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Development of Finite Element Model Technology for Composite Pipe with Sewage Pipe Renewal Method

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Abstract

The aim of this study is to evaluate the behaviour of buried pipes utilizing the Sewage Pipe Renewal (SPR) method through a finite element analysis. A finite element program, ABAQUS, will be used for the static analysis of the pipes. Maximum stresses and displacements are tabulated and plotted into graphs for the analysis. Varying lengths, materials, bedding angles, boundary conditions are considered. Lengths of 1m, 3m, 5m, and 10m meters are used, but only the 3 and 5 meter pipes are used for the modelling of pipes with various bedding angles and boundary conditions. Two sets of boundary conditions are used in this study to represent the bedding support on the pipe. A fixed boundary condition and a series of soil springs are used to model the bedding support of the pipes. Based on the FEM results, length of the pipes is not a factor for the magnitude of maximum stresses and deflections of buried pipes. However, increasing bedding angles of the buried pipes decreases the value of stresses and displacements. Additionally, pipes with soil springs applied as bedding support increases the stress and displacement remarkably. Analyses and concluding remarks are provided at the end of this study.

Keywords: Buried Pipes, Finite Element Analysis, Sewage Pipe Renewal

1. Introduction

With the attempt of achieving a high standard of living, a large amount of public works and infrastructures have been developed. High percentage of this infrastructures cover sewers for agriculture, residential and industrial water supply, waste water disposal, etc. It is estimated that most of these sewers have already reached their useful life or started deteriorating, especially in urban areas. As a result of this problem, with the aid of our modern technology, new methods for rehabilitating sewer pipes have been developed. One of these methods is the Sewage Pipe Renewal or SPR method. This study focuses on the static analysis of buried pipes employing the SPR method. This type of method rehabilitates pipes by forming PVC profile inside an old existing pipeline. These types of pipes are considered to be composite pipes, for they are composed of different materials acting as one to either maintain or increase the strength of the pipes. SPR method, which is an un-excavating rehabilitation method, was first introduced in 1986 and was only used for rehabilitation of small sewer pipes. Over the years, this method was developed, and it is now able to rehabilitate pipelines with small to large diameters. Also, it is now capable of rehabilitating pipelines with non-circular cross-sections. As of today, the SPR method is developed and used for copying various pipeline rehabilitation purposes providing lower costs, safety, and ease of installation[1]. This study evaluates the composite material though a Finite element analysis. behaviour of rehabilitated pipes having a composite material though a Finite element analysis.

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A comparison of an ordinary concrete pipe, PVC pipe, and the composite pipe will be provided. The results of this study may be used for the assessment of efficiency of the SPR method.

Figure 1. Pipe and box applied the SPR method.

2. Review of Related Literature

2.1 Fundamentals of SPR Method

TSPR method rehabilitates pipelines by forming PVC profile inside an existing pipeline by using a winding machine without excavating the soil above the pipe, which lowers the cost of the rehabilitation. The winding machine is placed inside the pipeline through an opening on the ground and continuously forms a liner inside the existing pipe by interlocking the ribs of the PVC profile strip. The gap between the existing pipe and the liner is filled with grout by using a special mortar. This forms a strong composite pipe consisting of the existing pipe, grouting mortar, and the PVC liner all acting as a one body. Figure 1 shows the cross-section of a circular and box pipes employing the SPR method.

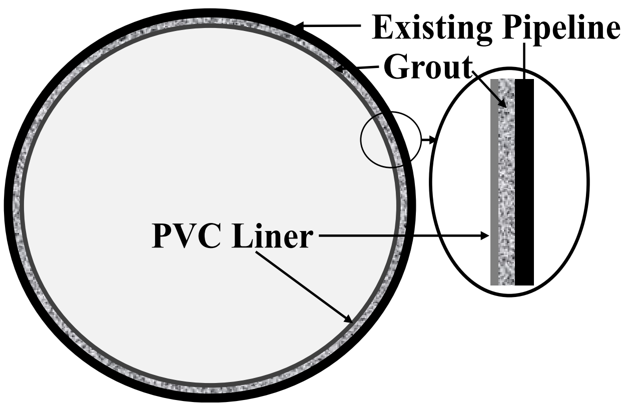

Figure 2. Cross-section of SPR circular pipe.

