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Rock Landslides Induced by Earthquakes: A Study on Influence of Strength Criterion on Limit Equilibrium Stability Analysis

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ABSTRACT

The stability analysis of landslides is important because they are major geological hazards in many parts of the world. In this paper, the most common and traditional methods for the analysis of slope stability — i.e., Limit Equilibrium Methods — are used to investigate the influence of using different strength criteria on stability analysis of rock landslides subjected to a seismic load. For this purpose, four different Limit Equilibrium Methods including (1) Bishop, (2) Janbu, (3) Spencer, and (4) Morgenstern-Price are used by incorporating Mohr-Coulomb and Generalized Hoek-Brown strength criteria to model slopes with different properties and rock types — (1) Siltstone, (2) Limestone, (3) Sandstone, and (4) Granite. This study shows that when Generalized Hoek-Brown criterion is used for slope stability analysis, the relative difference of both the predicted minimum factors of safety and areas of potential failure surface — with respect to the cases with Mohr-Coulomb criterion — increases as the strength of rock mass increases. Also, when Generalized Hoek-Brown criterion is used, lower values for both the minimum factor of safety and area of potential failure surface — compared to the cases with Mohr-Coulomb criterion — are predicted for weak rock masses. However, for rock masses with high strength, higher values for both the minimum factor of safety and area of potential failure surface are obtained when Generalized Hoek-Brown criterion is used. The findings of this study can help geotechnical, civil, and mining engineers select the appropriate rock strength criterion for slope stability analysis and design of slope stabilization measures, and to predict landslides.

Key Words: Rock Landslide, Slope stability Analysis, Earthquake, Limit Equilibrium Methods, Mohr–Coulomb.

1. INTRODUCTION

Rock landslides not only can cause huge economic losses but also can seriously threaten the safety of people's lives and properties [1–4], therefore it is important to predict them accurately by calculating the safety factor of the slopes. The methods used to analyze slope stability are (1) Limit Equilibrium Method [5−7], (2) Limit Analysis Method [8−10], and (3) Numerical Modeling Method [11−12]. Numerical methods used to analyze slopes are usually the Finite Difference Method (FDM) [13, 14], Finite Element Method (FEM) [15], Discontinuous Deformation Analysis (DDA) [16, 17], and Discrete Element Method (DEM) [18]. Analysis of rock slopes requires evaluation of factor of safety for the sliding mass and among these calculation methods, Limit Equilibrium Method is the most famous one for determination of factor of safety of any slopes against failure [19, 20]. The most important Limit Equilibrium Methods are Bishop, Janbu, Spencer, and Morgenstern-Price [21].

Mohr-Coulomb and Hoek–Brown strength criteria are the most popular strength criteria used for expressing rock mass behavior [19]. There is no research published on investigating the influence of strength criterion on stability analysis of rock slopes under seismic conditions using different methods of Limit Equilibrium although there are many studies on incorporating rock strength criteria and using them for slope stability analysis. For instance, Sarkar et al. [22] studied the stability of two excavated slopes in the Pakyong region of Sikkim Himalayas in India. They estimated the shear strength parameters using Generalized Hoek-Brown criterion. Deng et al. [23] proposed a new method for rock slope stability analysis that combines the Limit Equilibrium Method with a simplified form of the Hoek–Brown strength criterion derived using a Taylor series expansion. Kumar et al. [24] performed rock slope analyses using Nonlinear Hoek–Brown criterion with Equivalent Mohr–Coulomb strength parameters. For this purpose, they used Limit equilibrium technique-based Morgenstern–Price and Spencer's method to calculate factors of safety of the slopes. Kang et al. [25] used the Generalized Hoek-Brown criterion to assess rock slope stability of open pit mine Chaarat in Kyrgyz Republic. Michalowski and Park [26] analyzed a slope instability in a geomaterial governed by the Hoek-Brown criterion. Wei et al. [27] used Limit Equilibrium Method and proposed new and rapid stability charts for analyzing the stability of rock slopes based on Generalized Hoek-Brown criterion. Kang et al. [28] used Limit Equilibrium Method based on Generalized Hoek-Brown criterion to perform a probabilistic slope stability assessment under seismic conditions. Finally, Kumar et al. [29] developed stability charts of rock slopes using Limit Equilibrium Method and incorporating Generalized Hoek-Brown criterion to determine factors of safety of a rock slope against failure considering different horizontal seismic coefficients.

In this paper, four different Limit Equilibrium Methods—Bishop, Janbu, Spencer, and Morgenstern-Price—are used by incorporating Mohr-Coulomb and Generalized Hoek-Brown criteria to study the impact of strength criterion on limit equilibrium stability analysis. For this purpose, four different properties and rock types including Siltstone, Limestone, Sandstone, and Granite are considered to obtain a better understanding of the influence of strength criterion on limit equilibrium stability analysis.

2. ROCK STRENGTH CRITERIA FOR LIMIT EQUILIBRIUM SLOPE STABILITY ANALYSIS

Failure surfaces in Limit Equilibrium Method are divided into several slices based on force and/or moment equilibrium [30]. There are several methods that assume different interslice and equilibrium conditions to calculate force and/or moment equilibrium for the slices and the most important ones are Bishop, Janbu, Spencer, and Morgenstern-Price [21]. In this section, the most important rock strength criteria used for Limit Equilibrium slope stability analysis are presented.

2.1 Mohr–Coulomb Criterion

Mohr-Coulomb shear criterion has been widely used for slope stability analysis using Limit Equilibrium Method for both soil and rock slopes. In this criterion, it is assumed that failure is controlled by the maximum shear stress. The failure shear stress depends on the normal stress in Mohr-Coulomb criterion and can be written as [31]:

$$\tau = c - \sigma \tan\varphi \tag{1}$$

Where τ = shear stress; σ = normal stress; c = cohesion; and φ = friction angle.

2.2 Generalized Hoek-Brown Criterion

An empirical Hoek–Brown strength criterion for estimating shear strength parameter for hard rock mass from experimental studies performed on rock [32]. Later, nonlinear Hoek–Brown strength criterion for all classes of rock mass was developed [19]. The nonlinear Generalized Hoek-Brown criterion is well-known among the researcher for determining the strength of rock mass [24].

The Generalized Hoek-Brown criterion is expressed as follows [19]:

$$\tau = (\sigma_n - \sigma_3)\sqrt{1 + a\, m_b \left(\frac{m_b}{\sigma_{ci}}\sigma_3 + s\right)^{a-1}} \tag{2}$$

$$\sigma_n = \sigma_3 + \frac{\sigma_{ci}\left(\frac{m_b}{\sigma_{ci}}\sigma_3 + s\right)^{a}}{2 + a\, m_b\left(\frac{m_b}{\sigma_{ci}}\sigma_3 + s\right)^{a-1}} \tag{3}$$

where,

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

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

$$a = 0.5 + \frac{e^{\left(\frac{-GSI}{15}\right)} - e^{\left(\frac{-20}{3}\right)}}{6} \tag{6}$$

and σ_1 = major effective principal stress at failure; σ_3 = minor effective principal stress at failure; σ_{ci} = uniaxial compressive strength of the intact rock material; GSI = Geological Strength Index (A GSI value of 0 represents a rock mass of very poor quality and a value equal to 100 signifies intact rock with very good strength); D = disturbance factor to express the presence of initial disturbance in the rock mass caused by stress relaxation and damage.

