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SETTLEMENTS OF RIGID RECTANGULAR FOOTINGS ON LAYERED SOILS

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ABSTRACT

Solutions to calculate the settlement of footings resting on a semi- infinite or finite soil layer are readily available in the literature. Whitman and Richart (1967) proposed the vertical settlement factors for rigid rectangular footing resting on a semi-infinite layer of soil. The equation takes into consideration the aspect ratio, defined as ratio of length to width, L/B, of the footing through a parameter 'β_z'. Sovinc (1969) proposed the settlement factors for a rectangular footing on a finite layer of homogeneous soil underlain by a rigid base. He also considered the effect of L/B on the settlement of the footing. However, Sovinc's solution is given only for one Poisson's ratio value equal to 0.5.

In reality, the soil profile is seldom homogenous and typically consists of a layered system. In such cases, only approximate solutions are available in the literature to determine the settlement of footing. Rectangular shaped footings are commonly used in practice, and this study is proposed to determine the settlement of rigid rectangular footing on a two-layered system underlain by a rigid base.

The settlement values are proposed by means of settlement influence factor, $I_{\rho,r}$, for various normalized parameters, viz., L/B, E_1/E_2, H_2/B, and H_1/B, where E_1 and E_2 are the deformation moduli of top and the bottom layers, H_1 and H_2 are the thicknesses of the top and bottom layers, respectively. A finite-element method based software - PLAXIS 3D- was used to determine the settlement of the rigid footing. Linear elastic model was considered for the soil layers. Prior to estimating the settlement of rectangular footing on two-layered system, the model was validated with the solution available for rigid footing on semi-infinite soil layer. The settlement of footing on finite two-layered system due to rigid rectangular loading can be represented using the following expression

$$\rho = \frac{qB(1-\nu^2)I_{\rho,r}}{E_2} \qquad \text{(Eq. 1)}$$

where, ρ is the settlement of rigid rectangular footing under an applied load of intensity equal to q.

The settlement influence factors are proposed in the form of charts to estimate the settlement of footing on a two-layered soil system underlain by a rigid base for various footing dimensions and thicknesses of the soil layers.

Keywords: rigid footing, layered soil, finite layer, settlement influence factor

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ABSTRACT: Soil profile underneath a footing is seldom homogenous and typically consists of layered soils. Only approximate solutions are available to estimate the settlement of footing resting on layered systems. In this study, the settlement of rigid rectangular footing on a two-layered soil system underlain by a rigid base is proposed. The settlement values are proposed by means of settlement influence factor, $I_{\rho, r}$, for various normalized parameters, viz., L/B, E_1/E_2, H_2/B, and H_1/B, where L/B is the aspect ratio of the footing, E_1 and E_2 are the deformation moduli of top and the bottom layers, H_1 and H_2 are the thicknesses of the top and bottom layers, respectively. The settlement influence factors are proposed in the form of charts and are also compared with that of a flexible footing.

INTRODUCTION

Foundations in general are neither perfectly rigid nor flexible. In case of single reinforced isolated footings, the footings behave more like a rigid footing, while in the case of mat foundation they behave more like a flexible footing. Analysis of both extreme cases will help understand the general behaviour [1]. Settlements under the footing will be uniform in the case of rigid footing while the contact stresses will vary along the footing width. The variation of contact stresses along the width depends on the type of deposit (sands or clays). Sands have higher contact stresses at the centre, while saturated clays develop higher contact stresses near the edges.

Whitman and Richart proposed settlement influence factor, β_z, for rigid footings on a semi-infinite homogeneous layer of soil for rectangular footings of different dimensions to determine the settlement values. The factor, β_z, depends on the aspect ratio, L/B, of the footing [2].

Sovinc proposed solutions for a rigid footing on a finite soil layer by proposing a settlement factor, β, where β depends on the aspect ratio, L/B, and the normalised thickness of the layer with respect to the length of the footing, H/L [3].

The US Navy Soil and Foundation design manual has also proposed the settlement of footings on both semi-infinite and finite layer of soil. They have given the settlement factors for both rigid and flexible footings at the centre and at the corners of a rectangular footing for various dimensions. In the case of finite soil layer, Poisson’s ratio values equal to 0.33 or 0.5 were considered [5].

