Load-Settlement Behavior of Adjacent Strip Footings Resting on Slopes

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ABSTRACT

In many places of Kerala state the topography is sloping especially in the districts of Kottayam, Thiruvananthapuram, Kasaragod etc. A sloping ground is in unstable equilibrium, when compared with a level ground. When we construct structures on sloping ground, foundations will be placed on the slope at various levels. Applying loads on a slope of various levels may further degrade its stability and in addition, there will be interference between adjacent footings. Since the foundations are at different levels the stressed zones will overlap which may lead to differential settlement. This paper investigates the load - settlement behavior of footing resting on slopes, by carrying out a series of laboratory scale load tests on model footings resting at various levels along the slope surface. The parameters varied are eccentricity and slope angles. Finite element analyses are carried out with the FE software PLAXIS 2D and the results are compared with those obtained from laboratory scale load tests for validation. It is observed that the eccentricity and slope angle influence the load settlement behavior of footings considerably.

Keywords: Sloping ground; Unstable equilibrium; Eccentricity; Slope angles.

1 Introduction

Several studies have been conducted to analyse bearing capacity, settlement, and failure of footing resting on horizontal surfaces by various researchers (Terzaghi K., (1943), Meyerhof G (1951), Skempton A W (1951), Hansen B J (1970) and Vesic A S (1973)). Comparing to those studies, research related to foundations resting on or near the slopes are limited. The terrain in many places in the state of Kerala are sloping in nature and hence foundations of structures are located on or near the slopes. Building foundations, bridge pier which are situated in slopes are such examples. Bearing capacity is the major factor for any type of foundations. In this regard the assessment of bearing capacity for foundations which are situated on slope surface or crest of slope become complicated. Shields *et al.* (1977) reported that the ultimate bearing capacity increases by 2 to 3 times when the embedment depth of footing was doubled. The field investigation of Clarks et al (1988) on the behaviour of inclined footings at a natural slope reported that compared to horizontal ones, inclined footing with anchores is having more bearing capacity.

The effect of depth which is replaced with sand layer and offset distance between footing and slope crest under sinusoidal loading determined by Mostafa A. El Sawwaf (2012). Settlement reduction with increasing bearing capacity was found out. A numerical analyses on isolated shallow footings resting near the crest of slope was conducted using 3D finite element analysis by Acharyya and Dey (2017 & 2018) and various parameters were studied. They found out that beyond critical ratio of 4 for square and 6 for strip, there behavior was approaching similar to footing placed at horizontal ground. Also used soft computing and optimization techniques instead

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of standard techniques. Interference of strip footings located on slope crest was studied by Acharyya and Dey (2018 &2019) and reported that after a critical spacing ratio of 8, the interference of footing disappears.

Most of the researchers have investigated the behaviour of footings resting on the crest of the slope. In urban areas having sloping terrain, the footings may be placed at various levels along a slope. In this paper, the load - settlement behavior of footings resting at various levels along a slope are investigated by carrying out a series of laboratory scale load tests on model footings. The influences of different parameters like, eccentricity of footing from the edge and slope angle are investigated. Finite element analysis is carried out using the FE program PLAXIS 2D *connect edition V20* and the results are compared with those obtained from the laboratory model tests.

2 Laboratory Model Tests

The experimental programme reported in this paper involves a series of laboratory scale load tests on model footings resting at various levels along the slope surface, was carried out at Geotechnical Research Lab of LBS Institute of Technology for Women, Thiruvananthapuram.

2.1 Materials

The material used for slope preparation is locally available lateritic soil and properties of soil are given in Table 1.

Table 1: Properties of soil used in model tests

Sl No.	Properties	Values
1	Specific Gravity	2.6
2	Uniformity Coefficient (C_u)	6.67
3	Coefficient of Curvature (C_c)	1.2
4	Dry Unit Weight (kN/m^3)	18.84
5	Angle of Shearing Resistance, ϕ (^{0})	32
6	Cohesion, c (kN/m^2)	5
7	IS Designation	SW

2.2 Test setup

The load tests are carried out in a combined test bed and loading frame assembly. The test beds are prepared in a tank which is designed keeping in mind the size of the model and the zone of influence. The dimensions of the test tank are 1000 mm length x 750 mm width x 750 mm depth, which has 23 cm thick brick masonry walls on four sides. The loading tests are carried out in a loading frame fabricated with ISMB 300. The loads are applied using hand operated- mechanical jacks of capacity 50kN. The applied loads are measured using proving rings of capacities 50kN. The settlements of the two model strip footings are measured using two dial gauges each of 0.01mm sensitivity kept diametrically opposite to each other. The drawing of test setup is shown in Figure 1 and photograph in Figure 2.