3. METHODOLOGY AND MODELING

The geometry shown in Figure 1 is considered to perform an investigation on the influence of rock strength criterion on the slope stability analysis using Limit Equilibrium Method. As can be seen, the slope height and inclination angle are 10 m and 73°, respectively.

Four different cases including different properties and rock types — Siltstone, Limestone, Sandstone and Granite — with two different rock shear criteria — Mohr-Coulomb and generalized Hoek-Brown — are considered for this study. RocData software Version 5.0 [33] is used to obtain the rock mass properties for both criteria. The properties and rock types for each case are presented in Figure 2. It should be noted that the rock mass properties range from the weakest (i.e., Siltstone) to the strongest (i.e., Granite). The slope stability analysis for all the methods (Bishop, Janbu, Spencer and Morgenstern-Price) is carried out using SLIDE software version 9.008 [34]. A horizontal seismic load coefficient of 0.25 is considered for all cases.

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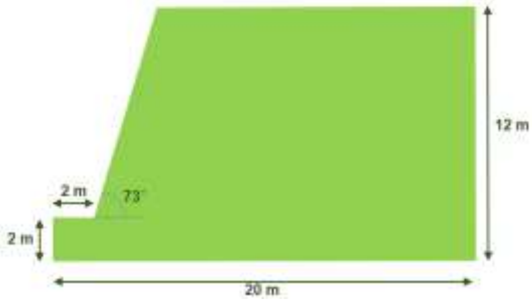

Figure 1: Geometry of slope used for this study

	Siltstone	Limestone	Sandstone	Granite
Hoek Brown Classification				
intact uniaxial compressive strength	35 MPa	75 MPa	100 MPa	250 MPa
GSI	10	40	50	81
mi	7	12	17	32
disturbance factor	0	0	0	0
intact modulus	13125 MPa	37500 MPa	27500 MPa	106250 MPa
modulus ratio	375	500	275	425
Hoek Brown Criterion				
mb	0.281	1.408	2.851	16.235
s	4.54e-005	0.001	0.004	0.121
a	0.585	0.511	0.506	0.501
Failure Envelope Range				
application	slopes	slopes	slopes	slopes
sig3max	0.199 MPa	0.254 MPa	0.28 MPa	0.343 MPa
unit weight	0.023 MN/m3	0.025 MN/m3	0.026 MN/m3	0.027 MN/m3
slope height	10 m	10 m	10 m	10 m
Mohr Coulomb Fit				
cohesion	0.044 MPa	0.306 MPa	0.6 MPa	7.501 MPa
friction angle	39.212 deg	60.874 deg	65.682 deg	70.887 deg

Figure 2: Rock Data results for rock mass properties

4. RESULTS

For this study, a total of 32 cases (8 models for each rock type) were modeled. The results obtained from modeling for each rock type are presented below.

4.1 Case 1: Siltstone

The model configuration, potential failure surfaces, and calculated minimum factor of safety obtained from the modeling for Mohr-Coulomb and Generalized Hoek-Brown criteria for case 1 (i.e., rock type of Siltstone) are presented in Figures 3 and 4, respectively. The minimum factors of safety for case 1 calculated using Bishop, Janbu, Spencer, and Morgenstern-Price methods with Mohr-Coulomb criterion are 1.265, 1.260, 1.278 and 1.290, respectively. Also, the areas of potential failure surface predicted by using Bishop, Janbu, Spencer, and Morgenstern-Price methods are 33.30 m^2, 36.50 m^2, 26.41 m^2, and 28.60 m^2, respectively. As can be seen, for this case, Janbu and Morgenstern-Price methods predict the minimum and maximum values of the minimum factor of safety, respectively, and Spencer and Janbu predict the minimum and the maximum values of the area of potential failure surface, respectively, when Mohr-Coulomb criterion is used for slope stability analysis.

For the case with Generalized Hoek-Brown criterion, using Bishop, Janbu, Spencer and Morgenstern-Price methods, the calculated minimum factors of safety are 0.969, 0.846, 0.915 and 0.917, respectively, and the predicted areas of potential failure surface are 17.74 m^2, 16.18 m^2, 17.46 m^2, 15.27 m^2, respectively. Therefore, the minimum and maximum values of the minimum factors of safety are obtained by using Janbu and Bishop methods, respectively. Furthermore, Morgenstern-Price and Bishop methods predict the minimum and maximum values of the area of potential failure surface, respectively. The results obtained by using Generalized Hoek-Brown criterion show that the slope is not stable, and a landslide is expected to occur because all the calculated minimum factors of safety are less than 1.0 in this case.

4.2 Case 2: Limestone

Figures 5 and 6 show the model configuration, potential failure surfaces, and minimum factors of safety obtained from the analysis using Bishop, Janbu, Spencer, and Morgenstern-Price methods for Mohr-Coulomb and Generalized Hoek-Brown criteria, respectively, for the rock type of Limestone. The minimum factors of safety for this case using Mohr-Coulomb criterion are 5.680, 5.836, 5.600 and 5.629 calculated using Bishop, Janbu, Spencer and Morgenstern-Price methods, respectively.