Solutions are available mainly for footings resting on semi-infinite, homogenous soil layer or on finite soil layer underlain by a rigid base. However in reality, the soil profile underneath a footing is seldom homogeneous or finite. In areas like Hyderabad, Hong Kong, and Bangalore, authors have come across soil profiles that consist of two different soil layers underlain by a rigid base [4]. This paper proposes the settlement factors for such a two-layered soil system and for a finite layer of soil underlain by a rigid base.

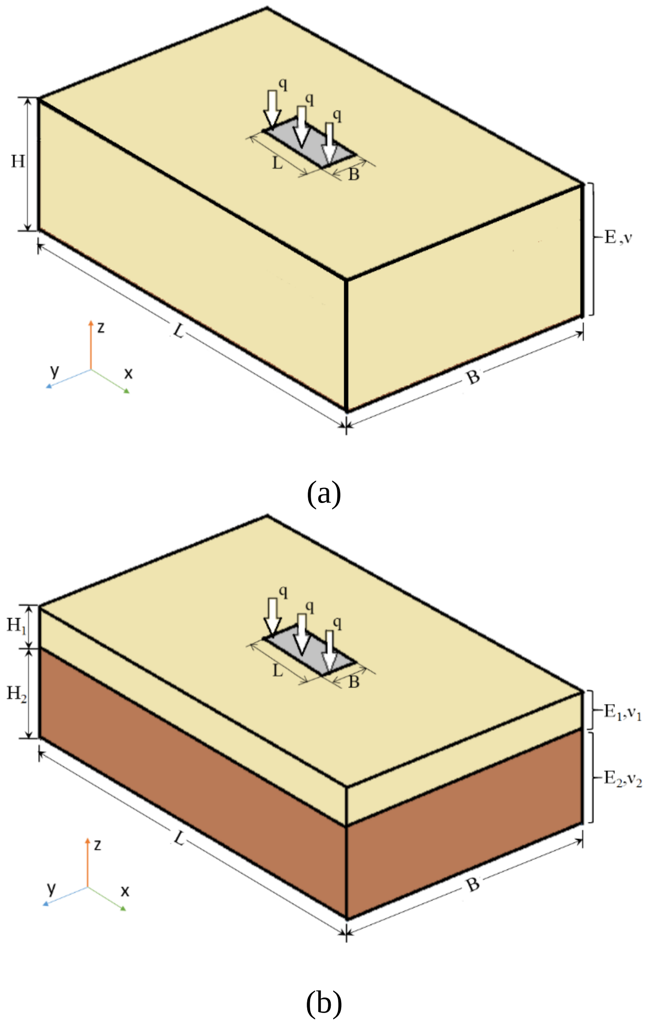


Fig. 1 Schematic showing a rigid footing resting on a) finite layer of soil, and b) two-layered soil system underlain by a rigid base

PROBLEM DEFINITION

A load of intensity, q, is applied on a rigid footing of dimensions equal to L and B, where L is the length of the footing and B is the width of the footing. The present study aims to estimate the settlement on footing resting on (a) a finite layer, and (b) on a two-layered soil system underlain by a rigid base (Fig. 1).

The settlement of two-layered system due to loading on rigid rectangular loading can be represented as given in Equation 1

$$\rho = \frac{qB(1-\nu^2)I_{\rho,r}}{E_2} \qquad \text{(Eq. 1)}$$

where, ρ is the settlement of rigid rectangular footing, ν is the Poisson's ratio of the soil, and E_2 is the deformation modulus of the bottom layer, and $I_{\rho,r}$ is the settlement influence factor.

The settlement influence factors for rigid footing are obtained for various geometric and elastic properties of the soil, and are also compared with the settlement influence factors obtained for flexible footing.

Finite Layer of Soil

The thickness of the soil is defined as H, and the elastic deformation properties- the deformation modulus and the Poisson's ratio- are defined as E and ν, respectively.

Two-Layered Soil System

The thicknesses of top and bottom layers are H_1 and H_2 and are underlain by a rigid base. The elastic deformation properties- deformation modulus and the Poisson's ratio- are represented as E_1, ν_1 and E_2, ν_2, respectively.

FINITE ELEMENT MODEL

Finite Element (FE) based software - PLAXIS 3D version 2013 - is used to model and obtain the settlement influence factor, $I_{\rho,r}$. Linear elastic model was considered for the soil layers. 10-noded triangular elements were used. Convergence study was done for both meshing and boundary distance. Fine refinement was chosen with local volume refinement of 0.125 times the element size. The boundary distance was chosen as 61 times the width of the footing. For example, the model depicted in Figure 2 has an average element size of 0.387 m with maximum and minimum element size equal to approximately 3.175m equal to 0.101m. Boundary condition at the top of the model was taken as free in all directions while it was fixed in all directions at the bottom. The boundary condition on front and back faces (parallel to length direction of the footing) were taken as fixed in y direction, i.e. u_y=0, and the boundary condition on lateral faces (parallel to the width direction) were taken as fixed in the x direction, i.e. u_x=0.

