Seismic Stability of Slopes in Cohesive Soils

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Abstract

The study of soil strength properties is of very substantial to assess the slope instability. Cohesion (c) and angle of internal friction (φ) are the two major parameters of soil and on the basis of these properties, the stability of slope segment can be evaluated. Also, stability of slopes is affected by the application of earthquake load. During recent years, earthquake has become one of the common catastrophic event throughout the world. During earthquakes, different types of slope related failure occurs which results in loss of life and economic damage. The purpose of this study is to analyze the relationship between cohesion of soil and factor of safety of slope under different combination of horizontal and vertical seismic coefficients for a pure homogeneous clay slope model. It is observed that, factor of safety goes on decreasing with the increase of horizontal earthquake co-efficient. Further analysis is performed which indicates that factor of safety increases with the increase of cohesion value and vice versa. LEM module of GEO5 software (2019 version) has been used for this analysis.

Keywords: *Cohesion, Earthquake, factor of safety, seismic coefficients.*

1 Introduction

Slope stability has always been one of the most explored topic due to engineering uses such as earth dams, embankments, abutments, retaining walls etc. being built on or near the slope. Constructed slope as well as natural slopes can fail due to variety of reasons such as change in stress conditions, rainfall, vacillation of ground water table, increasing seismic activity, change in geometry, weathering and improper protection and so on. Bangladesh being located in one of the most active seismic zones has always been a victim of slope related failure especially in CHT tracts. Recent incidents of slope related failures such as landslides due to earthquake in Sunamganj and Sylhet (2009), Chittagong (2017), Rangamati (2003) claimed numerous lives and added distresses to even more people. Therefore a quantitative evaluation of stability of slope is needed before judgment is made regarding a slope related issue.

Tayler and Burns (2005) reported that the earthquake is the greatest threat to the long term stability of slopes, particularly in earthquake active zones. In clay type soil with low cohesion the effect is even more severe. There are many methods of indicating stability of slope considering earthquake such as the pseudo-static method, Newmark's sliding block method and numerical techniques. For example slope stability analysis under seismic loading by Ismail et al. (2014), also seismic stability of homogeneous and layered soil slopes by LEM was by Sazzad et al. (2015), dynamic performance of cohesive slope under seismic loading by Sil et al. (2014) studies gives a significant idea about behavior of clay soil under seismic loading. However very few studies have been carried out showing the effect of both seismic activity and cohesion on stability of slope.

This study illustrates to correlate the effects of seismic activity and cohesion on stability of slope. Pseudo-static method has been adopted in which the earthquake loading is represented by a horizontal static force. This horizontal static force is computed by multiplying the weight of structure by the seismic coefficient. Also in this study cohesion, a shear strength parameter is varied in magnitude to observe the factor of safety shift with respect to it. GEO5 software has been used for numerical modelling and analysis of the slope in terms of factor of safety.

2. Methodology

2.1 Limit Equilibrium Method

Basic of LEM is to assume a potential failure mass and then analyze the cross section of the mass. Several Limit Equilibrium Methods have been developed by scientists over the years. Those methods vary due to factors such as shape of the failure surface, force and moment equilibrium conditions and interslice shear and normal forces. Fellenius (1936) first introduced the method by assuming an ordinary slip circle. Later Bishop (1955) derived a formula by taking interslice normal force into consideration which made the equation non-linear. However, Janbu (1954) around the same period developed the formula by considering any shape of slope failure. Further the method was developed for both general and advanced cases assuming various criteria for equilibrium conditions and interslice forces by Morgenstern-Price (1965), Spencer (1967) and others.

