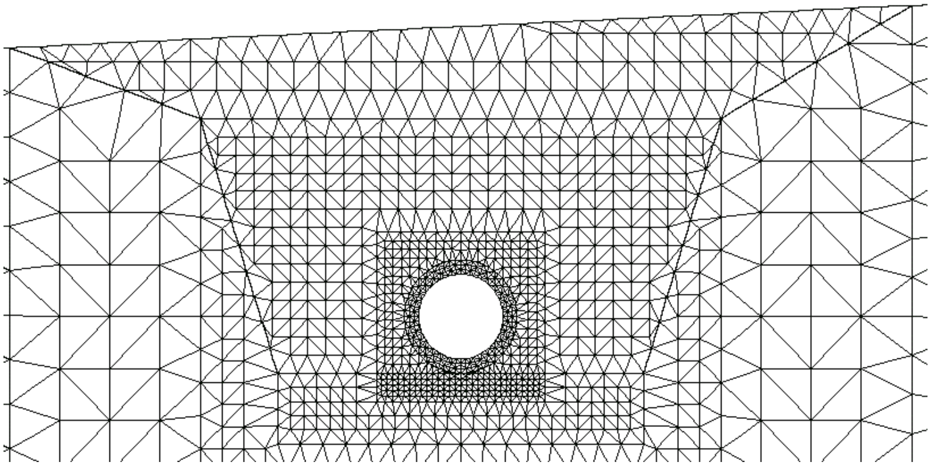
(July 27, 2000 to November 30, 2001)

Cell Group	Cell	Monthly Mean Values (kPa)		
		Min	Mean	Max
Invert	1	99.8	127.0	141.9
	11	214.4	291.8	319.9
	12	116.1	157.4	174.9
	8	71.1	87.0	99.1
Oblique	2	41.8	47.1	57.6
	3	39.4	43.4	46.2
Hor SpLn	4	55.1	60.6	66.9
	7	50.7	58.0	64.4
Ver SpLn	5	15.0	23.4	35.2
	6	16.2	23.6	32.8
Crown	9	29.7	41.3	53.2
	10	35.9	46.0	54.2

Finite Element Modeling

The Barrie Site was modeled using AFENA – A Finite Element Numerical Algorithm developed by R. L. Taylor and published in Chapter 24 of 'The Finite Element Method' (3rd Edition) by O.C. Zienkiewicz (McGraw-Hill, 1977). The geometry of the trench was considered with a sloped surface accounting for the ramp. Figure 3 shows the FEM mesh. Four types of material were used in the model: concrete pipe, native soil, haunch backfill and regular backfill. The model was used to simulate the construction sequence beginning with the excavation of the trench, placing of the pipe, and backfilling. The construction stages resulted in a number of non-linear stiffness relationship due to soil-pipe interaction. Because of the difficulty in achieving good compaction in the haunch region, three AFENA models with different haunch soil stiffness were developed.

Figure 3. AFENA FEM used for Barrie Site



SPIDA – Soil Pipe Interaction Design and Analysis, was developed to give a more precise design approach for concrete pipe (Heger et al., 1985). In the analysis, the pipe is represented by a reinforced concrete structure and the soil is represented by an hyperbolic stress relationship known as the Duncan Soil model (Heger et al., 1985). The computer output provides the normal stress distribution at the surface of the pipe, which then can then be compared to field measurements. Additional information provided by SPIDA includes the bending moments, shear forces and thrusts developed in the pipe.

