Assessment of an Innovative Double Wall Corrugated-HDPE Manhole Structure

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Abstract— Urban waste water management engineering featuring various conveyance and appurtenant structures connected by manholes is a very topical field in the context of increasing urbanism. While traditional manholes were generally made of brick and stone masonry, with the advancement in material science and engineering, new types of manholes have evolved; the double wall corrugated HDPE (DWC-HDPE) pipe system being one of the latest having inspired by the need of increased environmental sustainability, durability and faster construction, which also assists in better traffic management and business activities in the construction site. Despite a very promising solution, very less research has been done in this area of interdisciplinary structural engineering, and their structural behavior is poorly understood. In this paper, a prototype of DWC-HDPE manhole is subjected to vertical and lateral loads followed by an assessment of appropriate earth pressures, and its stress and buckling analysis is conducted. Manual calculations as well as simplified, linearly elastic, numerical modelling using FEM approach are adopted. The analyses results show that all the calculated parameters of the studied manhole structure are within acceptable limits; with the localization of stress occurring around the periphery of the opening. It is found that the intensity of tensile stress is largely dependent upon the discretization of support condition.

Keywords — Urban waste management, Innovative technologies, Interdisciplinary structural engineering, DWC-HDPE manhole, Stress analysis

I. Introduction

Urban waste water management (UWWM) as a part of drainage engineering is a very topical field in the context of increasing urbanism or the rebuilding of existing sewerage system in existing cities. It is more so in the developing countries like Nepal with less organized infrastructure planning and development of the past. Every UWWM features various conveyance and appurtenant structures including manhole not only as a transit of various flows but also as a platform for inspection and maintenance in the entire sewerage system during operation.

Traditionally manholes were made of brick masonry; however, with the advancement in material science and engineering, other types of manholes such as cast-in-place reinforced concrete, precast concrete, fiber reinforced concrete etc. also evolved. Lately, double wall corrugated (DWC) HDPE pipes are getting popular as horizontal sewers due to factors such as environmental sustainability, durability, faster construction etc. which further impacts traffic management and business activities of the communities in the construction site. In this paper, an innovative solution of manhole using the DWC-HDPE sewer pipe surrounded by a concrete ring surrounding it atop (proposed by an established local manufacturer in Nepal) is assessed for vertical and lateral loads, and its stress and buckling analysis is conducted followed by a comparison with its reinforced concrete manhole counterpart. Manual calculation procedure is applied, followed by a simplified, linearly elastic, and a nonlinear numerical modelling in the Finite Element programs. In doing so, an analysis on existing lateral earth pressure philosophies is also conducted to identity a more appropriate approach of their modelling.

II. Manual Structural Analysis

A. Lateral earth pressure assessment

Classical earth pressure theories [1,2] have been used extensively and many researchers [1, 4, 5, 6, 7] have scrutinized the lateral earth pressure acting on vertical wall, some of them being the circular retaining walls, for plain strain condition. However, these formulations do not always represent the actual behavior of circular shafts and structures [8]. Moreover, experimental studies have shown that the

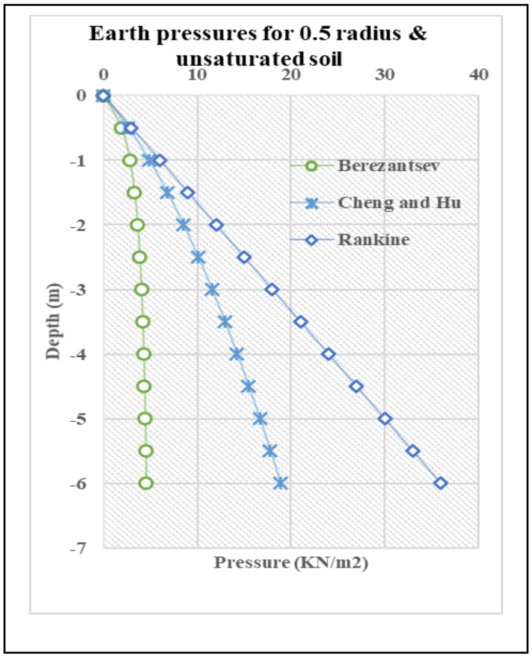

Figure 1-a Comparison of earth pressure by different theories for 0.5 m radius of pipe for saturated soil

