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LEM Stability Analysis of Landslides Induced byEarthquakes: Impact of a Weak Layer

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ABSTRACT: *In 2020, the author performed a comparison between the use of a numerical method called Finite Difference Method and the traditional method (i.e., Limit Equilibrium Method)for stability analysis of slopes containing a weak layer (Beyabanaki [1]). The authorassumed that the slope instability was due to gravity only. In thispaper, impact of a weak layer on the stability of slopes subjected to a seismic load isstudied. For this purpose, four different Limit Equilibrium Methods—(1) Bishop, (2) Janbu, (3) Spencer, and (4) Morgenstern-Price—are used to modelsimilar cases mentioned in the previous study—i.e.,(1) no weak layer, (2) a horizontal weak layer in the middle of a slope, (3) a horizontal weak layer close to the slope base, and(4) an inclined weak layer. The results show that the maximum effect of seismic on the stability of slopes occurs when the weak layer is inclined.Furthermore, all the Limit Equilibrium Methods used show that the area of potential failure surface would be largest when there is a horizontal weak layer close to the slope base.Moreover, the results of the modeling are compared for each method and each case.This study helps geotechnical, civil, and mining engineers select the more appropriate Limit Equilibrium Method for stability analysis of landslides induced by earthquakes when there is a weak layer in slopes.*

KEYWORDS: *Landslide, Slope stability analysis, Seismic, Limit equilibrium methods, Factor of safety*

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I. INTRODUCTION

Slope instability and landslides triggered by earthquakes are natural disasters that can destroy buildings and properties and kill people [2, 3]. To evaluate and analyze the stability of slopes and predict landslides, different approaches can be used. The most common ones are numerical modeling and Limit Equilibrium Methods (LEM) [4]. Numerical methods used to analyze slopes are usually the Finite Difference Method (FDM) [5, 6], Finite Element Method (FEM) [7], Discontinuous Deformation Analysis (DDA) [8, 9], and Discrete Element Method (DEM) [10]. LEM is the most popular approach in slope stability analysis and the most important Limit Equilibrium Methods are Bishop, Janbu, Spencer, and Morgenstern-Price [11, 12].

Weak layers, such as fractured zones or faults, contain sediment or rock that has strength significantly lower than that of adjacent units. These weak layershave significant effects on the stability of slopes [13] and cannot be overlooked in slope stability analysis due to their weak mechanical properties [14, 15]. There is no research published on investigating the impact of a weak layer on instability of slopes due to seismic using different methods of Limit Equilibrium for stability analysis, although there are many studies on the influence of weak layers on slope stability. For instance, Yasu [13] studied effects of a weak layer on the stability of slopes. A procedure based on LEM and Newmark's sliding block method was used by Deng et al. [16] to evaluate the displacement of slopes containing a weak layer. A numerical study of slope-stabilizing piles in slopes with a weak thin layer was performed by Ho [17]. A translational failure mechanism to evaluate the stability of slopes with a weak layer was developed by Zhou et al. [18]. The effect of a weak layer on slope sliding mode and stability was studied by Li and Li [14]. A three-dimensional analysis of complex open-pit mine rock slope stability affected by fault and weak layer was carried out by Li et al. [15]. Finally, Beyabanaki [1] performed a comparison between the use ofFinite Difference and Limit Equilibrium Methods for landslide analysis of slopes containing a weak layer.

In this paper, fourdifferent Limit EquilibriumMethods—Bishop, Janbu, Spencer, and Morgenstern-Price—are compared to study the impact of a weak layer on the stability of slopes subjected to a seismic load for different locations and slopes of a weak layer: (1) no weak layer, (2) a horizontal weak layer in the middle of a slope, (3) a horizontal weak layer close to the slope base, and (4) an inclined weak layer.

II. LIMIT EQUILIBRIUM METHODS

Failure surfaces are pre-assumed and are divided into several slices based on force and/or moment equilibrium in Limit Equilibrium Methods (LEM), which are the most widespread and common methods in slope stability analysis [11, 12]. These methods assume a constant factor of safety along the potential failure surface. Also, in these methods, different interslice and equilibrium conditions are assumed to calculate force and/or moment equilibrium for the slices [20]. The Fellenius method neglects the interslice forces and calculates factor of safety using the moment equilibrium for circular failure surfaces only. Because of these simplifications, this method was not used in the study. Another, theBishop method, satisfies moment equilibrium whileadditionally considering the interslice normal forces. In the Janbumethod, only horizontal force equilibrium of wedge is considered to achieve a factor of safety for the slope failure. Both force and moment equilibrium are considered in the Spencer and Morgenstern-Price methods so that they can be used to evaluate both for circular and noncircular potential failure surfaces [20].

III. METHODOLOGY AND MODELING

In this study, the slope, weak layer situations, and dimensions are similar to the ones used in the author's previous research published in 2020 [1], as shown in Fig. 1. As can be seen in this figure, first case does not contain any weak layer; in the second case, a horizontal 0.5 mthick weak layer is located at 5 m above the toe; the third case contains a horizontal 0.5mthick weak layer 1 m above the toe; and in the last case, the slope contains an inclined weak layer with a thickness of 0.5 m and an angle of 29° with respect to horizontal.

