Numerical Analysis of Flexible Pipes Buried in Cohesionless Soil

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Abstract. Pipelines are important element of modern infrastructure as they are the carrier of essential transportation materials. The proper knowledge of the soil-pipe interaction mechanism leads to the better performance of the buried pipe system. This paper describes the study of the behavior of a flexible pipe, buried in sandy soil. Numerical analysis was performed using MIDAS GTS NX finite element software. A pipe having an outer diameter of 0.45 m and 10 mm thickness, subjected to the strip surface load was modelled. The strip load was varied from 0 kPa to 100 kPa. Two types of pipe materials namely; Polyvinyl Chloride (PVC) and High-Density Polyethylene (HDPE) were examined. The analysis was performed in loose, medium dense and dense sandy soil; with different burial depths of pipe, having embedment ratio 1,2 and 3. The analysis revealed the decreasing nature of pipe deflection with the increase in embedment depth, whereas the crown stress was found to be minimum for the embedment ratio 2. The detailed analysis showing the influence of pipe stiffness, soil stiffness and pipe burial depth on the vertical pipe deflection and crown stress is presented in this paper.

Keywords: Buried Pipe, Cohesionless soil, Stiffness, Deflection, Crown stress.

1 Introduction

The establishment buried pipelines networks are increasing in the recently developing era, because of its advantageous aspects over ground transportation. Underground transportation is economical as well as safe from sabotage point of view. To achieve the desired life-span and for the satisfactory performance of the buried pipe, proper design and analysis of the pipe are necessary, which involves the determination of internal pressure as well as external load. Based on loading condition, the parameters like deflection, stress, strain etc. are obtained. The pipes are classified into two types based on the material from which they are made up of (1) Rigid and (2) Flexible (Moser, 2001). Flexible pipes can deflect at least 2% without showing sign of distress while rigid pipes show sign of distress without being deflected by 2% (Moser, 2001). Steel pipe, Polyvinyl Chloride (PVC) pipe, High-Density Polyethylene (HDPE) pipes are examples of flexible pipe. Concrete pipe, Vitrified Clay pipe, Cast Iron pipes come under the category of rigid pipe. The usage of flexible plastic pipes is increasing day by day because of its light unit weight, handling technique and corrosion resistant characteristic. Hence, these types of pipe have become the interest of analysis of many researchers.

The past researches show that both the experimental as well as the numerical investigation had been made by the researchers, to analyze the buried pipes. Zhan & Rajani (1997), assessed the effects of different trench backfill materials on the magnitude of load reaching to the buried PVC pipe. In addition to this, the authors also evaluated the effects of pipe burial depth and pipe material on the amount of load transferred. The authors analyzed the behavior of Controlled Low Strength Material (CLSM) as a trench backfill and compared its behavior with the traditional trench backfill material such as sand and clay. Field truck load tests as well as its finite element simulation were carried out. CLSM proved as best backfill material from protection point of view. Arockiasamy et al. (2006), conducted truck load test on different types of flexible pipe and recorded the response of vertical pipe deflection. The field results were simulated with CANDE – 89 Finite element software. Based on the analysis, the permissible limit of deflection was suggested. Gerscovich et al. (2008), evaluated mechanical behavior of pipe buried in trench numerically by using SIGMA software. The vertical load on the conduit was obtained from the height of soil column. The numerical results were compared with the theoretical values. Nirmala & Rajkumar (2015), theoretically obtained the value of pipe deflection from the equations, which had been proposed by Spangler and Waltkins. Nirmala & Rajkumar (2016); Rajkumar & Ilamparuthi (2008), evaluated effect of Standard Dimension Ratio (SDR) and embedment depth of Un-plasticized Polyvinyl Chloride (UPVC) pipe in loose and dense sand backfill. Qasim (2017), made a numerical attempt to analyze Foundation – Soil – Pipe Interaction, using ANSYS finite element tool. The author studied the effects of burial depth, embedment ratio, foundation thickness, soil type, pipe diameter and pipe rigidity on vertical displacement. Abbas (2017) applied strip load along the length of PVC pipe buried in loose and dense sandy soil. Crown deflection was obtained through the series of numerical assessment, with the help of PLAXIS 3D finite element software. The author investigated the effect of embedment ratio and soil density on the amount of crown deflection.

