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ORIGINAL RESEARCH ARTICLE

Comparison of General Limit Equilibrium Methods for Slope Stability Analysis

Azemeraw Wubalem

Department of Geology, College of Natural and Computational Sciences, University of Gondar, Ethiopia

E-mail: alubelw@gmail.com

ORCID: https://orcid.org/0000-0002-5965-6608

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Abstract

Slope failure becomes one of the most critical problems in geotechnical works, which resulted in damages to engineering structures, farmlands, and loss of lives. Therefore, slope stability analysis is very important to reduce damages due to slope failure. Soil samples on three-selected slope sections were taken and determined the internal friction angle, cohesiveness, and unit weight of soils in the laboratory test. Then, a factor of safety for three slope sections was calculated using different general limit equilibrium methods (GLEMs) under dry and wet slope conditions. The result showed a factor of safety less than one for slope section 1, which is unstable whereas the factor of safety for slope sections 2 and 3 under dry and wet slope conditions is greater than one that is stable. The results of a factor of safety for all GLEMs were computed and compared. Although Corps Engineering 1 and 2, Bishop, and L-KM showed a little factor of safety difference compared to the Sarma method (SM), Spencer method (SPM), and Morgenstern price method (MPM), all methods except the ordinary method, showed similar potential to slope stability analysis. However, SM, MPM, and SPM are good at satisfying all equation of statics and provides a factor of safety vs lambda graph which is impossible in other GLEMs.

Keywords: *slope failure; general limit equlibrium methods; slope stability analysis*

Introduction

Slope failure is a typical geological problem in the globe, which resulted in damage to engineering structures, environments, cultivated lands, and caused fatalities. Slope failure can be occurred due to natural and manmade conditioning and triggering factors (Abramson et al., 2002; Aryal et al., 2008; Thielen et al., 2005; Damtew et al., 2017; Shemelis 2009; Singh et al., 2016). Slope stability analyses are routinely performed and used in assessing the safe and functional design of excavation for road cuts, tunnels, reservoirs open-pit mining, and the equilibrium condition of natural slopes (Duncan, 1992; Duncan, 2000; Abramson et al., 2002; Aryal, 2008; Thielen et al., 2005; Singh et al., 2016). The techniques for slope stability analysis selection depend on the availability of input parameters, site conditions, potential mode of failure, suitability, and inherent weakness or limitations in each methodology (Abramson et al., 2002; Thielen et al., 2005; Aryal, 2008; Wubalem, 2020). Different types of techniques have been developed to evaluate the stability of the slope and they are broadly classified into conventional and finite element methods (Aryal, 2008; Raghuvanshi, 2019; Singh et al., 2016). Among that, limit equilibrium methods are one of the oldest and simplest conventional analytic methods used to determine the stability of the slope in terms of factor of safety (Duncan, 2000; Aryal, 2008; Singh et al., 2016). Limit equilibrium methods are routinely used in geotechnical engineering works due to their simplicity, and they required information about shear strength rather than information about stress-strain behavior of soil slopes, which can be answered by finite element methods (Matthews et al., 2014; GeoStudio international Iltd, 2004-2018). Although the finite element methods define the magnitude of movement and stress-strain condition of soil mass of the slope, it could not provide a direct measure of slope stability or factor of safety, which is possible in limit equilibrium methods (Duncan, 1992; Matthews et al., 2014; GeoStudio international Iltd, 2004-2018). Moreover, input parameters used to analyze the stability of the slope in limit equilibrium methods are often easily obtained than the parameters utilized in finite element methods (Chen and Lau, 2014; Matthews et al., 2014; GeoStudio international Iltd, 2004-2018). Many limit equilibrium methods are available and their difference is depending on (Abramson et al., 2002; Aryal, 2008; Chen and Lau, 2014; Matthews et al., 2014; GeoStudio international Iltd, 2004-2018; Wubalem, 2020): 1) what equation of statics are included and satisfied. 2) Which inter-slice forces are included 3) what is the assumed relationship between the inter-slice shear and normal forces? In addition, what type of failure is it? The ordinary method (OM) is one of the first limit equilibrium methods that ignored the assumption of all inter-slice force but satisfied only moment equilibrium. This method is adopting a simplified assumption that is used to compute a factor of safety using hand calculations, which was important since there is no computer program (Abramson et al., 2002; Aryal, 2008; Chen and Lau, 2014; Matthews et al., 2014; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). This method becomes useless after the development of Bishop Methods in 1955 that satisfied inter-slice normal force, but not satisfied inter-slice shear forces. After a time, the Jambu method is developed which is similar to the Bishop method in which it satisfied inter-slice normal force but not inter-slice shear force. Jambu method satisfies only horizontal force equilibrium but not moment equilibrium. Due to the advancement of computers, the limit equilibrium method upgraded to a more iterative procedure and mathematically more rigorous formulations (Spencer and Morgenstern –price) which satisfied all inter-slice forces and all equations of statics (Abramson et al., 2002; Aryal, 2008; Chen and Lau, 2014; Matthews et al., 2014; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020).

After the advancement of technology, general limit equilibrium methods, which embraces other key elements of limit equilibrium methods in slope/w package, has developed. The general limit equilibrium methods are applicable for slope stability analysis considering slices in which the soil mass above the critical failure surface can be divided into several vertical slices. Then the factor of safety can be calculated from the ratio of resisting force to driving force.

However, comparison among them is very limited so far. Therefore, comparing the results from these methods is very important to determine the most suitable method to calculate the factor of safety in a given slope.

Methods and Materials

Methodological Summary

The study's methodology included detail literature review, geotechnical investigation of soils (sampling and laboratory test), measurement of slope failure features such as length, width, and depth, as well as failure mechanism, selection of appropriate slope stability analysis methods and conducted slope stability analysis. Shear strength parameters (i.e., cohesion, and angle of internal friction) and unit weight of soil, sliding mass thickness, and slide size were evaluated in this investigation. Soil samples were taken in order to evaluate the characteristics of the soil. Undisturbed samples were taken at random in regions where slope collapses had occurred, particularly along the scar's flanks. Plastic bags were used to capture samples in their moist state. To prevent moisture loss, the plastic bags were knotted together. Soil samples were tested for three selected slope sections to determine parameters such as unit weight, angle of friction, and cohesiveness of soil. Slope stability analysis was then performed using these properties. The slope stability analysis was carried out using the GeoStudio Slope/W 20018 numerical modeling software tool. Using General limit equilibrium methods, all possible safety factors of the selected failed slope section was calculated based on half sine interslice function, constant interslice function, piezometric line, and Mohr's Coulomb failure criteria. The general flow chart for this study is summarized in Fig.1.