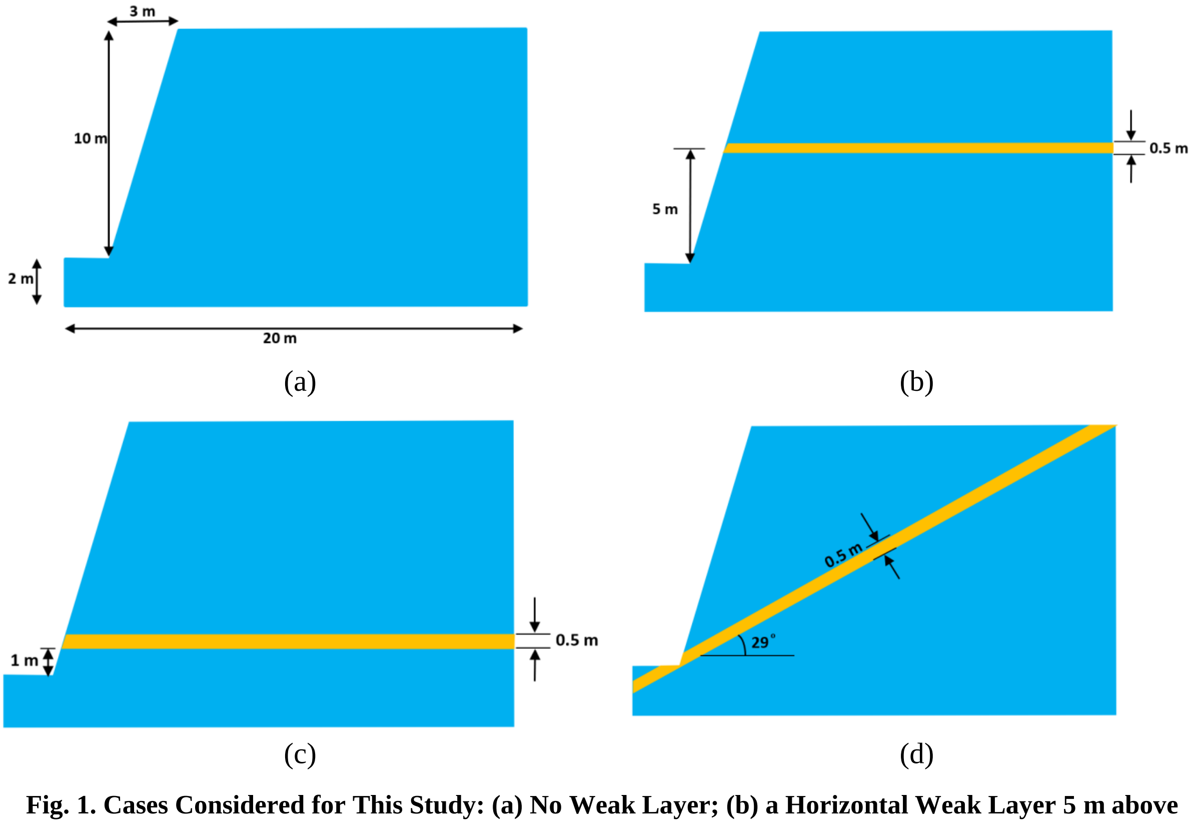


Fig. 1. Cases Considered for This Study: (a) No Weak Layer; (b) a Horizontal Weak Layer 5 m above Toe; (c) a Horizontal Weak Layer 1 m above Toe; (d) an Inclined Weak Layer with an Angle of 29° with Respect to Horizontal

Table 1 presents the properties of the rock and weak layer considered in this study. For the cases with seismic, a horizontal seismic load coefficient of 0.25 is considered.

Table 1. Properties of Rock and Weak Layer

Material	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (Degrees)
Rock (Siltstone)	27	44	39.2
Weak Layer	25	8	15.9

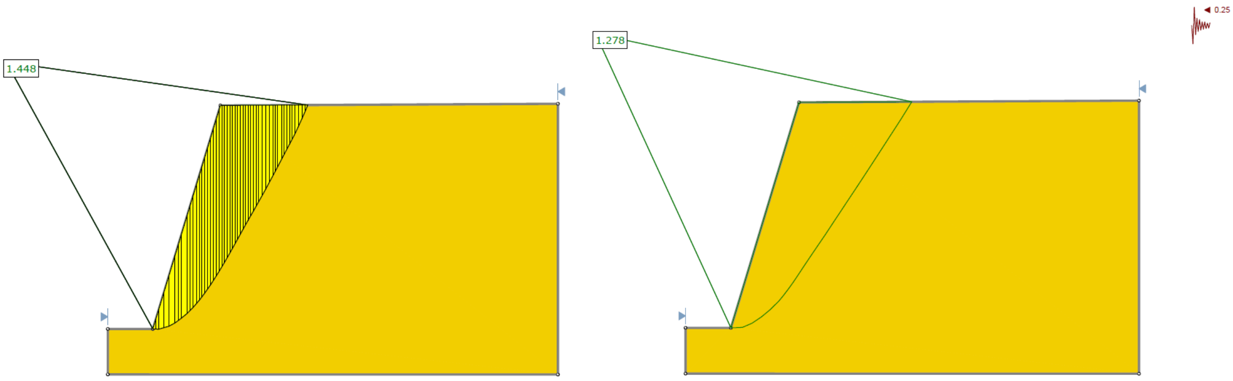
The slope stability analysis for all the methods (Bishop, Janbu, Spencer and Morgenstern-Price*)* was performed using SLIDE version 9.008 [19].

IV. RESULTS

A total of 32 caseswere modeled in this study. In this section, results for each case are presented and discussed.

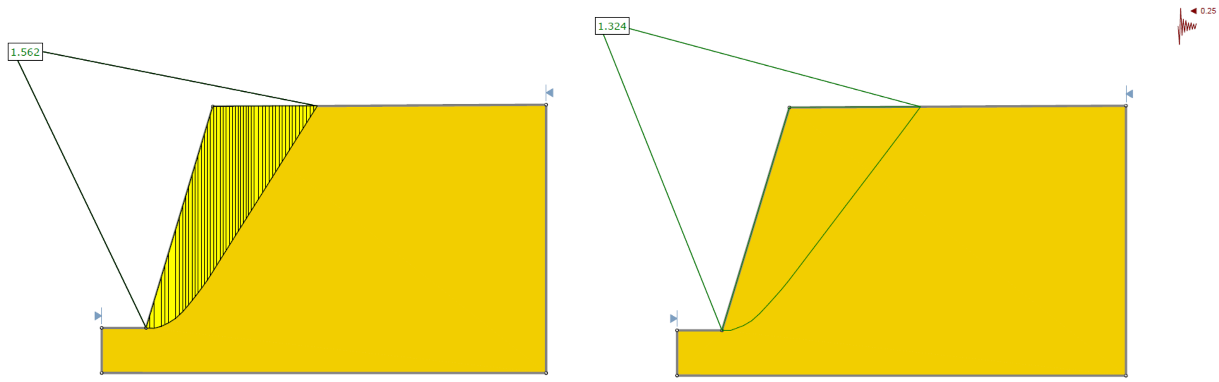
5.1 Case 1: No Weak Layer

The model configuration, potential failure surfaces, and results obtained from the modeling for case 1 are presented in Fig. 2 through Fig. 5. In this case, the slope does not contain any weak layer.