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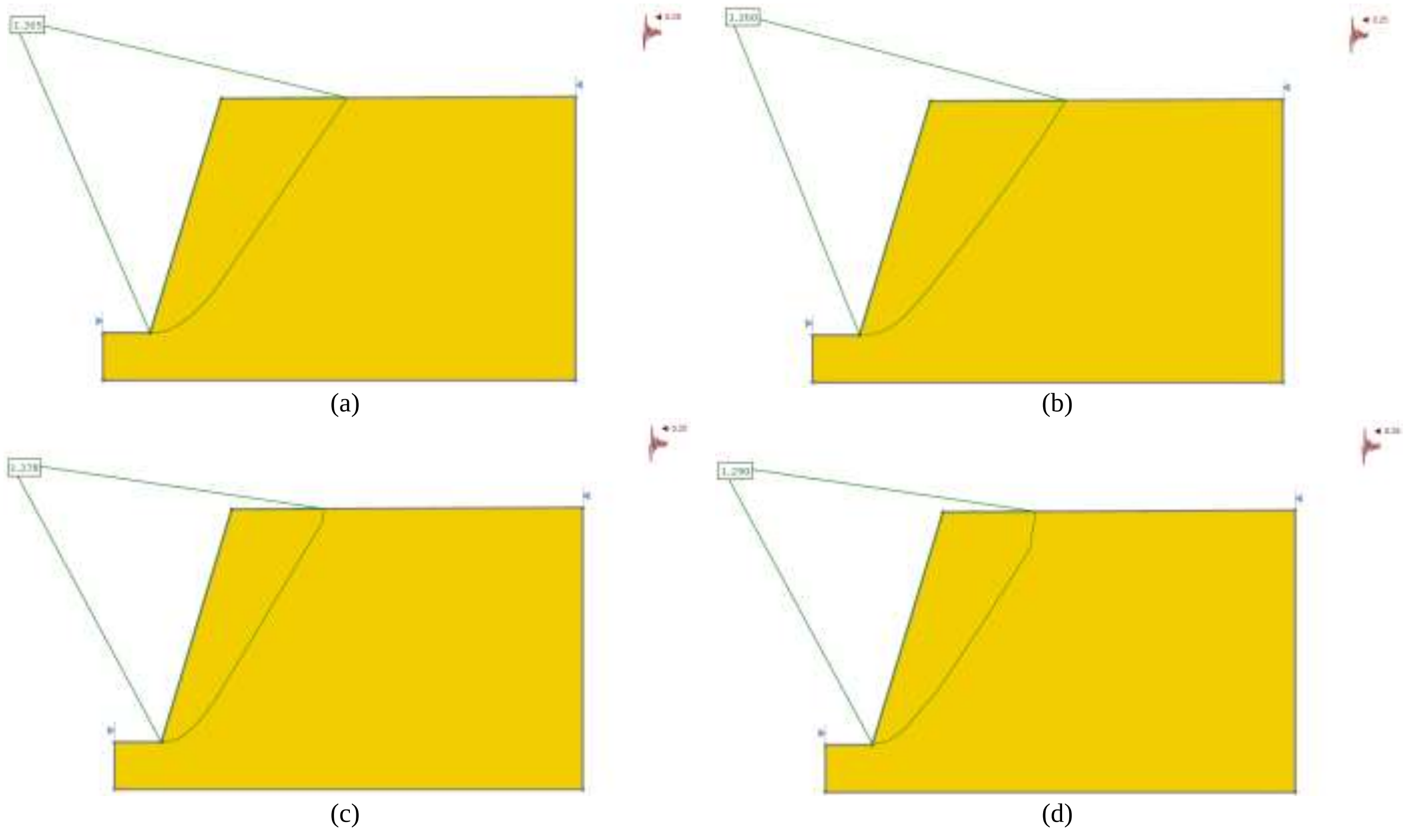

Figure 3: Results of Limit Equilibrium Stability Analysis for Siltstone using Mohr-Coulomb Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method

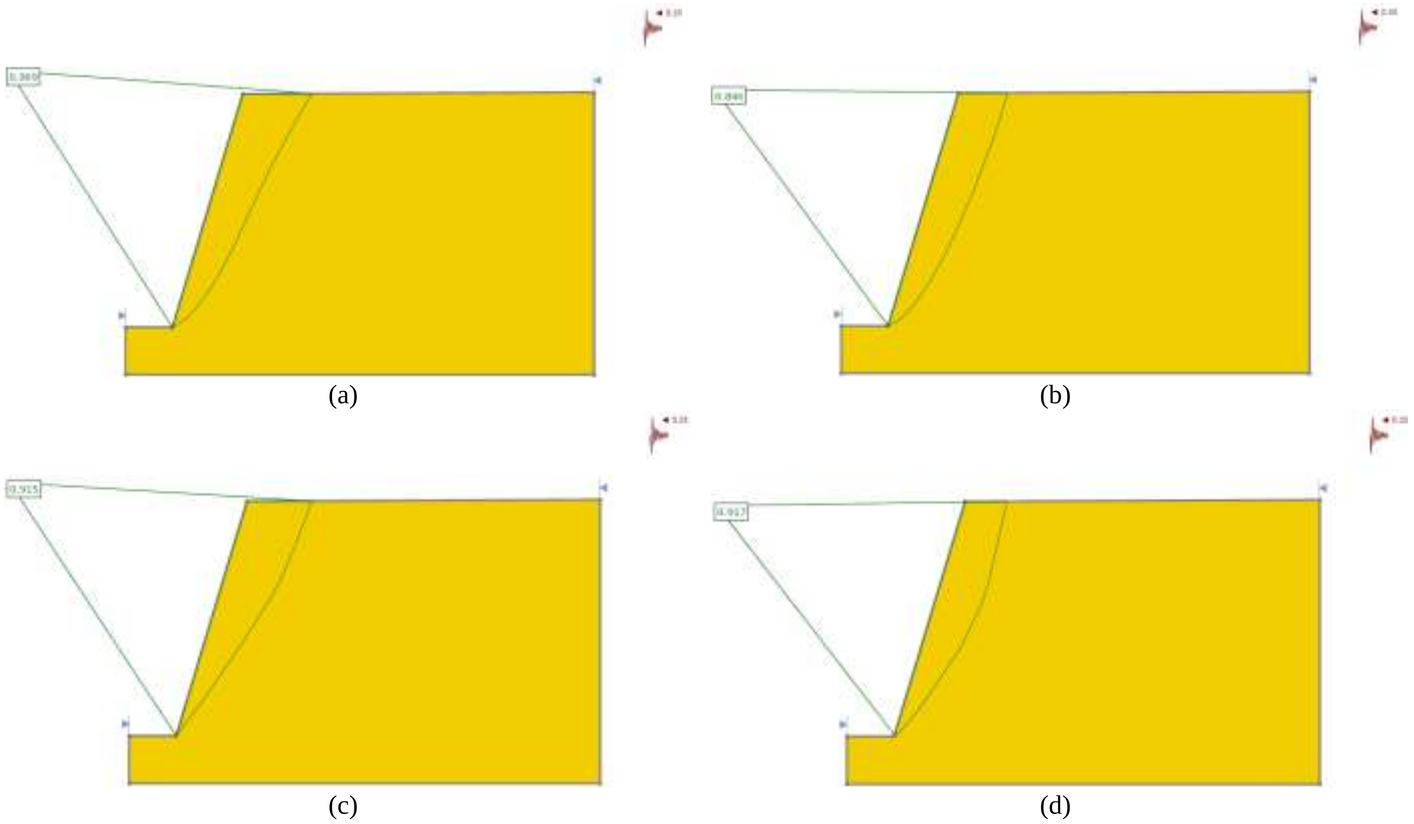

Figure 4: Results of Limit Equilibrium Stability Analysis for Siltstone using Hoek-Brown Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method

Moreover, the areas of potential failure surface predicted by using Bishop, Janbu, Spencer and Morgenstern-Price methods when Mohr-Coulomb criterion is used are 49.76 m^2, 55.99 m^2, 54.78 m^2 and 53.38, respectively. Therefore, the minimum and maximum values of the minimum factors of safety are obtained by using Spencer and Janbu methods with Mohr-Coulomb

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criterion, respectively. Also, Bishop and Janbu methods predict the minimum and maximum values of the area of potential failure surface, respectively.