The grout that is placed between the PVC liner and the existing pipe is a special type of mortar with a high viscosity. This mortar is highly thixotropic and of high viscosity, which means it does not drip even if it is applied on a vertical surface. Grouting is simultaneously injected with the forming of the liner, leaving no or very narrow gaps between the pipe and the liner. If the objective of the rehabilitation is to recover or improve the strength of the existing pipe, the profile strip can be reinforced with galvanized steel strips which are folded and locked together with the PVC profile. While if the SPR method is utilized on corrosion-protection or water tightness, profile strip without reinforcements are use.

The SPR method can adapt to different sewer pipes shape. It is capable of rehabilitating pipes with circular, rectangular, or horseshoe cross sections. Installation of the liner on a non-circular pipeline was a problem for the SPR method, but it was solved by making use of the elastic properties of the PVC profile strips. The self-running winding machine forms the liner inside the pipe by installing it as close as possible with the outside surface the pipe. It is possible to form a liner with a specified circumference and grout thickness or the internal diameter of the liner can be chosen. However in this study, only buried pipes with circular cross-section is used and the thickness of the grout is not specified.

2.2 Bedding Angle

Installation of buried pipes involves the selection of types of bedding. Bedding is provided for the distribution of the vertical reaction around the lower exterior surface of the pipe and reduces the stress concentrations within the pipe wall. The soil load that the pipe will support depends on the width of the bedding contact area[2]. The bedding angle defines the contact between the buried pipe and the bedding support. Bedding angles are represented in Figure 3. In this study, four different values of bedding angle are used. These angles are 180^{o}, 120^{o}, 90^{o}, and 60^{o}. For the analysis of various bedding angle, only 3 and 5 meter pipes are used in this study.

2.3 Modulus of Subgrade Reaction

To account for the soil-pipe interaction, modulus of subgrade reaction is used for the analysis of buried pipes. Modulus of subgrade reaction is considered to be the ratio of load per unit area of a horizontal surface of mass soil to the corresponding settlement of the surface. It is measured as Psi/in or MPa/m. One method for determining the modulus of subgrade reaction is the use of Winkler model3. In this approach, it is assumed that the subgrade soil behaves like an infinite number of linear elastic springs that the stiffness of the spring or spring constant (k) is named as modulus of subgrade reaction, as shown in Figure 4. This modulus is dependent on various parameters like soil type, size, shape, depth, bedding type, etc. The typical values of modulus of subgrade reaction range from 41 to 81 MPa/m (150 to 300 Psi/in). In this study, it assumed that the value of modulus of subgrade reaction is 41 MPa/m (150 psi/inch).

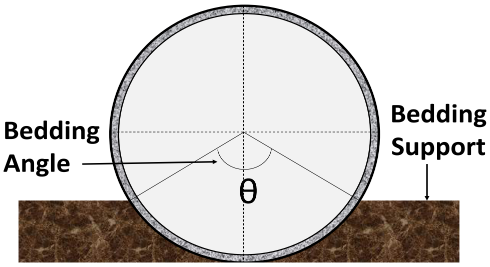

Figure 3. Bedding angles and support.

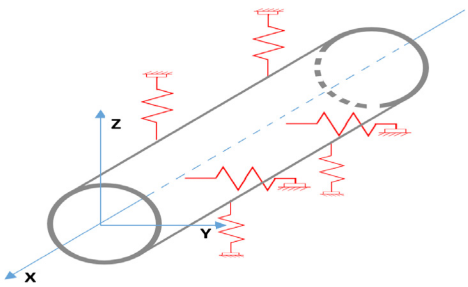

Figure 4. Winkler model, soil spring representation.