Automated boundary condition in PLAXIS 3D was adopted to account for these boundary conditions.

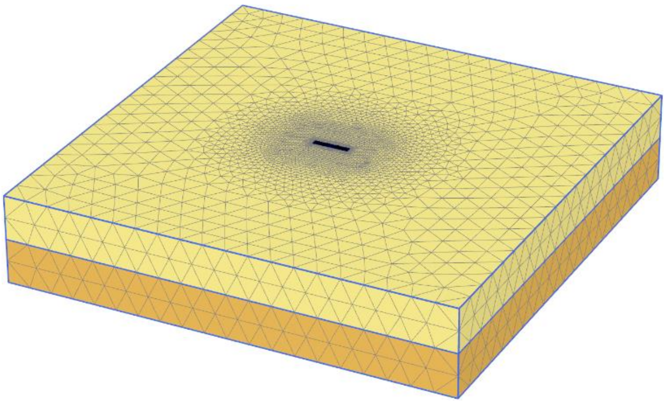


Fig. 2 Finite element model in PLAXIS 3D v 2013 for the case of L/B=5, H_1/B=6, H_2/B=6, E_1/E_2=100 for a two-layered soil system

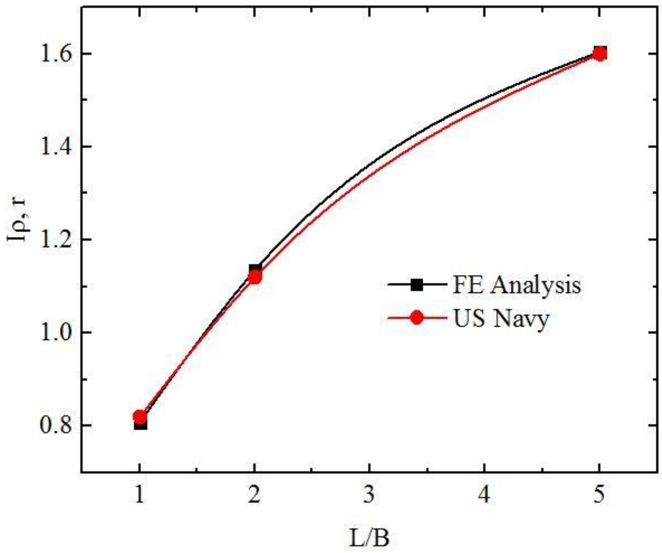


Fig. 3 Comparison of settlement influence factors from FE model and US Navy manual for the case of footing resting on a semi-infinite layer of soil

RESULTS AND DISCUSSION

Settlement influence factors for rigid footing has been proposed for infinite layer of soil, finite layer of soil with a rigid layer at the bottom, and two-layered soil system underlain by a rigid base. Settlement influence factor for rigid footing, $I_{\rho,r}$, has been proposed in the form of charts by varying L/B=1, 2 and 5, E_1/E_2=0.01, 0.1, 0.5, 2, 10 and 100, H_1/B=0.5,1, 2, 4 and 6, H_2/B=1,2, 4 and 6, and H/B= 1, 2, 4 and 6. Figure 4 shows the settlement influence factors $I_{\rho,r}$, for a finite layer of soil.

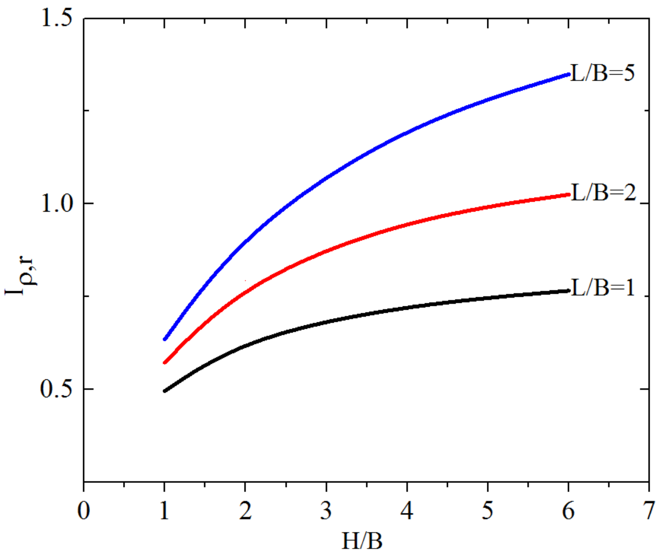


Fig. 4 Settlement influence factor for rigid footings resting on finite layer of soil