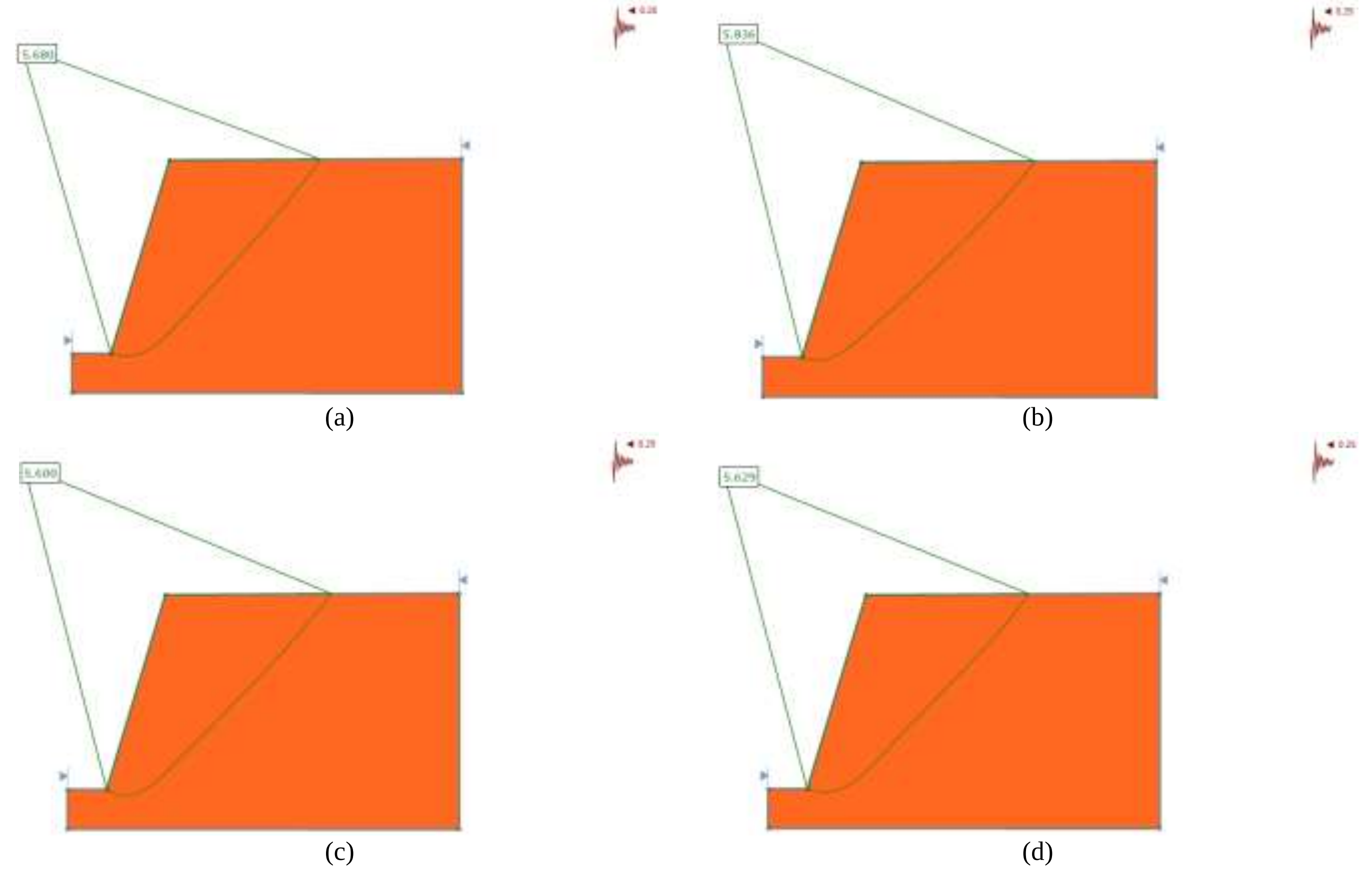


Figure 5: Results of Limit Equilibrium Stability Analysis for Limestone using Mohr-Coulomb Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method