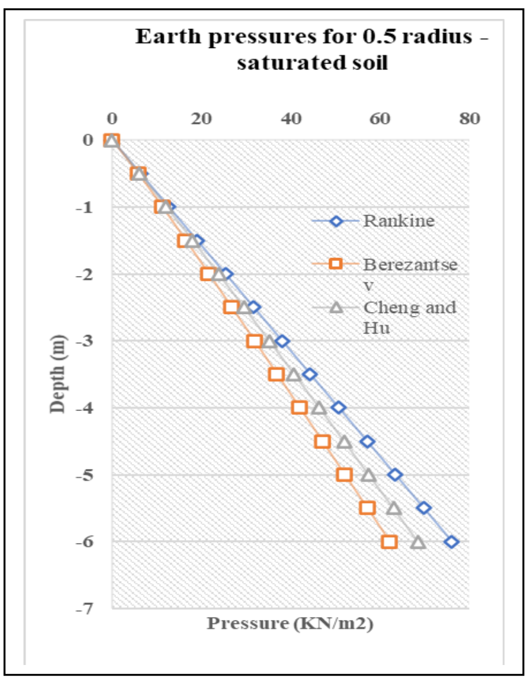

Figure 1-b Comparison of earth pressure for saturated soil

distribution of lateral earth pressure on circular shafts is nonlinear [8] and the classical method overestimates the lateral earth pressure fairly at a larger depth [9, 12]. Thus, in this study, earth pressure by some widely accepted methods [2, 5, 10, 11] are evaluated and a formulation with more realistic approach for estimating the earth pressure is adopted. In this study the following data are taken for calculation of earth pressure by different theories: Height= 6 m, unit weight of soil, γ = 18 KN/m^3, unit weight of water, γ_w = 10 KN/m^3, and angle of internal friction of the soil, θ = 30^0. The calculation by all three methods is summarized in Fig. 1-a and Fig. 1-b.

It is quite arduous to choose between the correct formulations, as the magnitude of earth pressure induced Earth pressures largely depend upon the radial wall movement (S1) induced. Fuji et al [14] concluded that the earth pressure generally shows decreasing trend until a point where the displacement is 0.2 % of wall height, where the pressure is equal to Berezantzev's solution. Likewise, Herten and Pulsfort [16] in their experiment found that the earth pressure was changed when there was displacement greater than 0.05% of wall height. Also, Chun and Shin' [15] experiment concluded that the earth pressure decreases and reaches its minimum value when the wall displacement is 0.6-1.8% of wall height. Similarly, Tobar and Meguid [13] found that for the full development of axisymmetric earth pressure, the wall displacement ranges between 0.2% to 0.3% of wall height. They concluded that when S1>0.1% H, the earth pressure values coincide with Cheng and Hu's solution, and when S1>0.3% H the pressure is in good agreement with Berezantzev's [5] solution. As the HDPE Pipe is flexible, the wall displacement for development of axisymmetric pressure is achievable, which is verified later on in this study. Hence, for this study, Cheng and Hu's Method [10] is adopted. Although, there is significant difference in earth pressure values for unsaturated soil (fig 1-a), the difference is minimized when we take the saturation of soil into consideration (fig 1-b).

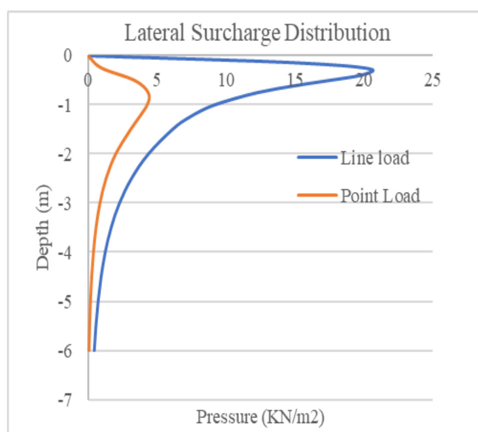

Figure 1-c Comparison of Lateral pressure due to surcharge using line and point load

Boussinesq's [17] solution has been adopted for the analysis of surcharge. The analysis is done considering two cases, case (i) surcharge analogy by point loads (for vehicle where the load is transferred through four tires) and case (ii) surcharge analogy by line loads for compacting rollers. For case (i) the weight of the vehicle considered is 12 ton and the distance of axel from the edge of manhole is considered to be 1m. Likewise, for case (ii), the weight of compacting roller is taken as 25 ton and the distance of its axel from the edge of manhole is taken as 0.5m. The results for unfactored load analysis are depicted in fig 1-c. It is evident that the effect of lateral surcharge decreases with increase in depth. However, the earth pressure due to surcharge at medium depth of nearly 6 m is greater than the value estimated by Boussinesq's as seen in Das [18], Spangler [19]. Hence, a conservative lateral pressure of $10KN/m^2$ is applied uniformly in this simplified analysis as NZTA [20] and AASHTO [21] suggests. This, lateral surcharge is factored by 1.5 on the analysis done later in this study.