(a) (b)

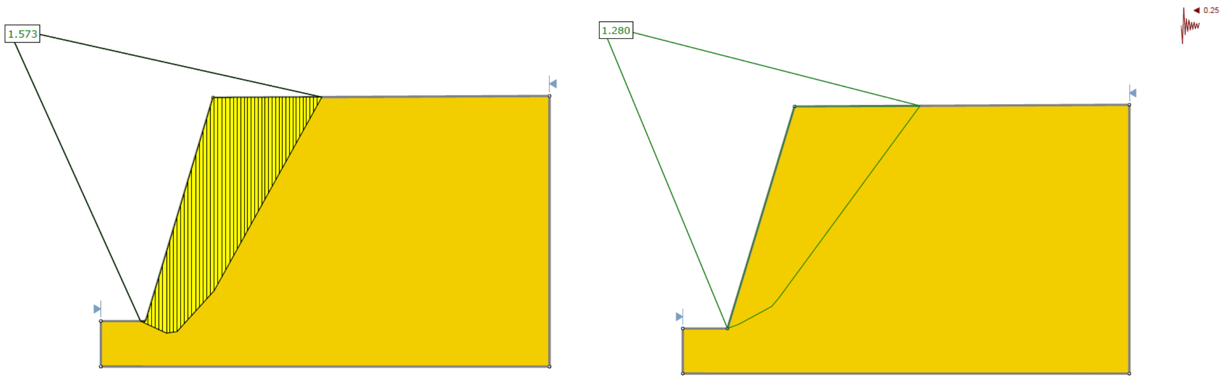
Fig. 2. Results of LEM Analysis using Bishop Method for Case 1: (a) No Seismic; (b) With Seismic



(a) (b)

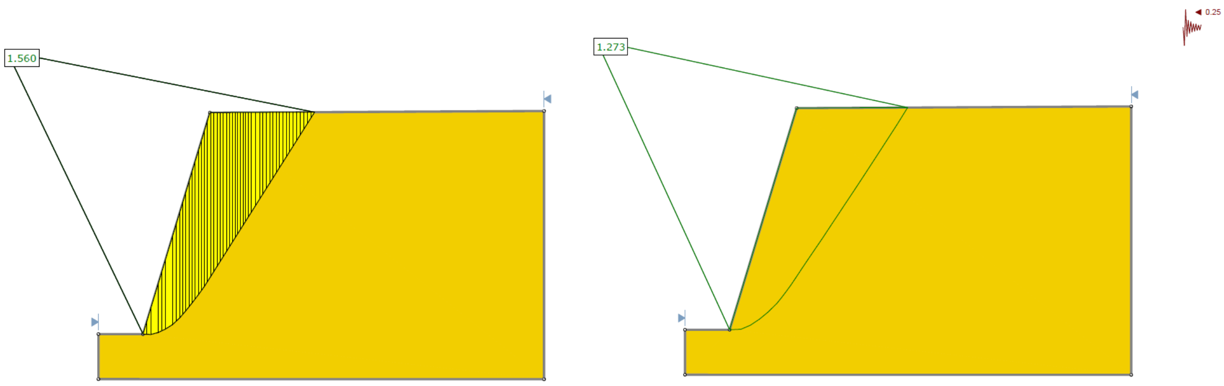
Fig. 3. Results of LEM Analysis using Janbu Method for Case 1: (a) No Seismic; (b) With Seismic

The minimum factors of safety for this case calculated by using Bishop, Janbu, Spencer, and Morgenstern-Price methods without seismic are 1.448, 1.562, 1.573, and 1.56, respectively. Also, the areas of potential failure surfaces predicted using Bishop, Janbu, Spencer, and Morgenstern-Price methods when there is no seismic are 26.87 m^2, 29.72 m^2, 35.68 m^2,and 29.72 m^2, respectively.As can be seen, for the slope without any weak layer, Bishop and Spencer methods predict the minimum value and the maximum value of both the minimum factor of safety and area of potential failure surface, respectively.



(a) (b)

Fig. 4. Results of LEM Analysis using Spencer Method for Case 1: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 5. Results of LEM Analysis using Morgenstern-Price Method for Case 1: (a) No Seismic; (b) With Seismic

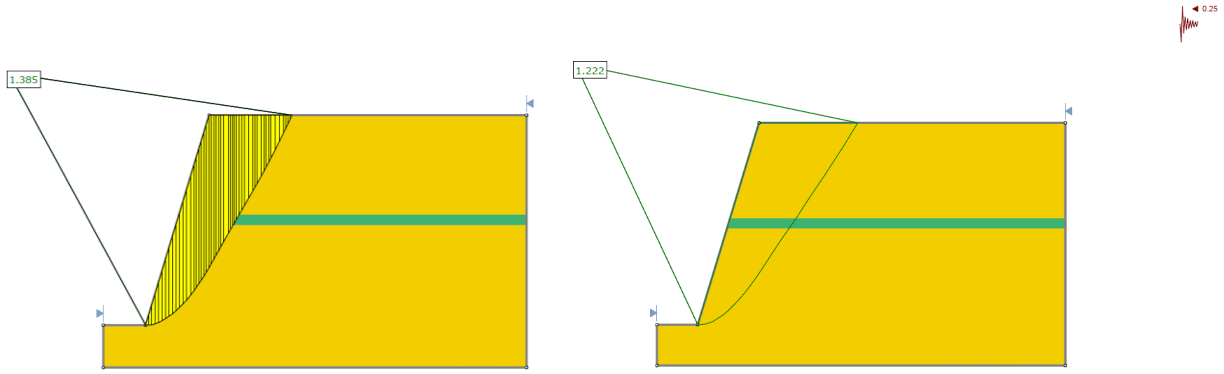
For the case with seismic, using Bishop, Janbu, Spencer and Morgenstern-Price methods, the calculated minimum factors of safety are 1.278, 1.324, 1.280, and 1.273, respectively, and the predicted areas of potential failure surfaces are 31.47 m^2, 35.02 m^2, 33.69 m^2, and 31.47 m^2, respectively. Therefore, when there is seismic, the minimum and maximum values of the minimum factors of safety are obtained using Bishop and Janbu methods, respectively. Furthermore, Bishop and Morgenstern-Price methods and Janbu method predict the minimum and maximum values of the potential failure surface, respectively.

5.2 Case 2: Horizontal Weak Layer in the Middle of Slope

Fig. 6 through Fig. 9 show the model configuration, potential failure surfaces, and minimum factors of safety obtained from the analysis using Bishop, Janbu, Spencer, and Morgenstern-Price methods, respectively, for the case with a horizontal weak layer in the middle of the slope.