Validation

Prior to performing a detailed parametric study, the FE results from the present model were validated against the results published by the US Navy manual for the case of footing resting on semi-infinite layer. From Figure 3, it can be concluded that the results obtained using Finite Element model used in the present study are in very good agreement with the results published in the US Navy manual.

Settlement of Footing on Finite Soil Layer

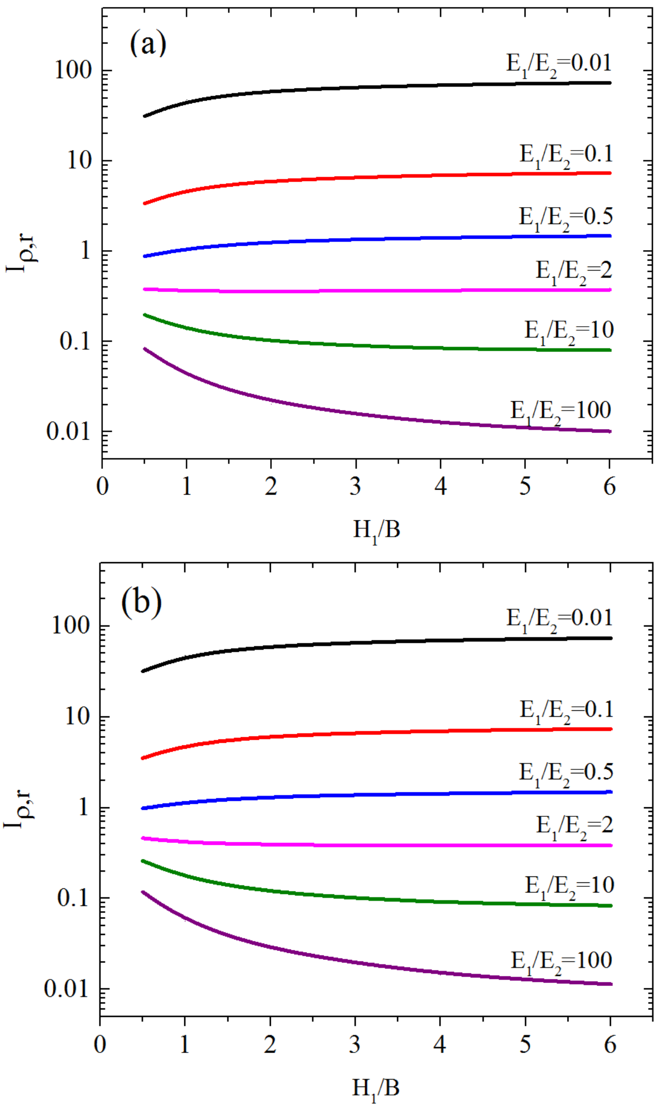
The settlement of footing on a two-layered soil system varies from that of footing resting on a single finite layer system when the thickness of the top layer is well within the depth of influence of loading on the footing.

Influence of L/B ratio

From Figure 4, it can be concluded that the settlement influence factor increases as the L/B ratio increases for a finite layer of soil underlain by a rigid base.

Influence of H/B

As H/B increases, the influence factor increases. However, the rate of increase is dependent on the depth of influence of footing of given aspect ratio of the footing. For example, in Figure 4, for L/B=1, the rate of increase becomes minimal for thickness of finite layer beyond 2.5B, while for L/B=2, the rate of increase is nominal beyond 4B.