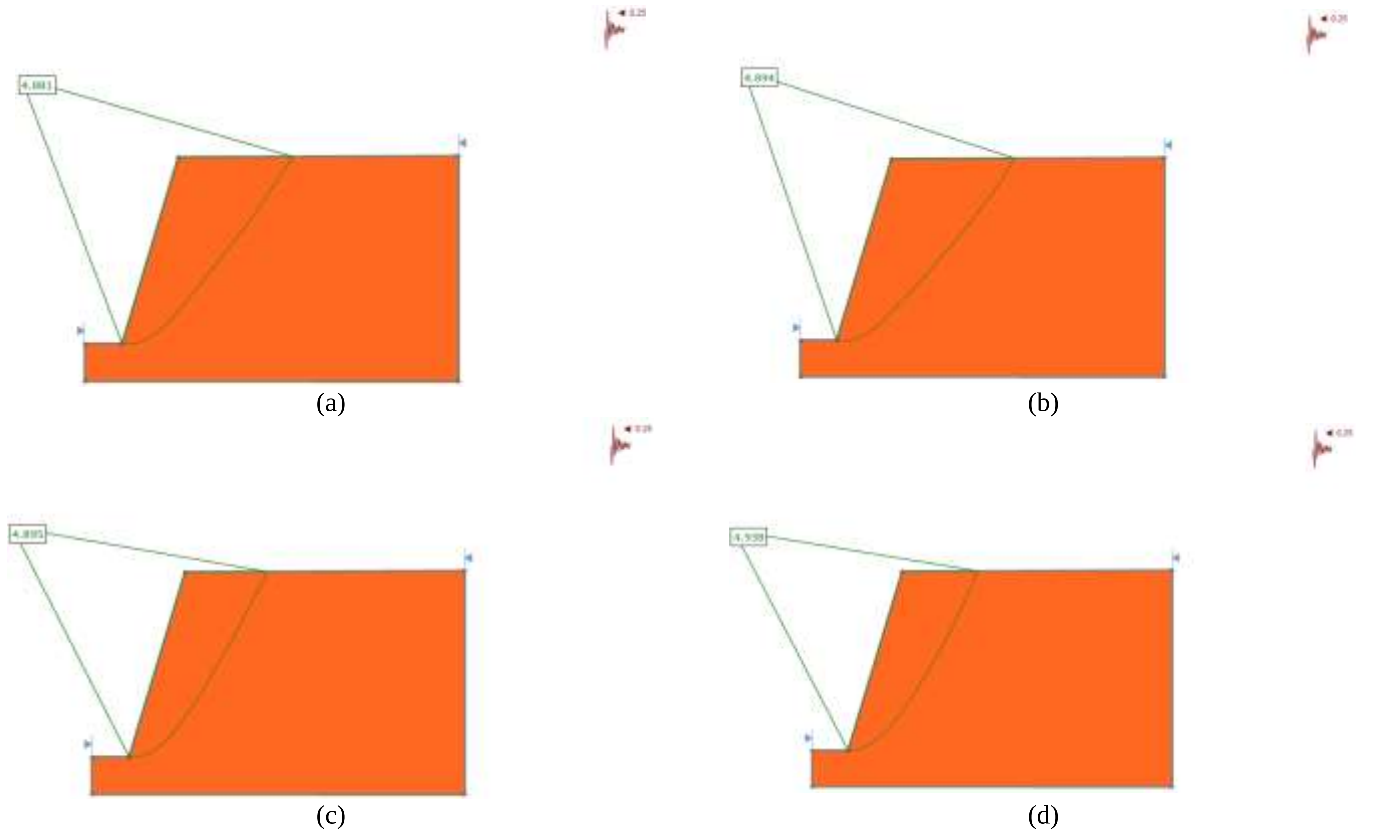


Figure 6: Results of Limit Equilibrium Stability Analysis for Limestone using Hoek-Brown Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method

DOI : 10.31695/IJERAT.2021.3744

For case 2, the calculated minimum factors of safety using Bishop, Janbu, Spencer, and Morgenstern-Price methods with Generalized Hoek-Brown Criterion are 4.881, 4.894, 4.895 and 4.938, respectively, and the predicted areas of potential failure surface are 39.59 m^2, 44.10 m^2, 30.93 m^2 and 30.45 m^2, respectively. As can be seen, for this case, Bishop and Morgenstern-Price methods predict the minimum and the maximum values of the minimum factor of safety, respectively. Moreover, the minimum and the maximum values of the area of potential failure surface are calculated using Morgenstern-Price and Janbu methods, respectively.

4.3 Case 3: Sandstone

The model configuration, potential failure surfaces, and results obtained from the modeling for the rock type of Sandstone (i.e., case 3) are presented in Figures 7 and 8 for Mohr-Coulomb and Generalized Hoek-Brown criteria, respectively.

The minimum factors of safety for this case calculated using Bishop, Janbu, Spencer, and Morgenstern-Price methods when Mohr-Coulomb criterion is used are 9.693, 10.029, 9.588 and 9.637, respectively. Also, the areas of potential failure surface predicted by using Bishop, Janbu, Spencer, and Morgenstern-Price methods are 56.32 m^2, 65.10 m^2, 66.31 m^2 and 65.51 m^2, respectively. The results show that, when Mohr-Coulomb criterion is used, Spencer and Janbo methods predict the minimum value and the maximum value of the minimum factor of safety, respectively. Also, Bishop and Spencer methods predict the minimum value and the maximum value of the area of potential failure surface, respectively.

For the case with Generalized Hoek-Brown criterion, using Bishop, Janbu, Spencer, and Morgenstern-Price methods, the calculated minimum factors of safety are 9.743, 10.022, 9.588 and 9.654, respectively, and the predicted areas of potential failure surface are 53.92 m^2, 61.19 m^2, 58.02 m^2 and 56.62 m^2, respectively. Therefore, when Generalized Hoek-Brown criterion is used, the minimum and maximum values of the minimum factors of safety are obtained by using Spencer and Janbu methods, respectively. Furthermore, Bishop and Janbu methods predict the minimum and maximum values of the area of potential failure surface, respectively.

4.4 Case 4: Granite

Figures 9 and 10 show the model configuration, potential failure surfaces, and minimum factors of safety obtained from the analysis using Bishop, Janbu, Spencer, and Morgenstern-Price methods for Mohr-Coulomb and Generalized Hoek-Brown criteria, respectively, when the rock type is Granite.

The minimum factors of safety for this case with Mohr-Coulomb criterion are 91.951, 96.264, 89.150 and 90.452 calculated using Bishop, Janbu, Spencer, and Morgenstern-Price methods, respectively. Moreover, the areas of potential failure surface predicted by using Bishop, Janbu, Spencer, and Morgenstern-Price methods for this case when Mohr-Coulomb criterion is used are 116.94 m^2, 114.77 m^2, 115.23 m^2 and 108.47 m^2, respectively. Therefore, the minimum and maximum values of the minimum factors of safety are obtained using Spencer and Janbu methods, respectively. Also, Morgenstern-Price and Bishop methods predict the minimum and maximum values of the area of potential failure surface, respectively, when Mohr-Coulomb criterion is used.

For case 4 with Generalized Hoek-Brown criterion, using Bishop, Janbu, Spencer, and Morgenstern-Price methods, the calculated minimum factors of safety are 96.278, 101.056, 93.617 and 94.798, respectively, and the predicted areas of potential failure surface are 117.32 m^2, 117.32 m^2, 111.62 m^2 and 105.31 m^2, respectively. As can be seen, using Hoek-Brown criterion, Spencer and Janbu methods predict the minimum and the maximum values of the minimum factor of safety, respectively. Moreover, the minimum and the maximum values of the area of potential failure surface are calculated using Morgenstern-Price methods and Bishop methods, respectively.

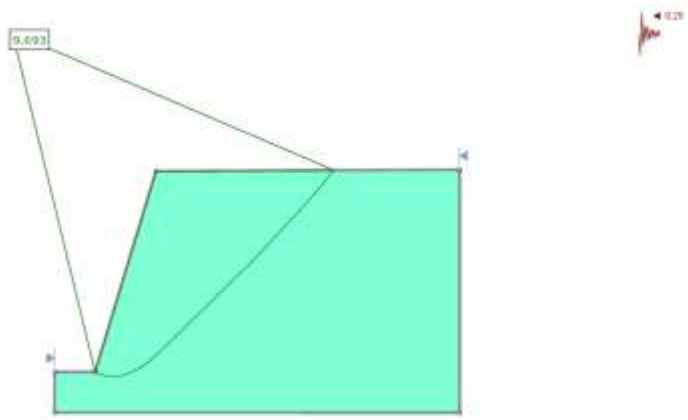
5. DISCUSSION

Tables 1 and 2 summarize the minimum factors of safety and areas of potential failure surface calculated using Bishop, Janbu, Spencer, and Morgenstern-Price methods for the four cases — Siltstone, Limestone, Sandstone and Granite — using Mohr-Coulomb and Generalized Hoek-Brown criteria, respectively. The calculated relative differences of safety factors and predicted areas of potential failure surface with respect to Mohr-Coulomb criterion cases are presented in Table 3 for all cases.

