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Numerical Investigations on Strip Footing Near Vertical Cut Rockmass Cliff

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Abstract. The experimental studies on the stability of rockmass cliffs due to a nearby foundation system is an unexplored area and needs further investigation. In this study, the effect of different height of vertical cut (*H/B*) and setback distance (*S/B*) on the stability of a strip footing placed over weightless rockmass is evaluated using a finite element limit analysis (FELA) based program. Where the *H* is the height of the cliff, *B* is the width of the strip footing and *S* is the distance between the cliff and strip footing. The rockmass is modelled using nonlinear Hoek and Brown failure model. The stability of footing is quantified in terms of variation in $N_{\sigma 0}$ for different horizontal setback distances (*S/B* = 0 to 15) and heights of rockmass cliff (*H/B* = 0, 1, 5, 10). The stability is evaluated for different rockmass parameters as Geological strength index (GSI), Hoek and Brown material constant (m_i), uniaxial compressive strength (σ_{ci}), Poisson's ratio (v) and modulus of elasticity (E). The present study results indicate a significant reduction in $N_{\sigma 0}$ values with increase in the height of rockmass cliff and decrease in the setback distance.

Keywords: Strip footing, Finite element limit analysis, Rockmass, Hoek and Brown failure model, Cliff, GSI and m_i.

1 Introduction

Natural landforms composed of rockmass, particularly when in the form of mountains and sea facing cliffs, possess natural beauty and attract a lot of tourist. With the rapid growth of population and urbanization, such cliffs are occupied and raise stability concerns for the current and future construction activity to be carried out in its vicinity. The damage caused due to failure of such cliffs may cause closure of major transportation routes, especially in the case of mountainous cliffs (Hoek, 2007). The design engineers have to consider the highly anisotropic nature of rockmass before construction over such vertical cut cliffs.

Understanding the factors affecting the stability of rockmass, evaluating the strength and ultimate bearing capacity of rockmass has remained a hot topic of research for the past few decades. Formulations provided by Hoek and Brown (1980) and its subsequent revisions often form the basis of obtaining the bearing capacity of the foundation system resting over the rockmass. With availability of more advanced finite element limit analysis (FELA) tools, the original formulations have been modified and are used to obtain precise results (Merifield et al., 2006; Serrano et al., 2000; Jaiswal et al., 2021). In the past, researchers have conducted studies to analyse the effect of basic rock parameters such as uniaxial compressive strength of intact rock (σ_{ci}), Geological strength index (GSI), Hoek and Brown material parameter (m_i) among others (Chen et al., 2022). Effects of other parameters such as groundwater level (Alencar et al., 2021), depth of embedment (Imani et al., 2020; Roy et al., 2022) and shape of footing (Chakraborty et al., 2015; Mansouri et al., 2019) placed over a jointed as well as intact rockmass have been explored and quantified by researchers in the past. Upper bound and lower bound FELA are often used in such cases and are found to give reasonably accurate results.

Assessment of rockmass slope stability on similar grounds has been carried out in the past by the researchers and detailed stability charts are available for varying slope angles (Li et al., 2008; Wei et al., 2020). When it comes to rockmass in the form of vertical cliffs, for both natural and cut slopes, stability is often quantified in terms of results based on rockmass classification system, angle of discontinuities present in the rockmass and prevailing natural conditions contributing in cliff erosion such as sea waves, rainfall, etc. (Bidyashwari et.al, 2021; Singh et al., 2020; Al-Bared et al., 2019; Budetta et al., 2000; Pantelidis, 2010). Wolters et al. (2008) in their study list the height of vertical cliff as an important parameter affecting the stresses being generated in the cliff. Also, as in the case of Zhang et al. (2015), the vicinity of the foundation system from cliff face is one such parameter that might influence the overall stability of cliff. Although the effect on the bearing capacity of strip footing founded on rockmass having slope in its vicinity has been explored in the past, both for seismic and static conditions (Saada et al., 2011; Wu et al., 2021), very few studies of the same nature are available when it comes to vertical rockmass cliffs, making this an unexplored topic which needs further investigation.