2.4 Loading Conditions

For the loading condition of the pipes, static loading is assumed acting on the top of the pipe. The vertical loading is calculated using the Sewer Facility Standards4. The self-weight of the pipes was also considered. Figure 5 displays the soil loading conditions that are used as a reference for the calculation of total pressure on the pipes. The total load acting on the pipe is calculated by adding all the vertical pressures acting on top of the pipe. Vertical earth pressure (Wd) or the weight of the soil directly above the pipe is calculated using the equation

$$Wd = \Upsilon\ sat \cdot d. \qquad (1)$$

with the value of 1.8 tf/m3 for the saturated unit weight (ϒsat). The calculated value of the pressure due to the weight of the soil is 17.66 kN/m^2. The weight of the pavement installed on top of the soil layer is also considered. The thickness of the pavement is 0.4m with a corresponding unit weight of 2.4 tf/m^3. The weight of the pavement (qu) is equivalent to 0.96 tf/m^3 and the equation used for the increase in vertical pressure on the pipe is

$$\Delta P = qu\ (4\sigma). \qquad (2)$$

with the value of σ equivalent to 0.0475. The pressure due to a uniform load on top of the soil layer is calculated to be 1.79kN/m^2. The pressure due to horizontal earth pressure (WH) can be evaluated by the using the formula

$$WH = C1\Upsilon B2. \qquad (3)$$

As the earth pressure coefficient C1 is different for every soil type, its value is assumed to be 1.5. Using Eq. 3, the horizontal earth pressure is equivalent to 6.62 kN/m2. The pipe load due to surface vehicle load (Wr) is estimated to be equal to

$$W = \frac{2p(1 + i)}{C(a + 2H\tan)} \qquad (4)$$

The vehicle load DB-24 uses a vehicle wheel load (ρ) of 9,600 N, with the length of the ground wheels (a) equal to 0.2 m and the width occupied by the wheels (C) is 0.275m. A value of 45o is used for the angle of distribution (Θ). Through Eq. 4 and all the given parameters, the final value of the vehicle load is 4.76 kN/m^2. Summing all the pressures acting on top of the pipe, the total vertical pressure is estimated to be 30.83 KN/m^2.

3. Finite Element Modelling

Three types of pipes are used for this study, one is an ordinary concrete or a PVC pipe and the other is a composite pipe. A composite Young's modulus of elasticity is used for the composite pipe. The modulus of elasticity used for ordinary concrete is 30 GPa, 2.35 GPa for the PVC pipe, and 16.18 GPa for the composite pipe. The thickness (t) of the pipes are assumed to be 10% of its outside diameter (D_o=300mm), which is 30mm. In analyzing buried pipes in various lengths, lengths of 1m, 3m, 5m, and 10m pipes are used for comparison of maximum stresses and displacements.

To investigate the effects of bedding angles, values of 180º, 120º, 90º and 60º are used. A fixed boundary condition and a series of soil springs are applied to the entire length of the pipe are used to represent the bedding support of the buried pipes. To account for the soil-pipe interaction, a value of 41 MPa/m is assumed for modulus of subgrade reaction, which is a recommended value by AASHTO[5].

To perform static analysis on the pipes, conventional shell elements are used. Standard large-strain shell elements are appropriate for most analysis. These shell elements include S4R, S3R, and SAX1. For this study, S4R shell elements are used for all the pipes. S4R elements are 4-noded doubly curved thin or thick shell, with uniformly reduced integration to avoid shear and membrane locking. S4R element is a general-purpose element that is suitable for a wide range of applications[6].

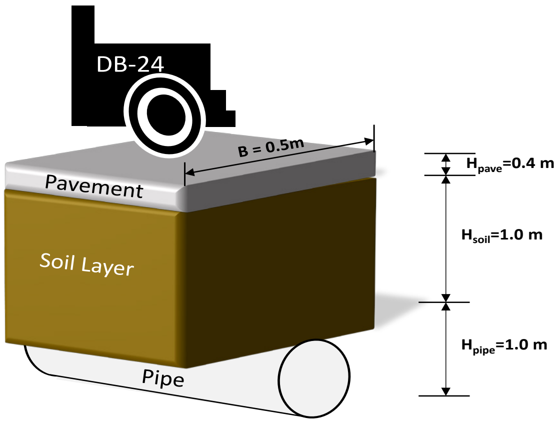

Figure 5. Soil loading conditions.

