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V–H Capacity Envelopes of Strip Footings on Cohesionless Soil Overlying Soft Rock Mass

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Abstract. This study presents a numerical investigation on development of vertical axial force-shear force (V-H) capacity envelopes of strip footing placed on the surface of cohesionless soil having different ϕ overlying on the soft rock with constant GSI, mi and D values. Force-based swipe analyses are conducted using OptumG2 following lower bound solution for finite element limit analysis. The results are presented in terms of, variation in bearing capacity ratio (B_{cr}) with soil-rock thickness ratios (T_s/B) and V-H capacity envelope varying with ϕ and T_s/B. It is found that, the normalized capacity envelope for strip footing placed at top of pure cohesionless soil is almost similar for any value of ϕ. Further, for a particular T_s/B, the shape of normalized V-H capacity envelope increases with the increase in higher ϕ values. The normalized capacity envelope was found unaffected by T_s/B value beyond 4.0, for a soil with any value of ϕ.

Keywords: *Strip Foundation, Cohesionless soil, Bearing capacity, Capacity envelope, Finite-element limit analysis (FELA)*

1 Introduction

Shallow foundations are widely used in practice, where the shear strength of upper strata is high and capable enough to support the associated structures. Many literature [1-3] and standards [4,5] are available to estimate the vertical bearing capacity of shallow foundations resting on flat homogeneous ground. However, in the case of offshore structures subjected to wind or seismic loading, the foundations are often subjected to interactive vertical/axial force (V) and shear force (H). The effect of the combined loading can be dealt by including the effect of horizontal shear as the load inclination factor and moment as the effective width of the foundation [4,5]. To deal with the shallow foundation subjected to the combined interactive loading, an alternate approach, the capacity envelope is used primarily for offshore structures. In the past, several researchers have estimated the normalized V-H capacity envelope for shallow foundation, using analytical solutions and developed empirical equations, resting either on homogeneous cohesive soil [6-14] or homogeneous cohesionless soil [15-24] or cohesive-frictional soil [25,26]. From the literature review, it has been found that the maximum shear capacity of foundation was achieved at vertical load, varying between 0.4 to 0.6 times of vertical capacity. In some cases, the foundation is constructed on a layered soil system with varying strength along the depth, supported by an overlying rock mass [27]. An ample of literature is available on estimation of the bearing capacity of shallow foundation resting on rock mass [28-38], using analytical and numerical methods. Recently, Das and Chakraborty [27] estimated the bearing capacity of strip footing resting on cohesionless soil overlying rock mass. In the author's capacity, the estimation of V-H capacity envelope for strip footing resting on cohesionless soil overlying soft rock mass has not been studied yet.

In this article, a numerical study has been conducted for the estimation of capacity envelope of the strip footing, located on the surface of cohesionless soil overlying soft rock, subjected to V-H combined loading using lower bound finite element limit analysis (LB-FELA). The vertical bearing capacity (V_0) of the considered strip footing located on the surface of cohesionless soil overlying soft rock mass has been estimated. The results are presented in the form of V-H capacity envelope varying with soil strength parameters and soil-rock thickness ratios (T_s/B, ratio of thickness of the cohesionless soil layer to the width of strip foundation.). The variation in bearing capacity ratio (B_{cr}, ratio of bearing capacity of cohesionless soil to the bearing capacity of cohesionless soil overlying rock mass) with T_s/B has also been presented, herein.

2 Problem statement

To develop V-H capacity envelope, a rough and rigid strip footing with width, B kept on the top surface of the homogeneous cohesionless soil with varying internal friction angle (ϕ) has been considered in this study, as shown in Fig. 1.

Table 1. Material properties

Properties	Cohesionless Soil	Rock
Unit weight (γ kN/m^3)	20	0
Poisson's ratio (ν)	0.3	0.3
Angle of internal friction (ϕ)	25°, 30°, 35°, 40°	-
Geological Strength Index (GSI)	-	10
m_i	-	7
D	-	1

In Fig. 1, the thickness of top soil layer consists of cohesionless soil following Mohr-Coulomb yield criteria, has been considered as T_s. Whereas the thickness of bottom layer consists of soft rock mass having Hoek-Brown parameters such as GSI (Geological strength index), m_i (Hoek-Brown yield parameter) and D (Disturbance factor), has been considered as T_r. Table 1 shows the material properties used in the present study.