B. Manual Analysis

The pipe is installed in such a way that there is no axial load on the pipe as the load is distributed uniformly around the pipe by the concrete rings used in the installation. Thus, no axial stress is assumed to be induced in the analysis. Ring bending, Compressive Ring Thrust, Pipe Wall Buckling (Underground water table, and over ground water table), Bending Stress, and Thermal stress are checked manually for the maximum load obtained from above.

Ring Stiffness: Ring stiffness indicates pipe's ability to resist the vertical deformation due to external loads. Pipe Stiffness is given in eqn. (1) [30].

$$\text{Pipe Stiffness (PS)} = \frac{F}{\Delta Y} \geq \frac{EI}{0.149r^3} \tag{1}$$

Ring Deflection: The normal response of flexible pipes to soil pressure is known as ring deflection. This response indicates the imitation of arching effect in the soil and leads to the redistribution of soil stress. The most commonly used method to determine the ring deflection i.e., the Modified Iowa formula [25, 26] is used in eqn. 2 and eqn. 3. The maximum allowable deflection is 7.5% of the pipe diameter [22, 23].

$$\frac{\Delta X}{D_I} = \frac{P}{144}\left(\frac{K_{BED}L_{DL}}{\frac{1.24(RSC)}{D_M} + 0.061F_S E'}\right) \tag{2}$$

$$RSC = \frac{6.44\ EI}{D_M^2} \tag{3}$$

Constrained Pipe Wall Buckling (Below Ground Water Level): Buckling is generally caused due to excessive compressive stress, which imitates a large undulation (dimple), and later grows to reverse curvature. Consequently, the structure will collapse. The vertical pipe is most prone to buckling during the compaction. Luscher's Equation [27] for Constrained Pipe Wall Buckling represented in eqn (4-6) is used to determine the permissible constrained buckling pressure [22, 23, 24]. The Buckling phenomenon has a rapid occurrence, but the long -term external pressure has a greater influence to the buckling then the instantaneous load of large intensity. Thus, while calculating the allowable buckling pressure, Elastic modulus of the 50-year value is used. [22].

$$P_{WC} = \frac{5.65}{N}\sqrt{RB'E'\frac{EI}{D_M^{\,3}}} \tag{4}$$

$$B' = \frac{1}{1 + 4\,e^{(-0.065H)}} \tag{5}$$

$$R = 1 - 0.33\frac{H_{GW}}{H} \tag{6}$$

Buckling above Ground Water Level: Incase the Soil is in Unsaturated State: Moore-Selig Equation for Constrained Pipe Wall Buckling is used. [22, 24]

$$P_{CR} = \frac{2.4\,\varphi\,R_H}{D_M}(EI)^{\frac{1}{3}}(E_S^*)^{\frac{2}{3}} \tag{7}$$

Compressive Ring Thrust: The direction of lateral earth pressure is radial, and it acts around the circumference of a pipe. As a result, compressive ring thrust is induced in the pipe wall, which is opposite to the Tensile Hoop Stress. Excessive Compressive thrust can lead to the crushing of pipe material or bucking of the pipe walls. Equation (8)[22, 24]. Is used to determine the compressive thrust induced due to lateral surcharge and Earth pressure.

$$S = \frac{(P_E + P_L)D_O}{288A} \tag{8}$$

Thermal Stress: Unrestrained pipe allows the expansion or contraction of pipe, and thus inducing stress of no structural significance. However, if the pipe is anchored on both ends, the pipe at restraint surface will exhibit thermal stress dependent upon the amount of change in the temperature. The magnitude of the thermal stress is calculated using eqn. (9) [22].