2.2 Horizontal and Vertical Seismic Coefficients

Horizontal and vertical earthquake force is defined by the following equations:

$$F_h = \frac{a_h * W}{g} = K_h * W \qquad (1)$$

$$F_v = \frac{a_v * W}{g} = K_v * W \qquad (2)$$

Here, a_h and a_v are, respectively, horizontal and vertical pseudo-static accelerations, g is the gravitational acceleration constant, and W is the slice weight. The acceleration ratio a/g is a dimensionless coefficient K. The inertia effect is specified as K_h and K_v, the coefficients of acceleration in horizontal and vertical directions, respectively. The recommendations for choosing earthquake coefficient value is given below:

Table 1. Recommended Horizontal Seismic Coefficients (Summarized by Cristiano Melo & Sunil Sharma)

Horizontal Seismic Coefficient, K_h	Description	
0.05 - 01.5	In the United States	
0.12 – 0.25	In Japan	
0.1	Severe earthquakes	Terzaghi
0.2	Violent destructive earthquakes	
0.5	Catastrophic earthquakes	
0.1 – 0.2	Seed, FOS≥ 1.5	
0.1	Major Earthquake, FOS > 1.0	Corps of Engineers
0.15	Great Earthquake, FOS > 1.0	

2.3 Geometry of Numerical Model

In all dimensions, SI unit was adopted. Lateral width of the model slope was fixed by taking minimum X axis distance as 0 and maximum X axis distance as 30 meter. Also the depth of model below the deepest interface point was set to 5.0 meter. After fixing up the ranges, the slope was plotted textually by the following co-ordinates shown in the following table sequentially.

Table 2. Co-ordinates of Model Slope

x (meter)	0	6	18	30
z (meter)	0	0	12	12

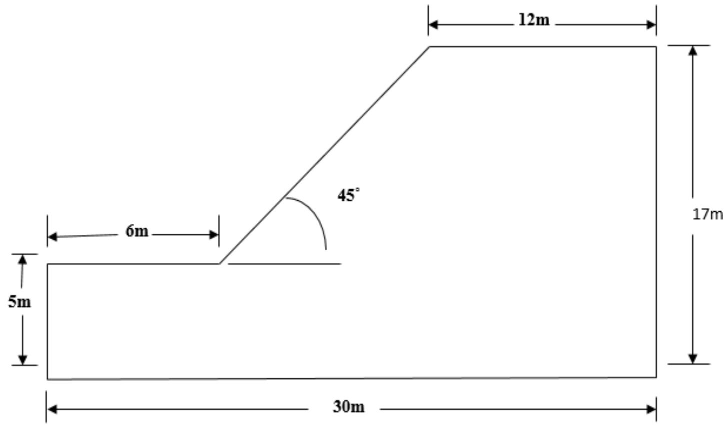

Figure 1. Geometry of Numerical Model.

Classification type of soil was set to Standard. CL, CI – Clay with medium or low plasticity was adopted for our study where the consistency of the soil was stiff consistency and degree of saturation, Sr < 0.8 (Easy to penetrate by nail). Stress state was considered effective without the effect of soil foliation. Mode of uplift pressure was considered standard.

Table 3**.** Properties of Soil used for this study

Properties	**Values**
Unit weight, γ (kN/m^3)	21.00
Angle of internal friction, ϕ_{ef} (˚)	19.00
Cohesion of soil, C_{ef} (kPa)	20-40
Saturated unit weight, γ_{sat} (kN/m^3)	21.00

Analysis was done by five methods which are Bishop, Fellenius/Petterson, Spencer, Janbu and Morgenstern-Price. For each method the slip surface of the slope was considered as circular and radius and coordinates of the center of the slip circle was put textually and it was being optimized while analyzing. After selecting a slip circle the seismic Kh and Kv coefficients were adjusted in the earthquake section of the software according to various ratio of Kv/Kh. In this study the ratios were 0.25, 0.50, 0.75 and 1.0. Then the analysis was performed for all the Kh and Kv values with different cohesion values ranging from 20 kPa to 40 kPa.

3 Results and Discussion

The analysis results are shown in table 4, table 5, table 6, table 7 and table 8 where ratio K_v/K_h is varied from 0.25 to 1.0 with an increment of 0.25. Value of horizontal seismic coefficient used in this study are 0.1, 0.2, 0.3 and 0.4. The cohesion values are gradually increased from 20kPa to 40kPa with an increment of 5kPa. In the analysis Bishop, Fellenius, Spencer, Janbu and Morgenstern methods were used for estimating factor of Safety. Following table 4 shows variation of Factor of Safety with respect to K_h value ranging from 0.1 to 0.4.