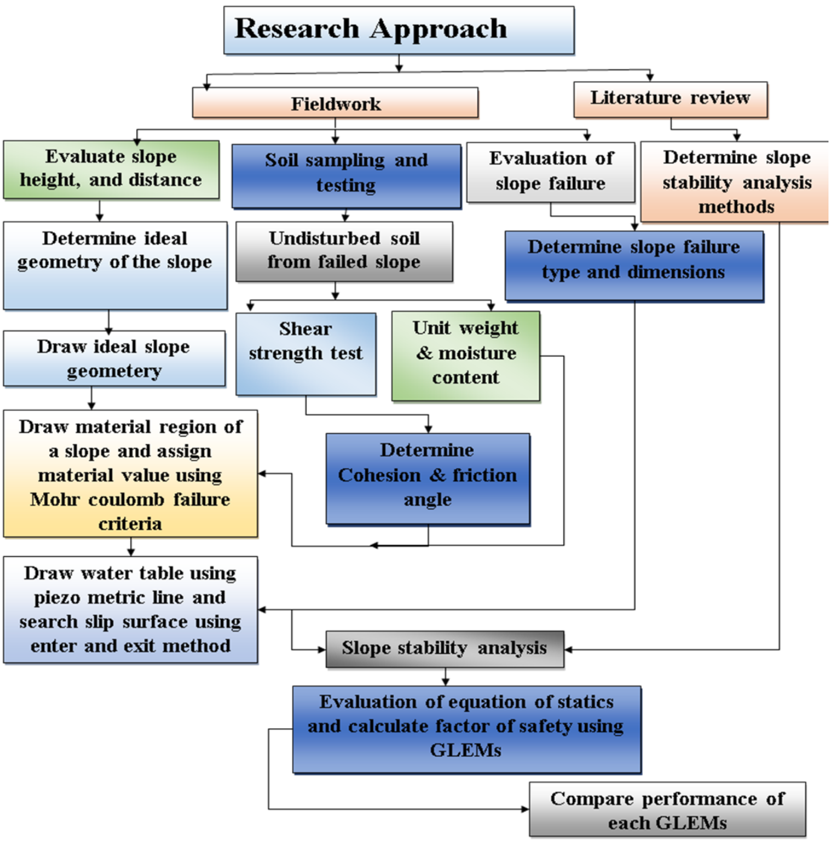


Fig. 1: General flow charts of research approaches

Software

For slope stability analysis, GEO-SLOPE International Canada's SLOPE/W was employed. The ideas and principles of limit equilibrium approaches are used to create this software. SLOPE/W (SLOPE/W 2002; Krahn 2004) is a program that calculates the factor of safety (FOS) for various shear surfaces, such as circular, noncircular, and user-defined surfaces. SLOPE/W was utilized to search for and refine the circular slip surface (CSS) using the slope's general input parameters. The CSS was found using the entry and exit search options, which was confirmed using the auto-locate option. Inter-slice forces were calculated using the Mohr Coulomb soil model and failure criterion, as well as a half sine and constant function. The factor of safety was then calculated using the critical slip surface.

Input Data and Slope Stability Analysis

The important elements in slope stability study are the determination of slope geometry, groundwater condition, shear strength parameters (angle of internal friction and soil cohesiveness) and unit weight of soil. The internal friction angle, cohesion and unit weight of soils of slope section 1, 2, and 3 are determined from laboratory test and summarized in Table 1. These parameters are used as input in slope stability analysis in addition to slope geometry, slip surface and groundwater condition. In this study, General Limit Equilibrium Methods (GLEMs) were employed to calculate the factor of safety for selected three slope sections under different geometry, and material properties by considering dry and wet slope conditions (Table 1). The general limit equilibrium methods include all limit equilibrium methods in slope/w software package and all methods can apply for any type of failure, which is the advantage of using General limit equilibrium method. In this method, what we have to bother is the equation statistics rather than the complexity of geometry and failure mechanisms. The geometry, material properties, pore water pressure, and potential slip surface for the three critical slope sections were defined. These can be described in the following sections.

Table 1 Input parameters for slope stability analysis

SS	Slope height (m)	Slope Distance (m)	Scale	Material	Unit weight (KN/m3)	Cohesion (KN/m2)	Angle of internal friction (Degree)	Slope conditions
1	1160	200	1:2	Silt sand	18.5	60	0	Dry/wet
	1160	200	1:2	SP	18.5	0	0	Dry/wet
	1160	200	1:2	SP	18.5	0	0	Dry/wet
				Sandstone	26	0	0	Dry/wet
2	1816	490	1:2	SP	21	0	35	Dry/wet
	1816	490	1:2	GC	20.5	6	30	Dry/wet
	1816	490	1:2	GW	22	0	38	Dry/wet
	1816	490	1:2	CH	18.5	21	15	Dry/wet
	1816	490	1:2	Limestone	24	0	0	Dry/wet
3	1685	246	1:2	GP	20	0	38.5	Dry/wet
	1685	246	1:2	Lime stone	25	0	0	Dry/wet

SS = slope section; SP = Poorly graded sand; GW = Well graded gravel; GC = Clayey gravel; CH = High plasticity clay

Geometry

Defining a working area with appropriate geometry, scale and unit are the most important activities to be done in slope stability analysis. This is the process to define the physically admissible ideal slope geometry of the study area. The geometry of an ideal slope was defined using points and polygons based on a scale of 1 to 2 and at different slope height (Table 1). If these points or polygons are not defined in the correct position, the model will be wrongly developed. Therefore, great care is very important to define this ideal geometry.

Slope Material

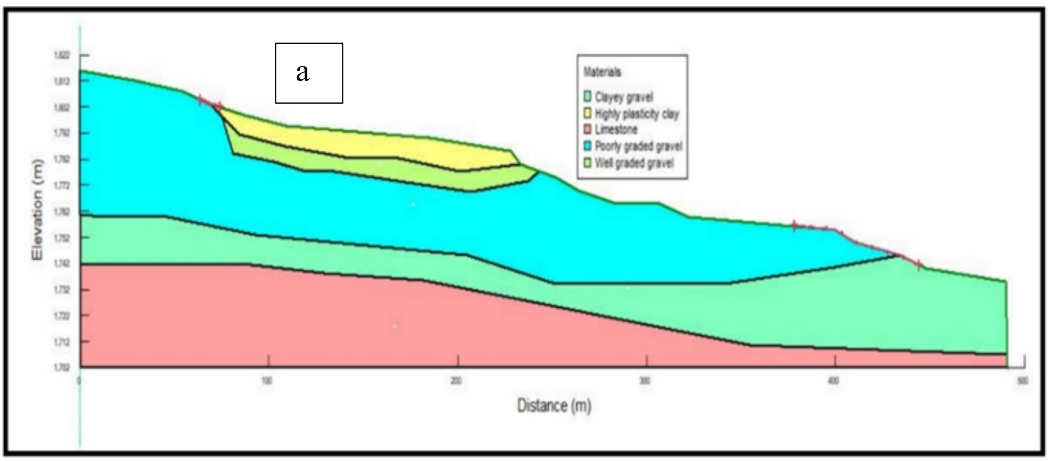
The material statement is one of the key elements in slope/w analysis (Abramson et al., 2002; GeoStudio international Iltd, 2004-2018; Singh et al., 2016; Wubalem, 2020). Various ways are available to define material in the slope stability analysis like Mohr's coulomb, undrained strength, and bedrock (impenetrable material) which depends on the data that we have for the analysis (Abramson et al., 2002; GeoStudio international Iltd, 2004-2018; Singh et al., 2016; Wubalem, 2020). In this study, Mohr-Coulomb criteria were used which includes the unit weight of soil mass, cohesion, and internal friction angle. As showed in Table 1 and Fig 2, the soil in this study is heterogeneous.

