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RESEARCH ARTICLE

Stress Analysis of Existing Underground Gas Pipeline due to New Road Crossing with ODOL Transportation

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Abstract

Pipelines are the main choice for transport oil and gas due to its resilience, reliability, safety, and lower cost. Most road crossing pipelines are located underground where protections from the loads can be used such as additional pavement. Underground road crossing pipelines withstand stresses caused by the internal load, earth load, and live load. These loads are affected by the pipe and fluid specifications, soil and environment data, and also the vehicle data. Over dimension and over loading (ODOL) vehicles are a very common problem found in Indonesia. Hence, a stress analysis towards the underground road crossing pipeline being crossed by ODOL vehicles are relevant. A manual calculation of the stress analysis can be done by using API RP 1102: "Steel Pipelines Crossing Railroads and Highways". A stress analysis using the finite element method (FEM) is conducted using a computer software, namely Abaqus, which also shows the displacement of the pipeline. The case study is an underground road crossing pipeline with depth of 8 feet and uses rigid pavement. The use of rigid pavements over the soil decreases the stress experienced by the pipeline. The results of the total effective stress show a value of 4,785 psi which is still within the allowable range. The stress is found to be directly proportional to the displacement value obtained using FEA. By conducting parametric studies, it is also found that the total effective stress decreases as the burial depth of the pipe is larger.

Keywords: Pipeline, Road Crossing, Underground, Stress, API RP 1102, Computer Software, Finite Element

1. Introduction

Oil and gas industry is one of the most crucial industries in the energy sector. As of now, fossil fuel is consistently on top of the list of main energies used in the world. According to data published in 2020 by the British Petroleum company, the three largest energy consumptions in the world are oil, coal, and natural gas (British Petroleum, 2021). Data obtained from SKK Migas shows that the energy productions in Indonesia in 2020 for crude oil and natural gas has high values of 708.5 thousand barrels of oil per day (MBOPD) and 6,679 million standard cubic feet per day (MMSCFD), respectively (SKK Migas, 2021). Electricity, vehicles, household needs, and power plants are among the many things fossil fuel energy are used for (Van Dyke, 1997). Noting the high demand towards the oil and gas industry, transportation or distribution system of the oil and gas produced is important to be accounted for.

Pipelines are one of the predominant methods to transport oil and gas from one facility to the other. In Indonesia, pipelines are still the main choice for transport oil and gas – among them being due to its safety, resilience, reliability, and lesser cost (Nugroho, 2006). Natural gas pipelines can be found underground and also subsea. Fluid properties, environmental conditions, economics, material, protection, environmental impact, and operation are just a few among the many aspects affecting the pipeline system.

Underground pipeline system may be placed under road crossing. A study by Tawekal and Idris (2012), discusses the design and analysis of a crossing pipeline. The load given by the vehicle crossing the pipeline would certainly have an effect towards the safety of the underground road crossing pipeline. In Indonesia, Over Dimension and Over Loading (ODOL) is a problem that is still highly common, with data from Indonesia's Ministry of Transportation in 2020 showing 59% out of 1,425,051 vehicles reviewed have tested ODOL (Puslitbang Jalan dan Perkeretaapian, 2021). The load of ODOL trucks in Indonesia could even reach 200 percent of its original weight. Aside from vehicles crossing – the soil, pavement, and design of the pipeline will affect the safety of the pipe. A study has been conducted by Mosadegh and Nikraz (2015), of the use of finite element analysis on buried pipeline subjected to traffic load with varying surface pressures and burial depths. While another study by Xi et al. (2019) has been conducted on the reliability of a buried polyethylene pipe that is also subjected to traffic load.

It is highly important to design and construct a pipeline in detail and in accordance to the guidelines set by the codes, standards, and government regulations. A study by Fahrudin et al. (2020) regarding the stress an underground road crossing pipeline using pipe material of API 5L X52 while this paper will review the material of API 5L X42. In this paper, the observed section of the gas pipeline is a buried or underground road crossing pipeline which will be crossed by heavy vehicle. The pipe specifications given shows that the pipeline was initially designed for residential crossings. Hence, the paper aims to analyse the stress and safety of the underground road crossing pipeline due using analytical approach using the recommended practice of API RP 1102: "Steel Pipelines Crossing Railroads and Highways" and using numerical method base on finite element using Abaqus software.

2. Material and methods

2.1 Data

In order to achieve this paper's objective, the following pipe and soil data are used to complete the analytical and numerical analysis of the underground road crossing pipeline using the recommended practice of API RP 1102 and Abaqus. Table 1 shows the technical data of the pipe, Table 2 shows the pipe material, and Table 3 shows the soil material which is classified using USCS (Howard, 1986).

Table 1. Pipe technical data.

Parameters	Value
Pipe Material	API 5L X42
Outside Diameter	6.625 inch
Wall thickness	0.561 inch
Operating Pressure	780 psi
SMYS	42,000 psi
Design Factor	0.72
Longitudinal Joint Factor (American Society of Mechanical Engineers, 2020)	1 90°F
Operating Temperature	
Temperature Derating Factor (American Society of Mechanical Engineers, 2020)	1
Type of Longitudinal Weld	Seamless

Table 2. Pipe material properties.