In the study, the numerical investigation has been carried out with the objective of determining the influence of height of vertical rockmass cliff and the horizontal setback distance from the rockmass to foundation system on stability of the foundation. Optum G2 is used to carry out FELA on a strip footing placed over a weightless rockmass vertical cliff using a nonlinear Hoek and Brown model. The stability of footing is quantified in terms of $N_{\sigma 0}$ by varying the heights of the vertical cliff (H/B = 0, 1, 5, 10) and the horizontal setback distances (S/B = 0 to 15) in terms of width of strip footing, B. The different combinations of basic parameters such as compressive strength of intact rock (σ_{ci}), Geological strength index (GSI), Hoek and Brown material parameter (m_i), Poisson's ratio (ν) and modulus of elasticity (E) are used in the model to evaluate the bearing capacity of rockmass. The disturbance factor is considered as zero throughout the analysis.

2 Problem Statement

In the present investigation, the stability of a strip footing of width B placed over a weightless rockmass cliff is evaluated. The schematic representation of the proposed study is shown in Fig. 1, which shows the proposed variation in the geometric variables with all the boundary conditions and supports. The footing is modelled as perfectly rough, weightless and rigid with its width as B = 1 m. The footing is placed on the surface and hence, it can be assumed that no surcharge is acting over the rockmass bed.

For the purpose of simplification, the rockmass bed was assumed to be undisturbed, homogeneous and isotropic. The geometry of the model is set such that no stresses are transferred to the boundaries. The extent of boundaries was set so that a minimum setback of $10B$ was provided to the footing in both vertical as well as horizontal directions for all variations in heights and setback distances. The boundary conditions were adopted as ‘standard fixities’ which are composed of roller support in the vertical direction and fixed supports in the horizontal direction. The height representing the vertical cut of cliff is set free to move.

The numerical investigation involved in this study was carried out using Optum G2 which is a geotechnical FELA software. This software uses an adaptive meshing technique by virtue of which the software by itself provides the required number of nodes and meshing pattern based on the failure envelope of the foundation material. For the purpose of this investigation, a rigorous upper and lower bound limit analysis was carried out until soil collapse and the average of the two values obtained was used to determine bearing capacity of footing resting on rockmass vertical cliff.

The numerical model used for the purpose of investigation is based on the 2007 version of the Hoek and Brown criteria provided by the software, which obtains strength of strip footing based on input values of basic rockmass parameters such as compressive strength of intact rock (σ_{ci}), Geological strength index (GSI), Hoek and Brown material parameter (m_i), Poisson’s ratio (ν) and modulus of elasticity (E) whose values are provided in Table 1. The Hoek and Brown model and various parameters will be discussed in the upcoming sections. It is noted that the values E and ν were default values provided by the software itself and same were used in the analysis.

Table 1 Material properties used in the analysis

Parameter	**Value/Description**
Footing type	Strip
Base	Rough
Width of strip footing, B (m)	1
Drained density of rockmass, γ (kN/m^3)	0
Uniaxial compressive strength, σ_{ci} (kN/m^2)	50
Young’s modulus, E (kN/m^2)	30000
Poisson’s ratio, ν	0.25
Geological strength index (GSI)	10, 50, 100
Hoek and Brown material constant (m_i)	5, 20, 35
Disturbance factor, D	0