Based on the sensitivity analysis, the width and depth of the FE model has been kept 20B and 10B, respectively.

The effect of the varying soil-rock thickness ratio, T_s/B (T_s/B = 0.5, 1, 1.5, 2, 3, 4, 5 and 6) on the vertical bearing capacity and V-H capacity envelope has been explored here.

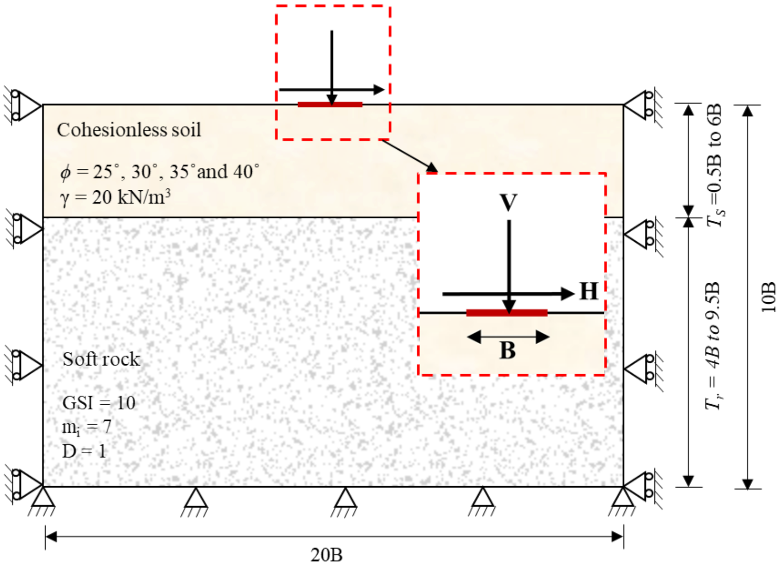


Fig.1 Problem geometry of strip footing placed on cohesionless soil overlying soft rock

3 FE Modeling and Analysis

In the present study, lower bound finite element limit analysis (LB-FELA) has been employed to evaluate the vertical bearing capacity and V-H capacity envelope of strip footing using OptumG2 [39] software. A 2-D plain strain FE model has been developed for a strip foundation lying on top of flat two-layered soil-rock system. Among these two layers, the top layer consists cohesionless soil obeying Mohr-Coulomb failure criterion with associated flow rule, whereas the bottom layer consists of soft rock following Generalized Hoek Brown failure criterion [40] with associated flow rule. The strip footing has been considered as weightless and modelled using rigid plate. Based on the sensitivity analysis, the width and depth of the FE model has been kept 20B and 10B, respectively. In this study, the value of T_s and T_r have been considered varying from 0.5B to 6B and from 4B to 9.5B, respectively as considered in past study [27]. In this study, as a special case T_s = 10B or T_r = 0 represents the pure cohesionless soil.

The interface element (with reduction factor, R = 1) has been used between the foundation and soil layer. Fan meshes has been used at both ends of the footing to handle stress concentration or singularity issue, The FE model consists of soil and rock mass has been discretize with three-noded triangular plane-strain elements. The number of elements utilized in each analysis has been varied from 8,000 to 10,000 with three adaptive iterations. The force-based swipe analysis [25,41] has been performed to obtain the limit load and to develop entire V-H capacity envelope, where V and H were applied at the mid-point of the strip footing in a fixed (H/V) ratio varying between 0.90 and 40. All the movements were restricted at the base of FE model, whereas only horizontal displacement was restricted at the lateral boundaries.