The present study shows the numerical analysis of flexible pipe buried in dry cohesionless soil. The magnitude of vertical pipe deflection and crown stress have been obtained with the help of the finite element tool. The parametric study has been done by changing the value of soil stiffness, pipe stiffness and pipe burial depth.

2 Finite Element Modelling of Buried Pipe

The buried pipe was modelled in MIDAS GTS NX (V 2019), finite element software. The outer diameter and thickness of the pipe were 0.45 m and 10 mm respectively. The model dimensions were kept 10 m x 6 m. The dimensions of the model were chosen in such a way to avoid boundary effect. The left-hand side and right-hand side boundaries were kept 5 m away from the pipe center (Zhan & Rajani, 1997). Side boundaries were restricted from the horizontal movement and allowed for the vertical movement. The bottom boundary was kept fixed, with restricted horizontal as well as vertical displacement; where as the top boundary was free. A strip surface load, ranging from 0 kPa to 100 kPa, was applied on the ground surface; on 0.3 m width, along the length of pipe. The model represents plane strain condition. The embedment ratio (H/D) of pipe was varied as 1, 2 and 3. Here H is the distance of the pipe crown from ground surface and D is the external diameter of the pipe.

2.1 Properties of Materials

Mohr-Coulomb failure criteria was considered while modelling the soil. The properties of cohesionless soil, taken for the analysis, is shown below.

Table 1 Properties of dry cohesionless soil

Properties	Loose Sand	Medium Dense Sand	Dense Sand
ϒ (kN/m^3)	15.8	18	20
E (kPa)	9000	35,000	80,000
ν	0.3	0.3	0.3
c (kPa)	0	0	0
Φ (degree)	30	36	42

ϒ = Bulk Unit Weight, E = Modulus of Elasticity, ν = Poisson's Ratio, c = Cohesion, Φ = Angle of internal friction

The pipe was considered as an elastic material and was modelled as a shell element. The properties of buried pipe are as below.

Table 2 Properties of pipe

Properties	PVC	HDPE
ϒ (kN/m^3)	15	9.5
E (kPa)	2750000	760000
ν	0.4	0.4
t (mm)	10	10

ϒ = Unit Weight, E = Modulus of Elasticity, ν = Poisson's Ratio, t = Thickness

For the soil-structure interaction problem, the strength at the soil-structure interface is lesser than that of the surrounding soil. 'Strength Reduction Factor' (R) is the parameter, which relates the strength of interface to the strength of surrounding soil. In the given numerical model, an interface was created around the pipe. The value of R was entered manually as 0.65 for all the three cases presented in this paper.

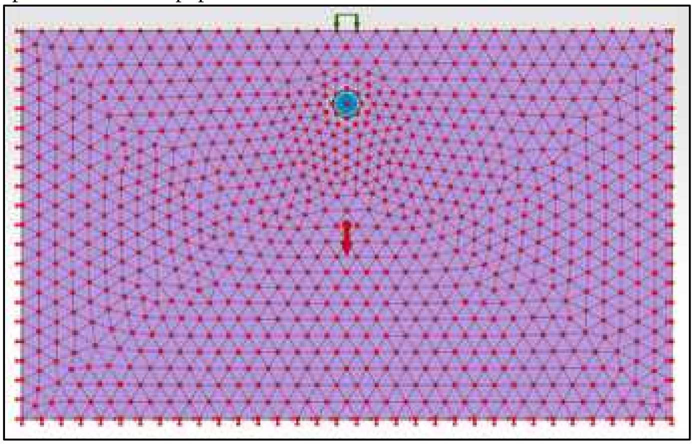

Fig. 1. Software View of Generated Mesh along with Boundary and Loading Conditions