For the determination of bearing capacity of strip footing resting on a rockmass, an equation similar to the case of bearing capacity of soil (Terzaghi, 1943) has been used which can be stated in the form of Eq. (1) (Rahman et al., 2022):

$$q_u = \sigma_{ci} N_\sigma + q_0 N_q \tag{1}$$

Where, N_σ and N_q are the non-dimensional bearing capacity factors corresponding to self-weight of the rockmass and surcharge, respectively. For the case of strip footing lying over a weightless rockmass having no surcharge, $q_0 = 0$ and the N_σ becomes $N_{\sigma 0}$ and with this q_u can be evaluated using Eq. (2):

$$N_{\sigma 0} = \frac{q_u}{\sigma_{ci}} \tag{2}$$

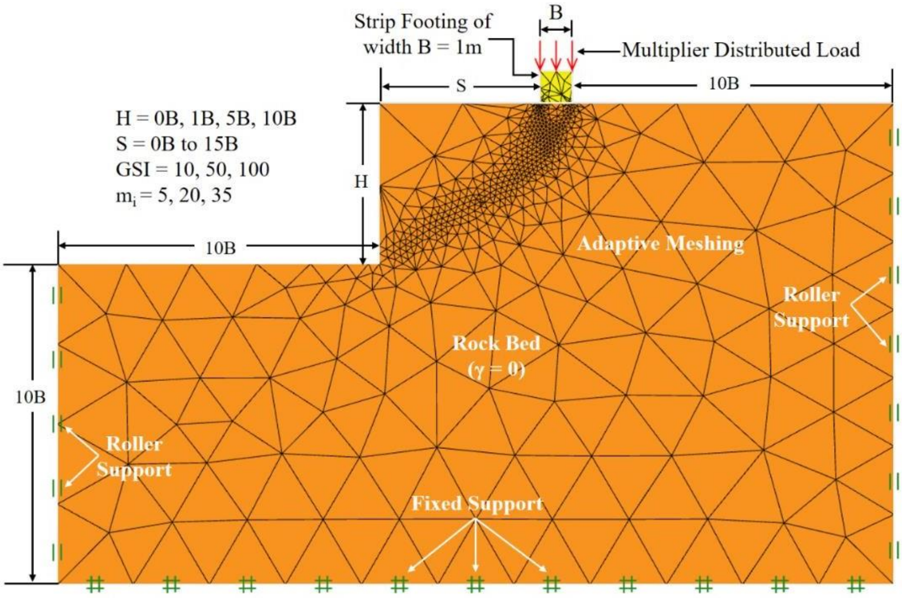


Fig. 1 FELA model of strip footing resting on weightless vertical cut rockmass cliff

3 FELA Model

In order to evaluate the effect of height of vertical cliff and horizontal distance of cliff face from strip footing on the stability of strip footing, the height of vertical cut H and horizontal setback distance S were varied in the terms of the width of strip footing B, as shown in Fig. 1. The stability of footing was quantified in the terms of $N_{\sigma 0}$ as defined earlier and the height of the vertical cliff and the horizontal setback distance were varied in the form H/B = 0, 1, 5, 10 and S/B = 0 to 15, respectively. Along with this, with each combination of cliff height and setback distance, the effect of variation in the values of basic rockmass material parameters i.e., GSI and m_i were also varied. The GSI values were varied as 10, 50 and 100. Similarly, m_i values was varied as 5, 20 and 35 for each variation of cliff height and setback distance. A multiplier distributed load of 1 kN/m^2 was applied on the rigid strip footing in uniform steps until the progressive failure of the rockmass underneath the footing occurred. The upper bound and lower bound limit analysis for each iteration was conducted and collapse load for each case was evaluated and then the $N_{\sigma 0}$ was obtain using Eq. (2). The average of the two values (upper bound and lower bound) is reported as results of the study.

