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Sensitivity Analysis of Stability of Rockmass Slope Using Finite Element Limit Analysis

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Abstract. The design of various geotechnical engineering structures within/over a rockmass slope necessitates evaluating the stability. Despite numerous research, the problem of rockmass slopes still presents significant challenges to the designers. The numerical methods use the strength reduction method to evaluate the factor of safety (FoS) for a rock slope, where the stability analysis is performed by reducing the shear strength of rockmass in stages until the collapse occurs. In this study, the finite element limit analysis is performed for rockmass slope stability using Optum G2. The strength reduction method is used to evaluate the stability of rockmass slope using non-linear Hoek-Brown failure model. The sensitivity analysis is performed to determine the effect of various parameters of rockmass on the FoS. The parameters considered are: geological strength index (GSI), material constant (m_i), uniaxial compressive strength (σ_{ci}), unit weight (γ), elasticity modulus (E), Poisson's ratio (ν), slope height (H) and slope inclination (i). The results are represented in the form of spider plot and tornado plot to arrive at the sensitivity of each parameter considered in the study. Based on the study it is found that the FoS of rockmass slope is dependent on GSI, m_i, σ_{ci}, γ, H and i, and is independent of E and ν.

Keywords: Finite element limit analysis, Sensitivity analysis, Rockmass slope, Strength reduction method, Hoek-Brown failure model, Factor of safety

1 Introduction

The presence of slope presents a significant challenge to the geotechnical engineers for the design of geotechnical structures. The analysis of soil mass slope has been extensively investigated, however the rockmass slopes still continue to be a major source of concern. The stability of slopes is often evaluated by the factor of safety. Limit equilibrium methods (LEM) like method of slices [1], Bishop's method [2], Janbu's method [3], Morgenstern and Prince's method [4], Spencer's method [5] use different methodologies to arrive at the factor of safety of a slope. However, all of them have the same basic definition of factor of safety as the ratio of shear strength to the shear stress. The conventional limit equilibrium methods do not account for the constitutive relationship between the stress and strain and also do not take into account the compatibility between the strain and displacement [6]. Finite element method can be used to overcome these drawbacks effectively. The versatile capability of finite element analysis includes modelling various aspects of real situations, namely nonlinear stress-strain behaviour, stress-dependent stress-strain behaviour, sequential changes in geometry during construction, and dissipation of pore pressures following the construction [7]. The finite element method is widely used method for examining the stability of slopes. Also, the fact that prior assumptions aren't required for analysis gives FEM an edge over LEM [8].

Finite element method (FEM) uses the strength reduction method, introduced by Zienkiewicz et al. [9] to evaluate the factor of safety (FoS). In the strength reduction method, the shear strength of soil is reduced in stages until the collapse occurs. The factor of safety is defined as the ratio of initial/available shear strength to the shear strength causing the failure [7, 10, 11, 12, 13, 14, 15]. For a case of soil slope, soil has been modelled considering the Mohr-Coulomb criteria. However, rocks generally have nonlinear failure characteristics, and the Hoek-Brown model can be used to model the rock slopes. Hoek-Brown criterion is an empirical failure criterion that estimates the strength of rockmass from laboratory test data and field observations. Hoek-Brown criterion is the most suitable and widely accepted criterion to investigate the rockmass, especially for studying the stability of rockmass slopes which has significant nonlinear characteristics [16, 17, 18, 19, 20, 21, 22]. Finite element limit analysis (FELA) is a versatile program which evaluates the stability considering upper bound and lower bound solutions. Therefore, in the study, the FELA is used to evaluate the stability of rockmass slope.

The factor of safety of a slope depends on numerous parameters such as geometry of slope, material properties of rockmass and external effects i.e., presence of groundwater table, rainfall, vegetation, etc. For reliability analysis of slopes, there is a need to evaluate the sensitivity of each parameter affecting the stability of slope [23, 24]. Sensitivity analysis is used to quantify the effect of each parameter on the outcome i.e., FoS in case of slope stability. The sensitivity analysis can help in examining and quantifying the parameters on which the factor of safety is most and/or least dependent [25, 26]. For a homogeneous slope, the sensitivity analysis is performed by Cheng and Jiang [26], Siddique and Pradhan [24], Ramanandan and Dodagoudar [27], Karthik et al. [25]. However, the sensitivity analysis of rockmass slope is not investigated in detail.