Table 4. Factor of safety for all values of K_v/K_h for cohesion c = 20kPa

K_v/K_h	K_h	0.1	0.2	0.3	0.4
0.25	Bishop	0.96	0.84	0.73	0.64
	Fellenius	0.93	0.81	0.70	0.61
	Spencer	0.96	0.84	0.75	0.70
	Janbu	0.96	0.84	0.79	0.71
	Morgenstern	0.97	0.85	0.79	0.71
0.50	Bishop	0.97	0.85	0.74	0.64
	Fellenius	0.93	0.82	0.71	0.71
	Spencer	0.97	0.85	0.78	0.71
	Janbu	0.97	0.85	0.79	0.71
	Morgenstern	0.98	0.87	0.80	0.70

K_v/K_h	K_h	0.1	0.2	0.3	0.4
0.75	Bishop	0.97	0.86	0.74	0.63
	Fellenius	0.94	0.83	0.72	0.61
	Spencer	0.98	0.86	0.80	0.71
	Janbu	0.97	0.86	0.81	0.72
	Morgenstern	0.98	0.88	0.83	0.71
1	Bishop	0.90	0.87	0.75	0.62
	Fellenius	0.95	0.84	0.72	0.60
	Spencer	0.99	0.87	0.81	0.71
	Janbu	0.99	0.88	0.82	0.72
	Morgenstern	1.00	0.9	0.83	0.72

Following table 5 shows variation of Factor of Safety with respect to K_h value ranging from 0.1 to 0.4

Table 5. Factor of safety for all values of K_v/K_h for cohesion c = 25kPa

K_v/K_h	K_h	0.1	0.2	0.3	0.4
0.25	Bishop	1.08	0.94	0.82	0.72
	Fellenius	1.05	0.91	0.80	0.70
	Spencer	1.08	0.94	0.86	0.79
	Janbu	1.08	0.95	0.88	0.79
	Morgenstern	1.09	0.95	0.90	0.82
0.50	Bishop	1.09	0.96	0.83	0.72
	Fellenius	1.06	0.93	0.81	0.70
	Spencer	1.09	0.96	0.88	0.80
	Janbu	1.09	0.96	0.90	0.80
	Morgenstern	1.10	0.98	0.92	0.84
0.75	Bishop	1.10	0.97	0.84	0.72
	Fellenius	1.07	0.94	0.82	0.69
	Spencer	1.10	0.97	0.90	0.80
	Janbu	1.10	0.98	0.91	0.87
	Morgenstern	1.10	0.99	0.93	0.82
1	Bishop	1.11	0.99	0.85	0.71
	Fellenius	1.08	0.92	0.82	0.69
	Spencer	1.12	1.00	0.92	0.81
	Janbu	1.11	0.99	0.93	0.89
	Morgenstern	1.13	1.01	0.95	0.82

Following table 6 shows variation of Factor of Safety with respect to K_h value ranging from 0.1 to 0.4.

Table 6. Factor of safety for all values of K_v/K_h for cohesion c = 30kPa

K_v/K_h	K_h	0.1	0.2	0.3	0.4
0.25	Bishop	1.20	1.05	0.91	0.80
	Fellenius	1.16	1.01	0.89	0.77
	Spencer	1.20	1.05	0.95	0.88
	Janbu	1.20	1.05	0.97	0.88
	Morgenstern	1.21	1.06	0.99	0.90
0.50	Bishop	1.21	1.06	0.93	0.80
	Fellenius	1.17	1.03	0.90	0.78
	Spencer	1.21	1.06	0.98	0.88
	Janbu	1.21	1.07	0.99	0.89
	Morgenstern	1.22	1.08	1.01	0.92
0.75	Bishop	1.22	1.03	0.94	0.80
	Fellenius	1.19	1.00	0.91	0.78
	Spencer	1.22	1.03	1.00	0.89
	Janbu	1.22	1.04	1.01	0.97
	Morgenstern	1.23	1.04	1.03	0.92