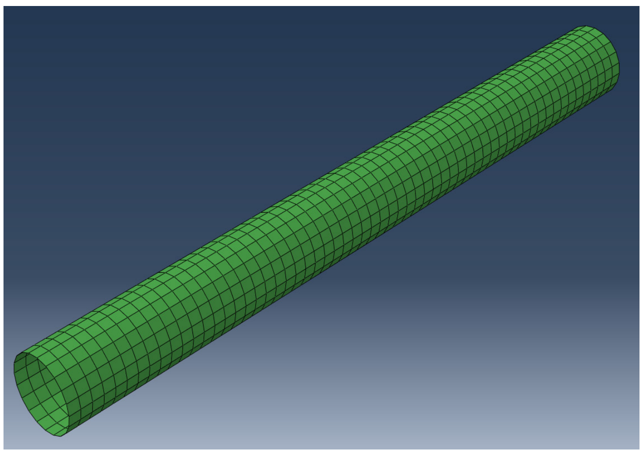

Figure 6. FEM of 3-meter buried pipe.

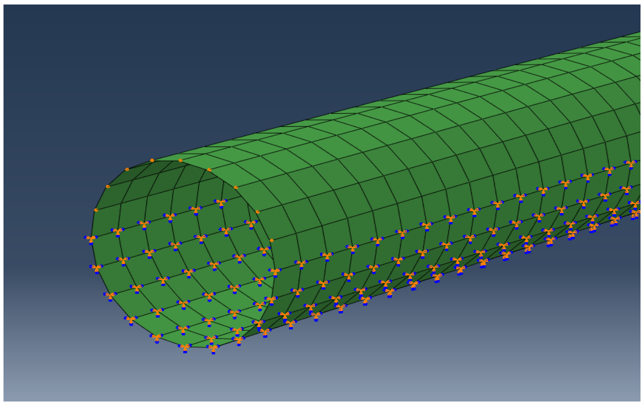

Figure 7. Fixed boundary condition at a bedding angle of 180º.

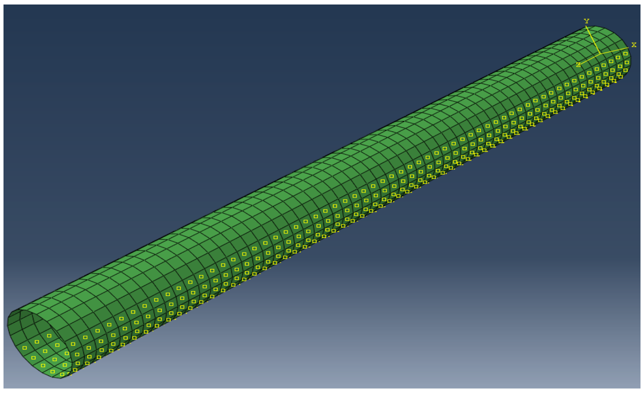

Figure 8. Soil springs applied over the length of the pipeline at a bedding angle of 180º.

The General-purpose finite element package ABAQUS provides an option for incorporating the soil and pipe interaction, which acts like springs to ground and is a simple way of including the stiffness effects of the support without modelling the details of the soil layers. This option is called elastic foundation, which can be found under the interaction module. This option can be used to simulate the Winkler's soil model by prescribing the foundation stiffness per area. In this case, the foundation stiffness per area used a value of 41 MPa/m. Application of the soil springs on the model of the pipe is shown in Figure 7. In this study, there are two sets of boundary conditions used to represent the bedding support of the pipes. First, a fixed boundary condition is applied over the entire length of the pipe, which is shown in Figure 6. Second, the bedding support of the pipe is represented by a series of soil springs. It is assumed that buried pipelines have infinite length. To take this into account, roller is considered to be the boundary condition of the end surfaces of the pipeline 7. Figure 5 shows the FEM model of a 3m buried pipe, in which, an element size of 50 are used for all models.

4. Result

For the comparison and analysis of data, all the results generated by ABAQUS are tabulated and plotted into graphs. The following tables and graphs are the results for the pipes with fixed boundary condition applied. Tables 1–2 and Figures 9 and 10 show the comparison of pipes in varying lengths while Tables 3–6, and Figures 11 to 14 display the results for pipes in different bedding angles.