The normalized vertical load, $\dot{V}$ and horizontal load, $\dot{H}$ have been obtained as:

$$\dot{V} = \frac{V}{V_o} \tag{1}$$

$$\dot{H} = \frac{H}{V_o} \tag{2}$$

4 Results and Discussions

In this section, the results of the present study have been discussed in terms of, (a) variation in bearing capacity ratio (B_{cr}) with T_s/B and (b) the capacity envelope varying with soil strength and T_s/B. Figure 2 shows the variation in bearing capacity ratio (B_{cr}) with T_s/B. It is interesting to note that, with the increase in the value of T_s/B for a particular soil having constant value of ϕ, the value of B_{cr} increases and become constant (= 1) at higher value of T_s/B. It can also be observed that, at a particular value of T_s/B, with the increase in the value of ϕ, the value of B_{cr} decreases.

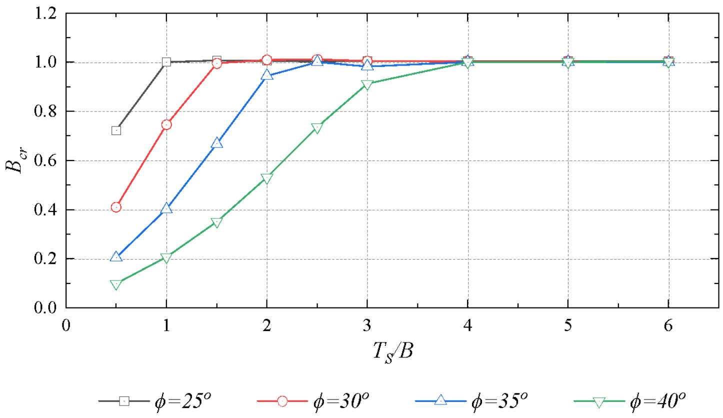


Fig.2 Variation in bearing capacity ratio (B_{cr}) with soil-rock thickness ratios (T_s/B)