The results show that for weaker rock masses (i.e., Siltstone and Limestone cases), when Generalized Hoek-Brown criterion is used, all the Limit Equilibrium Methods predict lower minimum factors of safety compared to the cases with Mohr-Coulomb criterion. However, when Generalized Hoek-Brown criterion is used for rock masses with higher strength (i.e., Sandstone and Granite cases), overall higher minimum factors of safety are predicted. Moreover, as the strength of rock mass increases – from case 1 to case 4, using Generalized Hoek-Brown criterion for slope stability analysis, the relative difference of the predicted minimum factors of safety with respect to Mohr-Coulomb criterion increases. For the weakest rock mass considered in this study

DOI : 10.31695/IJERAT.2021.3744

(i.e., Siltstone case), using Mohr-Coulomb predicts the slope is stable although using Hoek-Brown criterion, a landslide is predicted by all the Limit Equilibrium Methods. However, for the rock mass with the highest strength (i.e., Granite case), higher minimum factor of safety is predicted when Generalized Hoek-Brown criterion is used.



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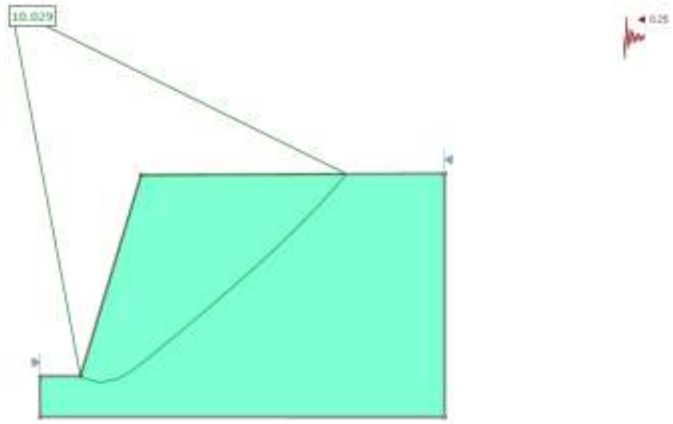

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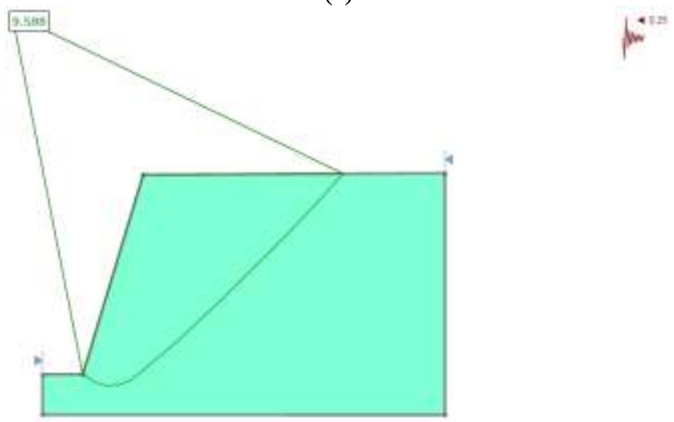

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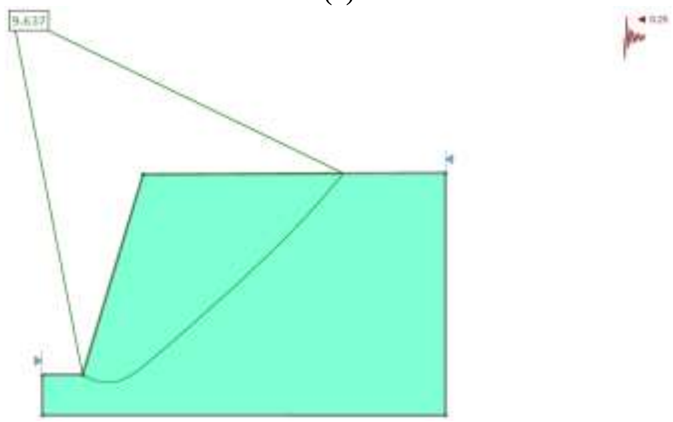
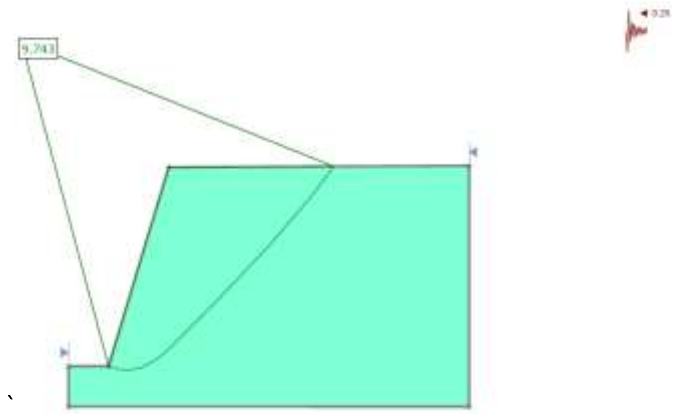


(d)

Figure 7: Results of Limit Equilibrium Stability Analysis for Sandstone using Mohr-Coulomb Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method



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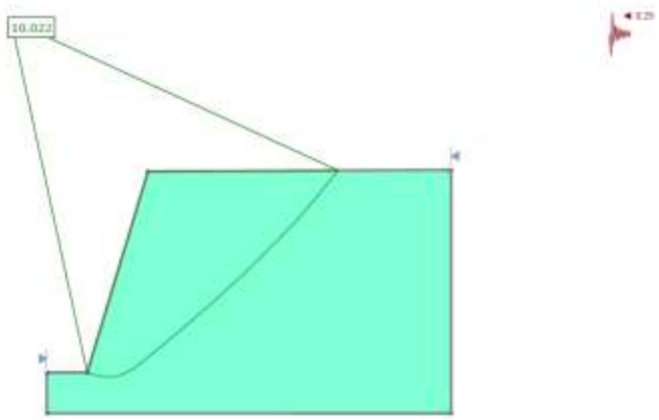