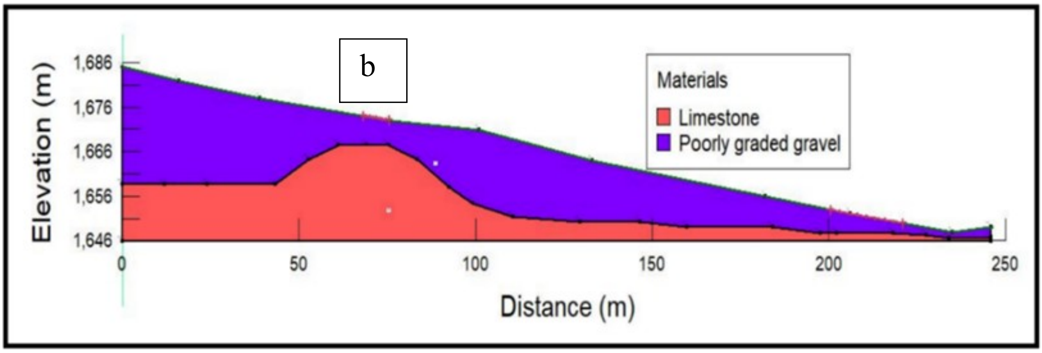
Pore Water Pressure

The pore water pressure is one of the key elements in any slope stability analysis (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). Most of the time, slope instability is faced because of the presence of pore water pressure in a given slope soil, therefore, a proper definition of pore water pressure regime is an essential component of slope stability analysis. Pore water pressure in GLEMs is commonly defined as piezo-metric line/s even if other methods of drawing are available. The pore water pressure in GLEMs can be determined from each slice base using height from slice base to piezo-metric line and unit weight of water. In this study, the pore water pressure is estimated using the piezo-metric line. The factor of safety was calculated for the three-slope section considering dry and wet slope conditions.

Critical Slip Surface

In slope stability analysis using GLEMs, defining the critical potential slip surface is a very important step to get a minimum factor of safety in a selected slope section using slope/w software (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). Slip surface searching can be performed using various searching options such as entering and exiting, grid and radius, and block specified searching options (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). However, in present slope modeling, a critical slip surface is defined using enter and exit search options (Fig. 2 and 8). Because it is suitable and can be controlled by the user to adjust the slip surface search until the most critical slip surface is found. The critical slip surface location, extent, and shape can affect by the shear strength parameters.





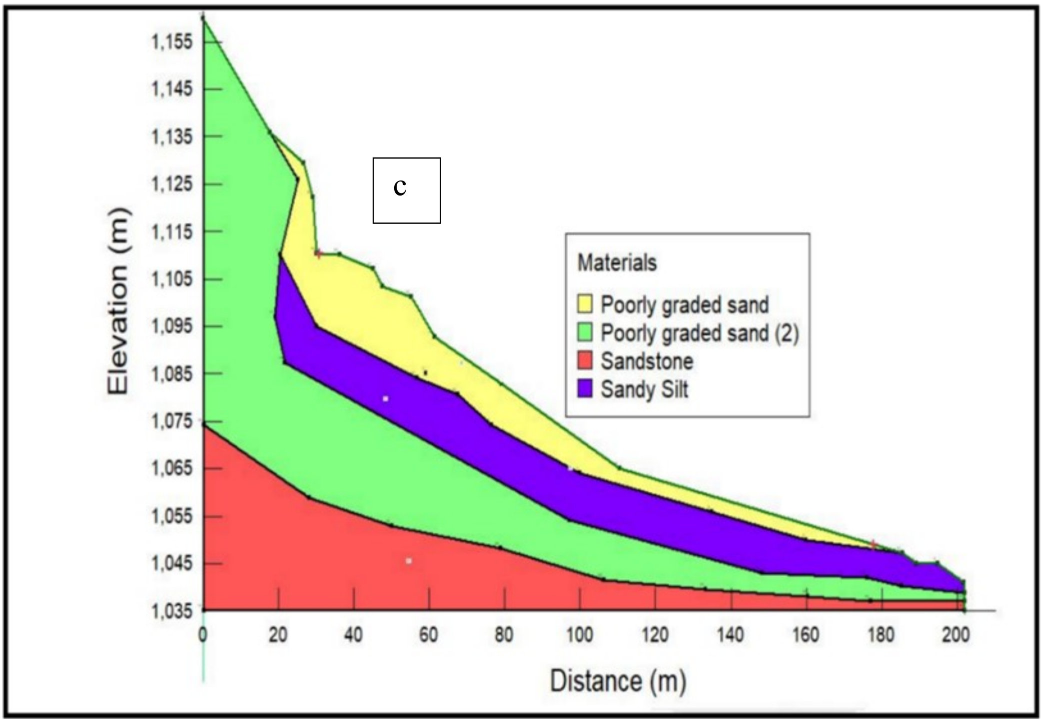


Fig.2:Geometry and materials for a) slope section 2 b) slope section 3 and c) slope section

Result

Factor of Safety Results

This study is conducted to determine whether the slope is far or close to failure as well as to compare the different general limit equilibrium methods based on the calculated factor of safety. It was conducted on three-selected slope sections using GLEMs considering dry and wet slope conditions. In general, the factor of safety calculated using various general limit equilibrium methods (GLEMs) under dry and wet slope conditions was presented in Table 2. The factor of safety for slope section 1 is less than one and greater than one for slope sections 2 and 3 (Table 2).

Table 2 Summary of Minimum Factor of Safety for each Slope Sections

Slope Sections	**Methods**	**A minimum factor of safety**		
		Dry Condition	Wet Condition	Slope Status in all condition
Slope Section 2	OM	3.997	2.263	Stable
	JM	4.014	2.21	Stable
	BM	4.175	2.176	Stable
	JMG	4.156	2.267	Stable
	Lowe K	4.18	1.97	Stable
	Corps Engineering1	4.201	2.267	Stable
	Corps Engineering2	4.196	2.29	Stable
	SM	4.169	2.263	Stable
	SPM	4.169	2.281	Stable
	MPM	4.169	2.263	Stable
Section 3	OM	4.165	2.394	Stable
	JM	4.69	2.328	Stable
	BM	4.698	2.332	Stable
	JMG	4.697	2.332	Stable
	Lowe K	4.698	2.333	Stable
	Corps Engineering1	4.698	2.333	Stable
	Corps Engineering2	4.697	2.332	Stable
	SM	4.698	2.332	Stable
	SPM	4.698	2.332	Stable
	MPM	4.698	2.332	Stable
Section 1	OM	0.347	0.347	Unstable
	JM	0.347	0.314	Unstable
	BM	0.347	0.347	Unstable
	JMG	0.486	0.486	Unstable
	Lowe K	0.49	0.491	Unstable
	Corps Engineering1	0.491	0.491	Unstable
	Corps Engineering2	0.487	0.487	Unstable
	SPM	0.347	0.347	Unstable
	MPM	0.347	0.347	Unstable

Discussion

Factors of Safety Using Ordinary Method (OM)

The ordinary method was applied to calculate the factor of safety for three selected failed slope sections under dry and wet slope conditions. As indicated in Fig.6, OM does not consider both normal and shear inter-slice forces and does not satisfy force in equilibrium. As a result, it is impossible to get a factor of safety vs lambda graph because lambda is undefined (Fig.9). OM satisfies only the equation of moment in equilibrium (Fig.9). The force polygon closure is one of the important elements when limit equilibrium methods are considered for calculating the factor of safety. The more the force polygon closure, the more accurate factor of safety will be (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). The slices are not in force equilibrium when lack of force polygon closure existed or is very poor. In OM, the force polygon closure is not possible as can be seen in the free body diagram in Fig. 6. It has worsened force polygon closure from the crest of the potential slid mass to the toe of the sliding mass. As shown in the force polygon on slice numbers 3 and 27, the force polygon closure is so poor (Fig.6). This can help to conclude that an ordinary method does not satisfy the overall force equilibrium. The factors of safety, calculated in this method, are unrealistic because the force polygon closure is so poor which means each slice is not in force equilibrium (Fig.6).