2.3 Preparation of Slope

At first, the lateritic soil is filled in the test tank to the required level of slopes with compaction done in layers of 10 cm thickness. The water content of the soil is maintained constant throughout the test procedure. To achieve the desired density of the soil, the layered filling technique is used. The lateritic soil is compacted by ramming.

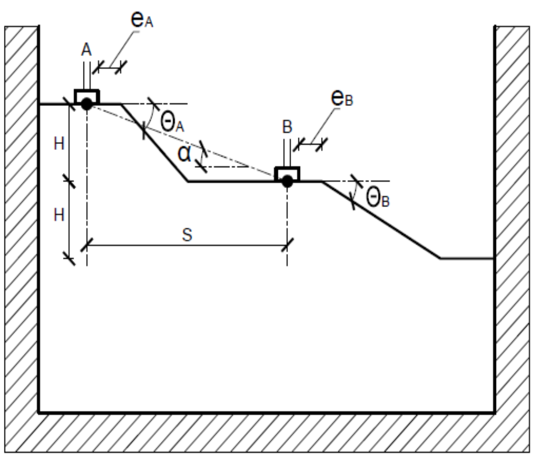

Figure 1. Drawing of Test Setup

Figure 2. Photograph of Test Setup

2.4 Testing Procedure

After preparing the slope, the slope surface is leveled, and the footing is placed at two levels of slope exactly at the center of the loading jack to avoid eccentric loading. The footing is loaded by a hand-operated hydraulic jack supported against a reaction frame. A precalibrated proving ring is used to measure the load transferred to the footing. The load is applied in small increments. Each load increment is maintained constant until the footing settlement is stabilized. The settlement is measured using two dial gauges and their average value is adopted. The details of testing programme are given in Table 2.

Table 2. Experimental Programme

Type	Series	e_a (cm)	e_b (cm)	θ_a (˚)	θ_b (˚)
Lateritic soil	A	5	0, 2.5, 5	30	30
	B	0, 2.5, 5	5	30	30
	C	5	5	30	30 , 45 , 60
	D	5	5	30 , 45 , 60	30

3 Finite Element Analyses

In the present study, loading test on slopes are simulated numerically using program PLAXIS 2D *Connect Edition V20* which is a finite element software package. In this study, Mohr-Coulomb model with drained condition is used to simulate the soil behaviour. Since strip footing is used in this study a plain strain model is used for the analyses. Here the footings are modelled with plate elements.

In the present study, instead of modeling the footing, settlement of the footing is simulated using non zero prescribed displacements. The initial geostatic stress states for the analyses are fixed according to the gravity loading. The soil is modeled using 15 noded triangular elements. A medium mesh size is adopted for the soil. The mesh boundaries are fixed according to tank dimensions. The boundary conditions are made in such a way that the displacement of the bottom boundary is restricted in all directions, while at the vertical sides; displacement is restricted only in the horizontal direction. To simulate the interaction between the footings and surrounding soil, interface elements are provided between the footings and surrounding soil.

4 Results and Discussions

4.1 Effect of Eccentricity

Vertical stress vs normalized settlement curves of footings resting on various levels of slopes with varying eccentricity values are shown in Figure 3 and 4. The settlement of footing S is expressed in non-dimensional form as S/B (%). Figure 3 presents the behaviour with constant upper footing eccentricity (e_a) and varying lower footing eccentricity (e_b). It is seen that when eccentricity e_b is zero the performance of upper footing is better than lower footing. When e_b increased to 0.5B and B where (B) is the width of footing, the performance of upper footing get reduced, due to the influence of upper footing even after increasing the eccentricity, the performance of lower footing getting reduced. From Figure 4, which represents vertical stress vs normalised settlement of footing with constant lower footing eccentricity(e_b) and varying upper footing eccentricity (e_a).