3 Validation of Numerical Work

To check the exactness of the modelling technique and preciseness of the results, the numerical work was validated with the work of Abbas (2017). The variation of 3% was observed while comparing the results. A theoretical validation was also made, using Boussinesq's equation. Fig. 2 represents the graph showing the behavior of crown stress with applied surface surcharge. From both the method of analysis, linear trend of variation was observed. However, the values from Finite Element Method (FEM) were found smaller compared to theoretical values (with 6% to 8% variation). The reason behind this is the flexible nature of pipe. Because of flexible ring deformation, the load is transferred to the surrounding soil and the pipe takes less than its fair share of load.

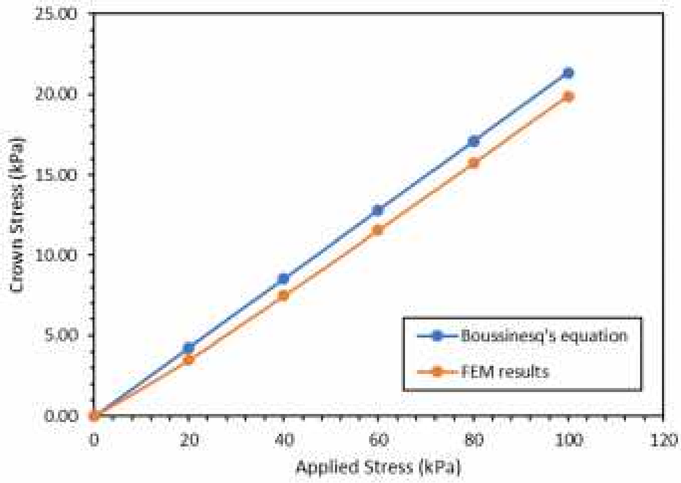

Fig. 2. Variation of crown stress with applied stress for PVC pipe (loose sand, H/D=2)

4 Results and Discussion

The section discusses the FE results of vertical pipe deflection and crown stress, followed by the sub-sections reflecting the effect of soil stiffness, pipe stiffness and embedment ratio. The effect of soil type and pipe material is graphically shown for the embedment depth H=2D. Its justification is given in section 4.2.

4.1 Vertical Pipe Deflection

The vertical deflection of buried pipe was obtained by subtracting invert displacement from crown displacement.

Effect of Soil Stiffness: For the pipe, embedded at a particular depth, the value of vertical pipe deflection was found to be decreased with increase in the stiffness of the soil. The relation between pipe deflection and surface surcharge was found linear. As shown in Fig. 3, the vertical pipe deflection was found to be decreased by 75% when medium dense backfill was provided instead of loose sand backfill. Similarly, a significant decrease of 90% was observed when dense sand backfill was provided instead of loose sand backfill (For PVC pipe having H/D=2, At 100 kPa surface surcharge). The same behaviour of deflection was found for all the three embedment ratios.

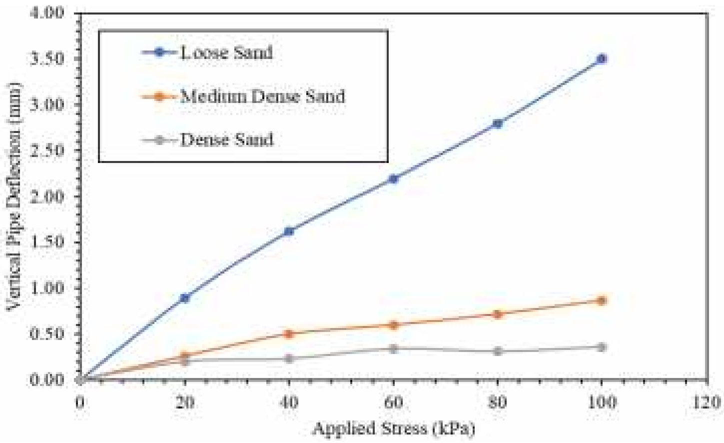

Fig. 3. Variation of vertical pipe deflection with applied stress for PVC pipe (H/D=2)

