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Numerical Analysis of Buried Pipelines Located in Slopes

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Abstract. Buried pipelines act as lifelines for the infrastructural development as they are extensively used as a carrier of essential materials such as oil, natural gas, chemicals etc for human need and for industrial growth. Present study deals with numerical investigation of buried pipe in soil slope using PLAXIS-3D. In addition, a footing was also installed to analyze the optimum position of buried pipe which will have minimum affect on the ultimate bearing capacity of footing. For this analysis angle of soil slope is taken as 20°, relative density is taken as 85% and ratio of setback distance to width of footing (b/B) is taken as 2. Typical load deformation curve were generated from PLAXIS-3D software considering different variable parameters to get the optimum position of buried pipe. From the result it is observed that the footing's bearing capacity gets increased as the pipe position going away from the stress bulb of footing in a downward direction. The safe vertical depth of buried pipe is taken as 3.5 times the width of footing and horizontal distance of buried pipe from nearest edge of footing is taken as 2 times the width of footing, where the affect of buried pipes on bearing capacity of footing is less.

Keywords: Buried pipelines, Soil Slope, Strip Footing, Finite element method, bearing capacity

1 Introduction

Transportation of fluids in all over the world is extensively executed by long distance pipelines, since an early stage of civilization. But due to high rate of urbanization and living standard, a problem regarding scarcity of land is arising rapidly. So, Engineers and practitioners are continuously trying to invent some alternatives such as underground infrastructure. Subsequently, the concept of buried pipes was innovated as a reliable approach for transporting drinking water, wastewater, natural gas, oil etc. Because of the long distance between the extraction sites and the utility point, buried pipelines need to be passed through different geological and topographical area. Consequently, various kinds of difficulties occur during installation of pipelines as well as during whole service life. The stability of buried pipelines mainly affected by soil motion or large ground movements or by slope failure.

The first analysis of the buried pipe was developed on the basis of Terzaghi's theory to determine the loads acting on the crown of the pipe [Marston; 1913]. It is noteworthy that Pipe failures may occur during their service life due to corrosion, external forces, or accidental pipe defects so a pipe should posses enough strength and stiffness. Meanwhile, the pipe should have enough resistance to withstand against loads come from soils, loads exerted by foundation, internal pressure, differential settlement, longitudinal bending etc [Moser and Folkman, 2008]. The stiffness of pipes and soil properties are very important parameters for calculating the flexible pipe deformation in lateral direction under loading condition [Spangler; 1941]. Further, a new elastic solution for the deflection of an elastic pipe in an infinite elastic medium was introduced [Hoeg; 1966]. Deformation of pipe generally gets influenced by pipe flexibility factor and is not proportional to the diameter of the pipe which was observed from the field test done on polyurethane pipes [Hurd 1986]. The strain of pipe in horizontal direction is smaller than strain of pipe in vertical direction for short term loading [Adams et al. 1989]. Throughout this study, the behavior of pipes embedded in sand slope and subjected to loads governed by strip footing was investigated by numerical analysis i.e. Finite element method in PLAXIS-3D.

2 Methodology

2.1 Numerical analysis

The evaluation of complex problem using numerical modeling can be done by differential calculation consists of two method i.e. finite element method and finite difference method. The concept of finite element method is based on splitting the complex structure into large number of finite element which can be interrelated using nodes. The elements describing the local coordinate system are calculated and summarized in global coordinate system to get the uncertain result present in the complex structure. One of the commercial available program based on the finite element method is PLAXIS 3D which is used in the study for evaluation of deformation, stress, strain and failure aspect of the given problems.

Overview of PLAXIS-3D

PLAXIS 3D is a software, based on finite element method which is developed for geotechnical engineering for the analysis of condition prevailing in geotechnical activities in three dimensional approach. The condition such as deformation, underground movement of water, stability can form complex equation of differential equation which leads to arise the needs of finite element method. Thus, PLAXIS 3D can solve the problem forming mesh of different element. In geotechnical applications, extra constituent models are required for simulating time-dependent, non-linear, anisotropic soil and rock in multiple layers of materials. Generally, the geotechnical projects are based on soil structure interaction. The complex problem is based on two nodes i.e. displacement (deformation) nodes which is at the corner of every element in the nodes present in mesh and other is stress nodes locates at the center area of the element in the nodes. Each element generated in mesh in PLAXIS 2D is in triangular shape and in PLAXIS 3D is in tetrahedron shape.