Factors of Safety Using Bishop Method (BM)

As shown from the factor of safety vs lambda graph, BM does not satisfy the horizontal force equilibrium but satisfies only the overall moment equilibrium (Fig.7). BM does not consider inter-slice shear force and it considers only inter-slice normal force (Fig.7). As indicated in Fig. 6, the force polygon closure was examined under a similar slice number is relatively good unlike the ordinary method of the slice. In the lambda, vs factor of safety graph, the factor of safety is fell in a moment equilibrium curve when lambda is zero. This again confirms that BM satisfied only moment equilibrium (Abramson et al., 2002; Singh et al., 2016; Damtew et al., 2017; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). Therefore, the sliding masses in the BM are almost in horizontal force equilibrium.

Factors of Safety Using Janbu Simplified Method (JM)

As indicated in Fig.9, Janbu simplified method is the third limit equilibrium method that is satisfied only with the overall horizontal force in equilibrium. This method considers inter-slice normal force like Bishop but it is ignored inter-slice shear force (Fig.7). As shown in Fig.7, the force polygon closure in this method is better than Bishop's simplified method (Abramson et al., 2002; Singh et al., 2016; Damtew et al., 2017; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). Thus, the slice of the slide mass is in horizontal force equilibrium. As designated in Fig.7 and Table 2, the factor of safety of Janbu is lower than the Bishop simplified method because the force in equilibrium in the Jambu method is sensitive to inter-slice shear force. Its ignorance of the inter-slice shear force is the cause for reduction of a factor of safety in the Janbu simplified method. However, Bishop's simplified method satisfied the overall moment in equilibrium and as a result, it is not sensitive for inter-slice shear force in a circular slip surface (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018).

Factors of Safety Using Janbu Generalized Method (JGM*)*

The factor of safety for the three-slope section was calculated using JGM (Table 2). The force polygon closure in JGM is quite good compared to OM, JM, and BM because JGM considered both inter-slice shear-normal forces (Fig. 5). However, the JGM is not used to draw the FOS vs lambda graph because JGM is not satisfied moment equilibrium like OM, and JM (Fig.9). The main difference between JM and JGM is inter-slice force. The JGM is considered both inter-slice shear-normal forces unlike JM (Fig.3).

Factors of Safety Using Corps Engineering Methods (1 &2*)*

These methods were used to calculate the factor of safety (FOS) under dry and wet slope conditions (Table 2). The only factor of safety concerning force in equilibrium was calculated because Corps Engineering 1 & 2 methods satisfied only force in the equilibrium equation of statics (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018). Therefore, the FOS in these methods is fell in the force equilibrium curve of the lambda graph (Fig.9). As indicated in Fig.3, 4, and Table 2, Corps Engineering methods (1 and 2) have very good force polygon closure and FOS compared to OM, BM, and JM like JGM, SM, SPM, and MPM because these methods are considered both inter-slice shear-normal forces.

Factors of Safety Using Lowe Karathiaf Method (L-KM*)*

The FOS calculated in the L-KM is fell in the force equilibrium curve because L-KM is satisfied only force in equilibrium in the equation of statics (Fig. 4) like JM, JGM, Corps Engineering 1&2 unlike SM, SPM, and MPM. The L-KM has very good force polygon closure and FOS compared to other methods in which inter-slice shear-normal force consideration is impossible (Fig. 5, 10 and Table 2).

Factors of Safety Using Sarma Method (SM)

The factor of safety is calculated for only sections 2 and 3 because the SM only applicable when the shear strength parameter or internal friction angle (ϕ) is different from zero Table 1 and 2 (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). The Sarma method is not advisable to use when cohesion is greater than zero and becomes large. The SM in slope/w is the same as SPM and MPM except for how inter-slice shear-normal forces are related. In this method, direct measurements of lambda graph are impossible like SPM and MPM other than the computed inter-slice shear-normal forces are adjusted with a global factor until all equation of statics satisfied. As indicated in Fig. 6, the force polygon closure and FOS is very good like SPM and MPM because it considered both inter-slice shear-normal forces.

Factors of Safety Using Spencer Method (SM)

FOS for the three-slope section is fell in moment and force equilibrium curves (Fig.9). SPM is satisfied both moment and force in equilibrium (Fig.4). This method considers both inter-slice forces (Fig.4) and adopted the constant relationship between inter-slice shear and normal force. As indicated in Fig.4, it has quite a good force polygon closure. Therefore, all slices are in force equilibrium. Unlike Bishop and Janbu, the value of lambda is greater than zero (Fig.4). Meaning, this method has both inter-slice shear and normal force because lambda is the ratio of inter-slice shear to the inter-slice normal force. This method is used to calculate two factors of safety like the factor of safety concerning moment and force equilibrium (Fig.4).

Factors of Safety Using Morgenstern Price Method (MPM)

FOS for the three-slope section is fell in moment and force equilibrium curves (Fig.9) due to MPM is satisfied with both overall moment and force equilibrium (Fig.9). Hence, MPM has considered both inter-slice shear-normal forces, it has very good force polygon closure (Fig.3). MPM is very important to calculate all possible factors of safety and to plot the factor of safety versus the lambda graph (Fig.9). The factor of safety calculated using MPM is similar to SPM, but MPM has various inter-slice force functions. Therefore, this method is the best of all the other limit equilibrium methods when somebody considers inter-slice force functions. This method satisfies all equations of statics and is used to plot the factor of safety vs lambda graph that is so important to compare the factor of safety in each method (Fig.9).

The factor of safety for all failed selected slope sections was calculated using slope/w software. As we know the factor of safety is the ratio of resistance force to driving force and it depends on the slope condition, material properties, and slope angle. As the result indicated in Table 2 and Fig. 10, a factor of safety for slope sections 2 and 3 is greater than one which is stable at current conditions, however, FOS for slope section 1 under dry and wet slope conditions is less than one which is unstable under the current slope condition. The minimum factor of safety and critical slip surface of three selected slope sections are calculated and searched for different general limit equilibrium methods by considering dry and wet slope conditions (Table 2 and Fig.8).

