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Influence of Underground Pipeline on Response of Subgrade Soil in Flexible Pavement

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Abstract

Subgrade soil plays a significant role in long-term performance of asphalt pavement design. Unavoidable pipe crossing weakens the performance of subgrade layer in pavement. Improper trench filling material in trench construction may be the reason of differential settlement in subgrade layer. This study focuses on evaluation of vertical displacement and plastic strain in the region of backfill for pipe crossing the road section. Three-dimensional finite element analyses are carried out using ABAQUS to evaluate vertical displacement and plastic strain at top of subgrade and backfill materials. Analyses were carried out on two types of model original road and road with buried pipe model. Original road model constitutes the section of the road consisting asphalt, base and sub-grade layer as per section of RLU 60 of Newfoundland. Road with buried pipe was modeled for same section of the road with incorporation of concrete bedding, pipe installation, and compacted backfill. Vertical displacement for all the layers and plastic strain at subgrade layers have been evaluated for applied wheel load at middle of road section. In another scenario, load was applied at joint of existing road and trench filled region. Significant differential vertical displacement and plastic strain are observed at connection point.

Keywords: *Underground pipe; Subgrade soil; Backfill material; Vertical displacement; Plastic strain.*

1. Introduction

Asphalt pavement plays significant role for transportation of people and goods all over the world. The widely used pavement of this category generally consists of three layers: subgrade soils, base course, and asphalt surface. Soil in subgrade layer needs to be compacted at a specified density and moisture content to assure an effective distribution of traffic loads in depth (Marcoes et al., 2017). Structural integrity and service life of thin and low-volume flexible pavement under traffic load is directly influenced by the subgrade performance (Li et al., 2019; Asefzade et al., 2017; Tang et al., 2015). Due to low stiffness properties, passage of transporter causes highest amount of vertical stain at top of subgrade layer. These strains lead to large vertical permanent (plastic) deformations in the pavement system.

Traffic load induced stress, permanent deformation of materials, material stiffness, stress history, and environmental factors are the controlling factors of rutting in pavement (Uzan, 2004). Two limiting criteria are followed in controlling permanent deformation- i) vertical strain at top of subgrade ii) cumulative permanent deformation of all layers (Yesuf and Hoff, 2015). Uzan (2004) explained two criteria of controlling permanent deformation in design. Both criteria are based on cumulative plastic strain developed based on single and repeated application of loads. Repeated application of loads has been observed in laboratory tests of fine-grained soils incorporating the effect of the stress state. (Brown, 1975; Chai and Miura, 2002; Li and Selig, 1996).

Underground infrastructures such as buried gas, water main etc., are the part of our modern civilization. Due to unavoidable circumstances, these utilities need to be installed by crossing the road. Backfill material at the crossing of underground utilities in road section also affect the performance of pavement. It is necessary to evaluate the characteristics of backfill materials for that specific trench construction zone. (Jensen et al., 2005). Brown et al. (1995) observed reduction of pavement life about 8 years instead of 20 years at the patched area where cut was made for installing underground utilities.

Authors observed maximum deformation within very short distance of cut zone. Hashemian et al. (2017) performed field and laboratory tests to find out suitability of sand for backfilling micro trench in cold-region. Yu et al. (2017) observed differential settlement at the overlapping area of new and existing road led the pavement to cracking. Durable of flexible pavement at zone of trench greatly depends on performance of supporting layers. Performance of subgrade layer to protect road section against permanent deformation is important in the design of successful and durable flexible pavements. This study focuses on evaluating the effect of installation of underground pipe on deformation and strain of subgrade layer. Uneven settlement at overlapping zone of backfill and subgrade has also been studied.

2. Objectives

Numerical models have been prepared to simulate the trench of Highway in Newfoundland and single axle single wheel load have been applied on backfill and subgrade soils. Vertical displacement and plastic strain have been evaluated. The objectives of the tests are:

1. To investigate the variation of vertical displacement and plastic strain of subgrade for due to installment of water main on crossing of highway.
2. To investigate uneven deformation at the connection of trench backfill and subgrade soil.

3. Trench Crossing Pavement

Newfoundland RLU 60 road section has been considered in this analysis to evaluate the effect of traffic load on backfill materials. RLU 60 is the road section passing through St. john's to Mount Pearl via topsoil road in Newfoundland. Section details are collected from The Department of Transportation and Works, Newfoundland (NLDTW) Specifications Book. Figure 1 shows the sections details of RLU 60.