2.2 Materials to be modeled

To find out the stability of buried pipes under the influence of slope and structural load such as strip footing, a model has been interpreted in PLAXIS 3D. The geometry of the model has been created by providing the footing (simulated by steel plate) nearer to the summit of the slope or to the face of the slope. The model's dimensions were selected in such a way that the 0.1q stress contour of footing (q is the stress transmitted by the footing) will never be intersected by the side and bottom edges of the model.

For numerical analysis in this context, Hardening soil model (HS) has been used in PLAXIS 3D for simulating soil layer. The properties of the soil layer have been shown in Table 1. Along with soil layer, plate has been also modeled to simulate strip footing and buried pipe.

Table 1. Values of hardening soil parameters for 85% relative density of soil used in PLAXIS-3D analyses

Parameters	value	Parameters	value
γ_{unsat}	18.20 kN/m^3	e_{init}	0.5000
γ_{sat}	21.02 kN/m^3	c'_{ref}	1.000 kN/m^2
e_{init}	0.5000	φ phi	38°
e_{min}	0.000	ψ psi	10°
e_{max}	999.0	υ'_{ur}	0.3000
E_{50}^{ref}	60.00E3 kN/m^2	p_{ref}	100.0 kN/m^2
E_{oed}^{ref}	60.00E3 kN/m^2	K_0^{nc}	0.3845
E_{ur}^{ref}	180.0E3 kN/m^2	c'_{inc}	0.000 kN/m^2/m
C_c	5.750E-3	z_{ref}	0.000 m
C_s	1.424E-3	R_f	0.900

In PLAXIS 3D, the plate has been modeled as a linear elastic material and plate elements are allowed to behave as a orthotropic material.

a) To simulate as a strip footing, the linear elastic steel plate was installed at ground surface nearer to the slope and subjected to a load of 100 kN. The properties of steel plate when simulated as strip footing are shown in Table 2

Table 2. Properties of steel plate as footing in model tank

Parameters	Value	Parameters	Value
D	0.2000 m	υ_{12}	0.3000
Y	78.50 kN/m^3	G_{12}	80.77E6 kN/m^2
E_1	210.0E6 kN/m^2	G_{13}	80.77E6 kN/m^2
E_2	210.0E6 kN/m^2	G_{23}	80.77E6 kN/m^2

b) To simulate as a buried pipe, the plate was embedded under the ground i.e. below structural load and nearer to the slope. The position of pipe has been changed vertically and horizontally to find out the safest position of pipe, where the influence of slope and structural load is minimum. The properties of steel plate as a pipe are shown in Table 3

Table 3. Properties of pipe

Parameters	Value	Parameters	Value
d	0.5000E-3 m	υ_{12}	0.3100
Y	13.83 kN/m^3	G_{12}	356.1E3 kN/m^2
E_1	933.0E3 kN/m^2	G_{13}	356.1E3 kN/m^2
E_2	933.0E3 kN/m^2	G_{23}	356.1E3 kN/m^2

2.3 Details of numerical model

The test tank used by Lee and Manjunath (2000) during experimental analysis is modeled in PLAXIS-3D. Since the size of the test tank is kept the same as that of experimental analysis, therefore model domain having dimensions 1.8m × 0.9m × 1m is provided to build the model tank within it. The reason behind selecting the HS model in spite of the availability of other soil models in PLAXIS-3D is because the magnitude of soil deformations can be modeled more precisely by assigning three input stiffness parameters corresponding to the triaxial loading stiffness (E_{50}), the triaxial unloading-reloading stiffness (E_{ur}), and the Oedometer loading stiffness (E_{oed}). Plate elements are used to simulate footing and pipe in the model. Pipe of diameter 75 mm is placed in this model at certain depth from footing. Pipe depth is varied to locate the safest position of pipe. The present model consists of 7944 triangular soil elements and 13287 nodes. The generated mesh of this model is presented in Fig 1.