3.1 Hoek and Brown Model and Input Parameters

Hoek and Brown model and its subsequent revisions are one of the most widely accepted and practiced for determining the shear strength of rockmass. It takes into account the limitations of other techniques such as RMR given by Bieniawski (1976) and Q-system given by Barton (2002) which do not account reasonably for rockmass of low strength. The results obtained from the Hoek and Brown model are fairly accurate and are often used for determination of bearing capacity, slope and tunnel stability among others (Merifield et al. 2006; Chakraborty et al., 2015; Li et al., 2008). The latest revision links the major and minor principal stresses [denoted by σ_1 and σ_3 respectively, given in Eq. (3)] developed within the rockmass with the compressive strength of intact rock (σ_{ci}), Geological strength index (GSI), Hoek and Brown material parameter (m_i) among other material parameters which are in turn dependent on GSI only, as can be seen from Eqs. (4) – (6) respectively. The GSI values quantifies with the strength of rockmass with values being varied from GSI = 10 (i.e., rocks of extremely poor strength) to GSI = 100 (i.e., rocks of excellent strength). The material parameter m_i has a range from 5 to 35. The factor D refers to the disturbance factor, which quantifies the disturbance caused in the rock structure due to blasting, impact loading or any other kind of sudden relaxation of stress. Its value is either 0 or 1 with D = 0 denoting intact rock and D = 1 denoting disturbed rock. For the purpose of this study, only intact rock was considered (i.e., D = 0).

$$\sigma_1 - \sigma_3 - \left[-m_b\sigma_1(-\sigma_{ci})^{(1-\alpha)/\alpha} + s(-\sigma_{ci})^{1/\alpha}\right]^{\alpha} \le 0 \tag{3}$$

$$m_b = m_i exp\left(\frac{GSI - 100}{28 - 14D}\right) \tag{4}$$

$$s = exp\left(\frac{GSI - 100}{9 - 3D}\right) \tag{5}$$

$$\alpha = \frac{1}{2} + \frac{1}{6}\left[exp(-GSI/15) - exp(-20/3)\right] \tag{6}$$

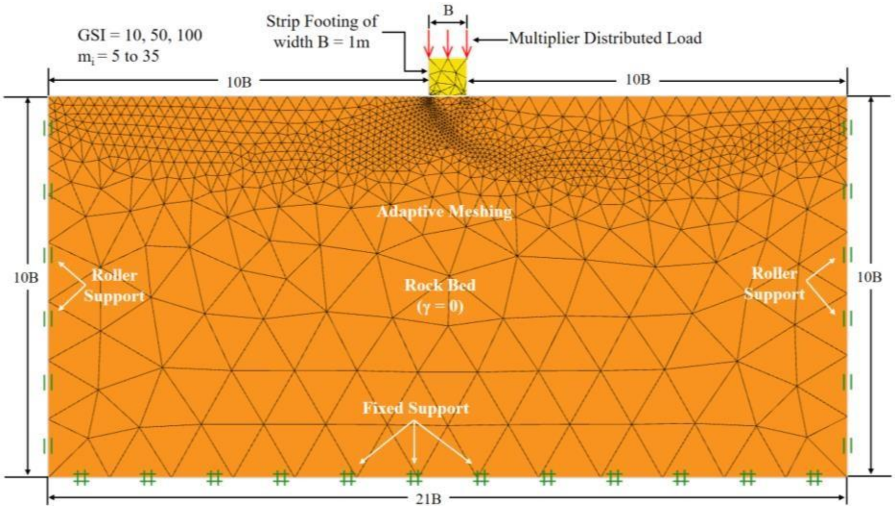


Fig. 2 FELA model of strip footing used for validation

3.2 Validation of FELA Model

For the purpose of validation of the FELA model under consideration, the stability of a strip footing of width B placed on horizontal weightless rockmass (i.e., H/B = 0) was evaluated in terms of $N_{\sigma 0}$. The schematic diagram of the same is provided in Fig. 2. The effect of variation of m_i was studied for GSI = 10, 50, 100. Keeping the rest of the boundary conditions the same as provided for FELA model shown in Fig. 1. The footing is subjected to a multiplier distributed load to obtain the failure load and finally the $N_{\sigma 0}$ values are obtained, then they are compared with the published literature. The comparison of present study results with published literature is provided in Fig. 3. It can be seen that the $N_{\sigma 0}$ obtained from present study are in good agreement with the results of others, especially for lower values of m_i. For higher values of m_i, the results are reasonably close to the literature. After this, the further analysis is carried out considering the footing resting on vertical cliff (i.e., H/B = 1, 5, 10).