Parameters	Value
Density	0.284 lb/in^3
Young's Modulus	30,000 ksi
Poisson's Ratio	0.3
Coefficient of Thermal Expansion	0.0000065 per °F

Table 3. Soil material properties.

Parameters	Value
Soil Type	CH
Modulus Soil Reaction	0.2 ksi
Resilient Modulus	5 ksi
Density	0.069 lb/in^3
Young's Modulus	725 psi
Poisson's Ratio	0.3
Cohesive Strength	3.6 psi
Friction Angle	20°
Dilation Angle	2°

The installation temperature of the underground road crossing pipeline will use the environment temperature at the location which is 86 °F (Badan Pusat Statistik, 2014). The burial depth from the top of the pipeline to the top soil will be varied by 3, 4, 6, 8, and 10 feet deep. While the pavement type evaluated will be rigid pavement and no pavement.

The study will review the safety of the underground road crossing pipeline using a vehicle that is over dimension and over load (ODOL) by 200%. Table 4 shows the data of the vehicle's front and rear axle weight that is multiplied by 200%.

Table 4. ODOL Vehicle's axle weight.

Parameter	Value
Front Axle	16 ton
Rear Axle	52 ton

To help visualize the case study conducted in this paper, an illustration of the case is shown in Fig. 1.

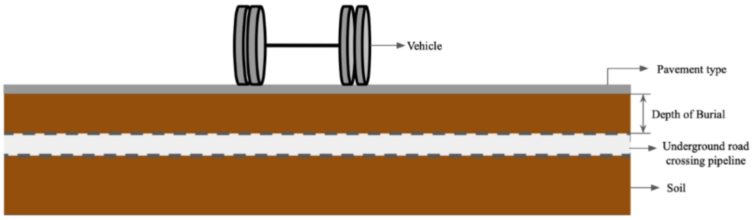

Fig. 1. Illustration of the underground road crossing pipeline (not drawn to scale).

2.2 API RP 1102 methodology

Shown in Fig. 2 is the flowchart of the calculation using the API RP 1102 methodology. The pipelines' Barlow internal pressure, total effective stress, fatigue girth weld, and fatigue longitudinal weld will be evaluated and checked against its' maximum allowable value (American Petroleum Institute, 2017). It is conducted to obtain whether the underground road crossing pipeline is safe when crossed by ODOL vehicles.

The API RP 1102 equations of the stresses experienced by the pipeline are shown below in accordance to the flowchart in Fig. 2.

1. *Circumferential stress due to internal pressure (barlow check)*

One of the required checks for the allowable stress is by using Barlow formula (Code of Federal Regulations (CFR), 2022). The Barlow formula is used to obtain the circumferential stress caused by the internal pressure, which must not exceed the allowable maximum value. The following will show the calculation to check the Barlow internal pressure (Eqn. 1).

$$S_{Hi\,(Barlow)} = \frac{pD}{2t_w} \leq F \times E \times T \times SMYS \quad (1)$$

Where:
$S_{Hi\,(Barlow)}$= Barlow formula
p= Operating pressure
D= Outside diameter
t_w= Wall thickness
F= Design factor
E= Longitudinal joint factor
T= Temperature derating factor
$SMYS$= Specified minimum yield strength

2. *Circumferential stress due to internal pressure* (Eqn. 2)