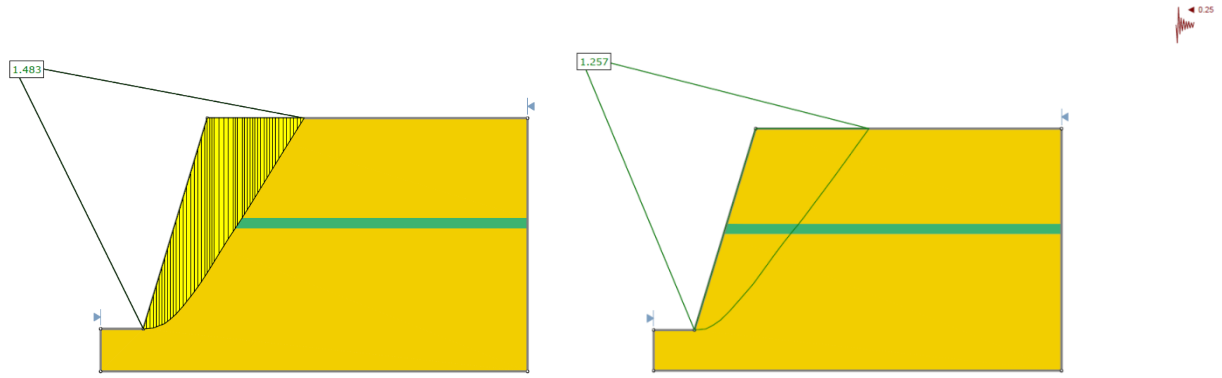
The minimum factors of safety for case 2 without seismic are 1.385, 1.483, 1.479, and 1.492 calculated by using Bishop, Janbu, Spencer and Morgenstern-Price methods, respectively. Moreover, the areas of potential failure surfaces predicted using Bishop, Janbu, Spencer and Morgenstern-Price methods when there is no seismic are 26.48 m^2, 28.62 m^2, 35.55m^2,and 35.55 m^2, respectively. Therefore, when there is no seismic, the minimum and maximum values of the minimum factors of safety are obtained using Bishop and Morgenstern-Price methods, respectively. Also, Bishop method, and Spencer and Morgenstern-Price methods predict the minimum and maximum values of the potential failure surface, respectively.

For case 2 with seismic, using Bishop, Janbu, Spencer, and Morgenstern-Price methods, the calculated minimum factors of safety are 1.222, 1.257, 1.237, and 1.281, respectively, and the predicted areas of potential failure surfaces are 30.27m^2, 33.14m^2, 35.29m^2, and 33.29 m^2, respectively. As can be seen, for the slope with a horizontal weak layer in the middle, 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 Bishop and Spencer methods, respectively.



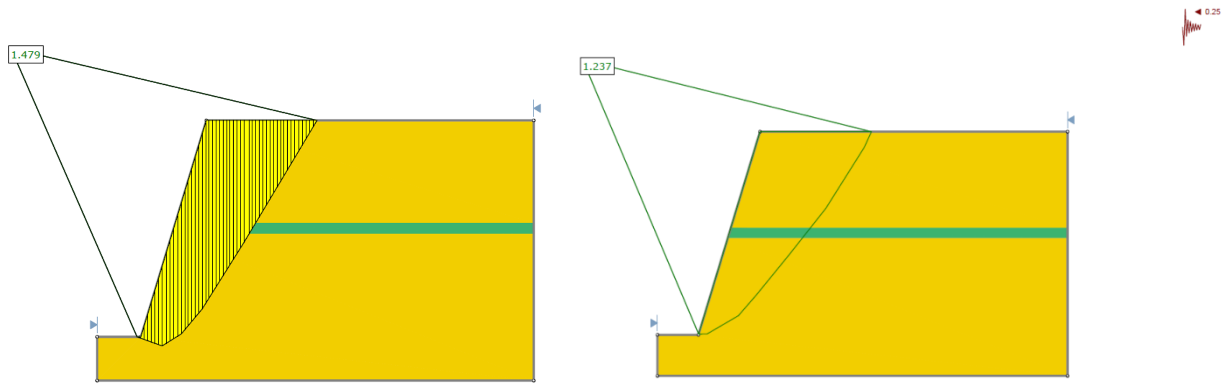
(a) (b)

Fig. 6. Results of LEM Analysis using Bishop Method for Case 2: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 7. Results of LEM Analysis using Janbu Method for Case 2: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 8. Results of LEM Analysis using Spencer Method for Case 2: (a) No Seismic; (b) With Seismic

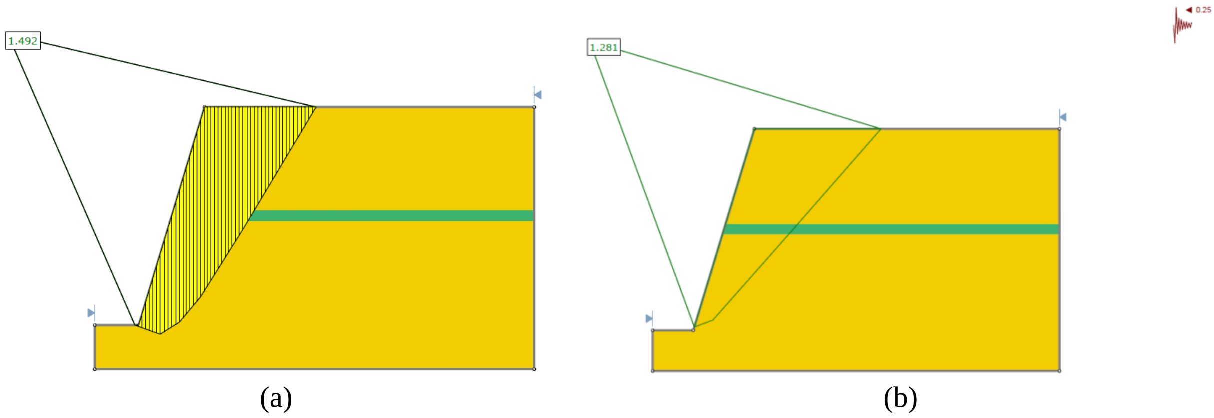


Fig. 9. Results of LEM Analysis using Morgenstern-Price Method for Case 2: (a) No Seismic; (b) With Seismic

5.3 Case 3: Horizontal Weak Layer Close to Slope Base

The model configuration, potential failure surfaces, and results obtained from the modeling for case 3 are presented in Fig. 10 through Fig. 13. In this case, the slope contains a horizontal weak layer close to the slope base.