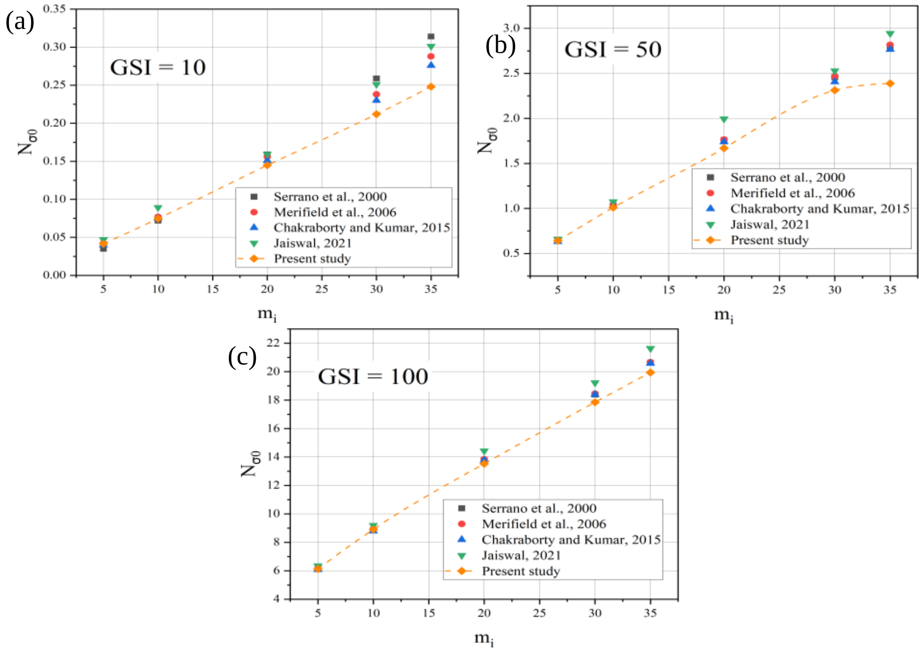


Fig. 3 Variation of $N_{\sigma 0}$ for (a) GSI = 10, (b) GSI = 50, (c) GSI = 100

4 Results and Discussion

The variation in bearing capacity factor $N_{\sigma 0}$ for H/B = 1, 5, 10, m_i = 5, 20, 35, GSI = 10, 50, 100 and setback distance S/B = 0 to 15 is presented in Figs. 4 to 6. Fig. 4 shows the variation of $N_{\sigma 0}$ with respect to changing m_i values for a constant GSI = 50. It is observed that $N_{\sigma 0}$ increases with increase in m_i values. This can be attributed to the fact that the degree of intactness of rockmass increases with increase in m_i values. It can also be seen from the figure that for any particular value of depth of vertical cut, the $N_{\sigma 0}$ values obtained are very less than the case for which depth of vertical cut equals 0 i.e., H/B = 0 which can be considered as a limiting value. These $N_{\sigma 0}$ values increase progressively with the increase in horizontal setback distance and tend to attain this limiting value at very large values of setback distance of ~12*B* for m_i = 5 and ~15*B* for m_i = 35. Also, the rate at which $N_{\sigma 0}$ values increase is more for lower values of m_i and decrease as m_i value increases.