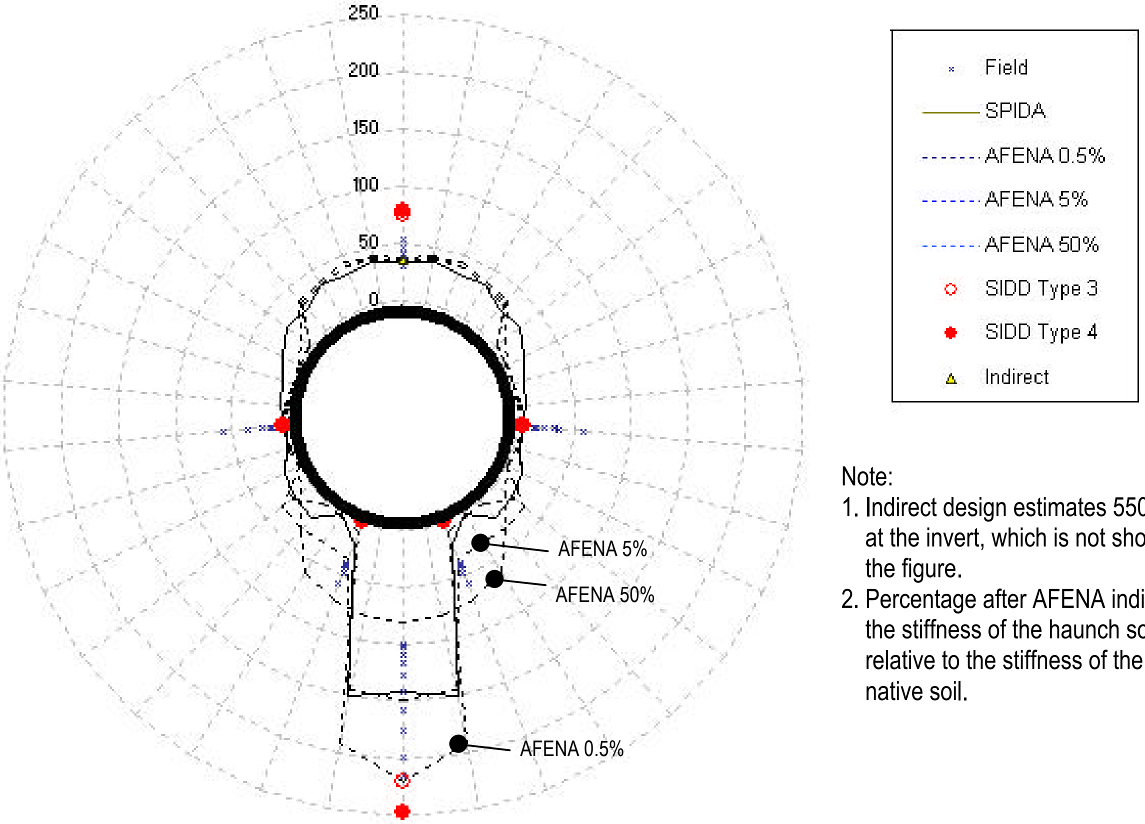
Discussions

Table 4 summarizes the overall results of static and long-term field measurements, predictions made using SIDD and the current Ontario Provincial Standard (i.e. indirect design method) and the stresses provided be the SPIDA and AFENA models. The values are also plotted in Figure 4 using a radial plot format.

Table 4: General Comparison

Values (kPa)	$S_{\mathbf{Invert}}$	$S_{\mathbf{oblique}}$	$S_{\mathbf{SpLn}}$	$S_{\mathbf{Crown}}$
Field Measurements				
Monthly Mean Max	175.1	52.1	29.0	54.5
Monthly Mean Min	100.0	40.2	15.2	29.6
Monthly Mean Avg	137.6	45.3	22.1	42.1
Predictions				
OPSS	547.5	N/A	N/A	35.4
SIDD (TYPE 4)	246.0	0	3.3	77.9
AFENA 0.5%	132.0	22.0	0.7	31.7
SPIDA	173.0	1.6	4.0	37.0

Figure 4: Normal Pressure Distribution (kPa)



Note:
1. Indirect design estimates 550kPa at the invert, which is not shown in the figure.
2. Percentage after AFENA indicates the stiffness of the haunch soil relative to the stiffness of the native soil.