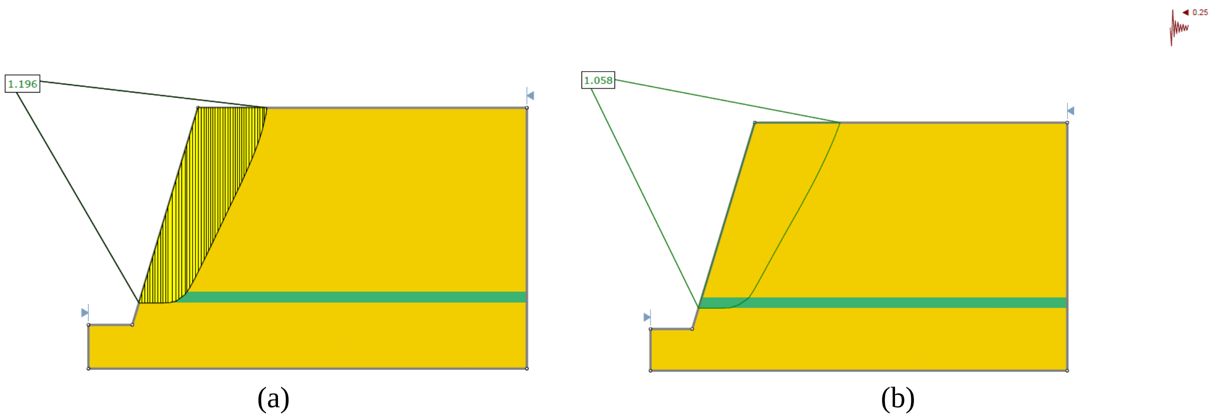


Fig. 10. Results of LEM Analysis using Bishop Method for Case 3: (a) No Seismic; (b) With Seismic

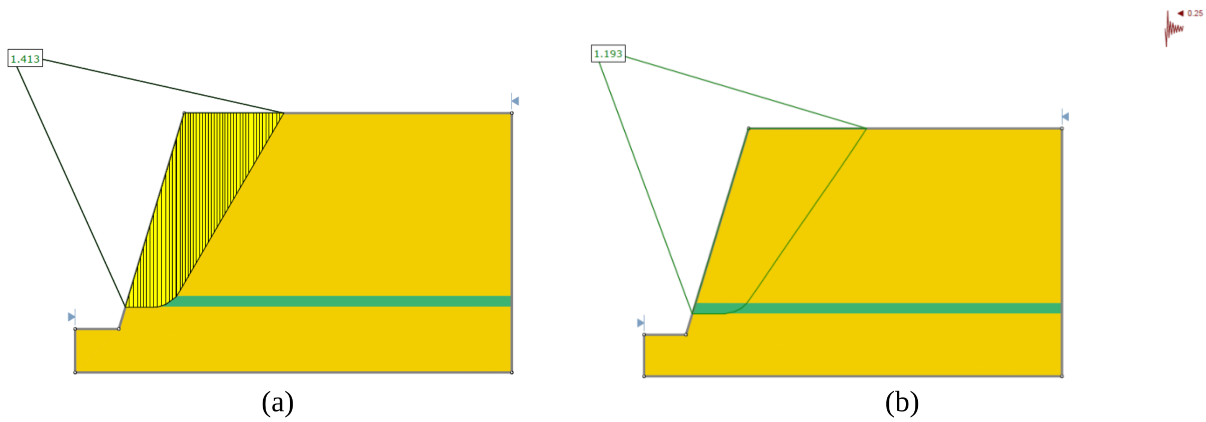
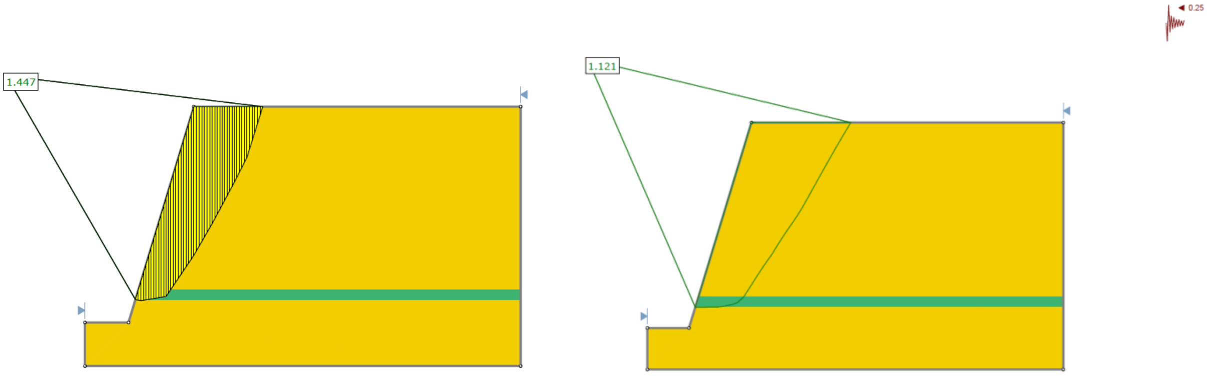
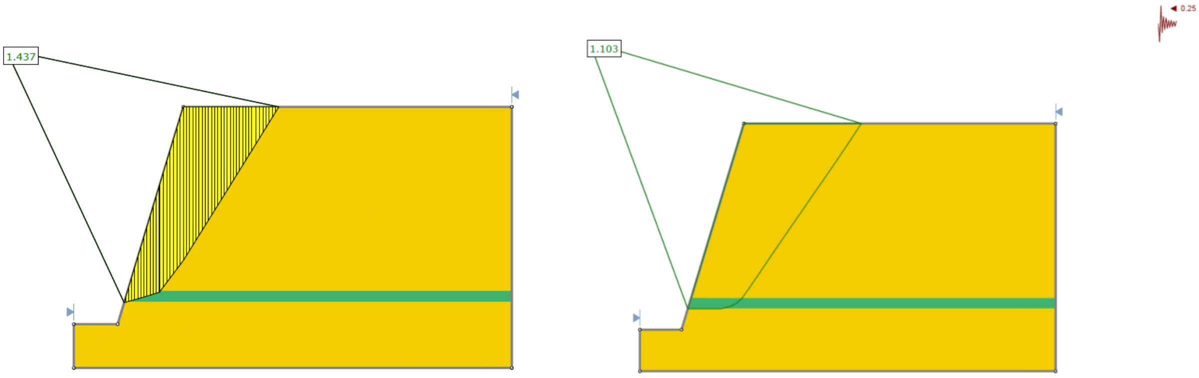


Fig. 11. Results of LEM Analysis using Janbu Method for Case 3: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 12. Results of LEM Analysis using Spencer Method for Case 3: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 13. Results of LEM Analysis using Morgenstern-Price Method for Case 3: (a) No Seismic; (b) With Seismic

The minimum factors of safety for this case calculated by using Bishop, Janbu, Spencer, and Morgenstern-Price methods without seismic are 1.196, 1.413, 1.447, and 1.437, respectively. Also, the areas of potential failure surfaces predicted using Bishop, Janbu, Spencer, and Morgenstern-Price methods when there is no seismic are 24.48m^2, 29.32m^2, 22.56m^2,and 25.65m^2, respectively. The results show that, for the slope with a horizontal weak layer close to the slope base, Bishop and Spencer methods predict the minimum value and the maximum value of the minimum factor of safety, respectively. Also, Spencer and Janbu methods predict the minimum value and the maximum value of the area of potential failure surface, respectively.