$$\sigma = E\alpha\Delta T \tag{9}$$

Table 1: Design properties

Description	Psi	MPa	Standards	Designation Code
Short Term Elastic Modulus	130000	896	ASTM D638[32]	PE 4710
50-year Elastic Modulus	29000	200	Material Designation	PE 4710
Allowable Compressive stress	1150	7.93	ASTMD695[33]	PE 4710
Tensile Stress	4600	32	ASTM D638[32]	PE 4710
Flexural Modulus	188500	1300	ASTM D790[34]	PE 4710
Coefficient of Thermal Expansion	$8*10^{-5}$	in./in ^{0}F		PE 4710
Density	0.96	g/cc	ASTM D1505[29]	PE 4710
Poisson's ratio	0.45			PE 4710
Modulus of soil reaction	1000	psi	ASTM D2487	Fine Grained Soil
			Howard 1997[31]	Liquid Limit <50

Material Properties: The properties used in Calculation are obtained from manufacturer conforming the design standards and material designation code [35] as shown in Table 1.

Results: The manual calculation results are tabulated in Table 2.

III. NUMERICAL ANALYSIS

A. Modelling Approach:

The combined effect of applied load can be obtained from Finite Element Method, which minimizes the assumptions and analogy used in manual design. Thus, more realistic results are obtained and more economical section can be designed. In this study, ring stiffness transformation is used to simplify the model. Though simplified the FEA model is in close representation with the actual structure. The procedure is described in this section.

Model of the Pipe:

The complex and erratic geometry of the corrugated pipe consisting crest and valley system imposes taxing effort in modeling as well as computational efficiency. Due to this reason, a simplified straight wall model is taken into analysis, in this study, by converting the 3D geometry into equivalent thickness.

Also, it has been found that the soil-structure interaction is identical in pipe with same ring stiffness, if the installation condition is similar for DWC pipe and straight walled pipe [36, 38]. Likewise, various field tests have corroborated that the equivalent straight-walled 2D model is suitable for obtaining deflection and strain in DWC pipe [37, 39, 40]. In this study, ring stiffness transformation method is used to obtain the equivalent thickness of straight-walled pipe by using equations 10 and 11.

Load and Material Assignment: A uniformly varying pressure obtained from Cheng and Hu's solution and simplified lateral surcharge distribution, for saturated soil, is applied to the simplified model as shown in fig 1-d. The Factor of Safety of 1.5 for load assignment is taken for the analysis. The lateral pressure is assigned to the model by assigning joint pattern as explained in CSI Reference Manual [41]. The corresponding shape and material parameters of the simplified pipe are summarized in Table 3 and Table 1 respectively.

Due to the linear behavior shown by the pipe for short-term load, the pipe is considered as an elastic material. The stress strain data used in the study is shown in fig 2.

Table 2: Manually calculated results

Parameters	Calculated	Allowable
Ring Deflection	3.10%	7.50%
Constrained Pipe Wall Buckling	14.5 psi	21
Compressive Ring Thrust	186 psi	1150
Bending Stress	352 psi	900
Thermal Stress	197.2 psi	1150

Table 3: Shape parameters

Ring stiffness (KN/m^2)	Nominal diameter (mm)	Wall thickness (mm)
8	600	25.17
8	800	33.56
8	1000	42

Table 4: Key results from FEA analysis

Parameters	Obtained Values
Max. deformation	5.5 mm
Max. Compressive Stress	3 N/mm^2
Max. Tensile Stress	3.6 N/mm^2