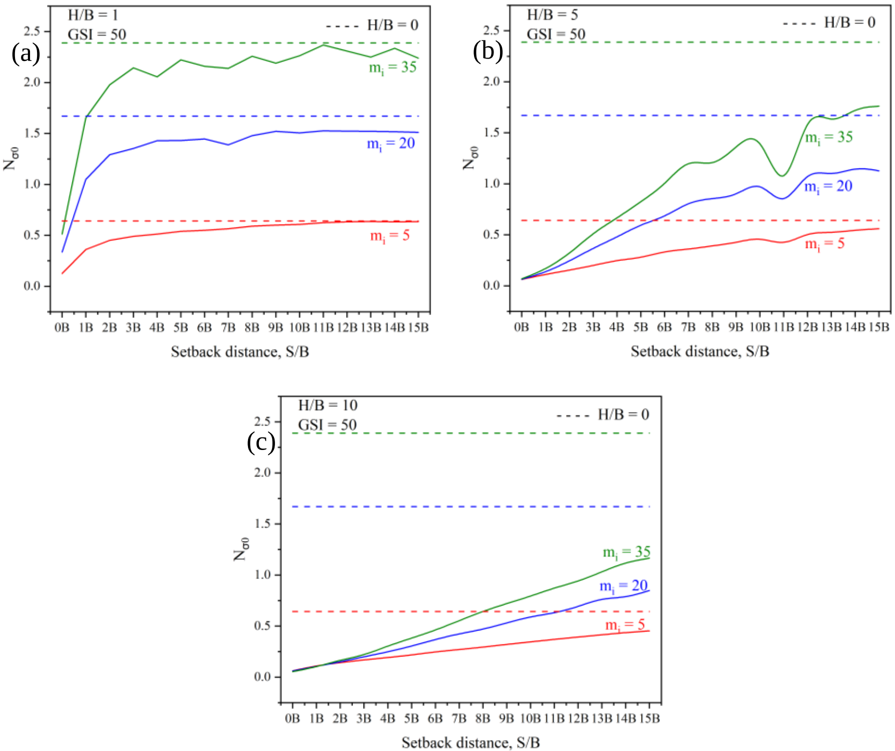


Fig. 4 Effect on $N_{\sigma 0}$ due to variation in m_i with changing setback distance for: (a) (H/B) = 1, (b) (H/B) = 5, (c) (H/B) = 10

Fig. 5 shows the variation of bearing capacity factor $N_{\sigma 0}$ with respect to changing GSI values = 10, 50, 100 for a constant $m_i = 20$. It is observed from the figure that $N_{\sigma 0}$ values are higher for higher values of GSI. This can be attributed to better condition of rockmass with few or widely spaced discontinuities when GSI of the rockmass is high. Such rockmass provide good strength, thereby $N_{\sigma 0}$ values obtained are higher. Similar to the case of m_i, $N_{\sigma 0}$ values increases with increase in setback distance and approaches to the limiting value i.e., $H/B = 0$.

Fig. 6 shows the variation in the $N_{\sigma 0}$ values obtained with changing depth of rockmass cliff for a constant value of GSI = 50 and $m_i = 20$. It can be seen from the figure that $N_{\sigma 0}$ values reduce significantly when depth of the cliff is increased from 0 to 10*B*. similar observations were noted by Wolters et al. (2008) where it was seen that cliffs of higher unsupported vertical cuts destabilize due to higher concentration of stress within the rockmass. The reduction in the values tend to stabilize with increasing setback distance from the cliff, with rate of stabilization being higher for smaller depths as compared to higher ones. The failure planes for the case of constant values of GSI = 50 and $m_i = 20$ are shown in Fig. 7. Based on the observation of failure envelopes, it can be inferred that failure begins from the top and progresses in the downward direction of the cliff. In most cases, the failure plane passes through the bottom tip of the cliff which might turn out to be the point of stress concentration in the rockmass cliff.