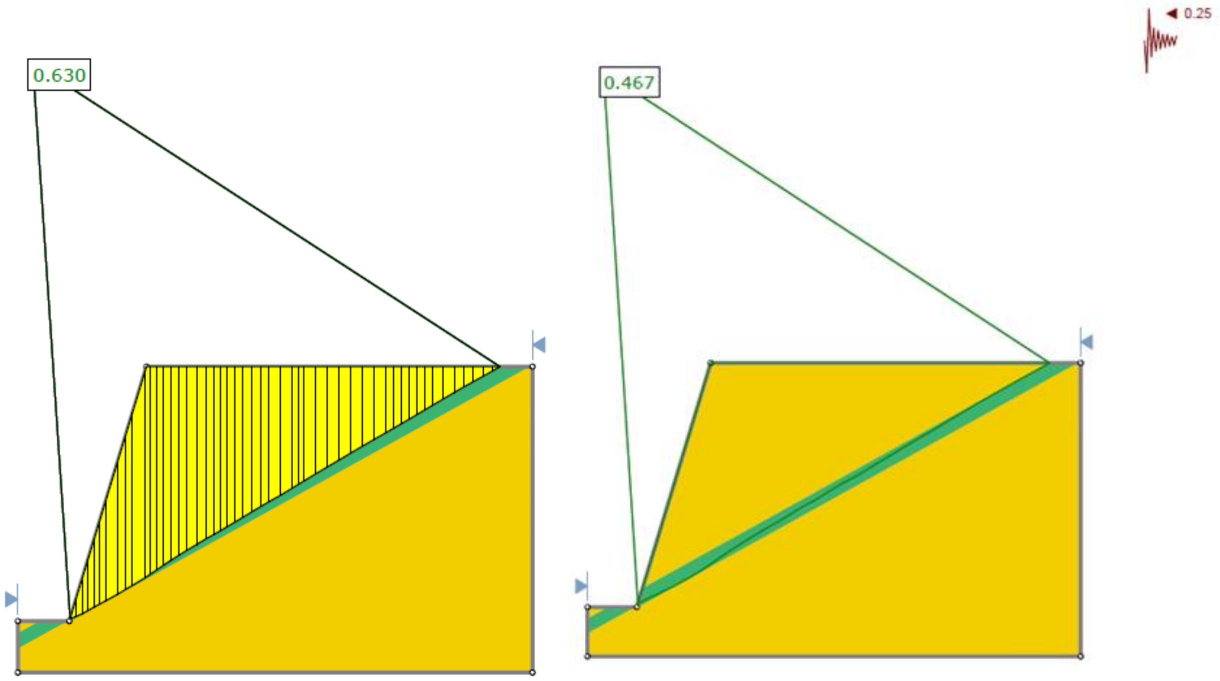
For the case with seismic, using Bishop, Janbu, Spencer, and Morgenstern-Price methods, the calculated minimum factors of safety are 1.058, 1.193, 1.121, and 1.103, respectively, and the predicted areas of potential failure surfaces are 28.84 m^2, 35.25 m^2, 30.82 m^2, and 35.25 m^2, respectively. Therefore, when there is seismic, the minimum and maximum values of the minimum factors of safety are obtained using Bishop and Janbu methods, respectively. Furthermore, Bishop method, and Morgenstern-Price and Janbu methods predict the minimum and maximum values of the potential failure surface, respectively.

5.4 Case 4: Inclined Weak Layer

Fig. 14 through Fig. 17 show the model configuration, potential failure surfaces, and minimum factors of safetyobtained from the analysis using Bishop, Janbu, Spencer, and Morgenstern-Price methods, respectively, for the case with an inclined weak layer.

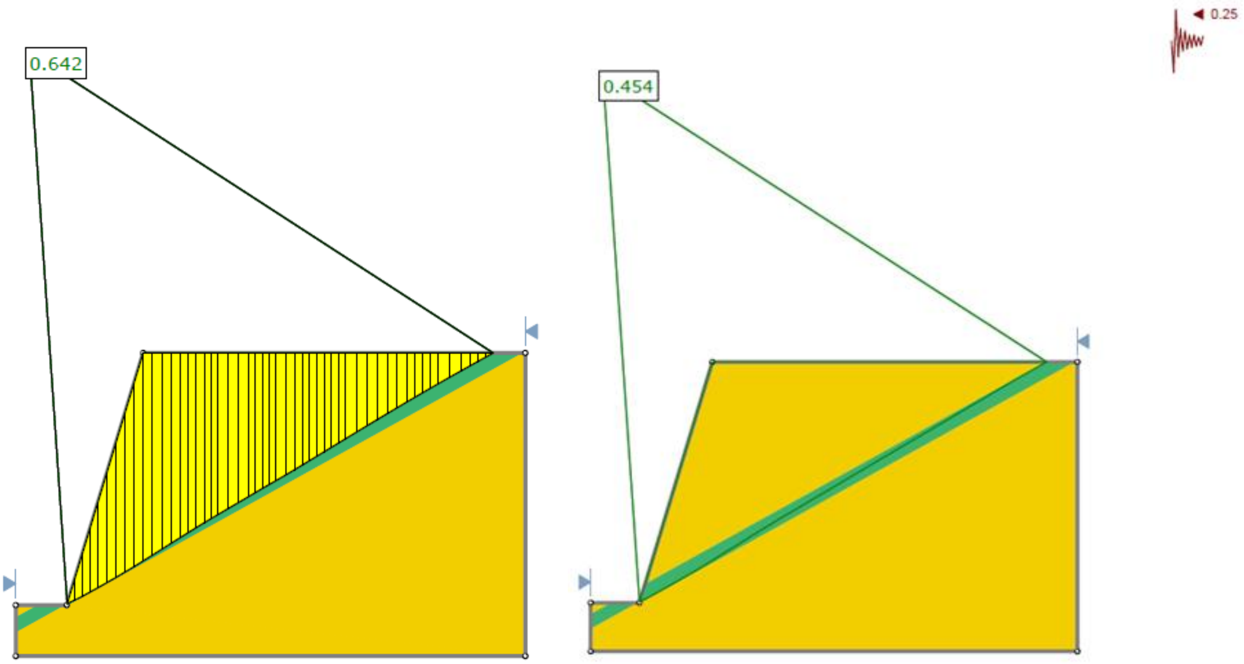
The minimum factors of safety for case 4 without seismic are 0.630, 0.642, 0.642, and 0.641 calculated by using Bishop, Janbu, Spencer, and Morgenstern-Price methods, respectively. Moreover, the areas of potential failure surfaces predicted using Bishop, Janbu, Spencer, and Morgenstern-Price methods for this case when there is no seismic are 67.43 m^2, 67.49 m^2, 67.43m^2,and 67.43 m^2, respectively. Therefore, when there is no seismic, the minimum and maximum values of the minimum factors of safety are obtained using Bishop and Janbu methods, and Spencer method, respectively. Also, Bishop and Janbu methods predict the minimum and maximum values of the potential failure surface, respectively.