Effect of Pipe Stiffness: The pipe deflection was found greater for HDPE pipe compared to PVC pipe, in loose sand. However, the difference in the value of deflection, between both the types of pipe, was found to be reduced for medium dense and dense sand. In dense sandy soil, both the pipes had same amount of vertical pipe deflection. HDPE pipe have a tendency to deflect more (compared to PVC pipe) because of having less value of elasticity modulus.

However, it is important to note that the load bearing capacity of HDPE pipe – soil system was found higher than PVC pipe – soil system. The larger deflection of the HDPE pipe implies a larger increase in the horizontal diameter, which develops the lateral soil support and hence increases the load carrying capacity of the ring.

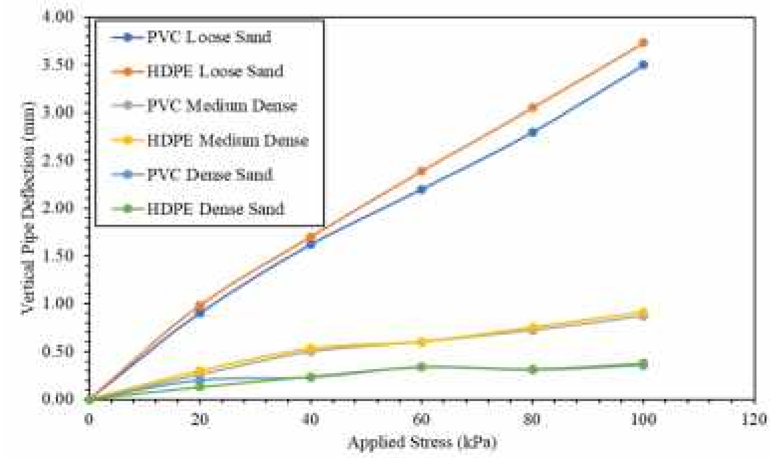

Fig. 4. Variation of vertical pipe deflection with applied stress for H/D=2

Effect of Embedment Ratio: Fig. 5 shows the variation of vertical pipe deflection with embedment ratio for PVC pipe buried in loose and medium dense sand. It was found that with increase in embedment depth vertical pipe deflection decreased, due to higher confinement and stress dispersion. For the denser backfill material, the effect of embedment depth became less significant. Hence, in case of denser backfill, one can opt shallower pipe burial depth. Consequently, the depth of excavation can be reduced and hence cost can be controlled.

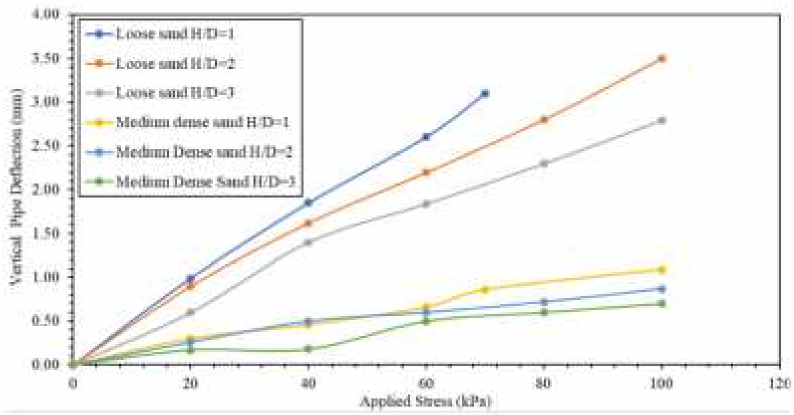

Fig. 5. Effect of embedment depth on the deflection for PVC pipe

4.2 Crown Stress

The external soil pressure at pipe-top is due to (1) Dead load of soil above the pipe, P_d and (2) Live load on the ground surface, P_l. Hence, the total vertical stress at crown (P) is given as