In this study, a sensitivity analysis of stability of rockmass slope, considering the Hoek-Brown criterion, is performed using finite element limit analysis. The rockmass is modelled as a plane strain problem considering the Hoek-Brown material model. The sensitivity analysis is performed to determine the effect of various parameters of rockmass (i.e., strength parameters: GSI, m_i, σ_{ci} and γ, deformation parameters: E and ν, and geometrical parameters: i and H) on the stability of the rockmass slope (i.e., factor of safety). The results are presented as variation of FoS with change in each parameter, and then the results are represented as spider plot and tornado plot.

2 Finite Element Limit Analysis

2.1 FELA Model

In the study, the finite element limit analysis software Optum G2 is used to perform the sensitivity analysis. The slope is modelled considering the plane strain nature of the problem. The finite element (FE) domain is adopted such that the formation of slope failure is within the FE domain, so as to avoid the boundary effects. The effect of disturbance factor of the rock mass was not considered in the study. The Optum G2 uses adaptive mesh technique in which the mesh refines based on the formation of failure zone.

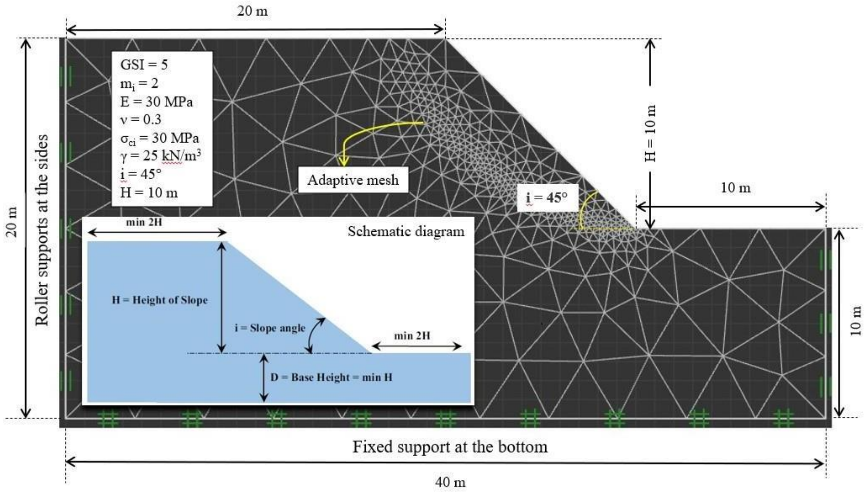


Fig. 1. FELA model and schematic of rockmass slope depicting the material properties, geometrical properties, adaptive mesh and boundary conditions

Table 1. Comparison of FoS of rockmass slope

Method	FoS	Reference
Direct Reduction	1.15	Wei et al. [28]
Globally Lowering Envelop	1.28	
Integral Linearization	1.18	
Local Linearization	1.42	
LEM	1.242	
FELA	1.241	Present Study