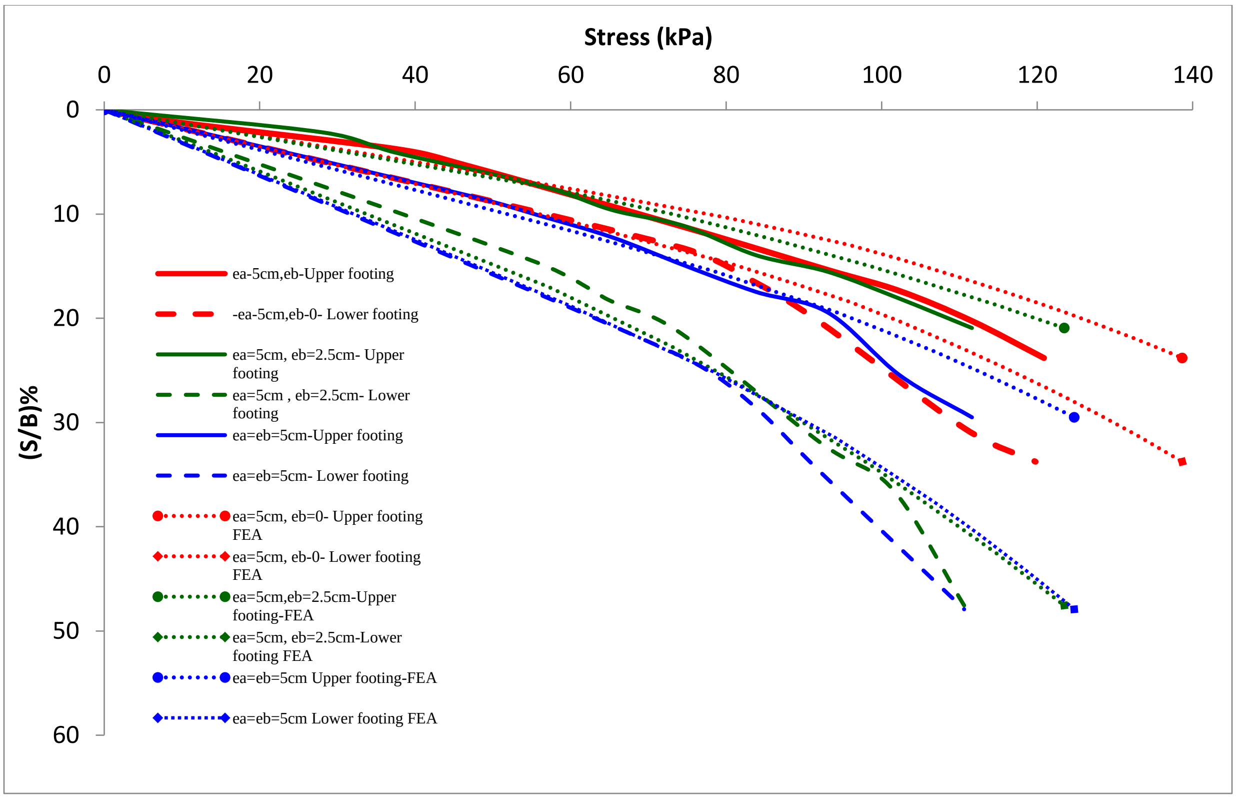

Figure 3. Vertical stress vs normalized settlement curves e_a= constant, e_b varying ($\theta_a = \theta_b = 30°$)

It is seen that when eccentricity e_a is zero the performance of upper footing is better than lower footing. When e_a increased to 0.5B and B where (B) is the width of footing, the performance of upper footing get reduced, and due to the influence of upper footing even with the constant lower eccentricity, the performance of lower footing getting increased. There is a reasonably good agreement of FEA results with experimental results.