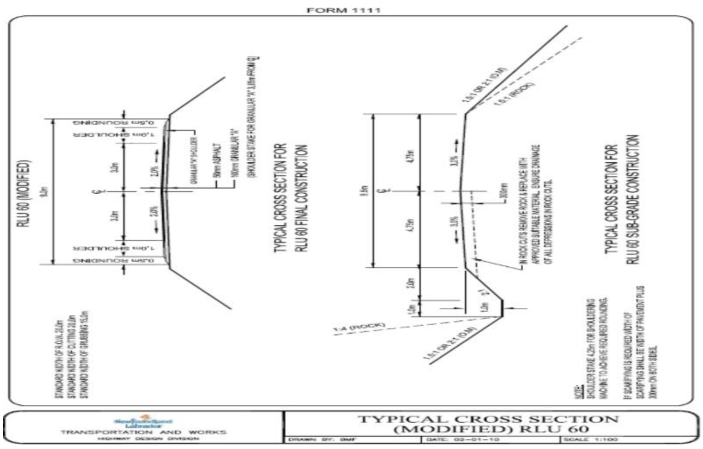

Figure 1: Road section of RLU 60

Newfoundland Municipal Water, Sewer and Road (NLMWS) Specifications book describes in details about trench excavation of water main crossing the pavement. According to this book, water pipe below 300 mm diameter encasement of pipe is not required. Pipe should have minimum 150 mm clearance on both sides. Concrete bedding with proper strength is recommended, but section is not provided. Transportation Association of Canada (TAC, 2013) provided guidelines for pipeline protection for crossing pavement section. Minimum cover 1.80 m form top of pavement surface to crown of pipe is recommended. Layout of pipeline crossing is shown in Figure 2.
TAC, 2013 recommended different pipeline protection details for encased and unencased pipe. In this modelling, cradled type pipeline protection was taken to place pipeline on top of concrete. This type of protection recommends minimum 150 mm concrete bedding all through the trench bed. Cradled type section details are presented in Figure 3.

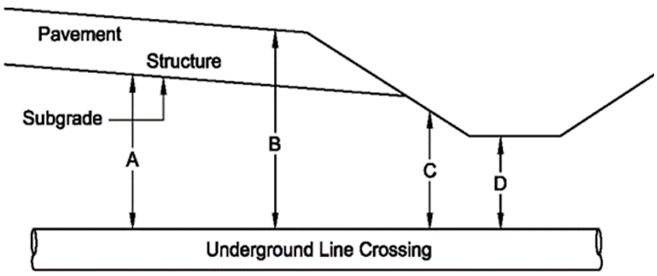

Figure 2: Layout of underground pipe layout

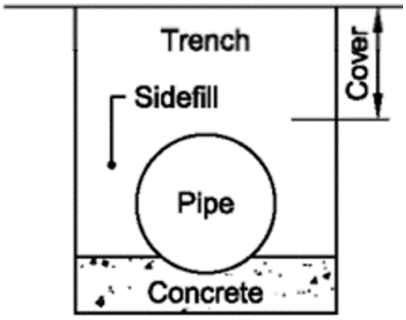

Figure 3: Cradled type trench for pipeline protection

NLDTW and NLMWS specification book recommend well compacted foundation for all structures placed below pavement. Compaction specified as 95% of the maximum standard proctor dry density (ASTM D698-12) for backfill.

4. Finite Element Modelling

Three-dimensional finite element analyses are carried out using ABAQUS to evaluate vertical displacement and plastic strain at top of subgrade and backfill materials. Analyses were carried out on two types of models- original road and road with buried pipe model. Original road model constitutes the section of the road as per section of RLU 60. Road with buried pipe model same section of the road with incorporation of concrete bedding, pipe installation, and compacted backfill. All the components are placed according to specifications shown in figure 4. In both models, half of the road section as 3.00 m was considered in transverse direction. In longitudinal direction, 2.00 m length was considered. Depth of road section was taken as 2.25 m to place pipe at minimum cover of 1.80 m from top of surface. Thickness of asphalt layer, base layer was modeled as 5 cm, and 10 cm respectively. Rest of the thickness was considered as subgrade. Concrete bedding having width of 600 mm was placed all through transverse direction of road. Cast iron pipe of outer diameter 220 mm and thickness of 10 mm was placed at top of concrete bedding. Trench of 600 mm was extended up to the bottom of base layer. This portion was filled backfill materials.