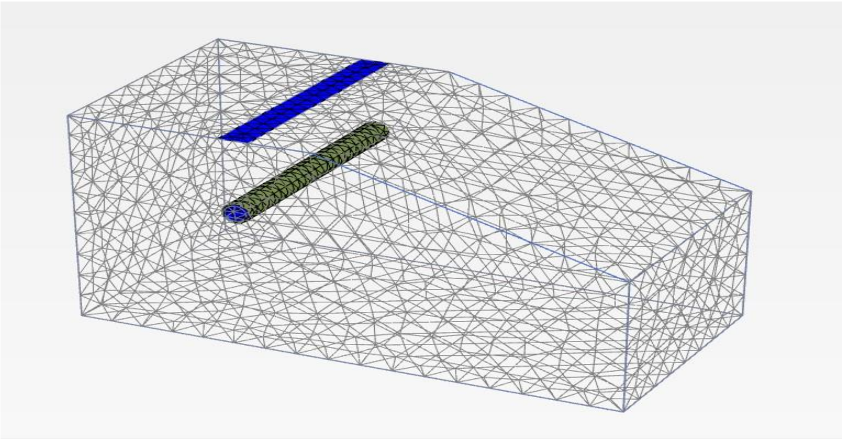

Fig. 1. Finite element mesh for model

3 Results and Discussion

3.1 Validation of finite element analysis against experimental result

A typical load deformation response of strip footing in slope obtained from finite element analysis has been compared with experimental results conducted by Lee and Manjunath (2000) as shown in Fig 2. Similar model dimension and properties for each material are considered in numerical analysis as mentioned in literature by Lee and Manjunath (2000). From Fig 2, it is seen that result of numerical analysis are almost same as experimental study. Hence it can be said that present numerical model can accurately simulate footing behavior in slope.

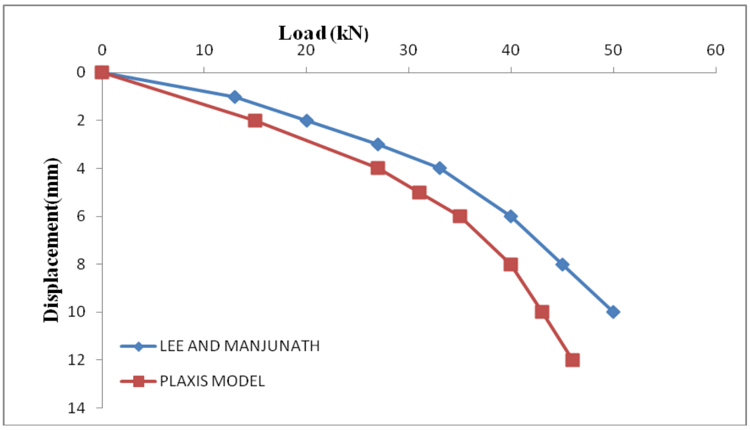

Fig. 2. Validation with experimental results (Lee and Manjunath, 2000)

3.2 Influence of footing distance from the slope crest on bearing capacity of footing

A series of numerical model were carried out on strip footing by keeping the setback to footing's width ratio (b/B) as 0, 1, 2, 3, 4, 5, and 6 on a sandy slope in order to investigate the impact of the footing distance with respect to the slope crest (b/B). In these test series, the angle of slope β have been adopted as 20°, the R.D of sand was 85% and the footing width was *B*=100 mm.

A non- dimensional factor, bearing capacity reduction factor (i_β) is introduced in the study to analyze the ultimate bearing capacity of footing with or without soil slope before inserting pipe in the slope. Bearing capacity reduction factor (i_β) of footing is defined as the ratio of the ultimate bearing capacity of footing resting on soil slope (q_{slope}) to the ultimate bearing capacity of footing resting on the flat ground surface (q_u) without any pipe. The bearing capacity reduction factor for different setback distance obtained in PLAXIS 3D have been shown in Fig 3 and tabulated in Table 4.