The monthly mean average of the field measurements for the invert stress is 137.6 kPa while the SIDD prediction is 250 kPa, a value greater by 50% than the measured value. The current OPS method (based on the indirect design method) was found to be 370% higher than the measured value. Considering the FEM analysis, SPIDA predicts 173 kPa (20% higher than the field measurement); and AFENA predicts 132 kPa, which falls in the range of field measurements. In this model, the stiffness of the haunch soil was selected to be 0.5% that of the stiffness of the native soil indicating no compaction effort. The FEM estimation of invert stress is sensitive to the relative stiffness of the haunch soil selected. The AFENA results vary from 70 kPa to 130 kPa with respect to the elastic modulus ranging from 0.5% to 50% of the stiffness of the native soil. In general, the SIDD prediction over-estimates the long-term monthly mean average value by 80% to 140%. The indirect design method over-estimates the field measurements by nearly 400%. Based on these results, it was concluded that SIDD provides a reasonable prediction with a safety factor of 1.4, while the conventional indirect design is overly conservative. Moreover, the stresses predicted using AFENA show that the invert stress is highly sensitive to the stiffness of the haunch soil, hence, to the degree of compaction effort. This sensitivity can be seen in Figure 4, as the field readings at the pipe invert exhibit a much higher variation compared to the field readings at the springling and crown. This high variation reflects the fact that the invert cells are very sensitive to the distance from the pipe invert due to the high stress gradient caused by the high stress concentration at the invert.

SIDD estimates zero stress in the haunch region because SIDD Type 4 installation assumes that the soil in the haunch region is inferior and poorly compacted. SPIDA estimates 1.6kPa in the haunch region, a value that is very close to SIDD Type 4 estimation. AFENA estimates 22.0kPa using the model with elasticity of 0.2MPa at the haunch region. By looking at these values with the monthly mean average value (45.3kPa) for haunch stress, the stress in the haunch region appears more likely to be a SIDD Type 3 installation due to the good quality of the soil, in which case SIDD provides an excellent prediction (see Figure 4).

The SIDD prediction for the lateral stress in the springline of the pipe is 85% lower than the monthly mean average of field measurement (8.4kPa). SPIDA and AFENA estimate it to be 4.0kPa and 0.7kPa, respectively. Higher lateral stress in the springline of the pipe provides higher confining pressure, which stabilizes the pipe and reduces the bending moment at the invert of the pipe. Therefore, SIDD prediction and the FEM estimations are conservative.

As for the crown stresses, SIDD estimates are approximately double the long-term monthly mean average at the crown of the pipe. SPIDA and AFENA estimate 37.0kPa and 31.7kPa at the crown of the pipe. A calculation based on the unit weight (γ) and the burial depth (z) predicted a value of 35.4kPa, which falls well in the range of the field values (30kPa to 55kPa).

Conclusions

Several conclusions can be drawn based on the findings presented.

1. The field data are consistent within each of the cell groups. The readings reflect certain field activities such as snow and traffic. Also, a seasonal oscillation due to ambient temperature was observed.

2. High variation of the invert data indicates the stress distribution to the sensitivity of the degree of contact and stiffness of the haunch soil.
3. SPIDA and AFENA predict similar stress envelopes around a rigid pipe placed in granular soil.
4. In AFENA, the invert stress is highly sensitive to the stiffness of the haunch. The lower the stiffness, the higher the invert stress.
5. The FEM results lie in the range of the field measurements at the invert of the pipe and provide an excellent estimation at the crown of the pipe.
6. High stress gradient is observed below the invert of the pipe, which could explain the high stress variation of the field measurement.
7. Indirect design provides a very conservative estimation for the stress at the invert of a rigid buried pipe.
8. SIDD provides a somewhat conservative estimate at the crown and invert. Field readings for springline stress are higher than SIDD estimation providing higher confining pressure and increasing the stability of the pipe.

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