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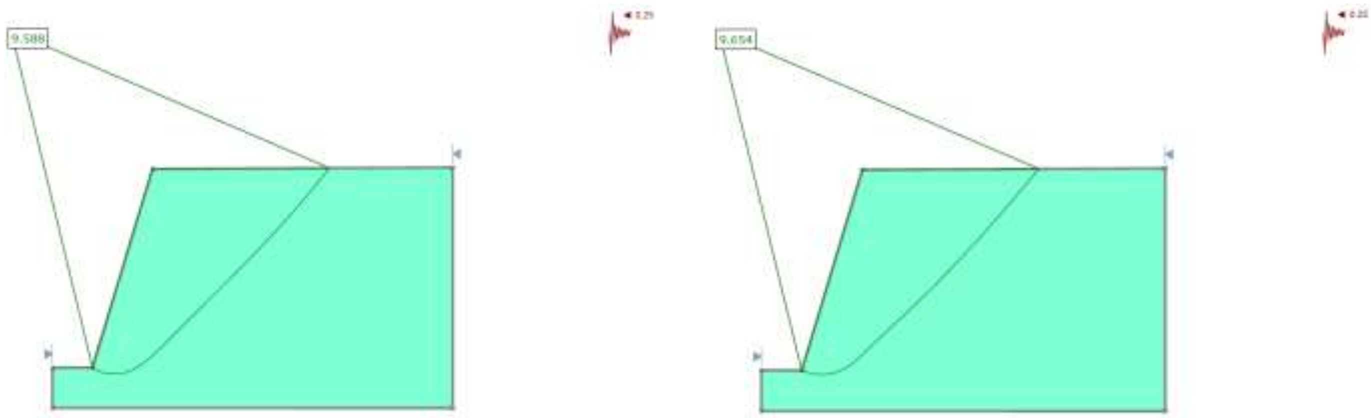
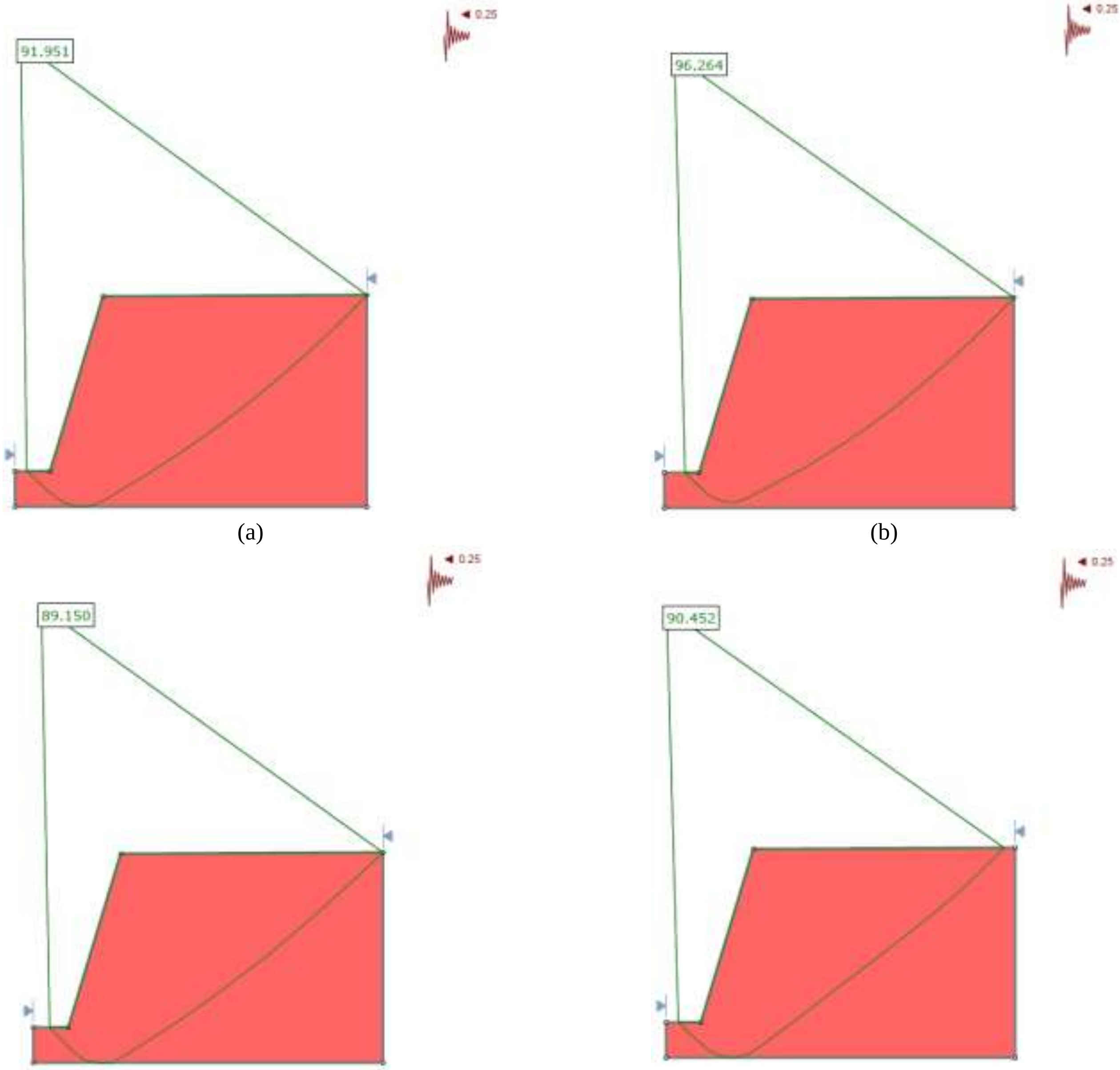


(c) (d)

Figure 8: Results of Limit Equilibrium Stability Analysis for Sandstone using Hoek-Brown Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method



(c) (d)

Figure 9: Results of Limit Equilibrium Stability Analysis for Granite using Mohr-Coulomb Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method

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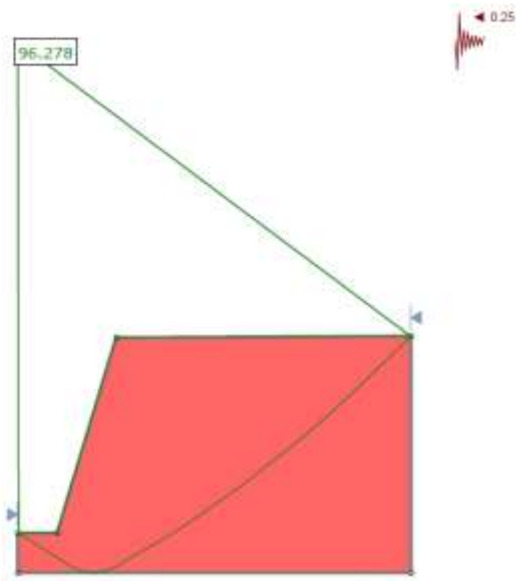
Table 1. Results of stability analysis using Mohr-Coulomb criterion

No	Rock Type	Calculated Minimum Factor of Safety				Predicted Area of Potential Failure Surface (m^2)			
		Bishop	Janbu	Spencer	Morgenstern-Price	Bishop	Janbu	Spencer	Morgenstern-Price
1	Siltstone	1.265	1.260	1.278	1.290	33.30	36.50	26.41	28.60
2	Limestone	5.680	5.836	5.600	5.629	49.76	55.99	54.78	53.38
3	Sandstone	9.693	10.029	9.588	9.637	56.32	65.10	66.31	65.51
4	Granite	91.951	96.264	89.150	90.452	116.94	114.77	115.23	108.47