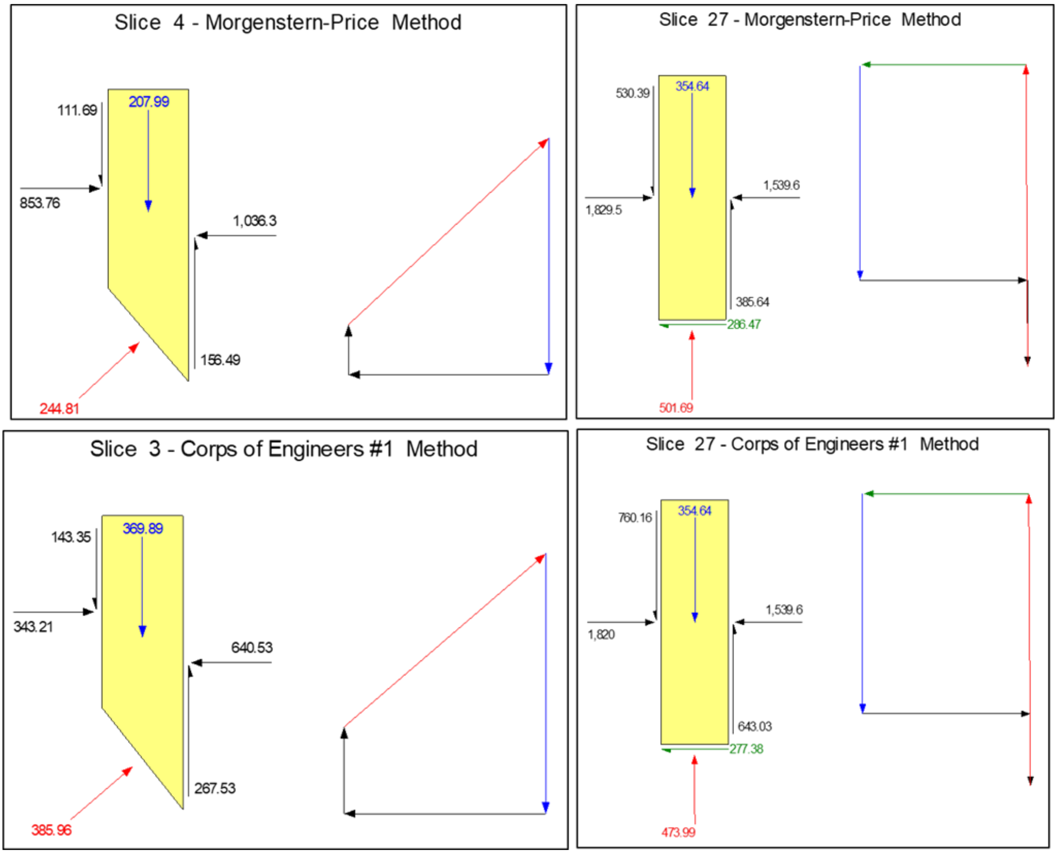


Fig.3:Free body diagram and force polygon closure in Morgenstern price and Corps Engineers 1 method

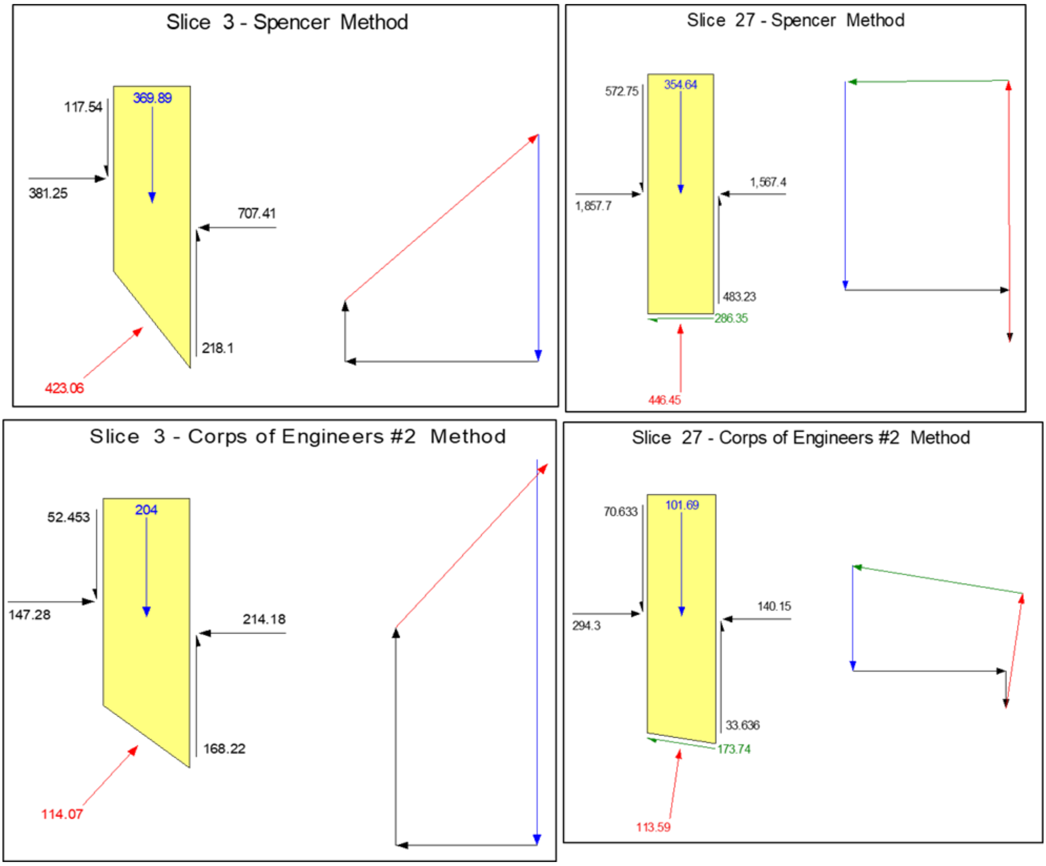


Fig.4: Free body diagram and force polygon closure in Spencer and Corps Engineers 2 methods

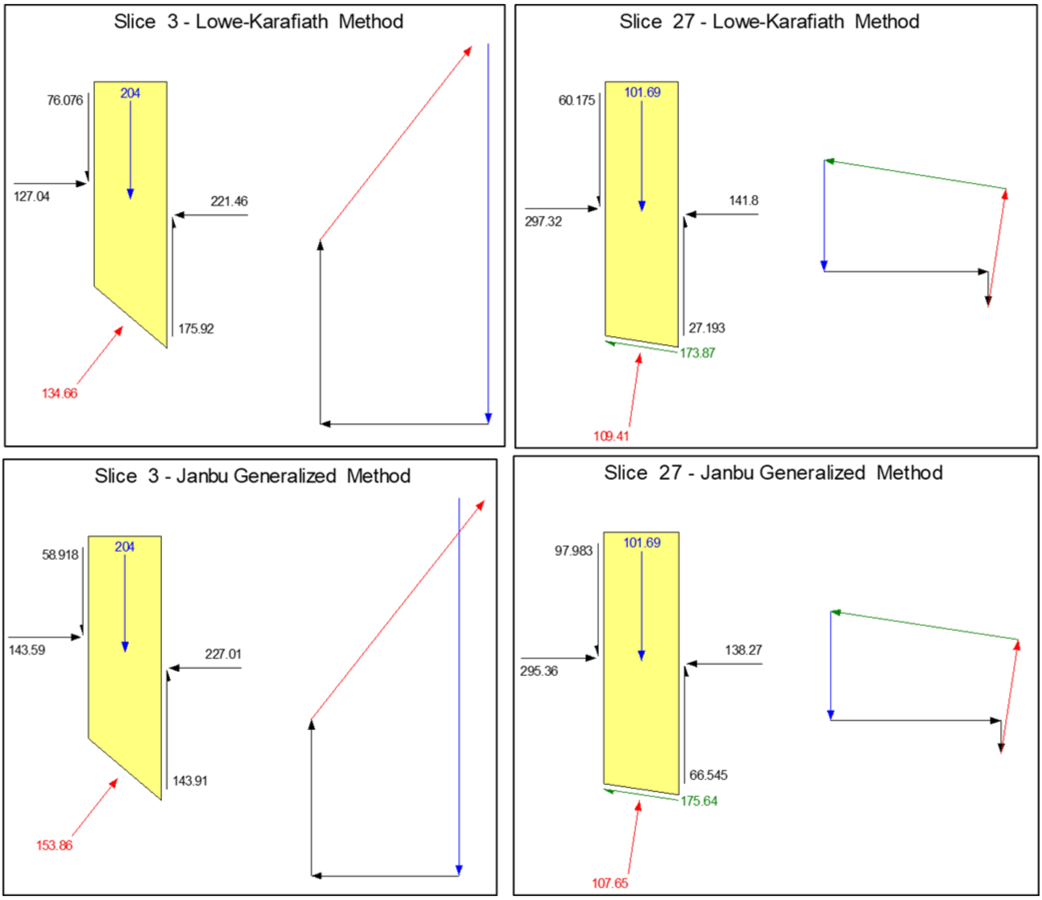


Fig.5: Free body diagram and force polygon closure in Lowe Karafiath and Jambu Generalized methods