$$S_{Hi} = \frac{p(D-t_w)}{2t_w} \quad (2)$$

Where:
S_{Hi}= Circumferential stress caused by internal pressure

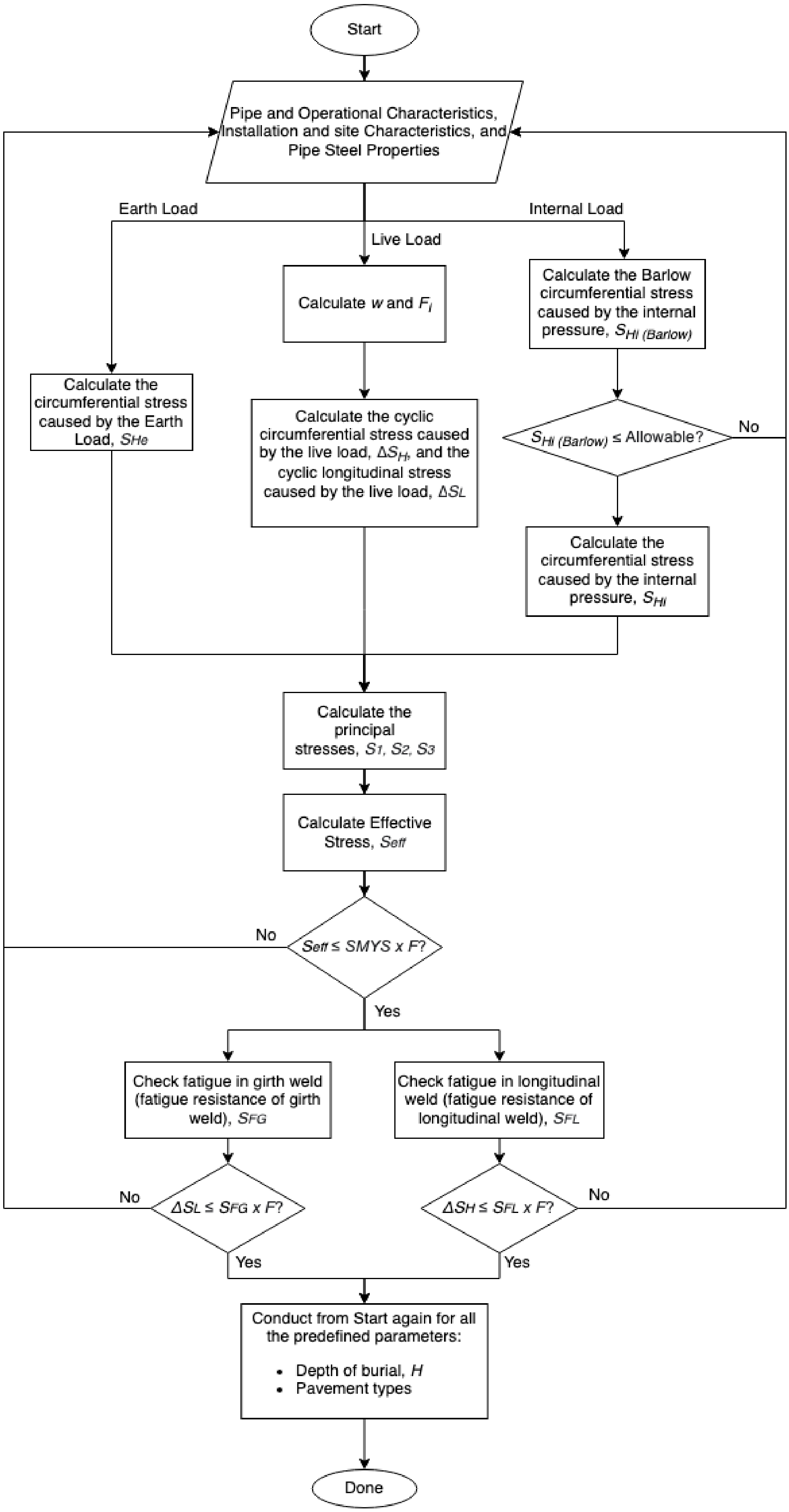

Fig. 2. API RP 1102 methodology.

3. *Circumferential stress due to earth load* (Eqn. 3)

$$S_{He} = K_{He}B_eE_e\gamma D \quad (3)$$

Where:
S_{He}= Circumferential stress due to earth load
K_{He}= Stiffness factor for circumferential stress due to earth load
B_e=Burial factor for circumferential stress due to earth load
E_e= Excavation factor for circumferential stress due to earth load

4. Impact factor due to live load

The impact factor is used to increase the live load acting on the pipe and it is a function of the burial depth, H. The impact factor value is found using the graph shown in Fig. 3.

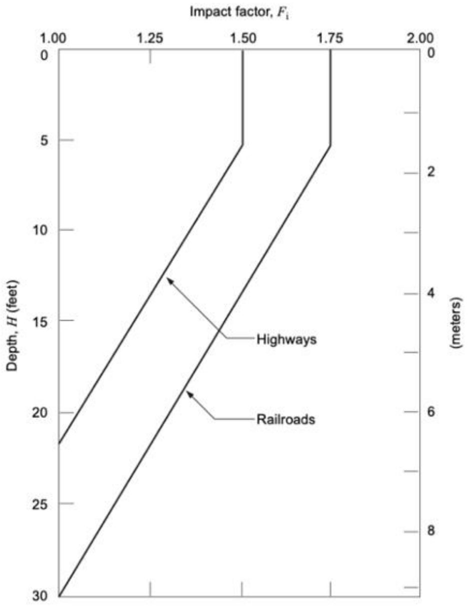

Fig. 3. Recommended impact factor versus depth.

5. *Applied design surface pressure* (Eqn. 4)

$$w = \frac{P_t}{A_p} \quad (4)$$

Where:
w = Applied design surface pressure
P_t= Design wheel load
A_p= Wheel contact area

6. *Cyclic circumferential stress due to live load* (Eqn. 5)

$$\Delta S_{Hh} = K_{Hh}G_{Hh}RLF_iw \quad (5)$$

Where:
ΔS_{Hh}= Cyclic circumferential stress due to live load
K_{Hh}= Stiffness factor for cyclic circumferential stress from highway
G_{Hh}= Geometry factor for cyclic circumferential stress from highway
R= Highway pavement type factor
L=Axle configuration factor
F_i= Impact factor

7. *Cyclic longitudinal stress due to live load* (Eqn. 6)

$$\Delta S_{Lh} = K_{Lh}G_{Lh}RLF_iw \quad (6)$$

Where:
ΔS_{Lh}= Cyclic longitudinal stress due to live load
K_{Lh}= Stiffness Factor for cyclic longitudinal stress
G_{Lh}= Geometry factor for cyclic longitudinal stress