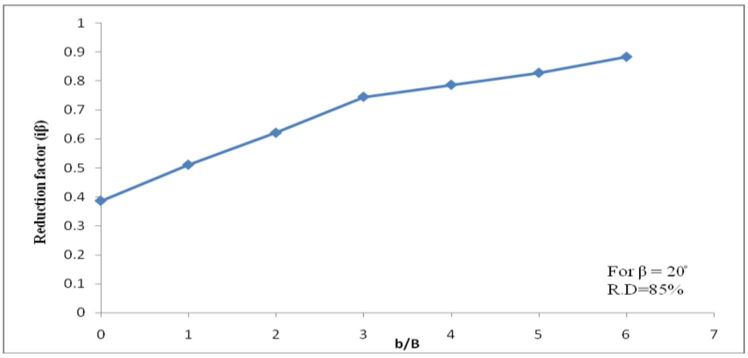

Fig. 3. Variations of reduction factor (iβ) with b/B

Table 4. Summarized the results of footing located at seven different position from the slope crest (β=20°, R.D=85%, B=100 mm)

b/B	Bearing capacity of footing on slope (q_{slope})	Non-dimensional reduction factor (i_β)
0	560	0.39
1	740	0.51
2	900	0.62
3	1080	0.75
4	1140	0.79
5	1200	0.83
6	1280	0.88
Level ground	1450	1

When the footing position is shifted away from the slope crest, the bearing capacity is increased. It is found that about 31% increase in bearing capacity when setback distance increases from b/B =0 to the b/B = 1. In a similar manner, 22% and 20% increase in bearing capacity is observed for change in setback distance from b/B =1 to b/B=2 and b/B=2 to b/B=3. Beyond b/B =3 the rate of increase in footing's bearing capacity get reduced. The ultimate bearing capacity of the footing on soil slope beyond the b/B value of 6 approaches to footing's bearing capacity on ground or flat level. Increased in the footing's bearing capacity with increase its distance from slope crest is due to effect of the resistance offer by passive zone of soil from the slope surface side toward the footing base.

3.3 Influence on bearing capacity after installation of pipe in soil slope

Influence of vertical position of pipe on bearing capacity

The influence of the embedment ratio (H/B) of the pipe in soil slope on the bearing capacity of footing was computed by model test series in PLAXIS-3D. Throughout the analysis, the diameter of embedded pipe (D) and widths of the footing (B) have been kept as 75 and 100 mm respectively. Slope angle (β) of 20°, R.D 85% and setback distance to the width of footing ratio (b/B) 2.0 were adopted for analysis. The model test analysis is performed for seven different H/B ratios such as 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5. Load-settlement curves for seven different embedment (H/B) ratios are presented in Fig 4 and have been tabulated in Table 5. Additionally the result of bearing capacity of footing in soil slope without any pipe was also represented in Fig 4, for comparison.

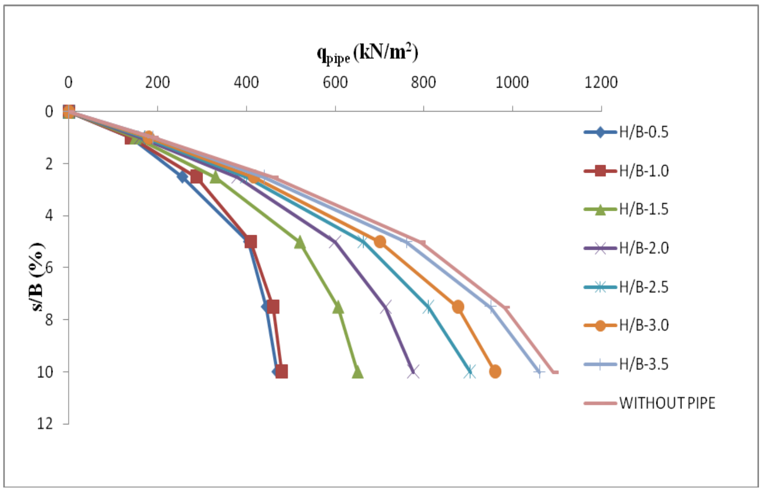

Fig. 4. Variations of load intensity (q_{pipe}) with s/B (%) for vertical position of pipe in different ratios of embedment (H/B)