K_v/K_h	K_h	0.1	0.2	0.3	0.4
1	Bishop	1.24	1.10	0.95	0.82
	Fellenius	1.20	1.07	0.92	0.78
	Spencer	1.24	1.10	1.03	0.91
	Janbu	1.24	1.12	1.03	1.02
	Morgenstern	1.25	1.13	1.06	0.92

Following table 7 shows variation of Factor of Safety with respect to K_h value ranging from 0.1 to 0.4.

Table 7. Factor of safety for all values of K_v/K_h for cohesion c = 35kPa

K_v/K_h	K_h	0.1	0.2	0.3	0.4
0.25	Bishop	1.31	1.15	1.00	0.87
	Fellenius	1.28	1.11	0.97	0.85
	Spencer	1.32	1.15	1.04	0.95
	Janbu	1.31	1.17	1.05	0.96
	Morgenstern	1.33	1.16	1.08	0.99
0.50	Bishop	1.32	1.17	1.01	0.88
	Fellenius	1.29	1.14	0.99	0.86
	Spencer	1.33	1.17	1.07	0.96
	Janbu	1.33	1.18	1.08	0.97
	Morgenstern	1.34	1.18	1.10	1.01
0.75	Bishop	1.34	1.19	1.03	0.89
	Fellenius	1.30	1.16	1.00	0.86
	Spencer	1.34	1.19	1.11	0.98
	Janbu	1.34	1.20	1.12	1.03
	Morgenstern	1.35	1.21	1.12	1.03
1	Bishop	1.36	1.21	1.04	0.89
	Fellenius	1.32	1.18	1.02	0.87
	Spencer	1.36	1.21	1.12	1.01
	Janbu	1.36	1.24	1.15	1.03
	Morgenstern	1.37	1.23	1.16	1.01

Following table 8 shows variation of Factor of Safety with respect to K_h value ranging from 0.1 to 0.4.

Table 8. Factor of safety for all values of K_v/K_h for cohesion c = 40kPa

K_v/K_h	K_h	0.1	0.2	0.3	0.4
0.25	Bishop	1.42	1.26	1.08	0.95
	Fellenius	1.39	1.21	1.06	0.94
	Spencer	1.43	1.24	1.14	1.03
	Janbu	1.43	1.25	1.13	1.04
	Morgenstern	1.44	1.26	1.15	1.07
0.50	Bishop	1.44	1.27	1.10	0.96
	Fellenius	1.41	1.24	1.08	0.93
	Spencer	1.44	1.27	1.18	1.05
	Janbu	1.44	1.27	1.17	1.06
	Morgenstern	1.45	1.28	1.19	1.11
0.75	Bishop	1.45	1.29	1.12	0.97
	Fellenius	1.42	1.26	1.10	0.95
	Spencer	1.46	1.29	1.19	1.07
	Janbu	1.46	1.32	1.20	1.16
	Morgenstern	1.47	1.31	1.22	1.11
1	Bishop	1.48	1.31	1.14	0.98
	Fellenius	1.44	1.29	1.11	0.96
	Spencer	1.48	1.33	1.22	1.11
	Janbu	1.48	1.34	1.23	1.11
	Morgenstern	1.49	1.34	1.26	1.10

Following figure 2 to figure 5 shows variation of factor of safety with cohesion value for different combination of K_v/K_h.