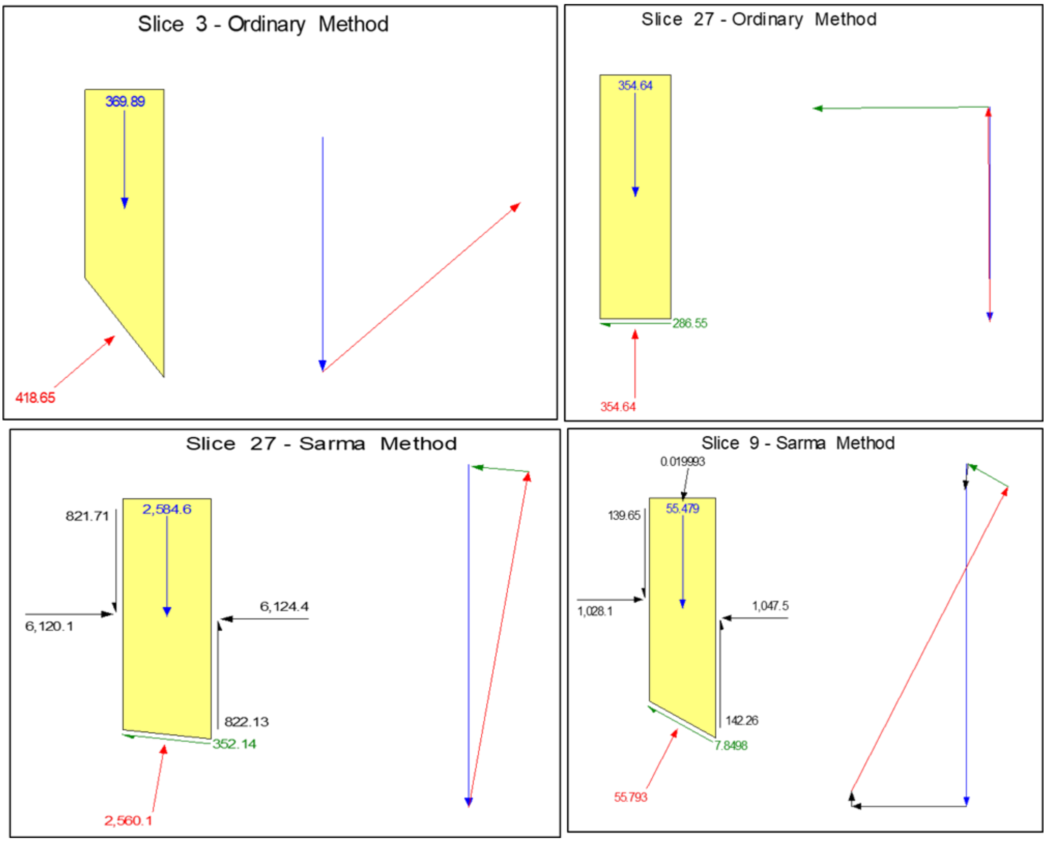


Fig.6: Free body diagram and force polygon closure in Ordinary and Sarma methods

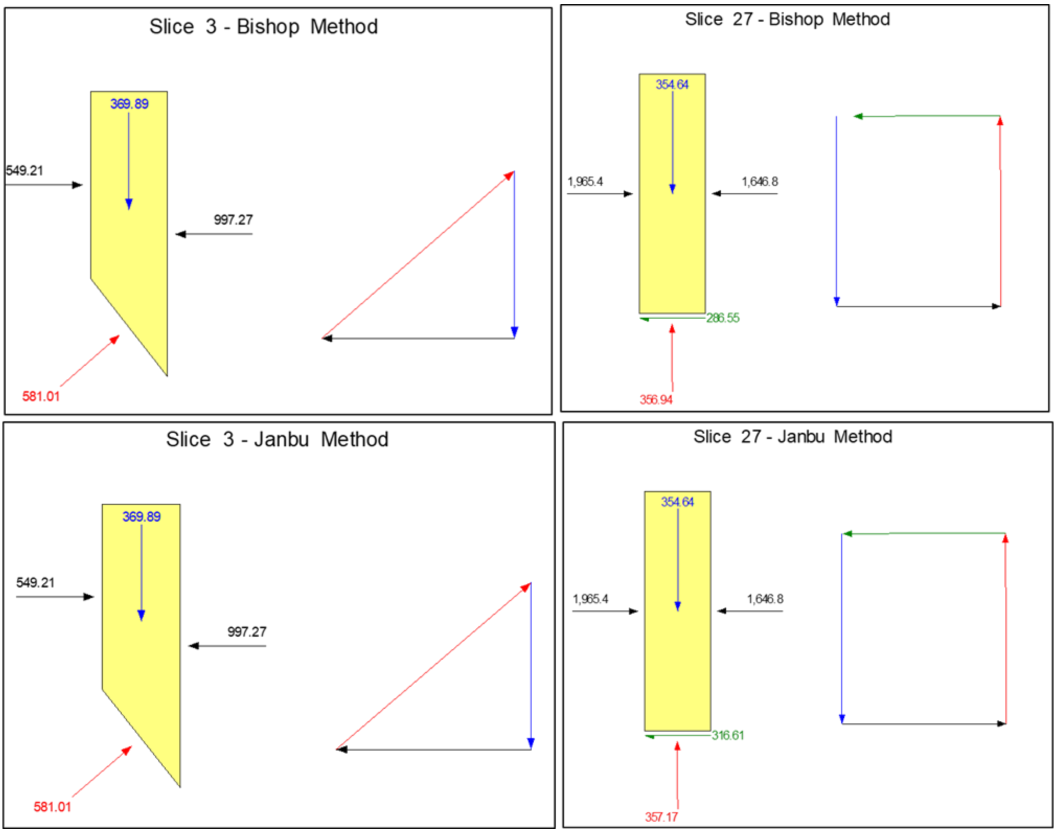


Fig.7: Free body diagram and force polygon closure in Bishop and Janbu methods

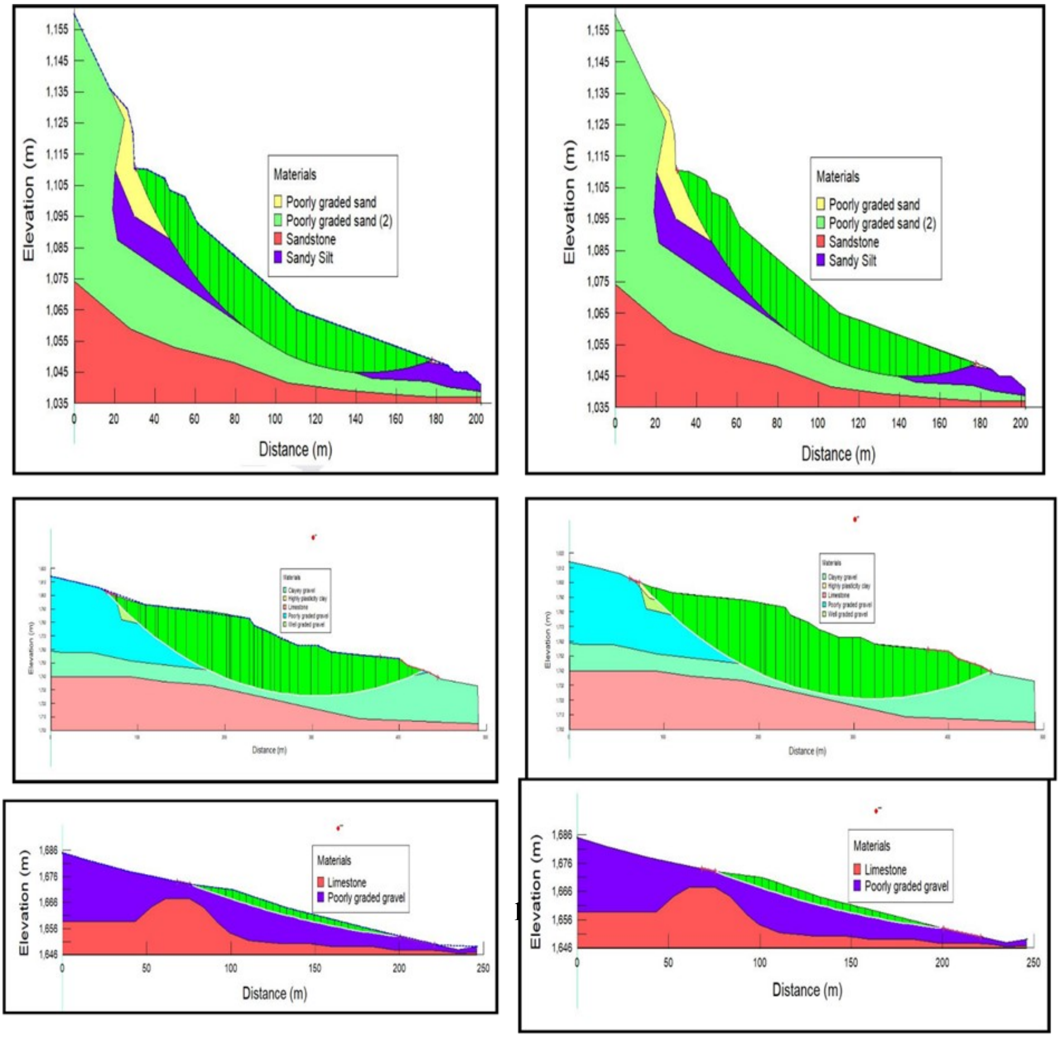


Fig.8: Critical slip failure surface of a slope section at b) dry and a) wet slope conditions

The Effects of Geometry, Material and Groundwater Conditions for Slope stability

The stability of slope is controlled by sets of independent variables including slope material, slope geometry, groundwater depth, intensity and length of rainfall and seismic condition of the region. As shown in Table 1 and 2, the slope section whose cohesion (c) and friction angle of soil grains (ϕ) is greater than zero, its FOS is greater than one or above equilibrium condition. However, the slope section whose c and ϕ is zero, its FOS is less than one or below equilibrium condition. This finding confirms that the nature of slope material can control the stability of slope under different conditions besides other constrains. This research finds out that as slope angle and height increase, the factor of safety decrease. However, as the cohesion and friction angle of the slope material increase, the factor of safety increases. This result is in line with the work of (Seid and Behrouz, 2017). Besides, the slope material condition can control the effects of water on slope stability. As shown in Table 1 and 2, the FOS for slope section one is same under wet and dry slope condition. These results may be linked to the hydraulic properties of slope material (Damew et al., 2017). For example, the FOS for slope section two, and three is changed under dry and wet slope condition even though the slope is stable at current condition. Because the slip surface of slope section 2 is characterized by high plasticity clay, and clayey gravel. These soils are poorly drainage soil. As the soil grains are poorly sorted and its texture is fine, it will has high water holding capacity that can lead for pore water generation between the adjacent soil grains. The developed pore water pressure can reduce the shear strength of soil by reducing normal stress in soil mass. Therefore, from this study, conclude can be drafted that the hydraulic behavior of soil mass can affect the developments of pore water pressure and its effect on slope stability.

The factor of safety that was calculated under wet slope conditions of the selected slope section (2 and 3) is relatively small compared to dry slope conditions (Table 1, 2 and Fig. 10). This showed clearly that the role of groundwater in slope stability is so critical. Because groundwater can be affected slope stability by increasing pore water pressure, increasing weight on a slope when the soil mass is fully saturated, decreasing effective stress, and loss of shear strength parameters. As a result, Fig 9 and Table, 1, and 2 showed, the factor of safety in the three slope sections is decreased as the slope gradient or slope height increased. This further confirms that slope gradient is one of the most important elements in slope stability analysis.