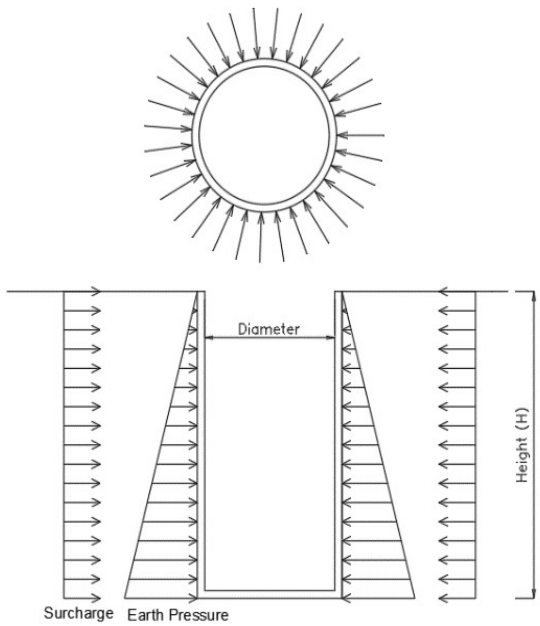

Figure 1-d: Simplified load distribution

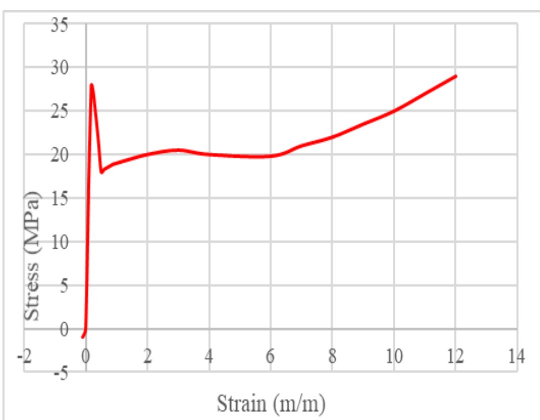

Figure 2: Stress-strain curve for HDPE pipe

B. Analysis Case and Results

Linear static analysis is performed for combination of dead load, lateral earth pressure and surcharge is performed. And the stress obtained from the analysis are within the accepted limits. Fig 3 shows the 3D model and Fig. 4 the deformation produced on the pipe. Fig 5-a shows the maximum principal stress (N/mm^2) and Fig 5-b shows the minimum principal stress (N/mm^2). Fig 6-a and fig 6-b show the normal stress in x and y direction (N/mm^2) respectively. The key results are presented in Table 4.