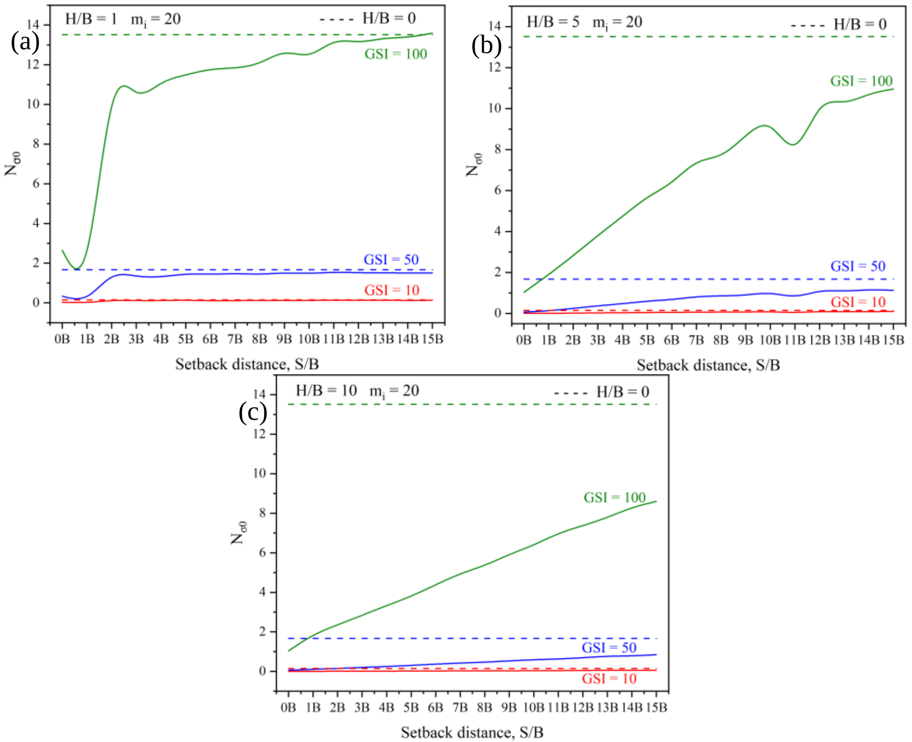


Fig. 5 Effect on $N_{\sigma0}$ due to variation in GSI with changing setback distance for (a) (*H/B*) = 1, (b) (*H/B*) = 5, (c) (*H/B*) = 10