Table 2 shows the maximum stresses of the three pipes in different lengths. The ordinary concrete pipe yielded the highest value for stress with a value of 0.3235 MPa, followed by the composite pipe with 0.3154 MPa, and with the least stress, the PVC pipe with a value of 0.3109 MPa. Figure 9 shows that stress of the buried pipe remains constant as the length of the pipe increases. As for the displacements, Table 2 shows that the PVC pipe has the highest displacement when compared to the concrete and composite pipe. The top portion of the PVC pipe displaced with a value of 0.03317mm, and 0.002693mm and 0.00518mm for the concrete and compiste pipe respectively. Like the stress analysis, Figure 10 shows that displacement of buried pipes neither increases or decreases with the length of the pipe.

Table 1. Maximum stress at varying lengths (MPa)

Length	Concrete		PVC		Composite	
	Fixed	Spring	Fixed	Spring	Fixed	Spring
1	0.3235	1.31	0.3109	1.584	0.3154	2.122
3	0.3235	1.636	0.3109	0.9608	0.3154	1.519
5	0.3235	1.637	0.3109	0.9602	0.3154	1.52
10	0.3235	1.673	0.3109	0.964	0.3154	1.54

Table 2. Maximum displacement at varying length (mm)

Length	Concrete		PVC		Composite	
	Fixed	Spring	Fixed	Spring	Fixed	Spring
1	0.002693	1.032	0.03317	1.463	0.00518	1.013
3	0.002693	1.055	0.03317	1.354	0.00518	1.089
5	0.002693	1.057	0.03317	1.356	0.00518	1.091
10	0.002693	1.093	0.03317	1.362	0.00518	1.095

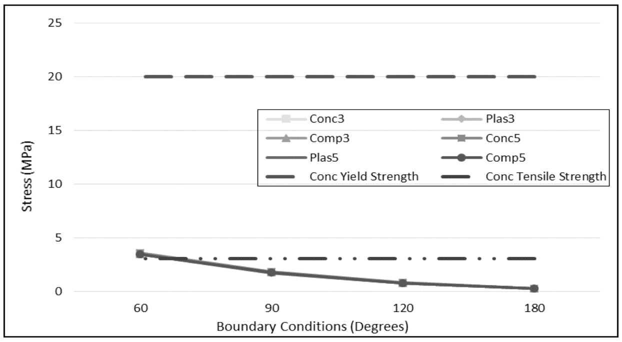

Figure 9. Comparison of maximum stresses of pipes with varying lengths (MPa).

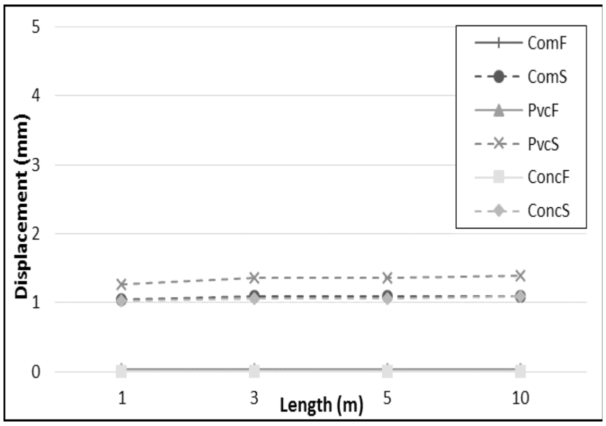

Figure 10. Comparison of maximum displacements of pipes with varying lengths (mm).

For comparison purposes, the maximum stresses for different bedding angles are compared with the materials' yield and tensile strengths. For an ordinary concrete pipe, a yield strength of 20 MPa is normally used for a lightweight concrete. The tensile strength is a proportion of it's compressive strength, which is calculated by

$$0.7\sqrt{(f'c)}. \quad (5)$$

with the use of Eq. 5, the calculated value of tensile strength of concrete is 3.13 MPa. As for the PVC pipe, 64.7 MPa and 39.2 MPa are used for he yield and tensile strengths respectively.