$$P = P_d + P_l \tag{1}$$

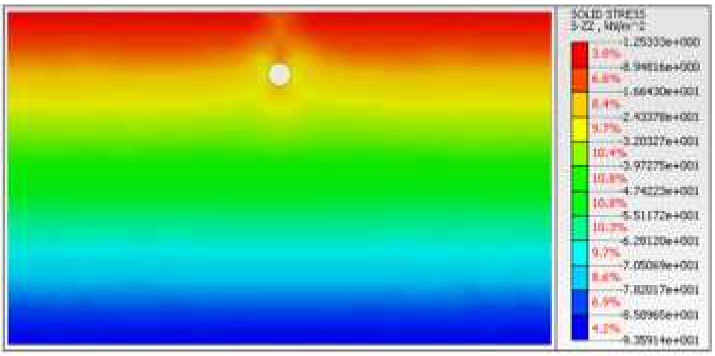

Fig. 6. Stress contour for vertical stress (Loose sand, PVC pipe, H/D = 2)

Table 3 Crown Stress for PVC pipe in loose sand

H/D	Surface Surcharge (kPa)	Crown Stress (kPa)		
		Total	Due to Dead Load P_d	Due to Live Load P_l
1	0	5.50	5.50	0.00
	20	12.06	5.50	6.56
	40	18.79	5.50	13.29
	60	25.54	5.50	20.04
	70	28.96	5.50	23.46
2	0	10.55	10.55	0.00
	20	14.05	10.55	3.50
	40	18.03	10.55	7.48
	60	22.10	10.55	11.55
	80	26.27	10.55	15.72
	100	29.44	10.55	19.89
3	0	16.44	16.44	0.00
	20	18.57	16.44	2.13
	40	21.05	16.44	4.61
	60	23.78	16.44	7.34
	80	26.68	16.44	10.24
	100	29.70	16.44	13.26

In order to understand the effect of dead load and live load, the magnitude of crown stress for the PVC pipe buried in loose sand in presented in Table 3.

Effect of Soil Stiffness: The variation of crown stress with the surface surcharge was found to be linear for all three types of soil (Fig. 7). The same trend was found with different embedment depth and different types of pipe materials.

In loose sand the value of crown stress found higher followed by medium dense and dense sand. Higher crown stress in loose sand is due to pressure concentration, while in dense sand arching action of soil occurs which helps to reduce stress at the crown.

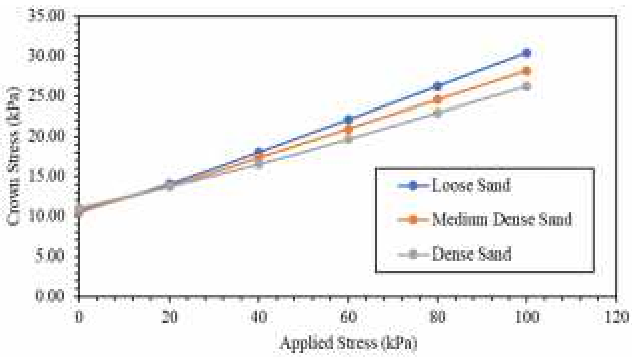

Fig. 7. Variation of crown stress with applied stress for PVC pipe (H/D=2)

Effect of Pipe Stiffness: The PVC pipe; being stiffer than the HDPE pipe, attracts more load compared to the HDPE pipe. Hence the value of crown stress was found higher for the PVC pipe as compared to the HDPE pipe. The behavior was the same for all the types of soil and at any embedment depth.