Table 5. Test results for different embedment ratio (H/B)

H/B	q_{pipe}
0.5	330
1.0	370
1.5	520
2.0	710
2.5	780
3.0	800
3.5	890
No pipe in slope	920

A significant increase in bearing capacity of footing was found when embedded pipe position changes from H/B= 0.5 to H/B=2.5. The increase rate in bearing capacity deceases after H/B value 2.5 and ultimately reaches near about 97% of case of without pipe. The footing's bearing capacity is directly get affected by a pipe installation within the stress bulb of footing. In this case, the footing's bearing capacity gets increased as the pipe position going away from the stress bulb (stress bulb generated under beneath of footing) in a downward direction. This observation can be discussed using vertical displacement contour. Displacement contour of model with and without pipe are presented in Fig 5 and Fig 6. It is clearly observed from displacement contour that pipe position for H/B ratio 3.5 lies in between the contour of lesser value (i.e. 2 mm to 5 mm). This signifies safe position of pipe with respect of footing load. The pipe position in vertical direction to footing's width ratio (H/B) has been adopted as 3.5 for safety consideration.

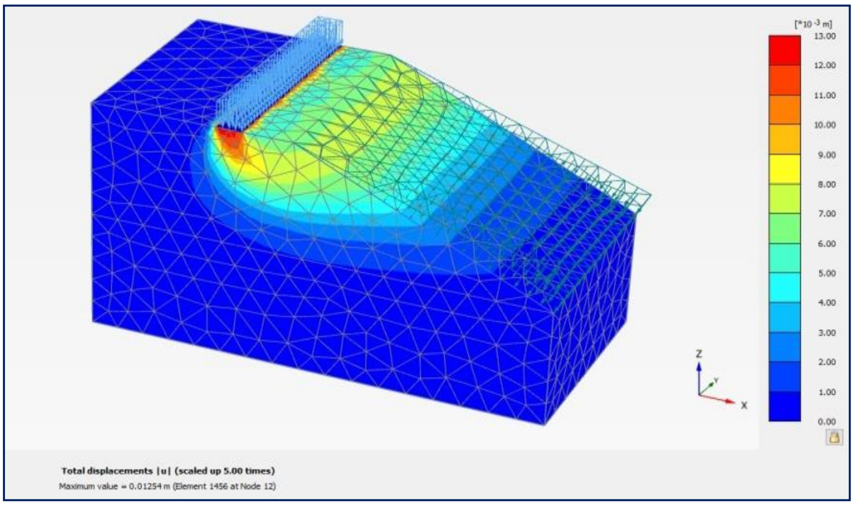

Fig. 5. Displacement contour without pipe

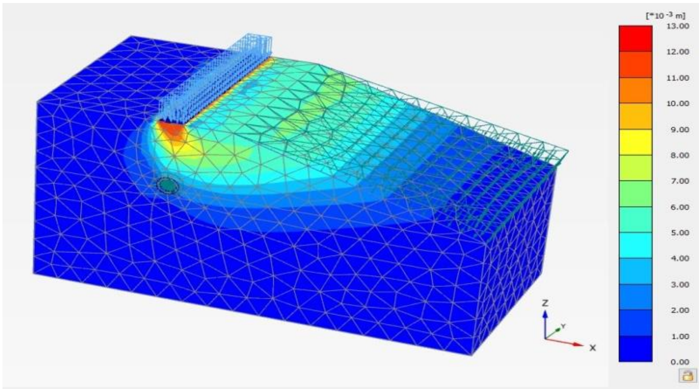

Fig. 6. Displacement contour with pipe: H/B = 3.5

Influence of horizontal distance of pipe on bearing capacity

The influence of the horizontal position of pipe to footing width (X/B) (i.e., the horizontal position X, taken from the nearest edge of the footing) on bearing capacity, was investigated by the sequence of model analysis on the soil slope. Analysis for X/B ratios of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 were performed at H/B value 3.5 and represented by load settlement curves in Fig 7 and tabulated in Table 6. There was a considerable increase in bearing capacity of footing in soil slope with pipe (near about value of 92 % of no pipe condition in slope) when the pipe is located at X / B = 1.0. The bearing capacity reached to 95% at X/B = 1.5 and become 100% in case of without pipe and at the location where X/B=2.0. It means that when the pipe is placed at X / B = 2, the bearing capacity reaches the same value as in the case of without pipe in soil slope.