2.2 Validation

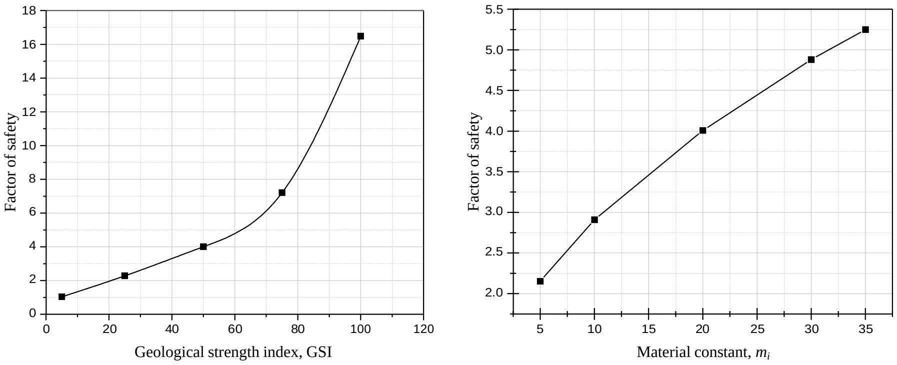
For validation purpose, the FELA model of rockmass slope is assigned with the input parameters as given by Wei et al. [28]. The parameters considered for validation model are: GSI = 5, m_i = 2, E = 30 MPa, v = 0.3, σ_{ci} = 30 MPa, γ = 25 kN/m^3, i = 45°, H = 10 m. The result obtained from the analysis in Optum G2 is validated by comparing the results with the published results. The present study results are compared with results available in literature and shown in Table 1. Based on the comparison it is noted that the finite element limit analysis results are found to match well with the FoS reported by Wei et al. [28].

2.3 Sensitivity Analysis

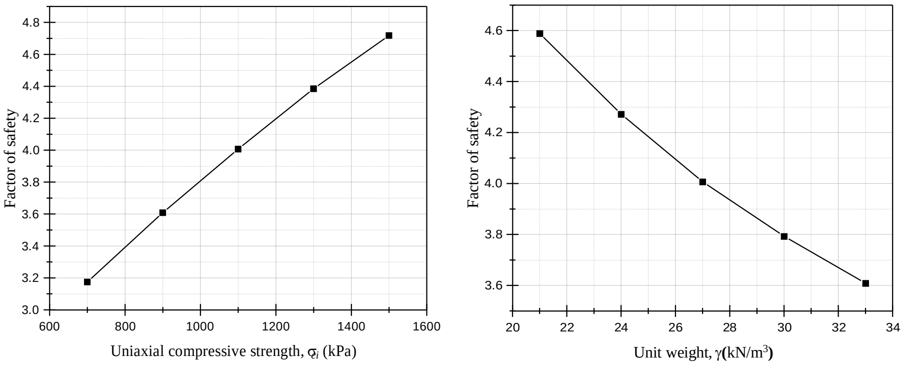
In the same validated model, the input parameters are revised as: GSI = 50, m_i = 20, E = 30 MPa, v = 0.2, σ_{ci} = 1100 kPa, γ = 27 kN/m^3, i = 45°, H = 10 m. The factor of safety is evaluated for the rockmass slope by varying only one parameter and keeping the other parameters as constant. The variation in each parameter considered for the study is provided in the Table 2. The effect of variation in the depth of foundation or the base height, D is insignificant [25, 8] and hence, the variation in D is not considered in the study i.e., the D is kept constant as D = 10 m.

Table 2. The variation of the input parameters in the finite element limit analysis

Parameter	Value
GSI	5, 25, **50**, 75, 100
m_i	5, 10, **20**, 30, 35
γ (kN/m^3)	21, 24, **27**, 30, 33
σ_{ci} (kPa)	700, 900, **1100**, 1300, 1500
E (MPa)	20, **30**, 40, 50
v	0.1, **0.2**, 0.3, 0.4
i (°)	30, **45**, 60
H (m)	5, **10**, 15



(a) (b)



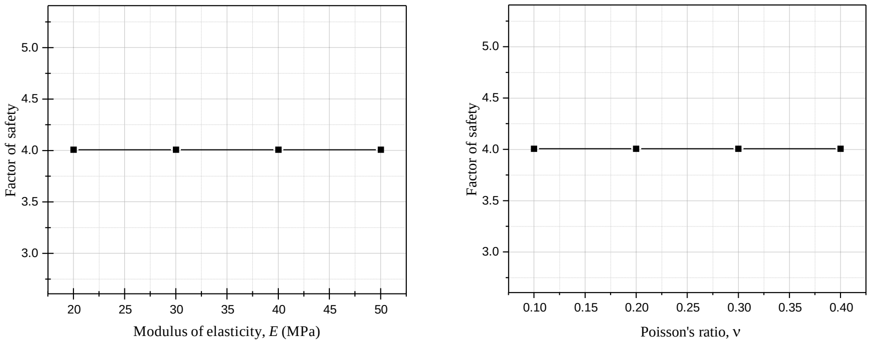
(c) (d)