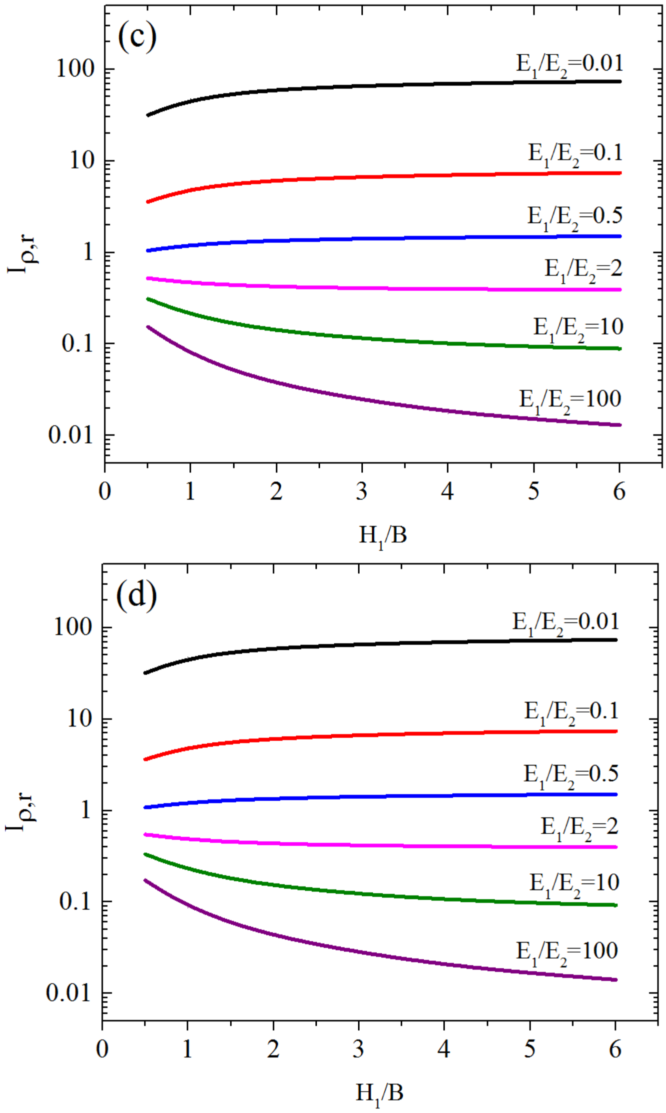


Fig. 5 Settlement influence factor for rigid footing for L/B=1 for various H_1/B and E_1/E_2 values corresponding to (a) H_2/B=1, (b) H_2/B=2, (c) H_2/B=4, and (d) H_2/B=6

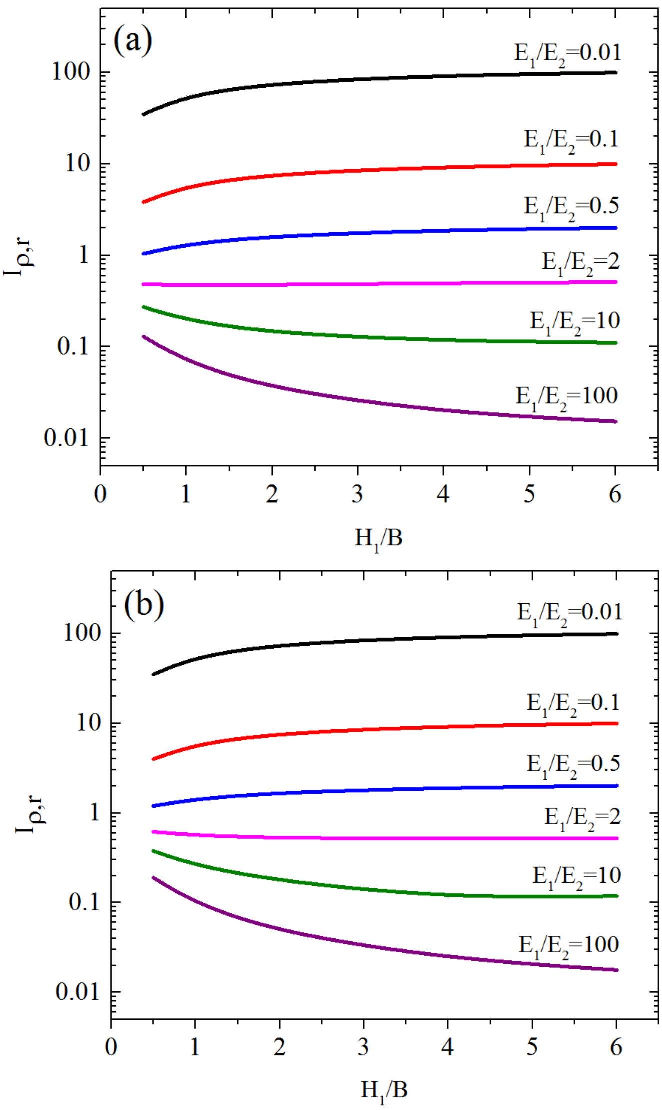
Two-Layered Soil System

Influence of L/B

As with the case of finite layer, in two-layered soil system the settlement influence factor increases as the L/B value increases. For example, for L/B=1 and 2 corresponding to H_1/B=2 and H_2/B=2 and E_1/E_2=0.01, it can be observed that the value varies by 16% while between L/B=2 and 5 for the same parameters, the variation is about 11% as seen from Figures 5(b), 6(b) and 7(b).