8. *Maximum circumferential stress* (Eqn. 7)

$$S_1 = S_{He} + \Delta S_H + S_{Hi} \quad (7)$$

Where:
S_1= Maximum circumferential stress

9. *Maximum longitudinal stress* (Eqn. 8)

$$S_2 = \Delta S_L - E_s\alpha_T(T_2 - T_1) + v_s(S_{He} + S_{Hi}) \quad (8)$$

Where:
S_2= Maximum longitudinal stress
E_s= Young's modulus
α_T= Coefficient of thermal expansion
T_2= Maximum or minimum operating temperature
T_1= Installation temperature
v_s= Poisson's ratio

10. *Maximum radial stress* (Eqn. 9)

$$S_3 = -p \quad (9)$$

Where:
S_3= Maximum radial stress

11. *Total effective stress*

The effective stress is used to check the yielding of the pipeline (Eqn. 10). It is examined by comparing the value of the SMYS multiplied by the design factor with the effective stress and ensuring that it is larger than the effective stress.

$$S_{eff} = \sqrt{\frac{1}{2}\left[(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2\right]} \quad (10)$$

Where:
S_{eff}= Total effective stress

The potential of fatigue occurring in the pipeline in the girth and longitudinal weld can also be estimated by referring the API RP 1102. Below are the equations to conduct the fatigue check in accordance to API RP 1102 methodology.

1. Girth Weld Fatigue (Eqn. 11)

$$\Delta S_{LH} \leq S_{FG} \times F \quad (11)$$

Where:
S_{FG}= Fatigue resistance of girth weld

2. Longitudinal Weld Fatigue (Eqn. 12)

$$\Delta S_{Hh} \leq S_{FL} \times F \quad (12)$$

Where:
S_{FL}= Fatigue resistance of longitudinal weld

2.3 Finite element analysis methodology

The finite element analysis will utilize Abaqus software to obtain the stress and displacement of the underground road crossing pipeline section being reviewed. The methodology of the finite element modelling in Abaqus will be depicted in Fig. 4.

The pipe and soil material properties, element load, and boundary conditions will be the main input of the pipe and soil modeling in Abaqus. The pipeline is modelled as a 3D deformable shell with the length of 98 ft, while the soil is modelled as a 3D deformable solid body as a block with the dimension of 98 ft x 32 ft x 32 ft. The thermal effects will also be given to the pipeline, with known thermal coefficient, initial temperature, and final temperature.

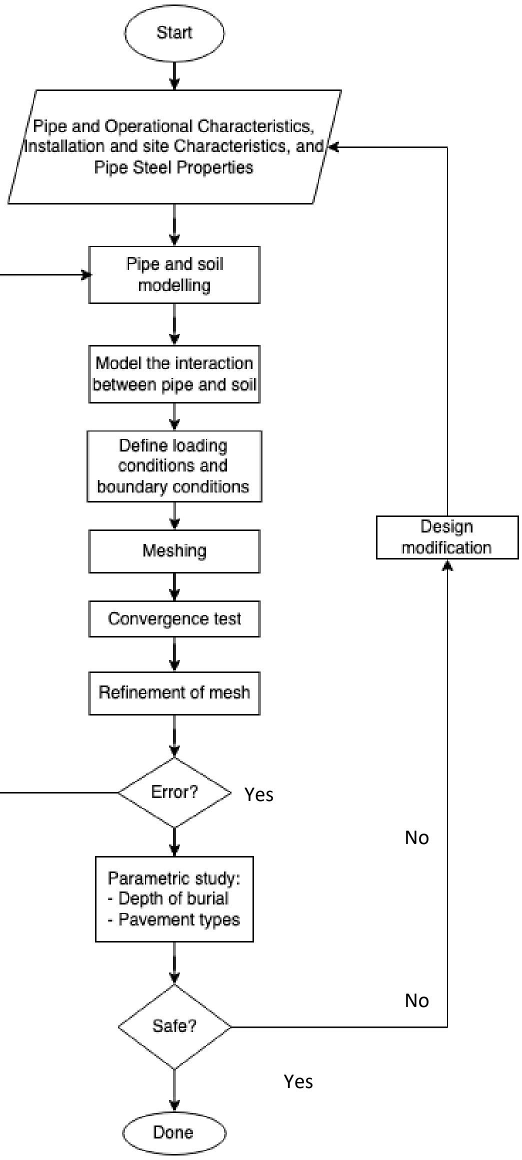

Fig. 4. Finite element analysis methodology.

An interaction of the pipe and soil will be created by defining the contact between the pipe and soil which is modelled to interact as a surface-to-surface contact between the external surface of the pipeline and the inner surface of the soil. The loading conditions will consist of the gravity, internal pressure, and the vehicle load on top of the soil. The gravity force and internal pressure will be constant throughout the analysis with values of 2.2 lbf and 780 psi, respectively. Meanwhile, the vehicle load given will depend on the area of contact between the vehicle and the soil.