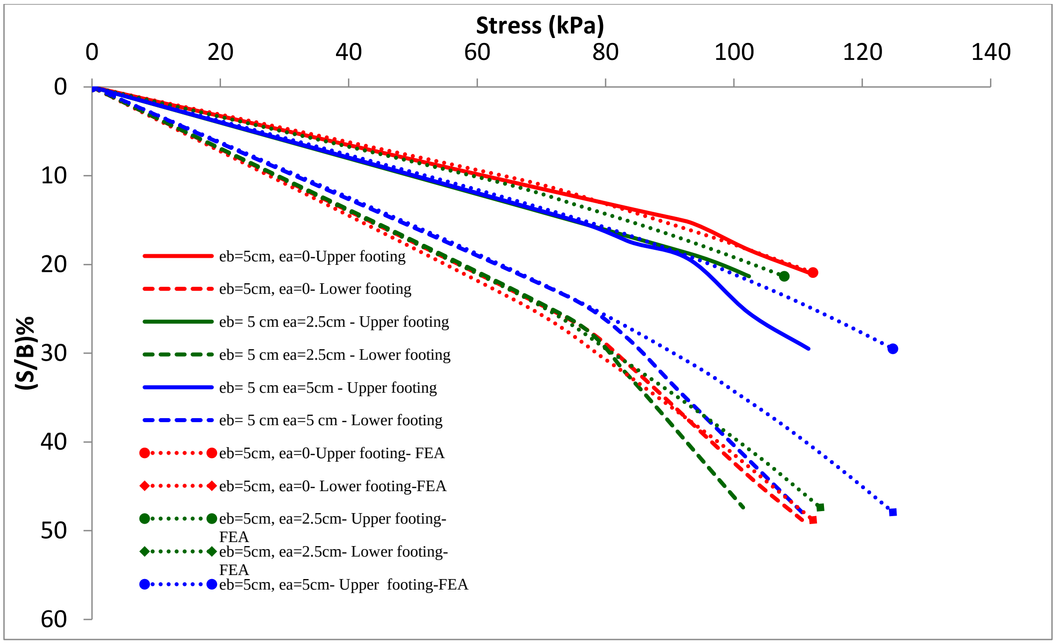

Figure 4. Vertical stress vs normalized settlement curves e_b= constant, e_a varying ($\theta_a = \theta_b = 30^{\circ}$)

4.2 Effect of Slope angle

Vertical stress vs normalized settlement curves of footings resting on various levels of slopes with varying Slope angle values are shown in Figure 5 and 6.

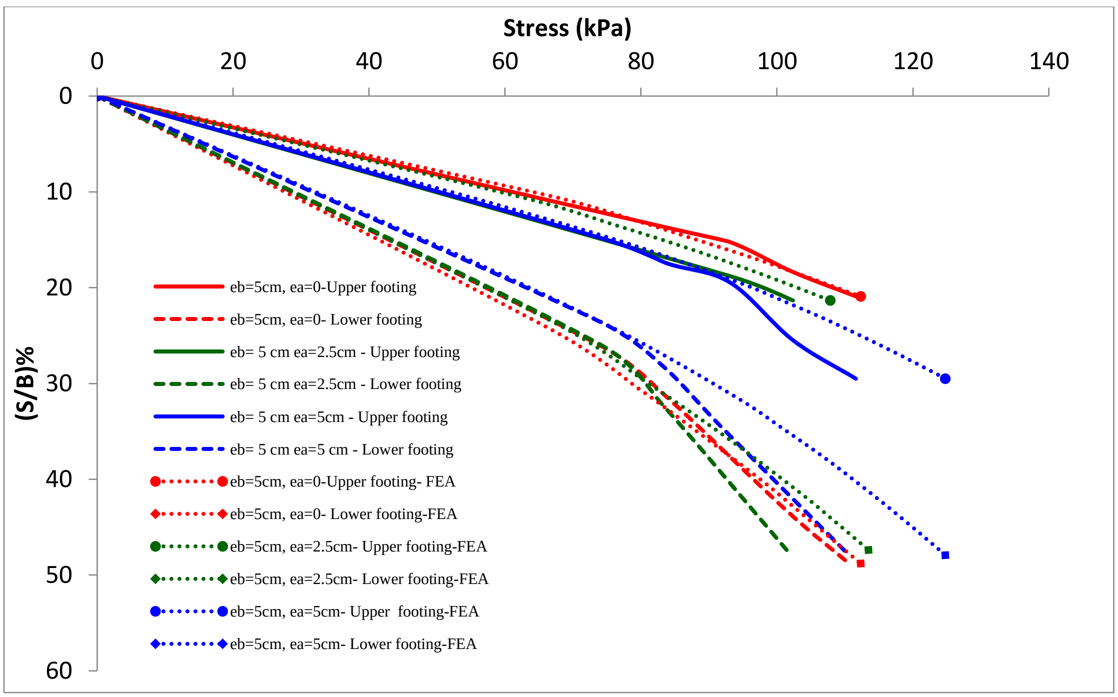

Figure 5. Vertical stress vs normalized settlement curves $\theta_a = 30^{\circ}$ and θ_b = varying (e_a=e_b=5 cm)

