Numerical Analysis of Buried Pipelines Located in Slopes

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1 Introduction

Transportation of fluids 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 standards, a problem regarding scarcity of land is rising 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 areas. Consequently, various kinds of difficulties occur during installation of pipelines as well as during the whole service life. The stability of buried pipelines is 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 [1]. 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 possess 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. [2]. The stiffness of pipes and soil properties are very important parameters for calculating the flexible pipe deformation in lateral direction under loading conditions [3]. Furthermore, a new elastic solution for the deflection

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of an elastic pipe in an infinite elastic medium was introduced [4]. 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 [5]. The strain of pipe in horizontal direction is smaller than strain of pipe in vertical direction for short-term loading [6]. 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 problems using numerical modeling can be done by differential calculation consists of two methods, i.e. finite element method and finite difference method. The concept of the 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 programs 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 the finite element method, which is developed for geotechnical engineering for the analysis of condition prevailing in geotechnical activities in three-dimensional approach. The conditions 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 of forming mesh of different elements. 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 are at the corner of every element in the nodes present in mesh, and the other is stress nodes, which locate 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, the 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, the plate has been also modeled to simulate strip footing and buried pipe.

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

(a) To simulate as a strip footing, the linear elastic steel plate was installed at the 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.

(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

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

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

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

the influence of slope and structural load is minimum. The properties of steel plate as a pipe are shown in Table 3.

2.3 Details of Numerical Model

The test tank used by Lee and Manjunath [7] 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 1.8 m × 0.9 m × 1 m 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 a 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 13,287 nodes. The generated mesh of this model is presented in Fig. 1.

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 [7] as shown in Fig. 2. Similar model dimensions and properties for each material are considered in the numerical analysis as mentioned in literature by Lee and Manjunath [7]. From Fig. 2, it is seen that the result of numerical analysis is almost the same as experimental study. Hence it can be said that the present numerical model can accurately simulate footing behavior in slope.

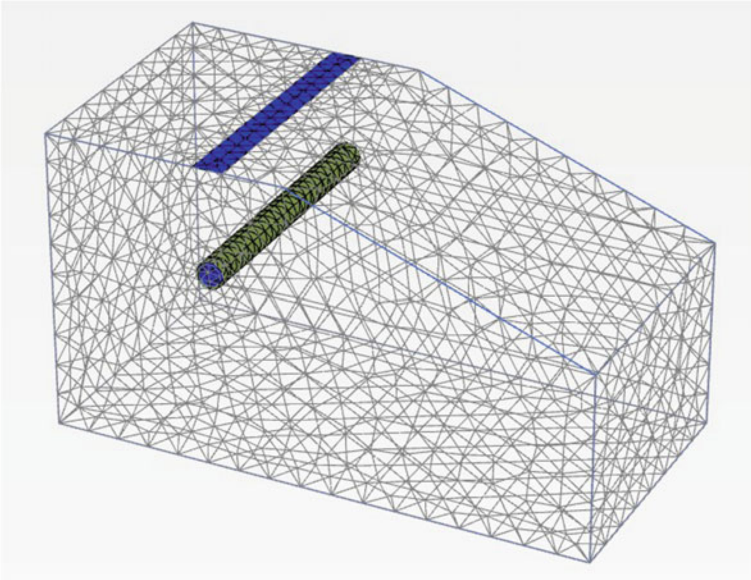

Fig. 1 Finite element mesh for model

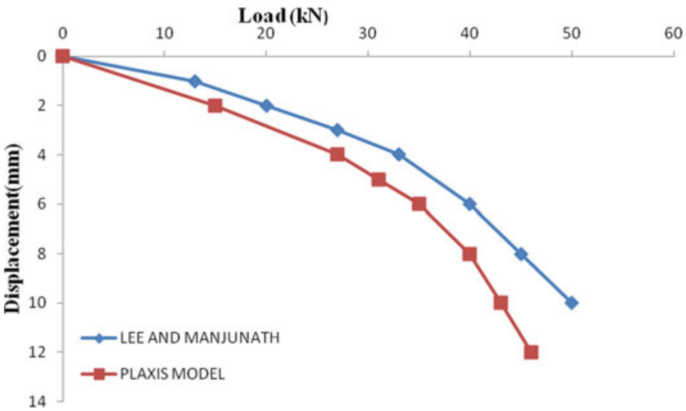

Fig. 2 Validation with experimental results [7]

3.2 *Influence of Footing Distance from the Slope Crest on Bearing Capacity of Footing*

A series of numerical models 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 has 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 distances obtained in PLAXIS 3D has been shown in Fig. 3 and tabulated in Table 4.