Next, the pipe and soil model are given boundary conditions. Boundary conditions of the soil's sides are given rollers. The reason is because the infinite or semi-infinite soil element is assumed to move only vertically when a critical amount of the soil element is considered in the finite-element analysis (Lee, 2010). To confine both horizontal and vertical movement of the bottom surface of the soil element, the part is given fixed boundary conditions. The ends of the pipe are given rollers to ensure that the pipe will still be able to move vertically and because an infinite length of pipe is considered in this analysis. It will make movement of the pipe due to the soil possible. Fig. 5 shows the boundary conditions applied to the pipe and soil model.

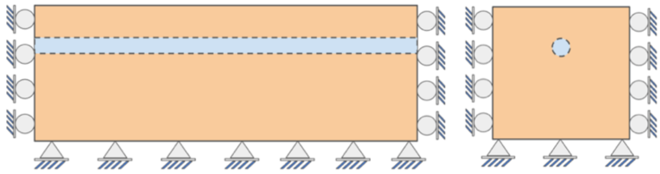

Fig. 5. Boundary conditions of the model.

After completing the steps mentioned before, the mesh will be generated and the analysis will be conducted by the software. A convergence test is then conducted to be able to refine the mesh. If the results are unsatisfying, a modification of the underground road crossing pipe should be performed. Same as the API RP 1102, the study will consist of the differing burial depths and pavement types. The burial depths reviewed are 4 and 8 feet with two pavement types which are rigid pavement and without any pavement.

3. Results and discussion

3.1 API RP 1102 calculation

Two pavement types are analysed in this paper with different burial depths, varying from 3, 4, 6, 8, and 10 feet. The pipe specifications passed the check using Barlow formula. The next check would be to calculate the total effective stress. The results when rigid pavement is applied with the varying burial depth are tabulated in Table 5 and is depicted in Fig. 6.

The results when no pavement is applied with the varying burial depth are tabulated in Table 6 and is depicted in Fig. 7.

The results show that the circumferential stress due to the internal pressure is not affected by the difference in burial depth and pavement type. While the circumferential stress caused by the earth load shows an increase as the burial depth gets deeper. This shows that the circumferential stress caused by the earth load is directly proportional to the burial depth but shows no difference between the two types of pavements. Therefore, it is only affected by the parameters of the soil and burial depth.

The cyclic circumferential and longitudinal stress caused by the live load both decreases as the burial depth increases. Although, there is no difference seen in the values for the burial depth of 3 and 4 feet. It is also seen that live load or vehicle's effect on the stress towards the pipe will have less effect when the pipe is buried deeper in the soil. Both the cyclic circumferential and longitudinal stress caused by the live load when no pavements are applied shows a significantly higher value of stress in comparison to using a rigid pavement. The decrease of the stresses due to the live load is more significant than the increase of the circumferential stress caused by the earth load, which affects the values of the maximum circumferential stress.

The maximum circumferential and maximum longitudinal stresses show a decrease as the pipe is buried deeper, except for the burial depth between 3 to 4 feet which shows a slight increase. It also shows that the use of rigid pavement will have a significantly lower stress value than no pavement. However, the maximum radial stress remains the same for all burial depths and pavement types due to it only being affected by the operating pressure of the pipe. The total effective stress obtained shows a decrease as the burial depth increases. This shows that the effective stress is inversely proportional to the burial depth. The total effective stress also shows a lower value of stress when a rigid pavement is applied. Although, with the increase in burial depth, there is a smaller difference of values of the total effective stress withstood by the pipe between the two pavement types. This shows that the pavement type will have a less significant effect as the burial depth gets deeper.

From the API RP 1102 calculations, in all burial depth reviewed, the girth weld and longitudinal weld fatigue assumed to be safe and have passed the check.

Table 5. Total effective stress results for rigid pavement.

Parameters \ Burial Depth (ft)	3	4	6	8	10
Circumferential stress from internal pressure (psi)	4215.62	4215.62	4215.62	4215.62	4215.62
Earth Load Circumferential Stress (psi)	143.36	162.56	170.24	172.80	174.08
Live Load Cyclic Circumferential Stress (psi)	861.66	861.66	665.63	495.89	377.72
Live Load Cyclic Longitudinal Stress (psi)	2921.59	2921.59	2560.67	2258.56	1996.32
Maximum Circumferential Stress (psi)	5220.64	5239.84	5051.48	4884.31	4767.42
Maximum Longitudinal Stress (psi)	3449.28	3455.04	3096.43	2795.09	2533.23
Maximum Radial Stress (psi)	-780	-780	-780	-780	-780
Total Effective Stress (psi)	5340.05	5355.35	5140.78	4961.38	4834.4
Allowable (psi)	30240	30240	30240	30240	30240
Pass/Fail	Pass	Pass	Pass	Pass	Pass
Factor of Safety	5.6	5.6	5.8	6.1	6.2