Influence of E_1/E_2

The ratio E_1/E_2 refers to the relative stiffness of top layer to that of the bottom layer. From the Figures 5 to 7, as E_1/E_2 increases, the settlement influence factor decreases. From Figure 5(a), for L/B=1, H_1/B=2, H_2/B=1, it can be seen that the settlement influence factor decreases by 378% as E_1/E_2 increases from 0.1 to 0.5. The top layer becomes stiffer when compared to the bottom layer as E_1/E_2 increases. Hence, the settlement decreases as the top layer becomes stiffer.



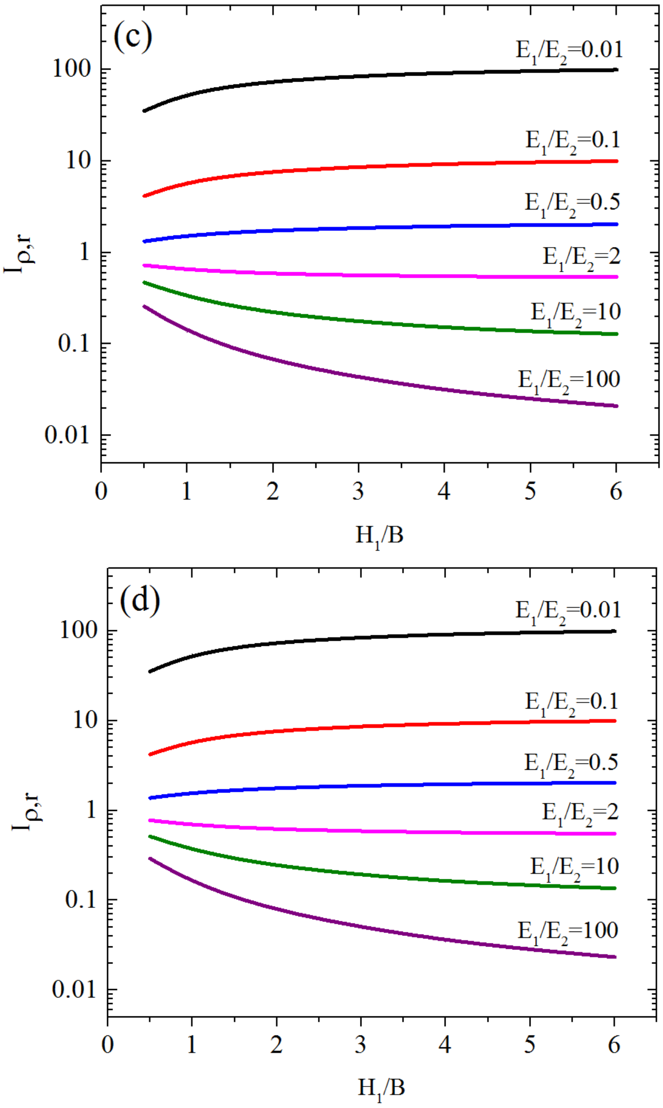
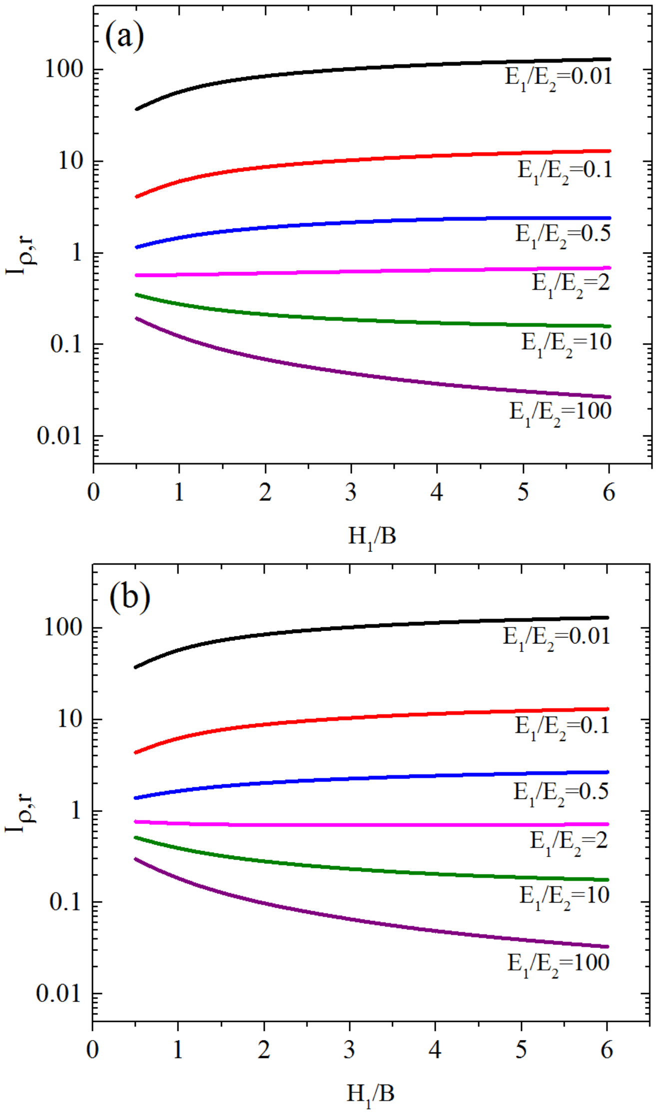