Fig. 2. Variation in FoS of the rockmass slope with varying strength parameters: (a) GSI (b) m_i (c) σ_{ci} (d) γ

3 Results and Discussion

3.1 Effect of Strength Parameters

Figure 2 provides the variation in the FoS with variation in GSI = 5 to 100, $m_i = 5$ to 35, $\gamma = 21$ to 33 kN/m^3, and $\sigma_{ci} = 700$ to 1500 kPa. From the figure, it is observed that the FoS of the rockmass slope increases with increase in the geological strength index (GSI), material constant (m_i) and uniaxial compressive strength (σ_{ci}) of the rockmass. Thus, it can be inferred that the stability of the slope in rockmass is high in rockmass having higher GSI, m_i, and σ_{ci}. However, the FoS of the rockmass slope decreases with the increase in the unit weight (γ) of the rockmass. Thus, the stability of the rockmass slope is lower for heavy rockmass slopes.

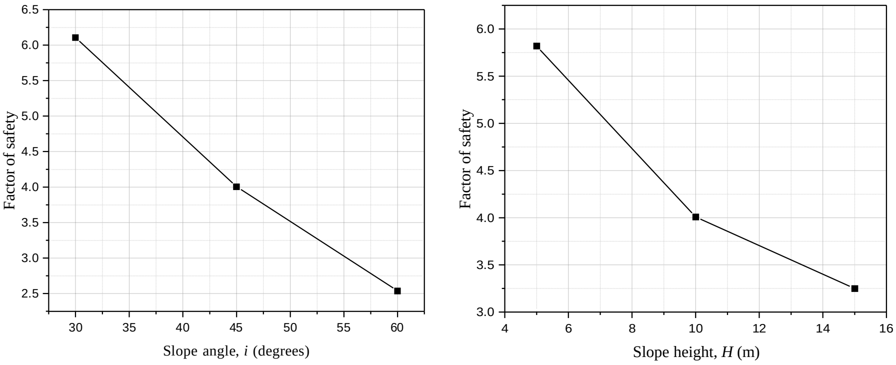


(a) **(b)**

Fig. 3. Variation in FoS of the rockmass slope with varying deformation parameters: (a) E (b) v

3.2 Effect of Deformation Parameters

Figure 3 provides the variation of FoS with variation in modulus of elasticity, E and Poisson's ratio, v. From the figure it is observed that the FoS of the rockmass slope does not vary with increase in the modulus of elasticity and the Poisson's ratio of the rockmass. Thus, it can be inferred that the stability of the rockmass slope evaluated using FELA is independent of *E* and *v* of the rockmass. Similar observations were reported by Karthik et al. [25] and Ramanandan and Dodagoudar [27] in case of soil slopes, that the FoS remains the same with change in *E* and *v* values.



(a) (b)

Fig. 4. Variation in FoS of the rockmass slope with varying geometrical parameters: (a) *i* (b) *H*

3.3 Effect of Geometrical Parameters

Figure 4 provides the variation of FoS for varying geometrical parameters, *i* and *H*. From the figure it is observed that the FoS of the rockmass slope decreases with increase in the slope angle and height of the slope. Thus, it can be inferred that the stability of the rockmass slope is high in case of gentle/mild slopes compared to steeper slopes and slopes having smaller height.

3.4 Spider and Tornado Representation

A spider plot is a simple way of studying the results of sensitivity analysis. It helps in interpreting the effect of uncertainty of each parameter on the FoS on the same graph [27]. The spider plot of the sensitivity analysis carried out in the present study is shown in Fig. 5. It can be inferred from the spider plot that the factor of safety of a rockmass slope is dependent on the geological strength index, material constant, unit weight, uniaxial compressive strength of the rockmass, the height of slope and the slope angle and is independent of the modulus of elasticity and Poisson's ratio of the rockmass.