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

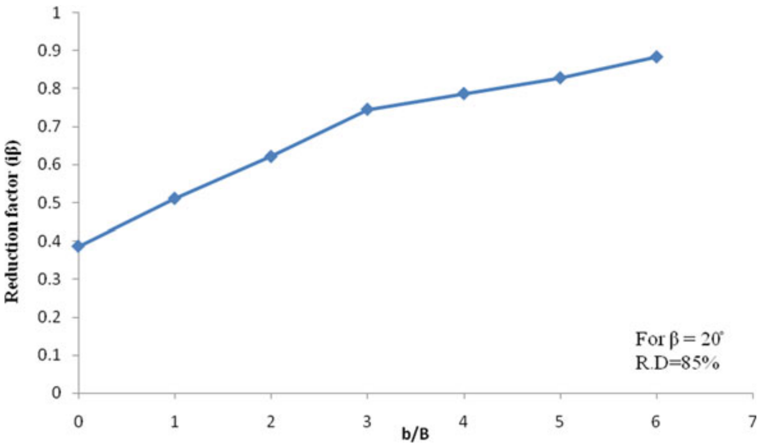

Fig. 3 Variations of reduction factor (i_β) with b/B

Table 4 Summarized the results of footing located at seven different positions 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

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 gets 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. The increase in the bearing capacity of footing with increase in 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.

A significant increase in the bearing capacity of footing was found when the embedded pipe position changes from H/B = 0.5 to H/B = 2.5. The increase rate in bearing capacity decreases after H/B value 2.5 and ultimately reaches near about

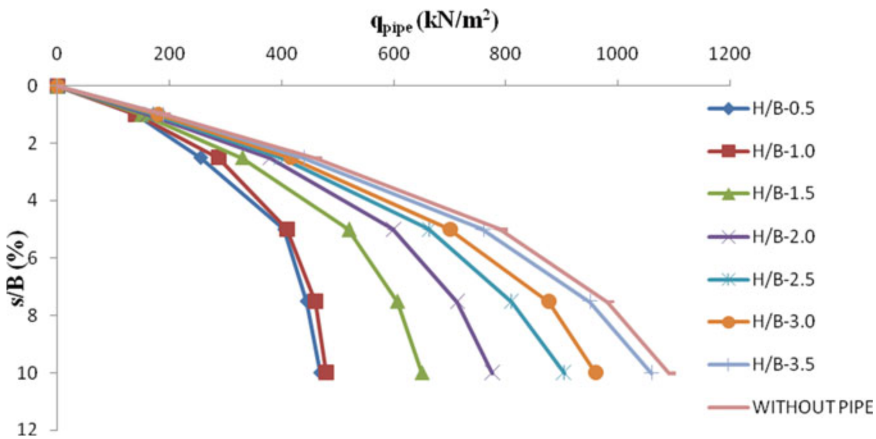

Fig. 4 Variations of load intensity (q_{pipe}) with s/B (%) for vertical position of pipe in different ratios of embedment (H/B)

Table 5 Test results for different embedment ratios (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

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 beneath of footing) in a downward direction. This observation can be discussed using vertical displacement contour. The displacement contour of model with and without pipe is presented in Figs. 5 and 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. 2–5 mm). This signifies safe position of pipe with respect to footing load. The pipe position in vertical direction to footing's width ratio (H/B) has been adopted as 3.5 for safety consideration.

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 was performed at H/B value 3.5 and