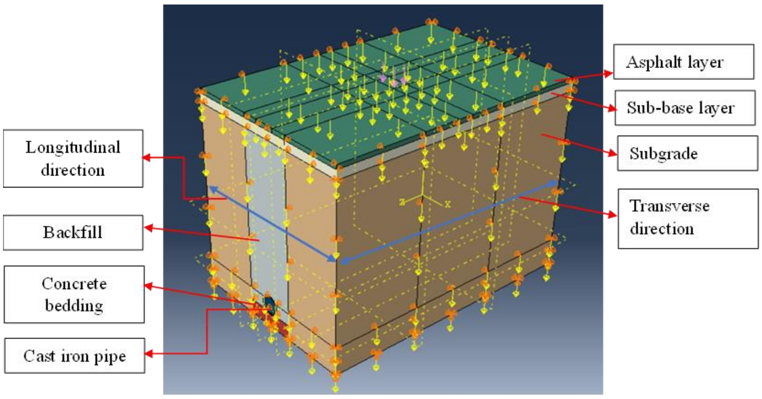

Figure 4: Model of road with pipe crossing

Elastic properties of asphalt, base and subgrade layer was collected from Rana et al. (2020). Authors used same properties in design of Newfoundland Road. Properties of cast iron pipe was taken from Debnath et al. (2019), determined from laboratory investigations. The reason behind of this study is to observe response of subgrade and backfill soil. In case of subgrade and backfill soil, Mohr-Columb elasto-plastic properties was implemented. Based on friction angle, dilation angle was selected relationship provided by Hamidi et al. (2010). Material properties for models are presented in Table 1.

Table 1. Material properties used in analysis

Materials	Properties	Value
Asphalt mixtures	Elastic modulus, (Mpa)	14000
	Unit wt., (kN/m^3)	24
	Poison's ratio	0.3

Base course	Elastic modulus, (Mpa)	207
	Unit wt., (kN/m3)	20.1
	Poison’s ratio	0.35
Subgrade and backfill	Elastic modulus, (Mpa)	24
	Unit wt., (kN/m3)	17.7
	Poison’s ratio	0.35
	Angle of internal friction, (º)	35
	Dilation angle, (º)	15
	Cohesion, (kPa)	0.1
Cast iron pipe	Elastic modulus, (Mpa)	125 X 10^6
	Unit wt., (kN/m3)	77.3
	Poison’s ratio	0.35
Concrete	Elastic modulus, (Mpa)	14 X 10^6
	Unit wt., (kN/m3)	2400
	Poison’s ratio	0.2

4.1 Load

Wheel load, gravity load and internal pressure of pipe are the loading in this study. Internal pressure of pipe is applied as 600 kPa and gravity load as usual manner. Wheel is the main load taken for pavement structural response. Wheel load in this model is applied as static load on top of pavement depending on wheel configuration. Uniformly distributed load is applied over contact area between tire and pavement. Contact area is calculated based on tire pressure. Tire pressure is considered as 700 kPa. Huang (2004) suggested rectangular contact area using the following equation:

$$L = \sqrt{\frac{\frac{Wheel\ load}{Tyre\ Pressure}}{Equivalent\ area}} \quad (1)$$

$$Equivalent\ area = length \times width = 0.8712L \times 0.6L \quad (2)$$

Details of length, area calculation are shown in Figure 5 and Table 2. For different load application, pressure was constant but equivalent contact area was changed in every case. For single axle double wheel load application, distance between center to center of two wheels is 0.350m.

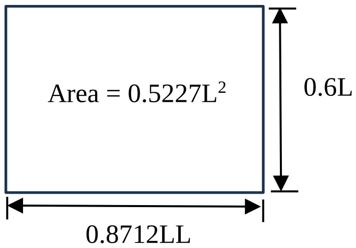

Figure 5: Equivalent contact area

4.2 Boundary Conditions

For buried pipe, internal pressure is applied from inside of the pipe. Bottom of model is restrained in from any movement. In the both side of XY and YZ symmetry plane, two displacement conditions *U3*=0 and *U1*=0 is applied respectively.

4.3 Contact

General contact algorithm that automatically select master and slave surface is used for soil pipe interaction. For the interface, the Coulomb’s friction model is used that defines the critical shear stress at which sliding of the surfaces occurs. The friction coefficient (μ) depends on interface characteristics and the slip rate between the soil and the pipe. In this study, μ is assumed to be 0.40.

4.4 Mesh Convergence Analysis

The size of the mesh has a significant effect on finite element modeling. Mesh convergence analysis is mainly performed to ensure that results of FEA analysis are no longer dependent on mesh size of elements. Mesh convergence analysis is shown in Figure 6.

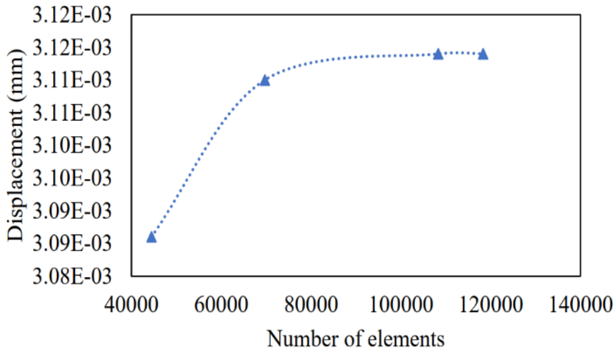

Figure 6: Mesh convergence analysis

5. Analysis of Results

Evaluation of vertical displacement and plastic strain in subgrade layers of pavement section has been performed in two scenarios. In first scenario, vertical displacement and plastic strain of existing road model was compared with model with pipe crossing. In this scenario, existing road was analyzed for pressure applied by wheel load and gravity load. In case of model with pipe crossing, everything was modeled described in model section. Vertical displacement from top of road and plastic strain from top of subgrade were compared with each other. Comparative analyses are shown in Figure 7 and Figure 8.