To understand the sensitivity of each parameter affecting the factor of safety of the rockmass slopes, a tornado representation of the sensitivity analysis results is plotted and presented in Fig. 6. The tornado plot represents the parameters to which the response parameter is most and least sensitive [5, 29]. It can be inferred from the tornado plot that the factor of safety of a rockmass slope is most sensitive to the GSI of the rockmass followed by the slope angle, slope height, unit weight, material constant and uniaxial compressive strength of the rockmass and it is insensitive to the deformation parameters (*E* and *v*) of the rockmass.

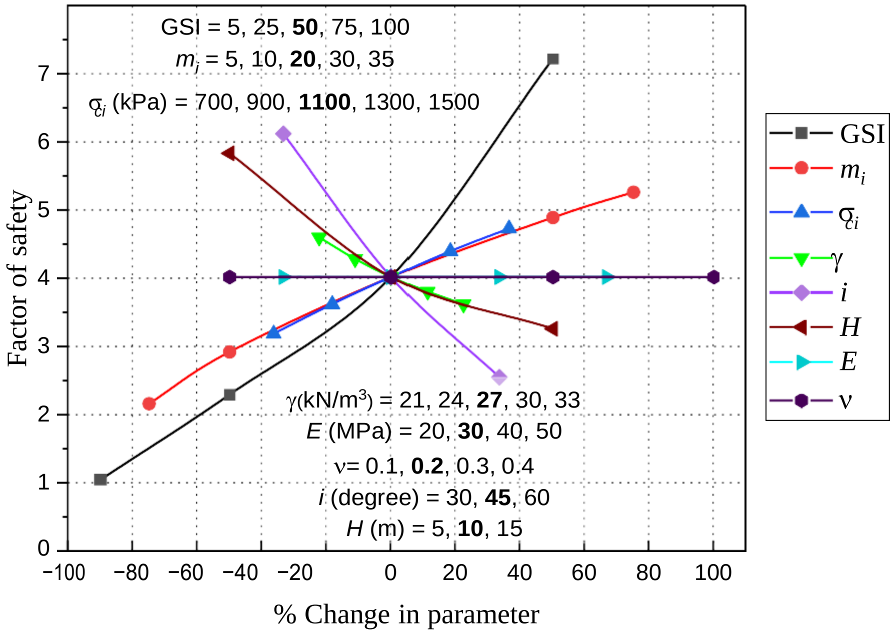


Fig. 5. Spider plot representation of the sensitivity of rockmass slope stability

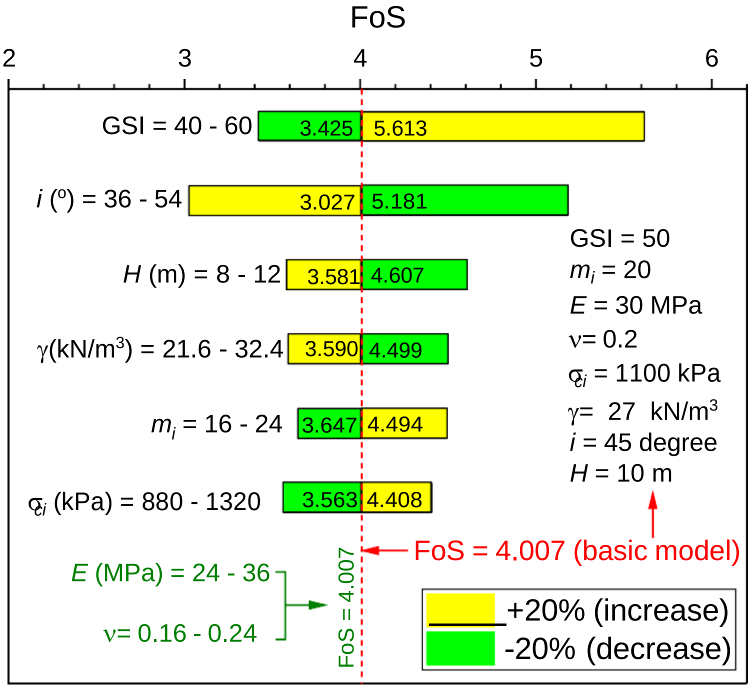


Fig. 6. Tornado plot representation of the sensitivity of rock mass slope stability