Table 2. Results of stability analysis using Generalized Hoek-Brown criterion

No	Rock Type	Calculated Minimum Factor of Safety				Predicted Area of Potential Failure Surface (m^2)			
		Bishop	Janbu	Spencer	Morgenstern-Price	Bishop	Janbu	Spencer	Morgenstern-Price
1	Siltstone	0.969	0.846	0.915	0.917	17.74	16.18	17.46	15.27
2	Limestone	4.881	4.894	4.895	4.938	39.59	44.10	30.93	30.45
3	Sandstone	9.743	10.022	9.588	9.654	53.92	61.19	58.02	56.62
4	Granite	96.278	101.056	93.617	94.798	117.32	117.32	111.62	105.31



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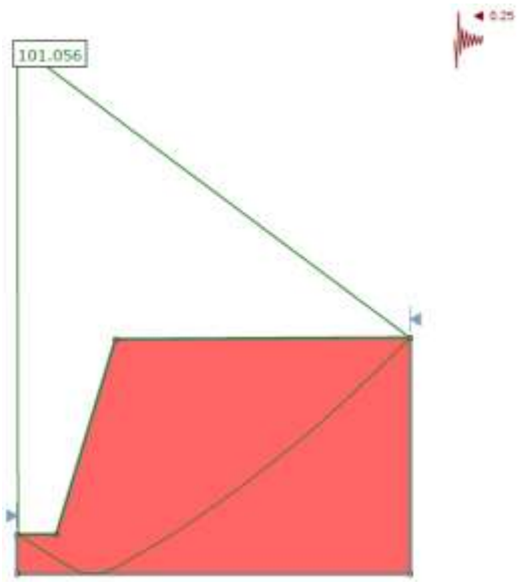

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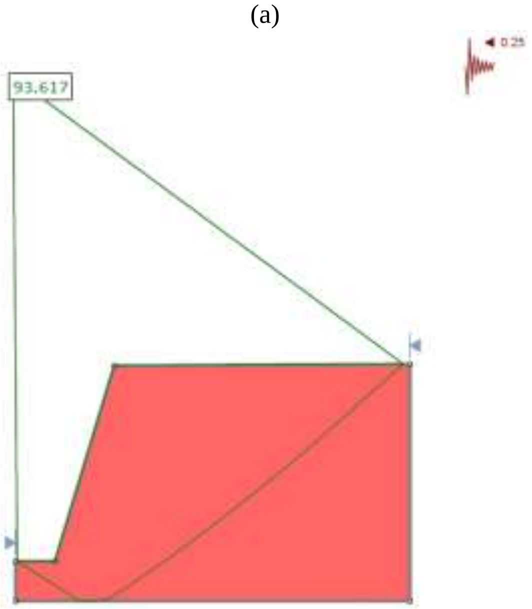

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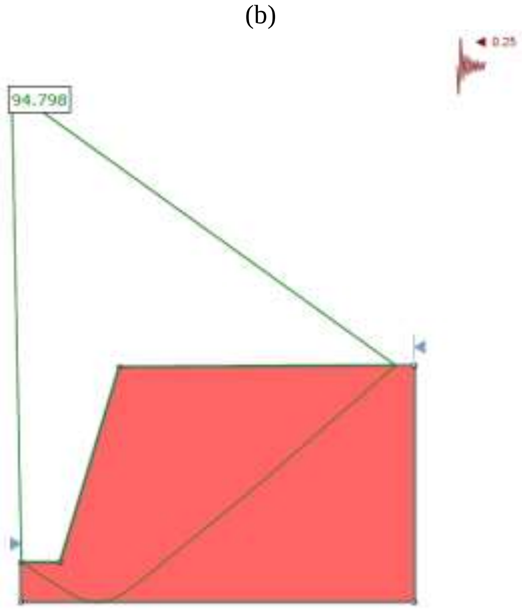

(d)

Figure 10: Results of Limit Equilibrium Stability Analysis for Granite using Hoek-Brown Criterion (a) Bishop Method; (b) Janbu Method; (c) Spencer Method; (d) Morgenstern-Price Method

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Table 3. Relative differences of safety factors and predicted areas of potential failure surface with respect to Mohr-Coulomb criterion cases (%)

No	Rock Type	Calculated Minimum Factor of Safety				Predicted Area of Potential Failure Surface (m^2)			
		Bishop	Janbu	Spencer	Morgenstern-Price	Bishop	Janbu	Spencer	Morgenstern-Price
1	Siltstone	-23.4	-32.9	-28.4	-28.9	-46.7	-55.7	-33.9	-46.6
2	Limestone	-14.1	-16.1	-12.6	-12.3	-20.5	-21.2	-43.5	-42.9
3	Sandstone	0.5	-0.1	0.0	0.2	-4.3	-6.0	-12.5	-13.6
4	Granite	4.7	5.0	5.0	4.8	0.3	2.2	-3.1	-2.9

Similar behavior is observed for the predicted area of potential failure surface so that as the strength of rock mass increases, the relative difference of the predicted areas of potential failure surface with respect to Mohr-Coulomb criterion increases when Generalized Hoek-Brown criterion is used. As can be seen from the results, for the weakest rock mass (i.e., Siltstone), all the Limit Equilibrium methods predict higher values for the area of potential failure surface when Mohr-Coulomb criterion is used. However, higher values of the area of potential failure surface are calculated when Generalized Hoek-Brown criterion is used for the strongest rock mass considered in this study (i.e., Granite).

6. CONCLUSIONS

In this research, the most important Limit Equilibrium Methods as well as different rock strength criteria are used and compared to investigate the influence of rock strength criterion on Limit Equilibrium stability analysis of slopes under seismic conditions. For this study, four different rock types with different rock mass strength are considered. The results obtained by using all the mentioned Limit Equilibrium Methods show that when Generalized Hoek-Brown criterion is used for slope stability analysis, the relative difference of the predicted minimum factors of safety with respect to the cases with Mohr-Coulomb criterion increases as the strength of rock mass increases. Also, when Generalized Hoek-Brown criterion is used, lower minimum factors of safety — compared to the cases with Mohr-Coulomb criterion — are predicted for weak rock masses. However, for rock masses with high strength, higher minimum factors of safety are obtained when Generalized Hoek-Brown criterion is used. The results obtained from this study show a similar behavior for predicting the area of potential failure surface so that when Generalized Hoek-Brown criterion is used, the relative difference of the calculated areas of potential failure surface with respect to Mohr-Coulomb criterion cases increases as the strength of rock mass increases. Also, using Mohr-Coulomb and Generalized Hoek-Brown criteria generally predicts higher values for the area of potential failure surface for weak rock masses and rock masses with high strength, respectively.

For the sake of caution, geotechnical, civil, and mining engineers should use the methods that predict the lowest minimum factor of safety and largest area of potential failure surface for slope stability analysis. Therefore, it is recommended that they use Mohr-Coulomb criterion to calculate the minimum factor of safety for rock masses with high strength and to obtain the area of potential failure surface for weak rock masses. Also, it is recommended that the engineers use Generalized Hoek-Brown criterion to calculate the minimum factor of safety for weak rock masses and to obtain the area of potential failure surface for rock masses with high strength.

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