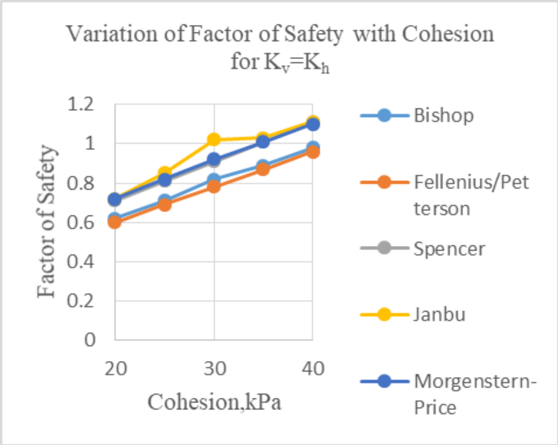

Figure 2. Variation of Factor of Safety with Cohesion for $K_v=K_h$

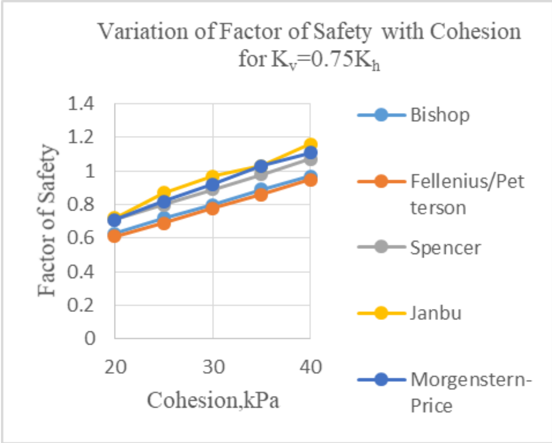

Figure 3. Variation of Factor of Safety with Cohesion for $K_v=0.75K_h$

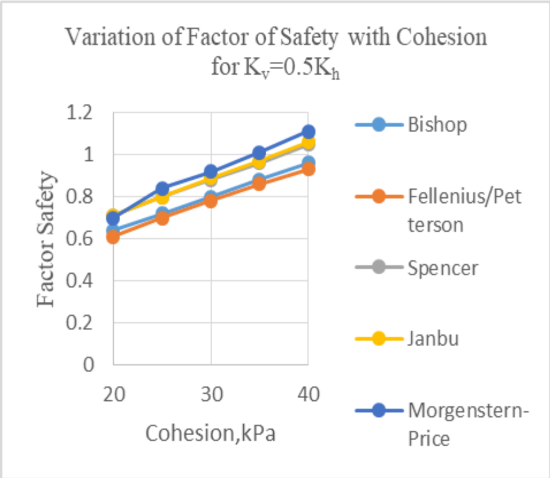

Figure 4. Variation of Factor of Safety with Cohesion for $K_v=0.5K_h$

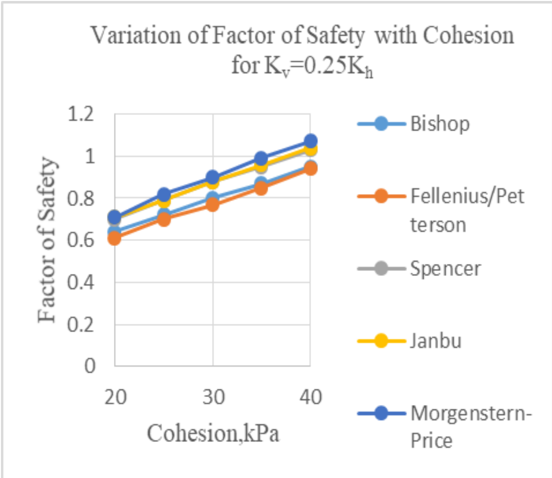

Figure 5. Variation of Factor of Safety with Cohesion for $K_v=0.25K_h$

4 Conclusions

LEM module of Geo5 software has been used to analyze a homogeneous slope model with clay type soil. The findings from the study can be summarized as follows:

a) For all ratios of K_v/K_h, factor of safety decreases with increase of horizontal seismic coefficient K_h. considering all methods of analysis.
b) For all ratios of K_v/K_h, factor of safety increases with the increase of cohesion value considering all methods of analysis.
c) While the Janbu and Morgenstern method yields larger values of FOS, Spencer method yields lowest value of FOS among of all the method considered in this study.

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