Fig. 6 Settlement influence factor of rigid footing for L/B=2 for various H_1/B and E_1/E_2 values corresponding to (a) H_2/B=1, (b) H_2/B=2, (c) H_2/B=4 and (d) H_2/B=6

Influence of H_1/B

From Figure 5, as H_1/B value increases the settlement increases for $E_1/E_2<1$, while it decreases for $E_1/E_2>1$. For example, in the same figure, for L/B=1, E_1/E_2=0.01, H_2/B=1, as H_1/B increases from 0.5 to 1, the settlement factor increases by 51%, while for E_1/E_2=10, the value decreases by 31% from the same increase in H_1/B. As the top layer is stiffer than the bottom layer ($E_1/E_2>1$), it will have significant effect in reducing the settlement of the footing. Similarly, for $E_1/E_2<1$, the top layer becomes less stiff compared to the bottom layer, and settlement of footing become large due to thicker soft layer.

From Figure 5, it is inferred that the rate of change decreases as H_1/B value increases. For example, for L/B=1, E_1/E_2=0.1, H_2/B=1, the variation between H_1/B=0.5 and H_1/B=1 is 51%, while between H_1/B=4 and 6, the variation is reduced to 5%. The reduction in the rate of change, either increase or decrease, is due to the fact that as the top layer thickness increases, the stratum behaves more like a one finite layer of soil and the influence of the bottom layer is eliminated, more so in the case of top layer with higher stiffness.