For case 4 with seismic, using Bishop, Janbu, Spencer, and Morgenstern-Price methods, the calculated minimum factors of safety are 0.467, 0.454, 0.480, and 0.473, respectively, and the predicted areas of potential failure surfaces are 67.12m^2, 67.63m^2, 66.79m^2, and 66.79 m^2, respectively. As can be seen, for a slope with an inclined weak layer, Janbu and Spencer 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 Spencer and Morgenstern-Price methods, and Janbu method, respectively.



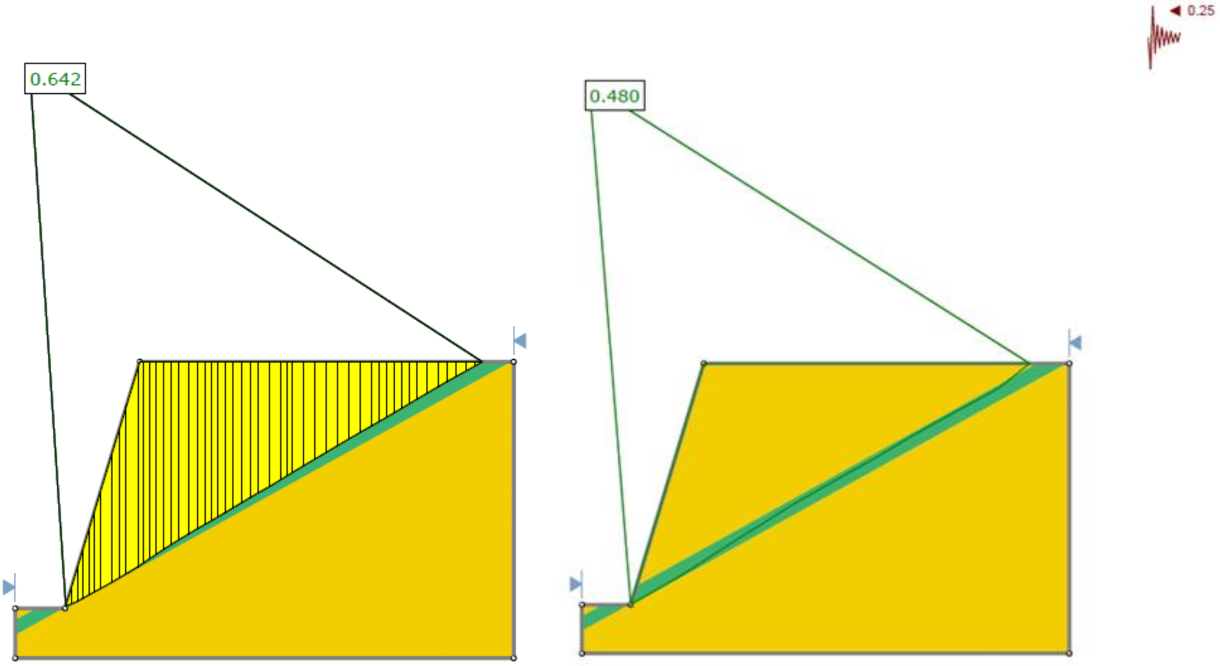
(a) (b)

Fig. 14. Results of LEM Analysis using Bishop Method for Case 4: (a) No Seismic; (b) With Seismic



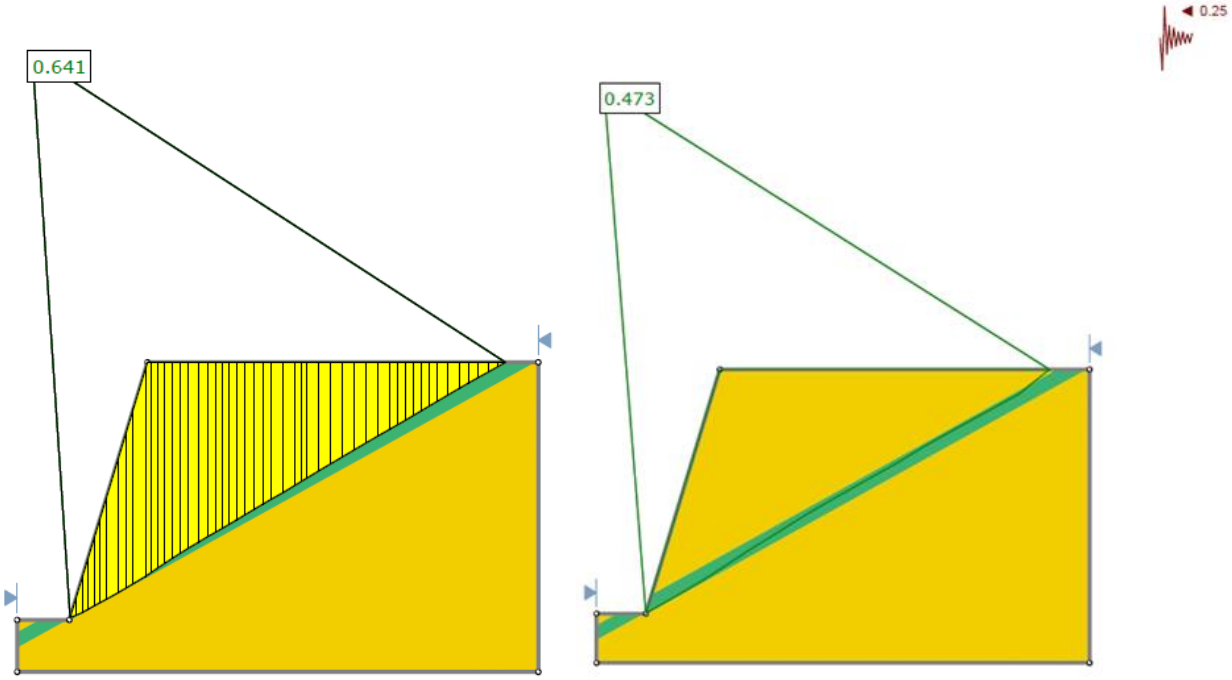
(a) (b)