Table 3. Maximum Stress at different bedding angles (MPa)

Type	Length	Bedding Angle			
		180°	120°	90°	60°
Concrete	3	0.3235	0.8569	1.861	3.636
	5	0.3235	0.8569	1.861	3.636
PVC	3	0.3109	0.8079	1.748	3.458
	5	0.3109	0.8079	1.748	3.458
Composite	3	0.3154	0.8264	1.781	3.516
	5	0.3154	0.8264	1.781	3.516

Table 4. Maximum displacement at different bedding angles (mm)

Type	Length	Bedding Angle			
		180°	120°	90°	60°
Concrete	3	0.002963	0.01823	0.05374	0.128
	5	0.002963	0.01823	0.05374	0.128
PVC	3	0.03317	0.2077	0.6129	1.455
	5	0.03317	0.2077	0.6129	1.455
Composite	3	0.00518	0.03212	0.09477	0.2254
	5	0.00518	0.03212	0.09477	0.2254

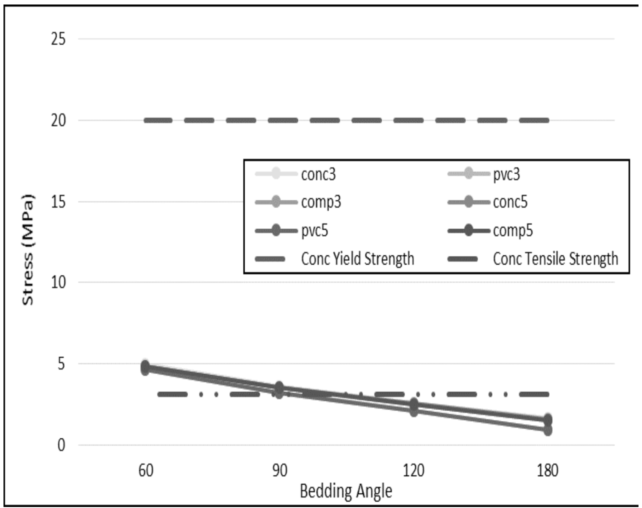

Figure 11. Comparison of stresses of the pipes in different bedding angles (MPa).

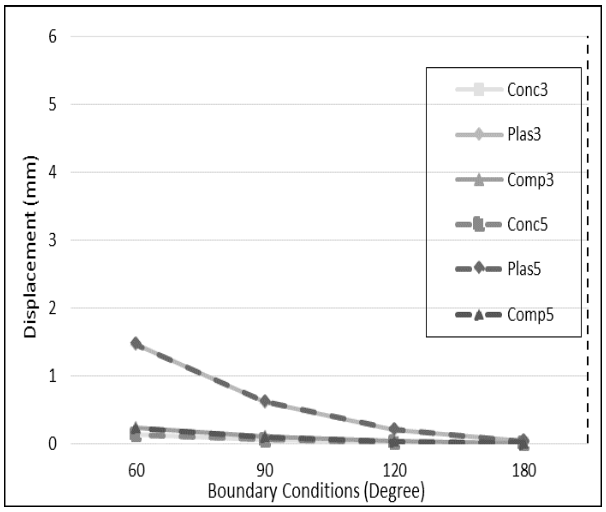

Figure 12. Comparison of displacements of the pipes in different bedding angles (mm).

Like the results in the previous analysis, the stresses and displacements remained unchanged as the length of the pipe increases even if the values of the bedding angles vary. Also, the ordinary concrete pipe still yielded the highest stress, followed by the composite pipe and then the PVC pipe. However, maximum stresses on the pipes increases remarkably as the bedding angle decreases. The increase is almost twice as the previous value. However, the comparison of the stresses shown in Figure 11 shows that the differences in stresses are small, unlike the values of for the displacements. Figure 12 shows that displacement of the PVC pipe is much higher compared to the other pipes. A displacement of 1.455 mm occurred on the PVC pipe while only 0.128mm and 0.2254mm occurred on the concrete and composite pipe respectively.