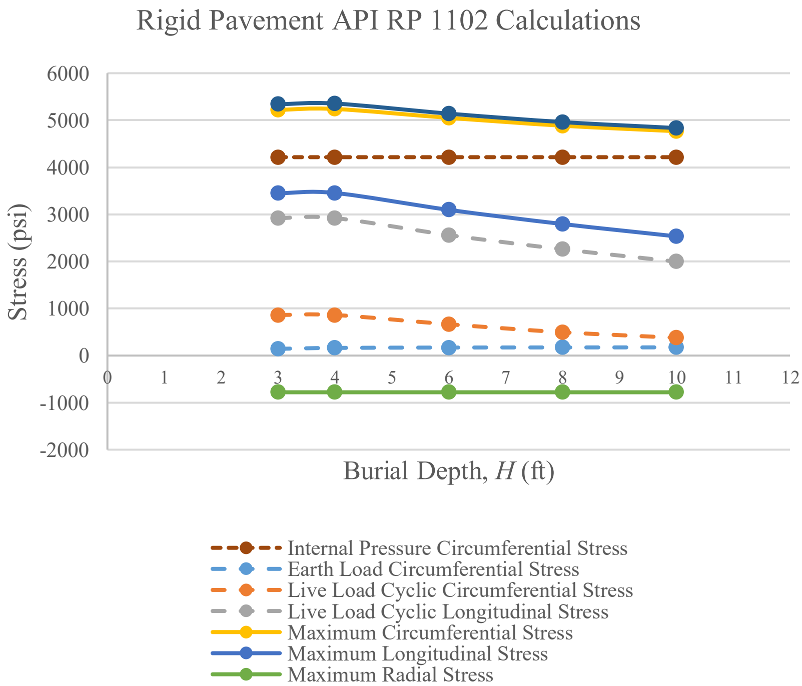

Fig. 6. Rigid pavement API RP 1102 calculation results.

Table 6. Total effective stress results for no pavement.

Parameters \ Burial Depth (ft)	3	4	6	8	10
Circumferential stress from internal pressure (psi)	4215.62	4215.62	4215.62	4215.62	4215.62
Earth Load Circumferential Stress (psi)	143.36	162.56	170.24	172.80	174.08
Live Load Cyclic Circumferential Stress (psi)	1053.14	1053.14	813.55	606.09	461.66
Live Load Cyclic Longitudinal Stress (psi)	3570.83	3570.83	3129.71	2760.46	2439.95
Maximum Circumferential Stress (psi)	5412.12	5431.32	5199.4	4994.51	4851.36
Maximum Longitudinal Stress (psi)	4098.53	4104.29	3665.46	3296.99	2976.86
Maximum Radial Stress (psi)	-780	-780	-780	-780	-780
Total Effective Stress (psi)	5651.01	5665.59	5379.05	5140.45	4966.88
Allowable (psi)	30240	30240	30240	30240	30240
Pass/Fail	Pass	Pass	Pass	Pass	Pass
Factor of Safety	5.35	5.33	5.62	5.88	6.09