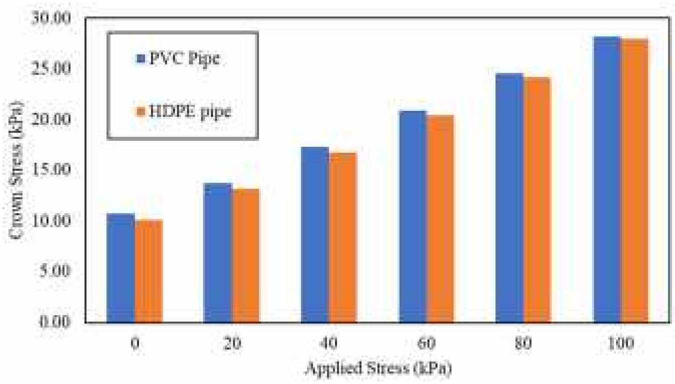

Fig. 8 Variation of crown stress with applied stress (Medium Dense Sand, H/D = 2)

Effect of Embedment Ratio: From the Table 3, it is clear that for lower embedment depth (H/D=1), the live load dominates over the dead load. For higher embedment depth (H/D=3), dead load dominates over the live load. For H/D=2, the value of total crown stress was found minimum. The same nature of stress variation was observed in all the types of soil, with both the types of pipe material. The bearing capacity of PVC pipe in loose sand for H/D=1 is, 70 kPa; hence to represent the comparable values the magnitude of crown stress at 60 kPa is presented below.

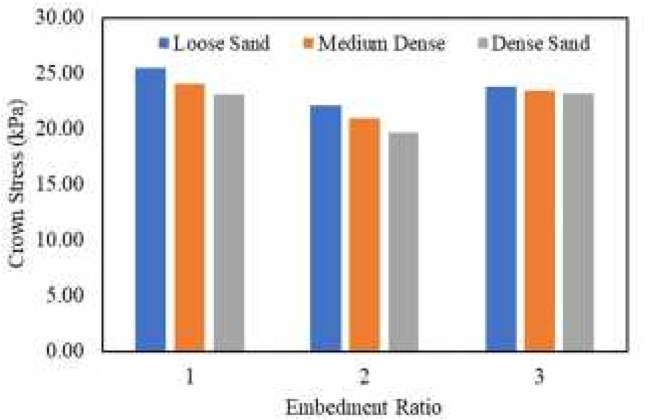

Fig. 9. Effect of embedment ratio for 60 kPa surface surcharge (PVC pipe)

5 Conclusion

Based on the numerical investigation, the following conclusions are drawn.

- For any pipe material, embedded at a particular depth, the value of pipe deflection decreases with increases in stiffness of soil. For both PVC and HDPE pipe, an average percentage decrease of 73% and 87% in the magnitude of pipe deflection was observed, when medium dense sand and dense sand backfill is provided instead of loose sand backfill respectively.
- HDPE pipe deflects more compared to PVC pipe because having less modulus of elasticity. The difference in the value of deflection between PVC and HDPE pipe is large in case of lesser stiff soil (here loose sand). As the stiffness of the backfill increases, both the pipes (PVC and HDPE) start behaving the same, in terms of deflection.
- The bearing capacity of the HDPE pipe – soil system is higher than of the PVC pipe-soil system, because of lateral soil support development in the case of HDPE pipe due to larger horizontal deflection.
- With the increase in soil stiffness, the effect of pipe burial depth decreases. By providing stiffer backfill, one can reduce the depth of pipe installation. Consequently, the excavation depth can be reduced and cost can be controlled.
- In the case of less stiff sandy soil, the amount of crown stress is higher, due to pressure concentration. For stiffer backfill, the stress reaching the crown decreases due to arching action.

- PVC pipe being stiffer than HDPE attracts more load and hence the value of crown stress is found higher of PVC pipe.
- For embedment ratio H/D=2, the value of crown stress has found minimum.

Pipelines, being the lifelines of the modern infrastructure, it is important to understand its interaction with the surrounding soil. To analyze the behavior of the pipe-soil system and to predict its failure, the detailed numerical as well as experimental study is necessary.

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