Table 5. Maximum stress at different bedding angles wth soil springs (MPa)

Type	Length	Bedding Angle			
		180°	120°	90°	60°
Concrete	3	1.603	2.542	3.57	4.882
	5	1.603	2.542	3.57	4.882
PVC	3	0.9272	2.112	3.208	4.684
	5	0.9272	2.112	3.208	4.684
Composite	3	1.503	2.507	3.548	4.88
	5	1.503	2.507	3.548	4.88

Table 6. Maximum displacement at different bedding angles with soil springs (mm)

Type	Length	Bedding Angle			
		180º	120º	90º	60º
Concrete	3	1.034	1.175	1.545	2.714
	5	1.034	1.175	1.545	2.714
PVC	3	1.358	2.22	3.286	5.043
	5	1.358	2.22	3.286	5.043
Composite	3	1.078	1.271	1.69	2.902
	5	1.078	1.271	1.69	2.902

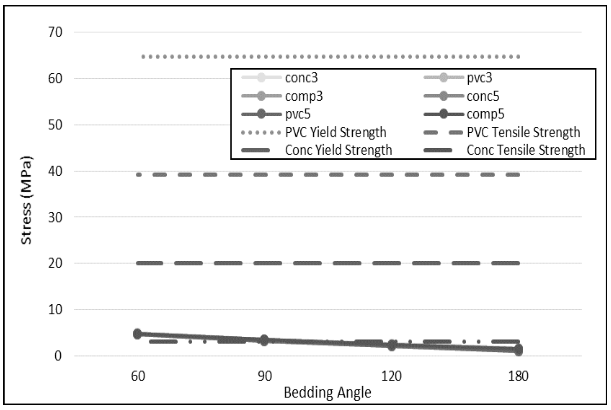

Figure 13. Comparison of stresses of pipes in bedding angles with soil springs (MPa).

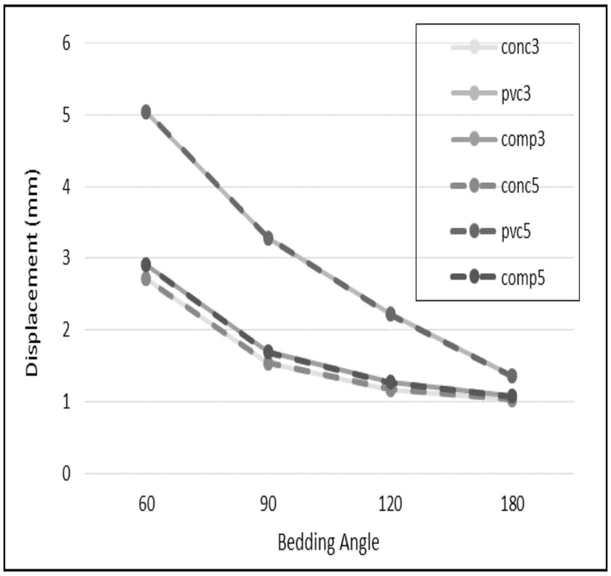

Figure 14. Comparison of displacements of pipes in bedding angles with soil springs (mm).

Tables 5–6 and Figures 13–14 are the results of pipe with soil springs as the bedding support. Data still show that stress and displacement decrease as the bedding angle increases. However, the magnitude of the stresses and displacements of the pipes increased remarkably compared to pipes in fixed boundary condition. Based on the FEM, the results of pipes in fixed boundary condition and pipes with soil springs are compared. Not only were the magnitude of the stresses and displacements of the pipes were affected by the different bedding support but also the behaviour and the location of the maximum stress and displacement.

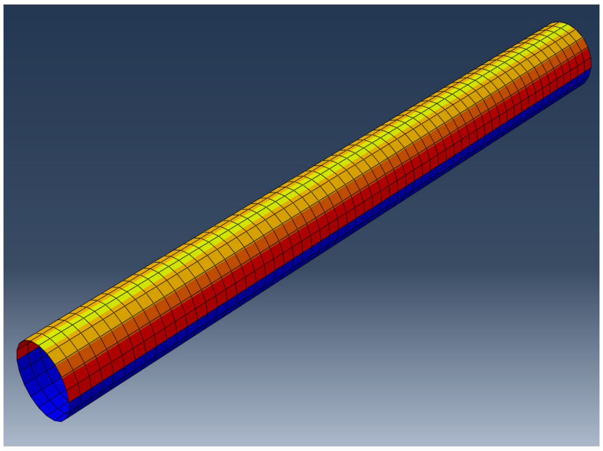

Figure 15. Von mises stress contour of pipe with fixed boundary condition.