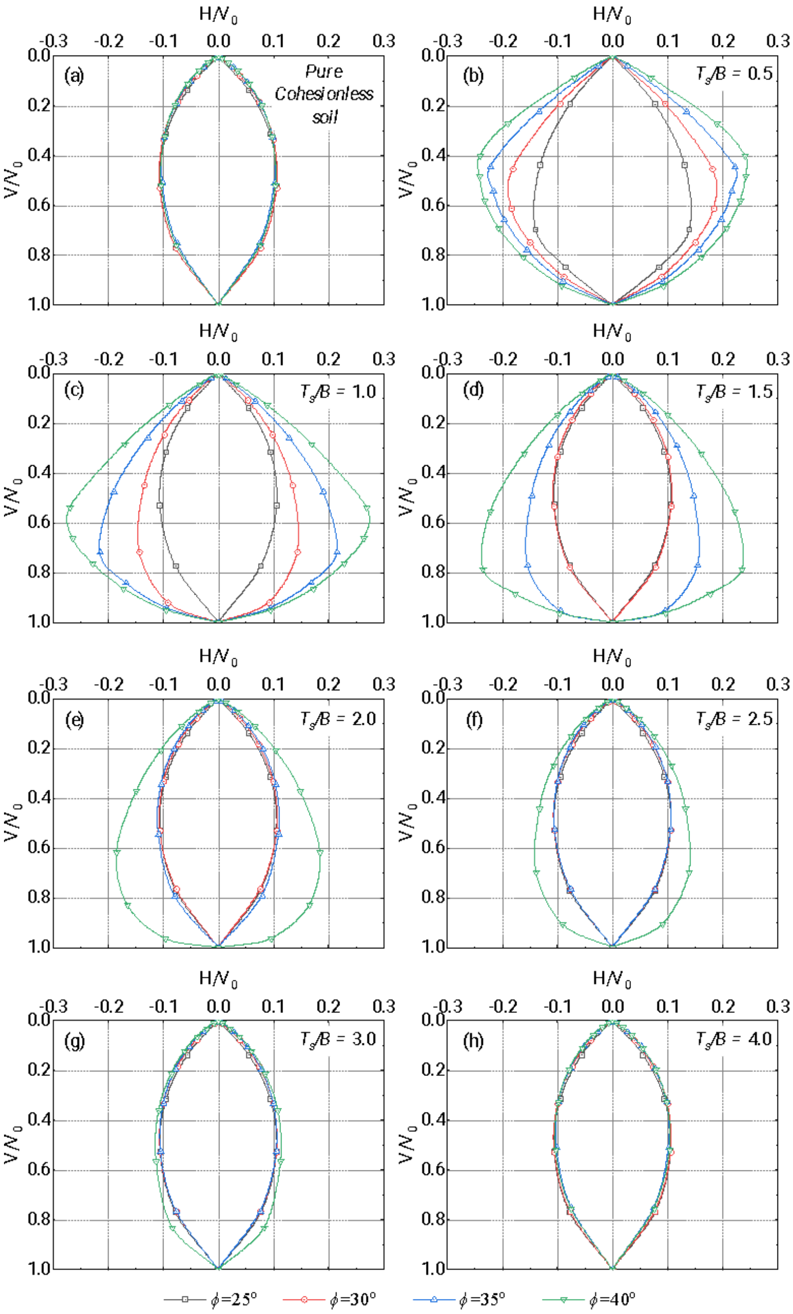
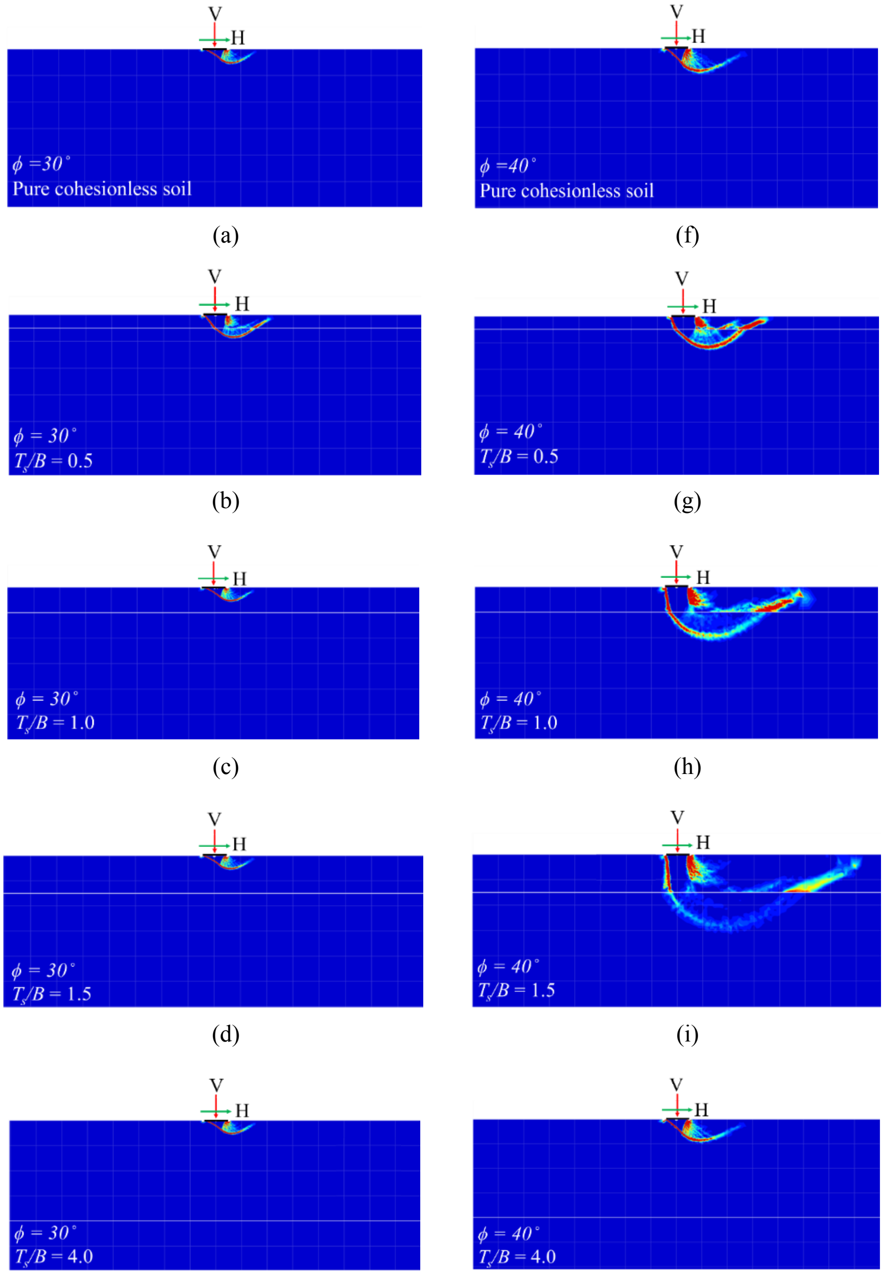