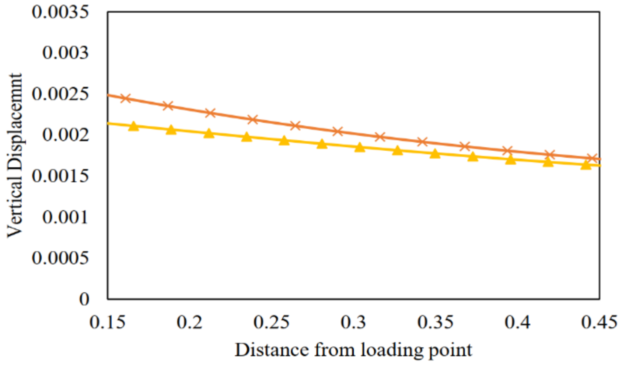

Figure 7: Comparison of vertical displacement for models of existing road and road with pipe

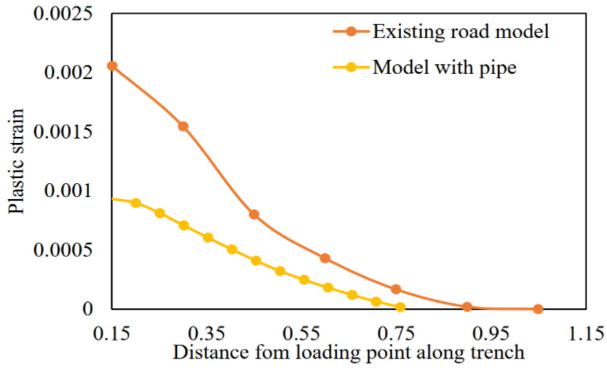

Figure 8: Comparison of plastic strain for models of existing road and road with pipe

From comparison, it is evident that vertical displacement and plastic strain values are reducing in the trench region. It might be because of the same properties of subgrade layer was used in the model. Installation of pipe with proper precautions is not affecting materials in trench region.

In second scenario, same pressure was applied at the end of the overlapping portion of trench and subgrade in longitudinal direction of road. In this case, undue vertical displacement and plastic strain is observed. Comparative results are presented in Figure 9 and Figure 10. From comparison, it is evident that at the connection point of trench and subgrade fill material are experiencing undue settlement. It may be the reason for earlier permanent deformation in the subgrade soil.

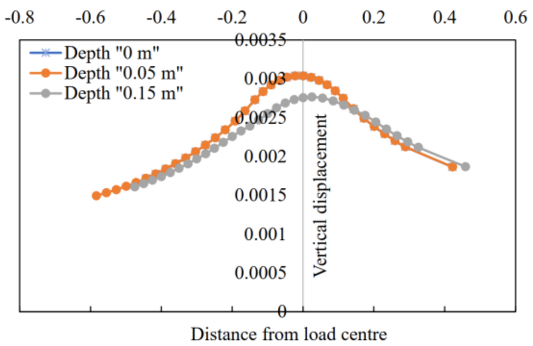

Figure 9: Undue vertical displacement for loading at overlapping zone

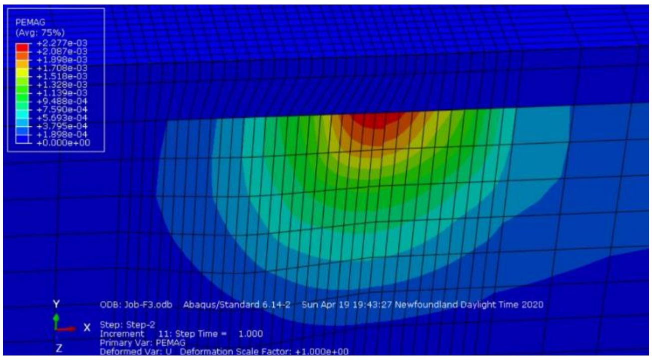

Figure 10: Undue plastic strain loading at overlapping zone

From comparison, it is evident that at the connection point of trench and subgrade fill material are experiencing undue settlement. It may be the reason for earlier permanent deformation in the subgrade soil.

6. Summary and Conclusion

Numerical investigations have been performed to observe the effect of water pipeline installation on subgrade soil properties. The main conclusions drawn from the analysis are as follows:
(a) Proper installation of pipe with protective measures might not affect subgrade soil at its initial stage in respect of vertical displacement and plastic strain.
(b) Wheel load at interface of backfill and existing road significantly produces differential settlement which might be premature permanent deformation of subgrade layer.

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