4 Conclusions

The finite element limit analysis (FELA) of the rockmass slope is carried out using the FELA software Optum G2. The FELA model was validated by comparing the present study results with the published literature. Then using the same validated model, the factors of safety corresponding to varying parameters were evaluated by performing the sensitivity analysis. The effect of the strength, deformation and geometrical parameters of the rockmass slope on the factor of safety of the rockmass slope is investigated. The results obtained from the study are represented in the form of spider plot and tornado plot to quantify the influence of each parameter on the factor of safety. The following conclusions are drawn from the present study:

1. The stability of rockmass slope is affected by the geological strength index, material constant, uniaxial compressive strength, unit weight of the rockmass and the height and inclination of the slope. However, the stability is unaffected corresponding to the variations in the modulus of elasticity and Poisson’s ratio of the rockmass.
2. The factor of safety of the rockmass slope (i.e., the stability) increases with increase in geological strength index, material constant and uniaxial compressive strength of the rockmass and decreases with increase in unit weight of the rockmass, inclination and height of the slope.
3. The stability of rockmass slope is most sensitive to the geological strength index of the rockmass and is least sensitive (insensitive) to the modulus of elasticity and Poisson’s ratio of the rockmass.

References

1. Fellenius W (1936) Calculation of stability of earth dam, In: 2nd Congress on large dams, Washington, Volume 4, Pages 445–462.
2. Bishop AW (1955) The use of the slip circle in the stability analysis of slopes, Geotechnique, Volume 5, Issue 1, Pages 7-17.
3. Janbu N (1954) Applications of composite slip surfaces for stability analysis, In: Proceedings of the European Conference on the Stability of Earth Slopes Stockholm, Volume 3, Pages 39–43.
4. Morgenstern NR, Price VE (1965) The analysis of the stability of general slip surfaces, Géotechnique, Volume 15, Issue 1, Pages 79–93.
5. Spencer E (1967) A method of analysis of embankments assuming parallel inter-slice forces, Géotechnique, Volume 17, Issue 1, Pages 11–26.
6. Krahn J (2003) The 2001 R.M. Hardy lecture: the limits of limit equilibrium analyses, Canadian Geotechnical Journal, Volume 40, Issue 3, Pages 643–660, https://doi.org/10.1139/T03-024.
7. Duncan JM (1996) State of the art: limit equilibrium and finite - element analysis of slopes, Journal of Geotechnical Engineering, Volume 122, Issue 7, Pages 577–596. https://doi.org/10.1061/(asce)0733-9410(1996)122:7(577).
8. Griffiths DV, Lane PA (1999) Slope stability analysis by finite elements, Geotechnique, Volume 49, Issue 3, Pages 387–403. https://doi.org/10.1680/geot.1999.49.3.387.
9. Zienkiewicz OC, Humpheson C, Lewis RW (1975) Associated and non-associated visco-plasticity in soil mechanics, Géotechnique, Volume 25, Issue 4, Pages 671–89.