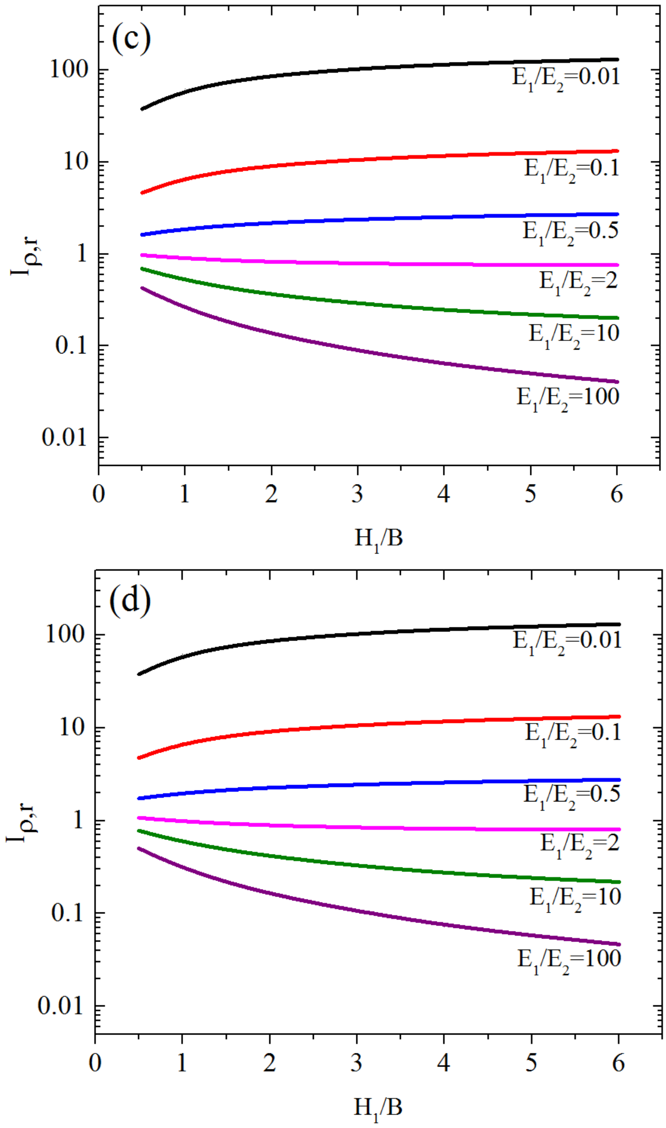


Fig. 7 Settlement influence factor for rigid footing for L/B=5 for various H_1/B and E_1/E_2 values corresponding to (a) H_2/B=1, (b) H_2/B=2, (c) H_2/B=4 and (d) H_2/B=6

Influence of H_2/B

From Figure 5(a) and (b), as the H_2/B ratio increases, the settlement influence factor also increases. For example, as H_2/B ratio increases from 1 to 2 for L/B=1, E_1/E_2=0.5, H_1/B= 0.5, the settlement influence factor increases by 1%. As the H_1/B value increases, the influence of H_2/B decreases. The influence of the bottom layer decreases as the top layer stiffness increases.

Comparison between flexible and rigid footings

Figure 8 shows the comparison between the settlement factors obtained for rigid and flexible footing at the centre of the footing. As expected, the settlement of the flexible footing is higher when compared to the settlement of the rigid footing at the centre. In flexible footings, the settlement at the centre is the maximum while it tapers at the extremes, while in rigid footings an average settlement is expected throughout the width of the footing.

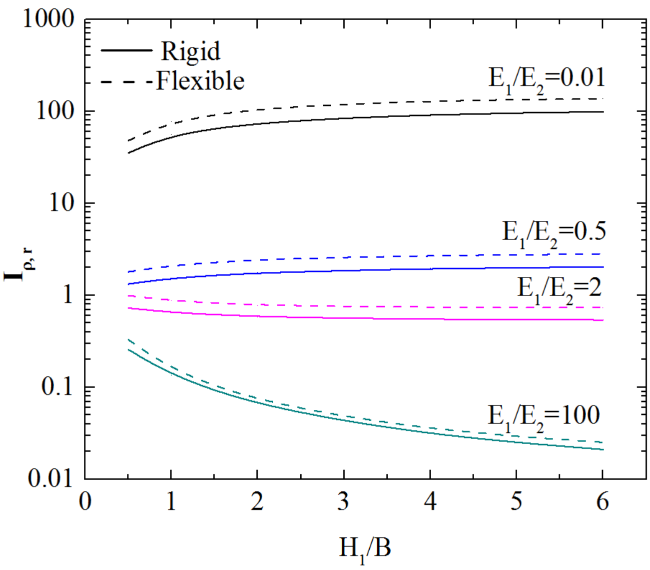


Fig. 8 Variation of settlement factors with H_1/B values for rigid and flexible footings for L/B=2, and H_2/B=4

CONCLUSION

The settlement influence factors have been proposed in the form of charts for rigid footing resting on finite layer underlain by a rigid base and on a two-layered soil system underlain by a rigid base. Various geometries of footing and of the soil thicknesses were considered. In addition, both a stiff layer overlying a soft layer and vice versa were considered. The settlement factors obtained for rigid footing were compared to that obtained for loading on a flexible footing.

REFERENCES

1. Salgado R., The Engineering of Foundations, *Tata McGraw Hill*, 2011 Edition.
2. Whitman R. V. and Rickart F. E. (1967), Design Procedure for Dynamically Loaded Foundations, *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 93, No. SM6, page 169- 193
3. Sovinc, I. (1969), Displacements and Inclinations of Rigid Footings Resting on a Limited Elastic Layer of Uniform Thickness, *Proceedings of 7th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, page 121
4. Soil and Foundations Design Manuals (1986), *US Navy*, *Washington D. C.*, DM-7.1
5. Umashankar, B., Yugandhar, D. and Madhav, M.R. (2013), Settlement due to Uniform Circular Load: On Finite Two-Layer System, *Geotechnical and Geological Engineering*, 31(1), 255- 265.