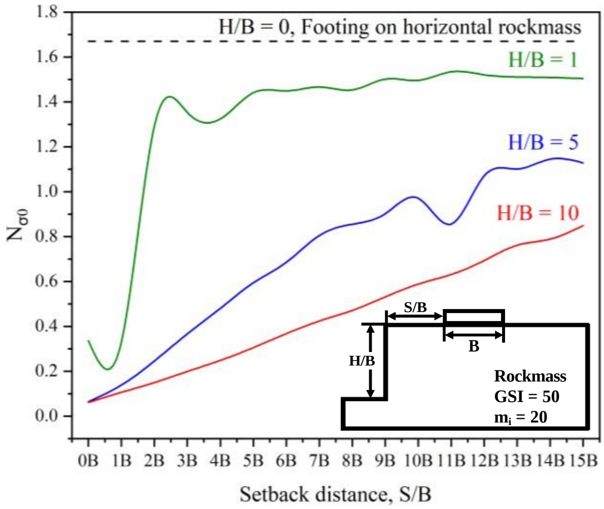
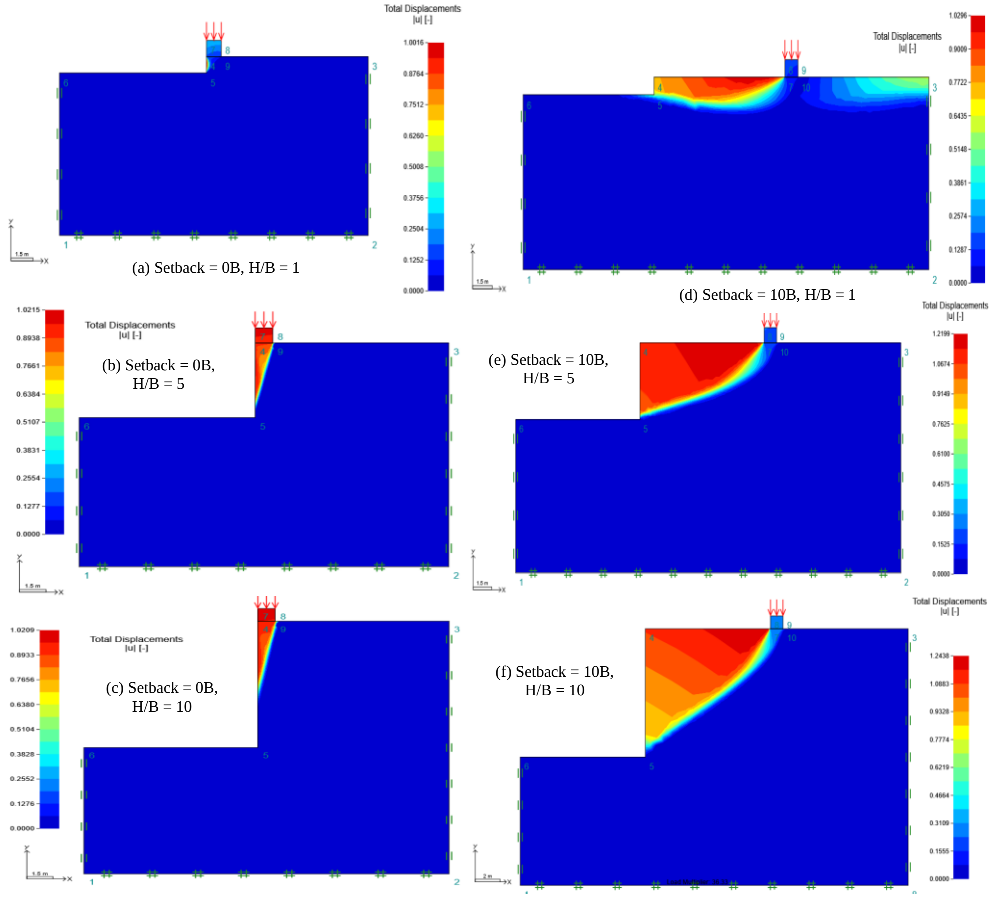


Fig. 6 Effect on $N_{\sigma0}$ due to variation in height for constant value of GSI = 50 and m_i = 20 values


(a) Setback = 0B, H/B = 1

(d) Setback = 10B, H/B = 1

(b) Setback = 0B, H/B = 5

(e) Setback = 10B, H/B = 5

(c) Setback = 0B, H/B = 10

(f) Setback = 10B, H/B = 10

Fig. 7 Failure planes for varying values of height and setback distance for a particular value of GSI (= 50) and m_i (= 20) values, of rockmass failure

5 Conclusions

The stability of a strip footing placed over a rockmass cliff is evaluated using FELA and by assigning the Hoek and Brown failure model to the rockmass. The results of the FELA were presented in the form of $N_{\sigma 0}$ values obtained from ultimate failure loads corresponding to upper and lower bound limit analysis. Based on the results obtained, it can be concluded that the height of the vertical cliff is an important parameter which greatly affects its stability. The $N_{\sigma 0}$ decrease significantly with increase in the height of cliff and tend to reach a limiting value at a great setback distance. The decrease in the $N_{\sigma 0}$ values can also be attributed to increasing instabilities in the rockmass cliff with increase in the height of the cliff. A small vertical cliffs and footing at a far setback distance can re-attain the capacity of footing on horizontal rockmass. Basic rockmass parameters GSI and m_i influence the $N_{\sigma 0}$ values; where higher $N_{\sigma 0}$ values are obtained for higher values of GSI and m_i implying that intact rockmass with highly spaced discontinuities are more stable and have higher bearing capacity as compared to soft rockmass with great many discontinuities.

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