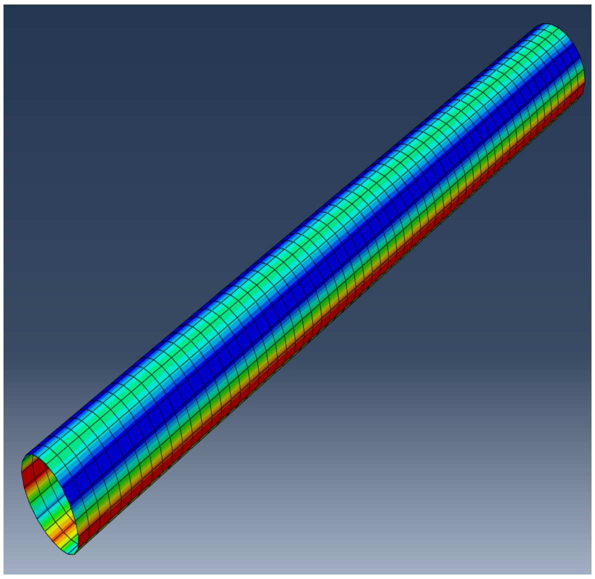

Figure 16. Von mises stress contour of pipe with soil springs.

Figures 15 and 16 shows where the maximum stress occurred on the pipe. The Stress for pipes with fixed boundary condition as the bedding support is more concentrated on the sides of the pipe. The maximum stress occurred on the end tips of the boundary condition. For Pipes with soil springs as the bedding support, the maximum stress consistently occurred on both sides and at the bottom of the pipe. As for the displacement of the pipes, whether which bedding support is used, the maximum displacement occurs on the top most of the pipe. However, due to the fixed boundary condition, only the upper half of the pipe deflected. It can also be added that the behaviour of the deflection of the pipe is more realistic for pipes with soil springs. The pipe deflected in an egg-shape or in an elliptical form of figure.

For Finite element modelling of buried pipes, it is recommended to use soil springs as the pipe's bedding support as it yields more realistic results compared to the fixed boundary condition. It can also be added that even though stress and displacement remained constant for varying lengths of the pipe, it is better to use a length of 3 or 5 meters for simplicity of results and modelling. As for the bedding angles, an angle of 60o is to be used for further modeling of pipes because it yielded more critical results when compared to other angles.

Table 7. Optimized FEM model for SPR

End-surfaceBoundary Condition	Length	Bedding Angle	Bedding Support	K
Rollers (U1 &U3)	3 m	60^{o}	Soil Springs	41MPa/m

5. Conclusion

Based on the results, the composite pipe behaves more like the ordinary concrete pipe rather than the PVC pipe, in terms of its maximum stress and displacement. However, the effects of the soil springs or the modulus of subgrade reaction on the pipes yields remarkable results, as it increases the values of stress and displacement significantly. On the Winkler soil model, it is assumed that the soil acts as linear soil springs on the pipe, which means that the displacement on the pipe is directly proportional to the pressure acting on the pipe. However, However, the pipes are subjected only to vertical pressure of 30.83 kN/m2, which is a very small load for the soil springs to affect the pipes. The pipe loading calculation only assumed a height of 1-meter on top of the buried pipe, increasing the height of soil for the next study may help analyze the effects of soil springs on pipe. In addition, the displacement and stress of pipeline are affected by soil, which means types of soil, such as sandy soil or cohesive soil, make the buried pipelines to act differently. This means that pipeline moves relatively to the soil. In this study, a fixed boundary condition was used to represent the contact between the pipe and the soil. This condition results the pipes to be restrained in multiple directions, thus, creates less displacement than the expected value. Comparing the results of the composite pipe to the ordinary concrete pipe, the values of the stress and displacement are close to one another, but even so, the strength of the composite pipe fails to exceed than of the concrete pipe.

6. Acknowledgement

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9. References

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