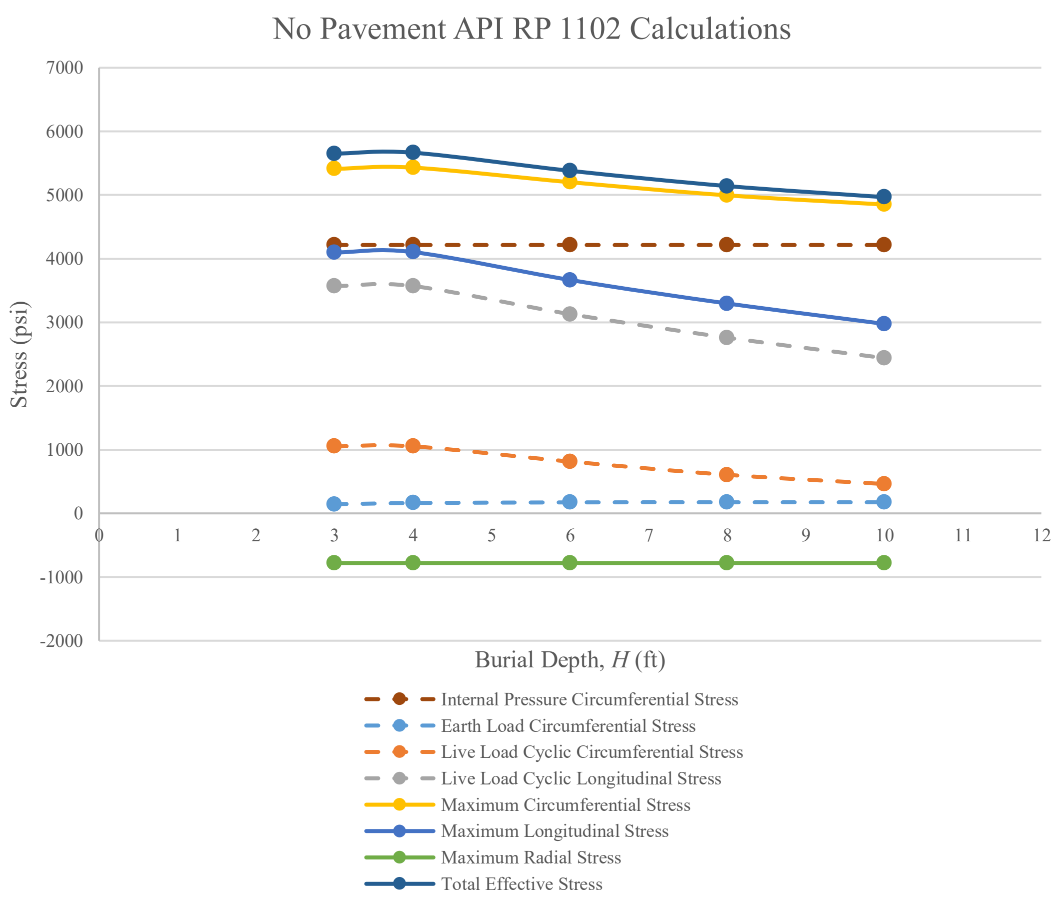

Fig. 7. No pavement API RP 1102 calculation results.

3.2 Finite element analysis using Abaqus

The finite element analysis is conducted with two types of pavements, namely rigid and without pavement, with varying burial depths at 4 and 8 feet. The results obtained from this analysis is the von-Mises stress and the pipe's displacement. Fig. 8 shows the loading conditions of the model, namely the gravitational force, internal pressure, and the vehicle load.

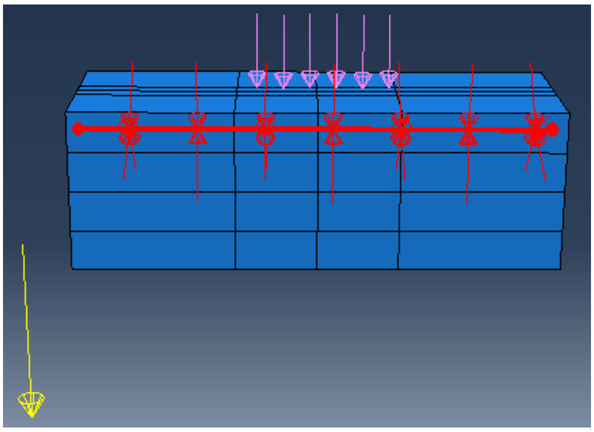

Fig. 8. Loading conditions of the model.

The results of the von-Mises stress obtained from Abaqus is compared with the results of the total effective stress from the API RP 1102 calculations since the total effective stress has the same formula as the von-Mises. The results of the von-Mises stress from Abaqus shows little error ranging from 3.4% to 4.9% in comparison to API RP 1102 stress results. One of the results obtained from Abaqus, which is the underground road crossing pipeline with burial depth of 8 feet and no pavement is shown in Fig. 9 for its von-Mises stress and Fig. 10 for its displacement results which are shown in SI units.

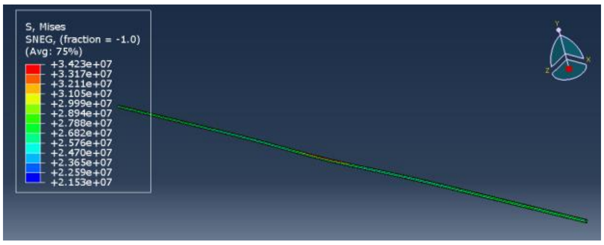

Fig. 9. von-Mises stress result for depth of 8 feet without pavement.

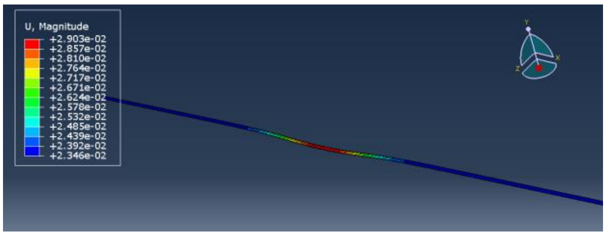

Fig. 10. Displacement result for depth of 8 feet without pavement.

The von-Mises stress from Abaqus and the total effective stress obtained from API RP 1102 is depicted in a graph shown in Fig. 11. The results of the von-Mises stress and displacement from Abaqus is tabulated in Table 7.

As seen in Fig. 11, the underground road crossing pipe of 8 feet depth and using the rigid pavement obtained using Abaqus has the lowest value of stress. While the highest stress value occurs when the underground road crossing pipe is of 3 feet depth and does not use any pavements when calculated using API RP 1102. All the stress results show the same trend of gradually decreasing as the burial depth rises.