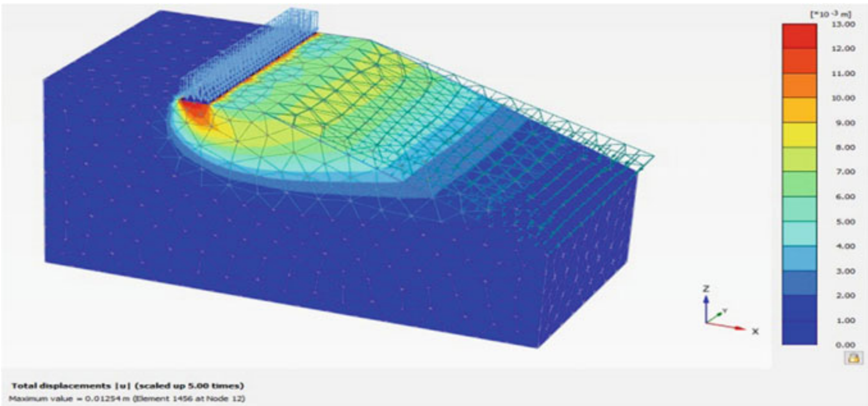

Fig. 5 Displacement contour without pipe

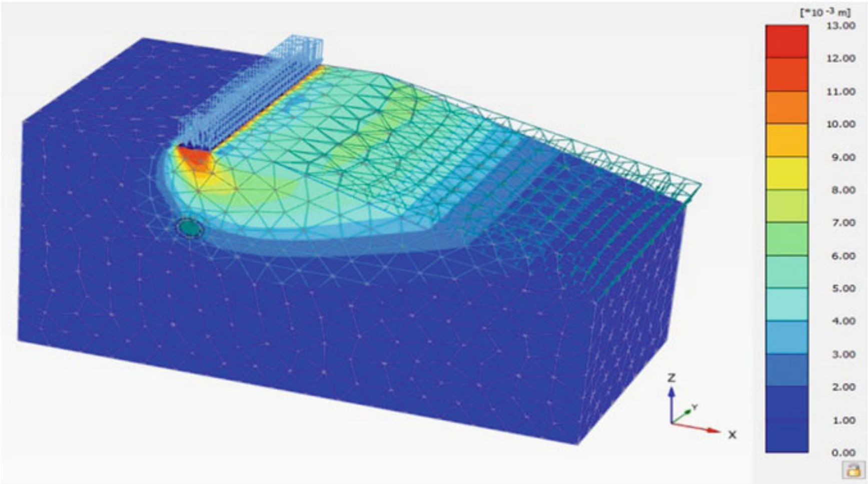

Fig. 6 Displacement contour with pipe: H/B = 3.5

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.

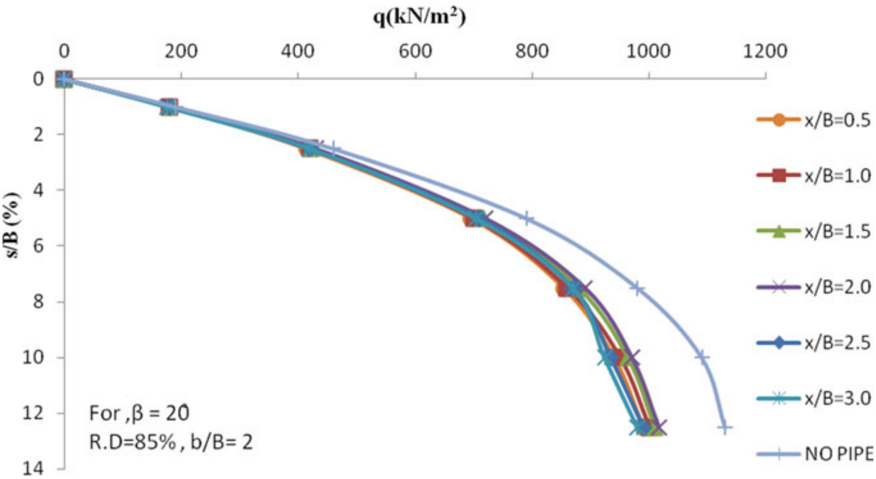

Fig. 7 Variations of load intensity (q) with settlement (s/B %) for different horizontal positions of pipe and no pipe conditions

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

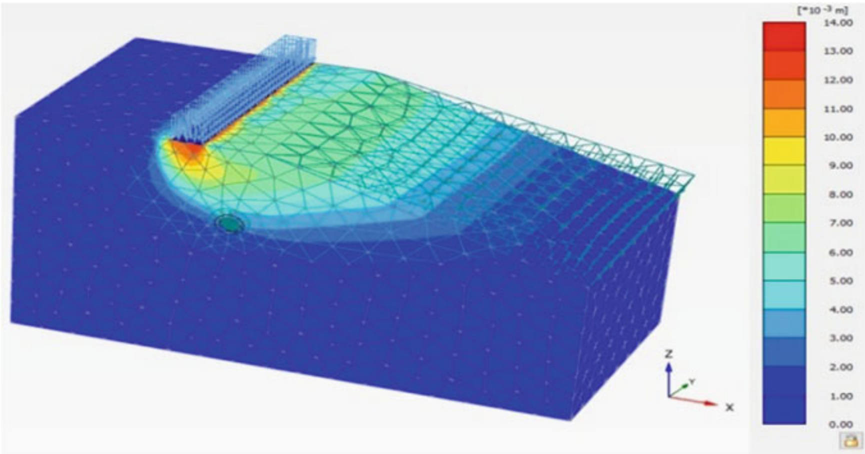

Fig. 8 Displacement contour with pipe: H/B = 3.5 and X/B = 2

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

4 Conclusions

1. The result indicated that, with increasing the setback distance (b), the bearing capacity of soil slope also increased up to b/B = 6, after that slope behaves like a level ground and the 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 consideration.

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 of increment in bearing capacity after a certain H/B ratio, the change in the bearing 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, an optimum depth of pipe is fixed at H/B ratio 3.5.
4. 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.
5. Based on observation, the optimum position of pipe with respect to footing is fixed at H/B ratio 3.5 and X/B ratio 2 from the point of view of safety and serviceability.

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