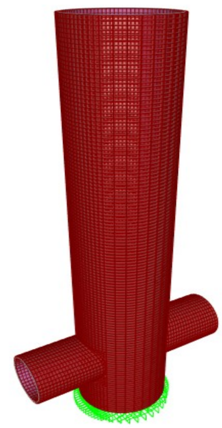

Figure 3: 3D Model of the simplified pipe

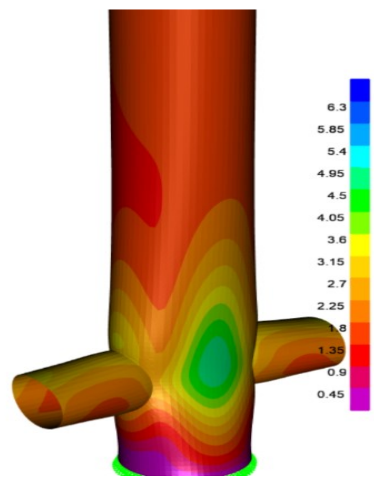

Figure 4: Deformation pattern on HDPE pipe due to combined loading

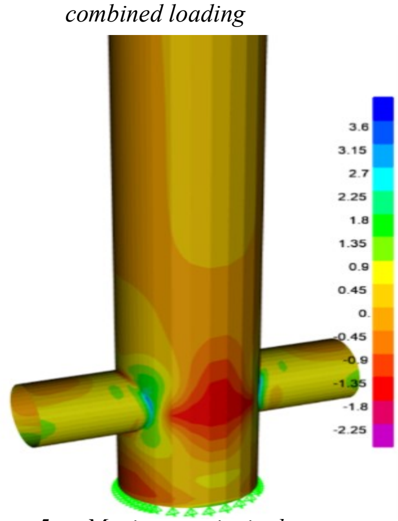

Figure 5-a: Maximum principal stress

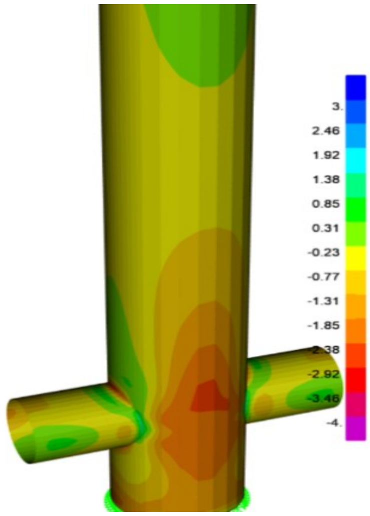

Figure 5-b: Minimum principal stress

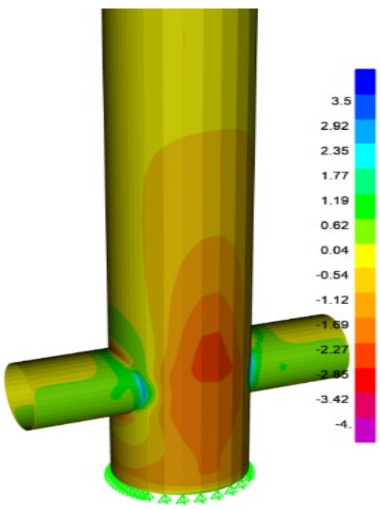

Figure 6-a: Normal stress in X direction

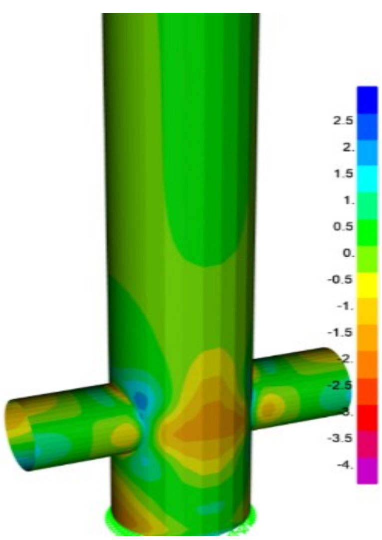

Figure 6-b: Normal stress in X direction

IV. DISCUSSION, CONCLUSION, AND RECOMMENDATION

In this study, manual calculation as well as numerical simulation (linearly elastic) of a DWC-HDPE manhole is conducted. The pipe is simplified using the ring stiffness transformation method. The obtained results are compared with the allowable values from different standards. Subsequently, the following conclusions are drawn followed by a recommendation.

- The obtained value for ring deflection, constrained pipe wall buckling, compressive ring thrust, and thermal stress, both from manual as well as numerical simulation, are within the acceptable limits.
- The FEA analysis is a close representation of the actual condition as it gives the result with the combination of the bending, axial, and compressive stresses.
- Due to the flexible nature of the DWC-HDPE, the deflection obtained is enough to radially initiate the axisymmetric earth pressure. This earth pressure is lower than the earth pressure at rest, which is the main design criteria for design of rigid structures, and thus from design perspective, the DWC Manhole seems economical too.
- It is observed that the stress localization occurs around the periphery of the opening of the manhole, and this could be addressed through proper attention in the connection.
- Moreover, tensile stress seems to be concentrated at the bottom, and is dependent upon the discretization of the support. Further, a more realistic support discretization produces accurate distribution of the tensile stress near support.
- Although, no axial stress is assumed to be induced in this study, in reality some axial stress is produced due to surcharge skin drag on the pipe. Thus, a more robust non-linear analysis involving soil structure interaction is necessary to predict the negative skin drag along with the realistic long-term buckling behavior of the pipe, which shall be covered in future works.

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conduct this research, in the context of its applicability.

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PS= Pipe Stiffness, psi
F= Force, lbs/in
ДY= Vertical Deflection, in.
E= Modulus of Elasticity, psi
r= Mean Radius of Pipe, in.
ΔX = Horizontal deflection, in

KBED = Bedding factor, typically 0.1
LDL = Deflection lag factor
P = Lateral soil pressure due to earth load and surcharge, psf
E' = Modulus of Soil reaction, psi
FS = Soil Support Factor
RSC = Ring Stiffness Constant, lb/ft [ASTM F 894]
DR = Dimension Ratio, DO/t
DM = Mean diameter (DI+2z or DO-t), in
z = Centroid of wall section, in
t = Minimum wall thickness, in
DI = Pipe inside diameter, in
DO = Pipe outside diameter, in
P_{WC} = Allowable constrained buckling pressure, lb/in^2
N = Safety factor
R = Buoyancy reduction factor
HGW = *Height of ground water above pipe, ft*
H = *Depth of cover, ft*
e = *Natural log base number, 2.71828*
E = *Apparent modulus of elasticity, psi (of 50 year)*
I = *Pipe wall moment of inertia, in4/in*
PE = Lateral soil pressure due to earth load, psf
PL = Lateral soil pressure due to surcharge, psf
S = Pipe wall compressive stress, lb/in2
DO = Pipe outside diameter (for profile pipe DO = DI + 2HP), in
DI = Pipe inside diameter, in
HP = Profile wall height, in
A = Profile wall average cross-sectional area, in2/in (Profile wall area from the manufacturer of the profile pipe)

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