Fig.3 Comparison of V-H capacity envelope for strip footing placed on cohesionless soil having different ϕ values and overlying soft rock mass with: (a) T_s/B = 10 (pure cohesionless soil); (b) T_s/B = 0.5; (c) T_s/B = 1.0; (d) T_s/B = 1.5; (e) T_s/B = 2.0 and (f) T_s/B = 2.5; (g) T_s/B = 3.0 and (h) T_s/B = 4.0.



(a) (f)

(b) (g)

(c) (h)

(d) (i)

(e) (j)

Fig.4 Failure surface represented by shear dissipation profile for the strip footing subjected to interactive V-H loading and located on cohesionless soil overlying soft rock with: (a) $\phi = 30^\circ$, $T_s/B = 10$; (b) $\phi = 30^\circ$, $T_s/B = 0.5$; (c) $\phi = 30^\circ$, $T_s/B = 1.0$; (d) $\phi = 30^\circ$, $T_s/B = 1.5$; (e) $\phi = 30^\circ$,

T_s/B = 4.0; (f) ϕ = 40°, T_s/B = 10; (g) ϕ = 40°, T_s/B = 0.5; (h) ϕ = 40°, T_s/B = 1.0; (i) ϕ = 40°, T_s/B = 1.5; and (j) ϕ = 40°, T_s/B = 4.0.

Figure 3(a-h) presents the variation in the shape of normalized capacity envelope (H/V_0 with V/V_0) with varying ϕ and T_s/B values. It can be observed from the Figure 3(a) that, the effect of varying ϕ value has no significant influence on the normalized capacity envelope for strip footing placed at top of pure cohesionless soil [21].

It is interesting to note that, the T_s/B value (ranging from 0.5 to 3.0) has significant influenece on the normalized capacity envelope for a particular soil with higher value of ϕ. Further, the normalized capacity envelope was found unaffected by T_s/B value beyond 4.0, for a soil with any value of ϕ. It can also be observed that, the maximum value of normalized shear capacity (H/V_0) for soil-rock system was found 1.7 times that of the pure cohesionless soil with ϕ = 40°, at T_s/B = 1.0.

Figure 4(a-j) shows the failure surface represented by shear dissipation profile for foundation resting on soil (with ϕ = 30° and 40°) overlying soft rock system with different values of T_s/B and subjected to combined V-H loading. It can be noted that, the failure surface is always asymmetric or one-sided for all the considered cases. It is also found that the shape and depth of the failure surface dependent on the both T_s/B and ϕ values.

5 Conclusions

The V-H capacity envelope for strip footing placed on cohesionless soil overlying soft rock has been develop by performing LB-FELA using OptumG2. The effect of T_s/B and ϕ on bearing capacity ratio (B_{cr}), shape of capacity envelope and corresponding failure surface of soil-rock system, has been explored here in details. It was noted that, with the increase in T_s/B value for a particular soil, the value of B_{cr} increases and then become constant (= 1) at higher value of T_s/B. It was also observed that, at a particular T_s/B value, the B_{cr} decreases with the increase in ϕ. For strip footing place on top of two layered soil-rock system, a significant variation in capacity envelope has been seen with increasing ϕ value and T_s/B ranging between 0.5 and 3.0, whereas for T_s/B greater than 4.0 the variation in capacity envelope is insignificant and became indepent of both T_s/B and ϕ values. The present analysis has been performed by assuming the soil and rock consists of homogenous material and limit loads are obtained using LB-FELA, hence the results are restricted to the investigated case only. For more realistic understanding, a comprehensive study considering material shear strength varying spatially, is required.

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