Comparison of the Performance of All General Limit Equilibrium Methods (GLEMs)

As shown in Fig.10 and Table 2, under dry slope conditions, Corps Engineering 1 is produced a relatively high factor of safety (FOS = 4.201) followed by Corps Engineering 2 (FOS=4.196), L-KM (4.18), BM (FOS=4.175), SM (FOS= 4.169), SPM (FOS=4.169) and MPM (FOS=4.169). Corps Engineering 1 has a 0.5-20.4% FOS difference compared to the other GLEMs, but a 3.2% difference to SM, SPM, and MPM. BM is also showed a relative FOS (0.6%) difference compared to SM, SPM, and MPM. In general, under dry conditions, except Corps Engineering 1, Corps Engineering 2, L-KM, SM, SPM, and MPM, other methods provide almost the same amount of factor of safety, but OM has produced a small factor of safety (FOS=3.997). In dry slope conditions, Sarma, Spencer, and Morgenstern Price methods are produced an equal amount of factor of safety for three critical slope sections. Because Sarma, Spencer, and Morgenstern Price methods have satisfied overall moment and force equilibrium but they differ in inter-slice force function (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). The Spencer method (SM) has used constant inter-slice force function while the Morgenstern Price method (MPM) has used a various user-selected inter-slice force function like half-sine, constant, trapezoidal, clipped – sine, and data point specified, but their factors of safety are almost equal (Table 2). Although the Sarma method used material properties to related inter-slice shear-normal forces using quasi-equations than SPM and MPM, Sarma has provided an equal amount of factor of safety (Table 2 and Fig9 and 10). As indicated in Fig. 9,10and Table 2, the factor of safety of Janbu's simplified method (JM) is less than Bishop's method (BM). Because JM is sensitive to inter-slice shear force in circular slip surface, but BM is not sensitive to inter-slice shear force for circular slip surface (Abramson et al., 2002; Singh et al., 2016; Aryal, 2008; GeoStudio international Iltd, 2004-2018). Although the corps engineering 1 and 2, showed a little difference of factor of safety compared to all other GLEMs, all methods showed approximately equal potential to calculate factor of safety in slope stability analysis. Therefore, considering this study results, conclusion can draft that all GLEMs except ordinary method are capable in slope stability analysis to calculate factor of safety. Although the ordinary method showed the potential to calculate factor of safety, it is not realistic because it does not consider both inter-slice shear and normal forces. Therefore, it is not recommendable to use ordinary method for slope stability analysis program for practical purpose rather than for demonstration case (Abramson et al., 2002; Aryal, 2008; GeoStudio international Iltd, 2004-2018). However, for more elaboration, comparison and considering equation of statics as well as inter-slice function, the MPM method is preferable in slope stability analysis. Because it provides:

A factor of safety with various user-selected force functions; it provides a factor of safety against the lambda graph that helps us to compare the factor of safety for different methods and satisfied all equation of statics as well as applicable for all types of failure (Abramson et al., 2002; Singh et al., 2016; GeoStudio international Iltd, 2004-2018; Wubalem, 2020). Therefore, it is advisable to use MPM than the other limit equilibrium methods in slope stability analysis when comparison among GLEMs require.

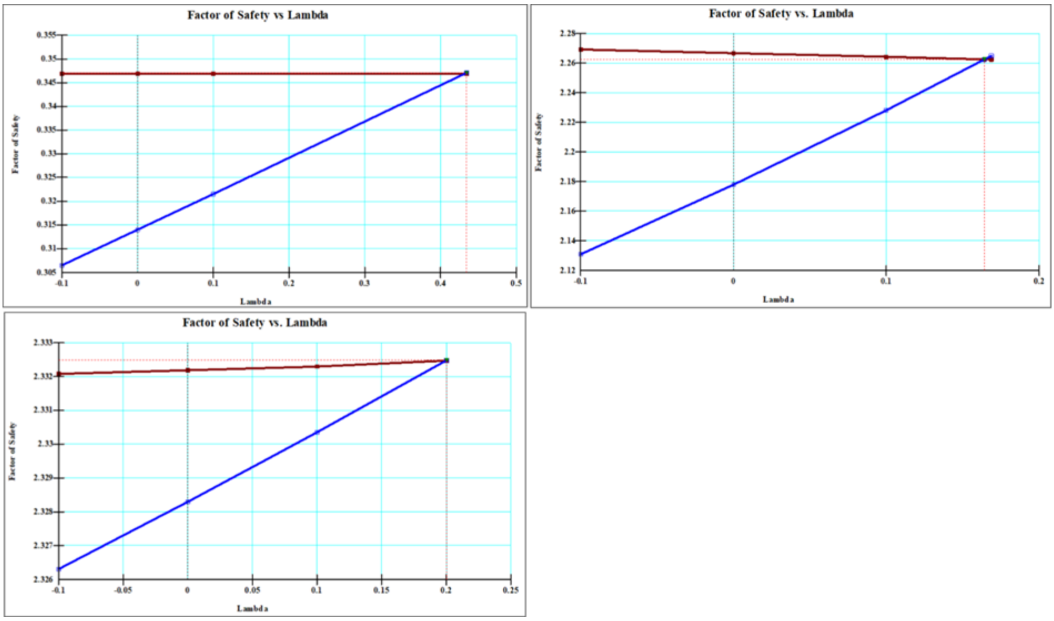


Fig.9: Factor of safety Vs Lambda graph for a) slope section 1 b) slope section 2 and c) slope section 3

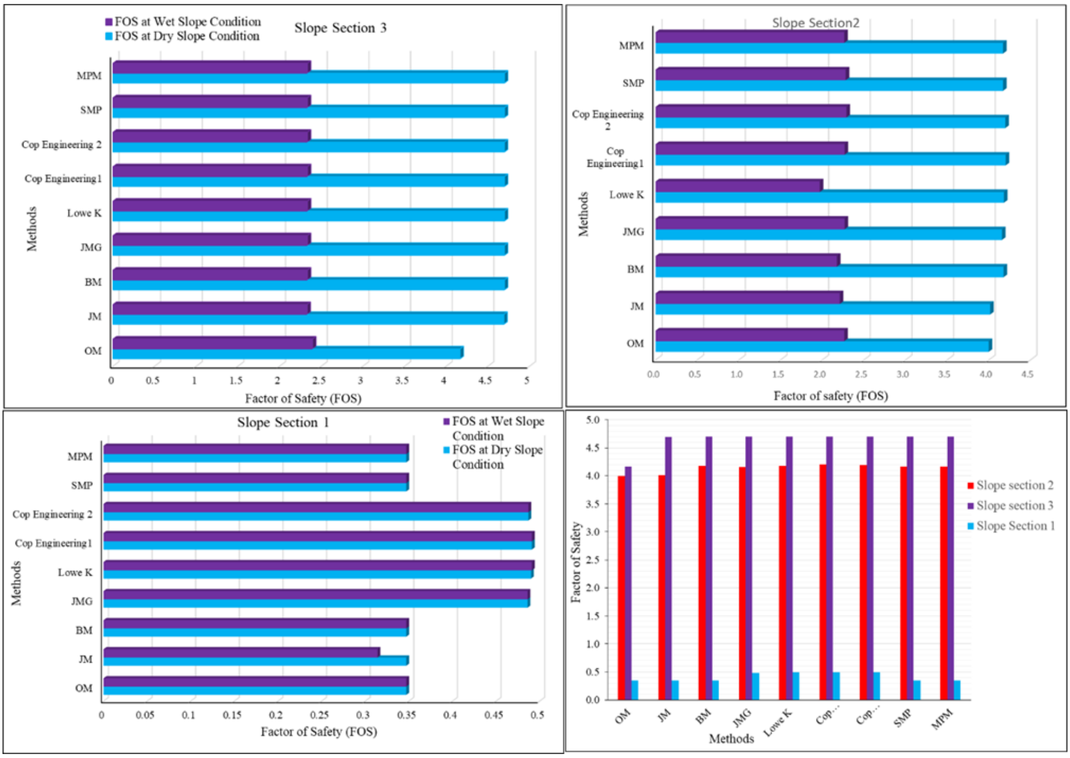


Fig.10: Factor of safety *comparison with dry and wet slope conditions for different GLMs*

Conclusion

General limit equilibrium methods were applied to calculate factor of safety in slope stability analysis. The factor of safety is decreased as the slope gradient and moisture content is increased. Besides, when the slope degree increased, the factor of safety decreased for the three slope sections. From these results, this study can conclude that slope geometry, groundwater, and slope material conditions are the most critical parameters in slope stability. In this study, different general limit equilibrium methods were employed for three slope sections with different geometry and shear strength parameters at dry and wet slope conditions. The factor of safety for slope section 2 and 3 is greater than one, but for slope section 1, the factor of safety is less than one. All methods except ordinary method, showed approximately equal potential to calculate factor of safety in slope stability analysis. Therefore, considering this study results, conclusion can draft that all GLEMs except ordinary method are capable in slope stability analysis to calculate factor of safety. However, for more elaboration, comparison, failure type, and considering equation of statics as well as inter-slice function, the MPM method is preferable in slope stability analysis. Because it provides a factor of safety with various user-selected force functions, used for all failure type, and it provides a factor of safety against the lambda graph that helps us to compare the factor of safety for different methods.

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Availability of data and material

All the datasets that have been used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The author declared that there are no competing interests.

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