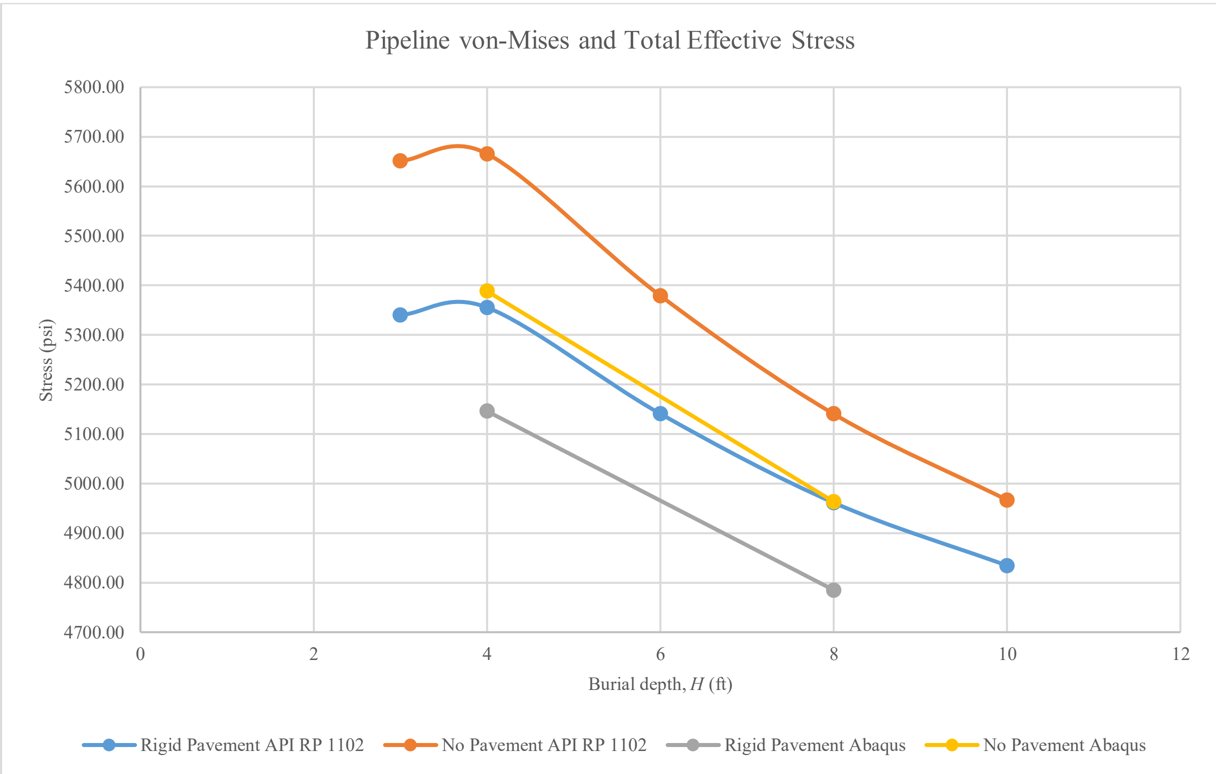

Fig. 11. Pipeline Abaqus and API RP 1102 stress results.

The displacement of the underground road crossing pipeline was also obtained using Abaqus. Since the error between the API RP 1102 calculations and Abaqus shows a small amount of difference, it is safe to assume that the displacement obtained using Abaqus is valid.

Table 7. Von-Mises stress and displacement results from Abaqus.

Burial Depth (ft)	Rigid Pavement		No Pavement	
	Von-Mises Stress (psi)	Displacement (in)	Von-Mises Stress (psi)	Displacement (in)
4	5,146	1.56	5,388	1.79
8	4,785	0.94	4,963	1.14

Table 7 shows that the von-Mises stress modelled using a concrete slab or rigid pavement is lower than the results shown without any pavement protection. The trend of the stress withstood by the pipe is the same as the calculation results by using API RP 1102, whereas the von-Mises stress decreases as the depth of burial increases. As for the displacement, the stress being given to the pipe is directly proportional to the displacement of the pipe. The displacement occurred is affected by other values being input in the model, such as the density, Poisson's ratio, and the modulus of elasticity of the soil. From the finite element analysis, the largest displacement happens to occur when the pipe is buried 4 feet deep and does not use any pavements. The smallest amount of displacement occurs when the underground road crossing pipeline is protected by a rigid pavement and is buried with a depth of 8 feet.

From the results, it can be recommended that the best option for the underground road crossing pipe would to be use rigid pavement and to be buried with a burial depth of 8 feet or 10 feet. According to the stress and fatigue results, the pipe is assumed to be safe. The underground road crossing pipeline is found to still be able to withstand the stresses, even when the worst case was analysed which was having the vehicles being over dimension and over loading (ODOL).

4. Conclusion

The stress of the underground road crossing pipeline obtained from the API RP 1102 ranges between 5,355 – 4,834 psi when using rigid pavement and 5,665 – 4,966 psi when not using pavement with varying burial depths. The stress values are all still within the allowable value of 30,240 psi. The results of the von-Mises stress obtained from the Abaqus software shows values within the range of error of 3.45% – 4.9% in comparison to the results obtained from API RP 1102. The displacement of the underground road crossing pipeline is known to be in the range of 0.94 – 1.79 in obtained from the Abaqus analysis. The stress and displacement experienced by the underground road crossing pipeline are affected by the pipe and soil materials, fluid specifications, as well as the live load and gravitational force. The protection given towards the underground road crossing pipeline by using a concrete slab plays a significant role in lowering the stress experienced by the pipe. The analysis towards the varying burial depths shows that the total effective stress decreases as the pipe is buried deeper. The underground road crossing pipeline are still safe and within the range of the maximum allowable stress and fatigue limit.

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