From Figure 5, which presents the vertical stress vs normalized settlement of footing with constant slope angle for top level of slope, θ_a and varying slope angle for bottom level of slope, θ_b. It can be seen that when top and bottom slope angles were same (30°), the performance of upper footing is better than lower footing. The

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reduction in lower footing performance is due to the influence of upper footing. When the lower slope angle changes to 45° the upper footing performance increased and lower footing get reduced. But when the angle increased more than 45°, the performances got reverse action ie, upper footing performance reduced and lower gets increased. From Figure 6, which presents the vertical stress vs normalized settlement of footing with constant slope angle for bottom level of slope, θ_b and varying slope angle for top level of slope, θ_a. It can be seen that when top and bottom slope angles were same (30°), the performance of upper footing is better than lower footing. The reduction in lower footing performance is due to the influence of upper footing. When the upper slope angle changes to 45° the upper footing performance increased and lower footing get reduced. But when the angle increased more than 45°, the performances got reverse action ie, upper footing performance reduced and lower gets increased. There is a reasonably good agreement of FEA results with experimental results for both cases.

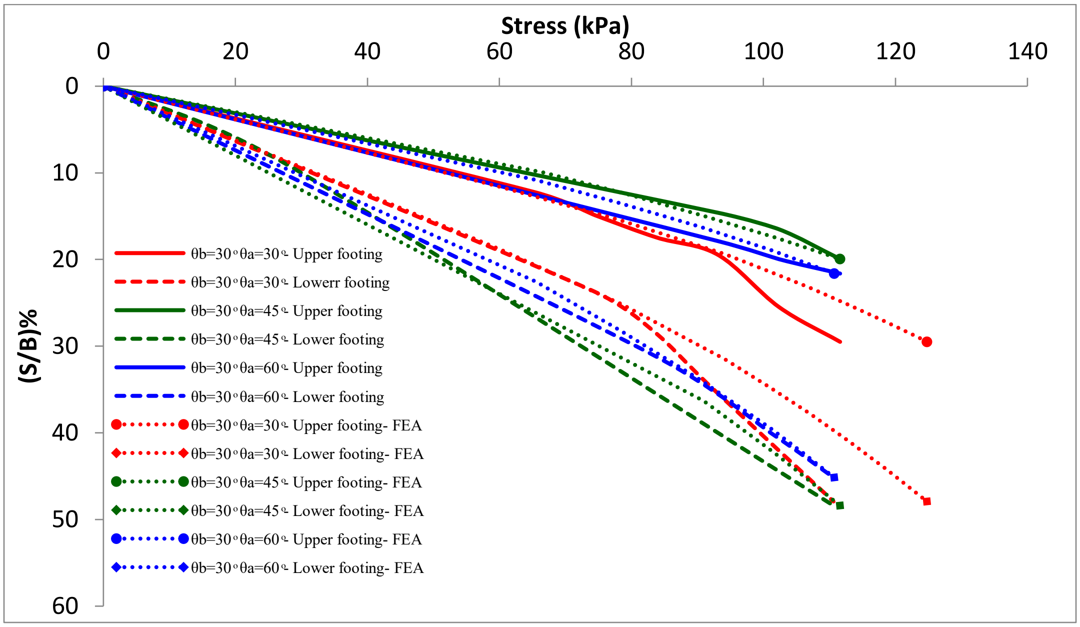

Figure 6. Vertical stress vs normalized settlement curves θ_b = 30° and θ_a = varying (e_a= e_b =5 cm)

In all the cases lower footing performance is lower than upper footing, it is mainly due to the influence of upper footing on the lower footing. Further it causes differential settlement for footings.

5 Conclusions

Based on the results obtained from experimental and finite element studies, the following conclusions can be made on the load - settlement behavior of footing resting on slopes.

1. Eccentricity and slope angle are major factors which affect the load settlement behavior of footing resting on slopes.
2. The upper footing adversely affects the load settlement behavior of lower footing.
3. The Performance of upper footing increased up to a slope angle of 45°.

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