10. Krahn J (2007) Limit equilibrium, strength summation and strength reduction methods for assessing slope stability, International Journal of Life Cycle Assessment, Volume 14, Issue 2, Pages 175–83.
11. Sun C, Chai J, Xu Z, Qin Y, Chen X (2016) Stability charts for rock mass slopes based on the Hoek-Brown strength reduction technique, Engineering Geology, Volume 214, Pages 94–106.
12. Sun GH, Cheng SG, Jiang W, Zheng H (2016) A global procedure for stability analysis of slopes based on the Morgenstern-Price assumption and its applications, Computers and Geotechnics, Volume 80, Pages 97–106.
13. Yuan W, Bai B, Li XC, Wang HB (2013) A strength reduction method based on double reduction parameters and its application, Journal of Central South University, Volume 20, Pages 2555–2562.
14. Zheng H, Sun GH, Liu DF (2009) A practical procedure for searching critical slip surfaces of slopes based on the strength reduction technique, Computers and Geotechnics, Volume 36, Issues 1–2, Pages 1–5.
15. Dawson E, You K, Park Y (2000) Strength-reduction stability analysis of rock slopes using the Hoek-Brown failure criterion, Trends in Rock Mechanics, Pages 65-77, https://ascelibrary.org/doi/abs/10.1061/40514(290)4.
16. Hoek E (1983) Strength of jointed rock masses, 23rd Rankine Lecture, Géotechnique, Volume 33, Issue 3, Pages 187–223.
17. Erik E (2012) The Hoek-Brown failure criterion, Rock Mechanics and Rock Engineering, Volume 45, Pages 981–988.
18. Jimenez R, Serrano A, Olalla C (2008) Linearization of the Hoek and Brown rock failure criterion for tunnelling in elasto-plastic rock masses, International Journal of Rock Mechanics and Mining Sciences, Volume 45, Pages 1153-1163. https://doi.org/10.1016/j.ijrmms.2007.12.003.
19. Fu W, Liao Y (2010) Non-linear shear strength reduction technique in slope stability calculation. Computers and Geotechnics, Volume 37, Pages 288–298. https://doi.org/10.1016/j.compgeo.2009.11.002.
20. Shen J, Karakus M, Xu C (2012) Direct expressions for linearization of shear strength envelopes given by the generalized Hoek–Brown criterion using genetic programming, Computers and Geotechnics, Volume 44, Pages 139-146. https://doi.org/10.1016/j.compgeo.2012.04.008.
21. Shen J, Pries SD, Karakus M (2012) Determination of Mohr-Coulomb shear strength parameters from generalized Hoek-Brown criterion for slope stability analysis, Rock Mechanics and Rock Engineering, Volume 45, Pages 123–129. https://doi.org/10.1007/s00603-011-0184-z.
22. Li AJ, Merifield RS, Lyamin AV (2008) Stability charts for rock slopes based on the Hoek–Brown failure criterion, International Journal of Rock Mechanics and Mining Sciences, Volume 45, Issue 5, Pages 689-700, ISSN 1365-1609, https://doi.org/10.1016/j.ijrmms.2007.08.010.
23. Chavda JT, Dodagoudar GR (2018) Finite element evaluation of ultimate capacity of strip footing: assessment using various constitutive models and sensitivity analysis, Innovative Infrastructure Solutions, Volume 3, 15. https://doi.org/10.1007/s41062-017-0121-4.
24. Siddque T, Pradhan SP (2018) Stability and sensitivity analysis of Himalayan Road cut debris slopes: an investigation along NH-58, India, Natural Hazards, Volume 93, Issue 2, Pages 577–600. https://doi.org/10.1007/s11069-018-3317-9.
25. Karthik AVR, Manideep R, Chavda JT (2022) Sensitivity analysis of slope stability using finite element method, Innovative Infrastructure Solutions, Volume 7, 184. https://doi.org/10.1007/s41062-022-00782-3.

26. Cheng Y, Jiang P (2012) Sensitivity analysis of factors affecting slope stability. Applied Mechanics and Materials, Volume 170, Pages 1072–1075. https://doi.org/10.4028/www.scientific.net/AMM.170-173.1072.
27. Ramanandan S, Dodagoudar GR (2020) Reliability analysis of slopes stabilized with piles using response surface method, Geomechanics and Engineering, Volume 21, Issue 6, Pages 513–525. https://doi.org/10.12989/gae.2020.21.6.513.
28. Wei Y, Jiaxin L, Zonghong L, Wei W, Xiaoyun S (2020) A strength reduction method based on the Generalized Hoek-Brown (GHB) criterion for rock slope stability analysis, Computers and Geotechnics, Volume 117, 103240, ISSN 0266-352X, https://doi.org/10.1016/j.compgeo.2019.103240.
29. Raychowdhury P, Hutchinson TC (2010) Sensitivity of shallow foundation response to model input parameters, Journal of Geotechnical and Geoenvironmental Engineering, Volume 136, Issue 3, Pages 538–541. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000227.