Fig. 15. Results of LEM Analysis using Janbu Method for Case 4: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 16. Results of LEM Analysis using Spencer Method for Case 4: (a) No Seismic; (b) With Seismic



(a) (b)

Fig. 17. Results of LEM Analysis using Morgenstern-Price Method for Case 4: (a) No Seismic; (b) With Seismic

V. DISCUSSION

Tables 2 and3summarize the minimum factors of safety and areas of potential failure surface, respectively, calculated by using Bishop, Janbu, Spencer, and Morgenstern-Price methodsfor all cases.

Table 2. Minimum Factors of Safety Calculated by using Different Methods

No	Weak Layer Situation	Calculated Minimum Factor of Safety							
		No Seismic				With Seismic (Seismic Load Coefficient=0.25)			
		Bishop	Janbu	Spencer	Morgenstern-Price	Bishop	Janbu	Spencer	Morgenstern-Price
1	No weak layer	1.448	1.562	1.573	1.560	1.278	1.324	1.280	1.273
2	Horizontal in middle	1.385	1.483	1.479	1.492	1.222	1.257	1.237	1.281
3	Horizontal in toe	1.196	1.413	1.447	1.437	1.058	1.193	1.121	1.103
4	Inclined slope	0.630	0.642	0.642	0.641	0.467	0.454	0.480	0.473

Table 3. Areas of Potential Failure Surface Predicted using Different Methods

No	Weak Layer Situation	Calculated Area of Potential Failure Surface (m^2)							
		No Seismic				With Seismic (Seismic Load Coefficient=0.25)			
		Bishop	Janbu	Spencer	Morgenstern-Price	Bishop	Janbu	Spencer	Morgenstern-Price
1	No weak layer	26.87	29.72	35.68	29.72	31.47	35.02	33.69	31.47
2	Horizontal in middle	26.48	28.62	35.55	35.55	30.27	33.14	35.29	33.29
3	Horizontal in toe	24.48	29.32	22.56	25.65	28.84	35.25	30.82	35.25
4	Inclined slope	67.43	67.49	67.43	67.43	67.12	67.63	66.79	66.79

Tables 4 and 5 presents the changesin the minimum factors of safety and areas of potential failure surface due to seismic for all cases, respectively.

Table 4. Change in Minimum Factors of Safety Due to Seismic

No	Weak Layer Situation	Effect of Seismic on Minimum Factor of Safety (%)			
		Bishop	Janbu	Spencer	Morgenstern-Price
1	No weak layer	-11.7	-15.2	-18.6	-18.4
2	Horizontal in middle	-11.8	-15.2	-16.4	-14.1
3	Horizontal in toe	-11.5	-15.6	-22.5	-23.2
4	Inclined slope	-25.9	-29.3	-25.2	-26.2

Table 5. Change in Areas of Potential Failure Surface Due to Seismic

No	Weak Layer Situation	Effect of Seismic on Potential Failure Surface Area (%)			
		Bishop	Janbu	Spencer	Morgenstern-Price
1	No weak layer	17.1	17.8	-5.6	5.9
2	Horizontal in middle	14.3	15.8	-0.7	-6.4
3	Horizontal in toe	17.8	20.2	36.7	37.4
4	Inclined slope	-0.4	0.2	-0.9	-0.9

The results show that the maximum reductions in the minimum factor of safety due to seismicfor cases 1 to 4 when the seismic load coefficient is 0.25 are 18.6%, 16.4%, 23.2%, and 29.3%,respectively. As the results obtained by using all the methods show, the maximum effect of seismic on the stability of slopes occurs when the weak layer is inclined. Also, the increases in the predicted area of potential failure surface for cases 1 to 4 for the same seismic load coefficient are 17.8%, 15.8%, 37.4%, and 0.2%, respectively. Therefore, when the slope contains a horizontal weak layer close to the slope base, the area of potential failure surface would be maximum.

As can be seen, the maximum effect of seismic on the minimum factor of safety is obtained when Spencer method is used for cases 1 and 2, Morgenstern-Price method is used for case 3, and Janbu method is used for case 4. The maximum effect of seismic on the predicted area of potential failure surface, in terms of increase in area, is obtained whenJanbu method is used for analyzing cases 1 and 2, and Morgenstern-Price and Janbumethodsare used for cases 3 and4, respectively.

VI. CONCLUSIONS

In this study, to investigate the impact of a weak layer on the stability of slopes subjected to a seismic load, four different of Limit Equilibrium Methods (Bishop, Janbu, Spencer, and Morgenstern-Price) are compared in a slope stability analysis. The results obtained by using all the methods show that the maximum effect of seismic on the stability of slopes occurs when the slope contains an inclined weak layer. Also, the area of potential failure surface would be largest when there is a horizontal weak layer close to the slope base.

The results show that, for the cases with no weak layer, a horizontal weak layer in the middle of the slope, a horizontal weak layer close to the slope base, and an inclined weak layer, Spencer, Spencer, Morgenstern-Price, and Janbu methods calculate the maximum effect of seismic on the minimum factor of safety, respectively. Furthermore, it was found that using Janbu method for analyzing cases with no weak layer and a horizontal weak layer in the middle of the slope and using Morgenstern-Price and Janbu methods for analyzing cases with a horizontal weak layer close to the slope base and an inclined weak layer predicted a larger area of potential failure surface due to seismic. For the sake of caution, it is recommended that engineers use the methods that predict the lowest minimum factor of safety and largest area of potential failure surface based on location and situation of weak layers in slopes.

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