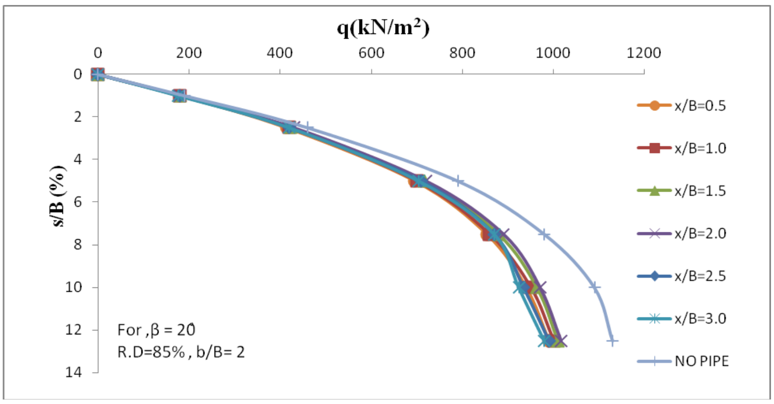

Fig. 7. Variations of load intensity (q) with settlement (s/B %) for different horizontal position of pipe and no pipe condition.

Table 6. Test Results for X/B variations

X/B	q_{slope}
0.5	840
1.0	850
1.5	876
2.0	920
2.5	780
3.0	760
Without pipe in slope	920

Vertical displacement contour for this position is presented in Fig 8. It is also found that pipe position lies in between lesser value (i.e. 2 mm to 5 mm). This also indicates the safe position of pipe.

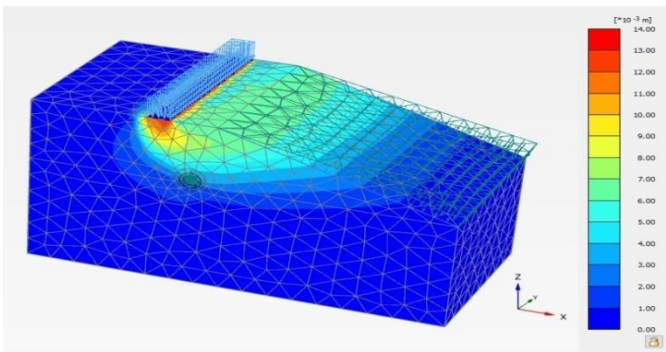

Fig. 8. Displacement contour with pipe: H/B = 3.5 and X/B = 2

4 Conclusions

1. The result indicated that, with increasing the setback distance (b), the bearing ca pacity of soil slope also increased up to b/B = 6, after that slope behaves like a level ground and corresponding bearing capacity is nearly equal to the bearing capacity on level ground. When footing at setback distance b= 2B, they achieve 62% of bearing capacity at level ground, which was adopted for economy consid eration.
2. It was also concluded that when the pipe depth was increased with respect to the lower surface of the strip footing, then the bearing capacity of the footing also get increased which signifies lesser effect on pipe.
3. Increasing the H/B ratio of pipe leads the way to an increase in the percentage rate
4. of increment in bearing capacity after a certain H/B ratio, the change in the bear

ing capacity of soil on the slope is negligible. Moreover, if the pipe is placed at H/B=3.5, the bearing capacity tends to nearly equal to the same bearing capacity that in the case of without embedded pipe in soil slope. On the basis of present observation, optimum depth of pipe is fixed at H/B ratio 3.5.

5. The bearing capacity reached 95% at X/B = 1.5 and the bearing capacity reaches 100% in the case of without pipe in soil slope which is the same as in the case of X / B = 2. Further increase in the horizontal position of pipe tends to decrease in the bearing capacity of the soil slope with an embedded pipe.
6. Based on observation, the optimum position of pipe with respect to footing is fixed
7. at H/B ratio 3.5 and X/B ratio 2 from the point of view of safety and serviceability.

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