Exploration of Methods for Slope Stability Analysis Influenced by Unsaturated Soil

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ABSTRACT

This study will lead to the analysis of unsaturated soil using Bishop's Simplified method (1955) which is one method to analyze slope stability in method of slices. In this study, the original formula for Bishop's Simplified method (1955) of saturated soil were modified by adding the element of matric suction, $(\mu_a - \mu_w)$ together with unsaturated friction angle, ϕ^b which is applicable for the analysis of unsaturated soil. In this study, 0 kPa, 20 kPa and 40 kPa of matric suctions were applied in the analysis for both methods. From the analysis, the result indicate that the factor of safety (FOS) value of Bishop's Simplified method (1955) was 7.65 % higher than Fellenius's method for 0 kPa suction, which mean that the soil is in saturated condition. For 20 kPa suction, the FOS of Bishop (1955) was 4.83 % higher than Fellenius (1936). Bishop (1955) also gave higher FOS value compare to Fellenius (1936) by 4.41 % for 40 kPa suction. It can be concluded that, the reason for the relative accuracy of the Bishop's Simplified method (1955) is that in considering only the vertical equilibrium of any slice, there is no need to account for the horizontal components of the inter-slice forces.

KEYWORDS: Soil suction, Bishop, Unsaturated soils

INTRODUCTION

A slope failure can be considered as one of the most frequent disasters that occur in Malaysia as well as other countries. A common reason for this is the rising of development all over the world whether for developed or other countries which may lead to extensively cutting the existing slopes during the development. According to Sutejo and Gofar (2015) failures occurring in man-made slopes are caused by design errors including geometric design i.e. slope inclination, slope height, and the inability to determine the load that may affect the slope together with the soil strength.

Landslides or mass movement of soil, rocks, or a combination of both, are actually natural phenomena where a natural look for a new balance due to the disturbance or the factors that affect and cause reduction in shear strength as well as increase in shear stress (Suryolelono and Rifa'i, 2003). As suggested by Mizal-Azzmi *et al.* (2011), there are many factors that contribute to slope failure such as soil type, groundwater, seepage, soil stratification and also slope geometry. It is very important to conduct the analysis for slope stability. Generally, the analysis of slope stabilization was done by using method of slices which the potential failure surface was assumed to be circular or non-circular.

According to (Ali *et al*, 2012), there are some man-made slopes: cuts and fills for highways and railways, earth dams, dykes for containment of water, landscaping operations for industrial and other developments, banks of canals and other water conduits and temporary excavations. Slopes may also be naturally formed at hillsides or streambanks. (Uchaipichat, 2012) has suggested that, the slope stability play a very important role in geotechnical analysis and design of the earth structures particularly for construction of dam, road and other types of embankments.

This study aims to determine the factor of safety (FOS) of unsaturated soil slopes by using one method from method of slices which is Bishop's Simplified method (1955). The original formula of Bishop's Simplified method (1955) for saturated soil will be modified in order to include the element of matric suction, $(\mu_a - \mu_w)$ together with unsaturated friction angle, ϕ^b. The FOS that been determined from the calculation using Bishop's Simplified method (1955) will be analyzed and finally, a comparison of FOS between Bishop (1955) with Fellenius (1936) will be done in order to determine which method gave higher and more accurate FOS for slope stabilization.

LITERATURE REVIEW

Unsaturated Soil

Fredlund and Morgenstern (1977) has suggested that unsaturated soil consist of three phases which are solid, water and air phases, different from saturated soil which consist only solid and water. These three phases of unsaturated soil give rise to the two types of pore pressure known as pore water pressure, u_w and pore air pressure, u_a which resulted in a boundary between water and the air known as contractile skin. The difference between u_w and u_a is known as the matric suction. Matric suction exists in unsaturated soil is the reason that causes the difference between saturated and unsaturated soil (Zhan-yong and Jian-jun, 2014). Due to the existence of contractile skin and matric suction, a complex hydro mechanical behavior of the unsaturated soil element had happened due to the interaction between solid, water and air (Prasetyowati, 2007). Soil-water characteristic curve (SWCC), is the relationship between the amount of water in the soil and suction drawn.

Shear Strength of Unsaturated Soil

In the current work, a reasonably simple framework has been sought that will permit the first assessment of the influence of soil suction changes on soil shear strength. For this purpose, the following relationship provided by (Fredlund *et al.*, 1978) appears suitable:

$$\tau = c' + (\sigma_n - \mu_a)\tan\phi' + (\mu_a - \mu_w)\tan\phi^b \qquad (2.1)$$

where $(\mu_a - \mu_w)$ is the matric suction and ϕ^b is the angle indicating the rate of increase in shear strength relative to matric suction. $(\sigma_n - \mu_a)$ is the net normal stress, c' is the effective cohesion and ϕ' is angle of friction.

In equation 2.1, the matric suction and the net normal stress are used to describe unsaturated shear strength while only one stress variable, effective normal stress is required for saturated soil. To calculate FOS for a slope, these two state variables must be specified, however, ϕ^b is the only new strength parameter introduced. Fredlund *et al*., (1978) described ϕ^b as the angle indicating the increase of shear strength, when matric suction was also increased. ϕ^b was always less or equal to the friction angle of saturated soil, ϕ' .

Fredlund and Rahardjo (1993) show the relationship on how shear strength, matric suction together with net normal stress give a three dimensional failure surface, as shown in Figure 1. This figure show a planar failure surface that has a slope angle ϕ^b with respect to the matric suction axis. Many factors that will affect this angle, for example; degree of saturation, void ratio, mineral composition, density, stress history and also strain rate of the soil.

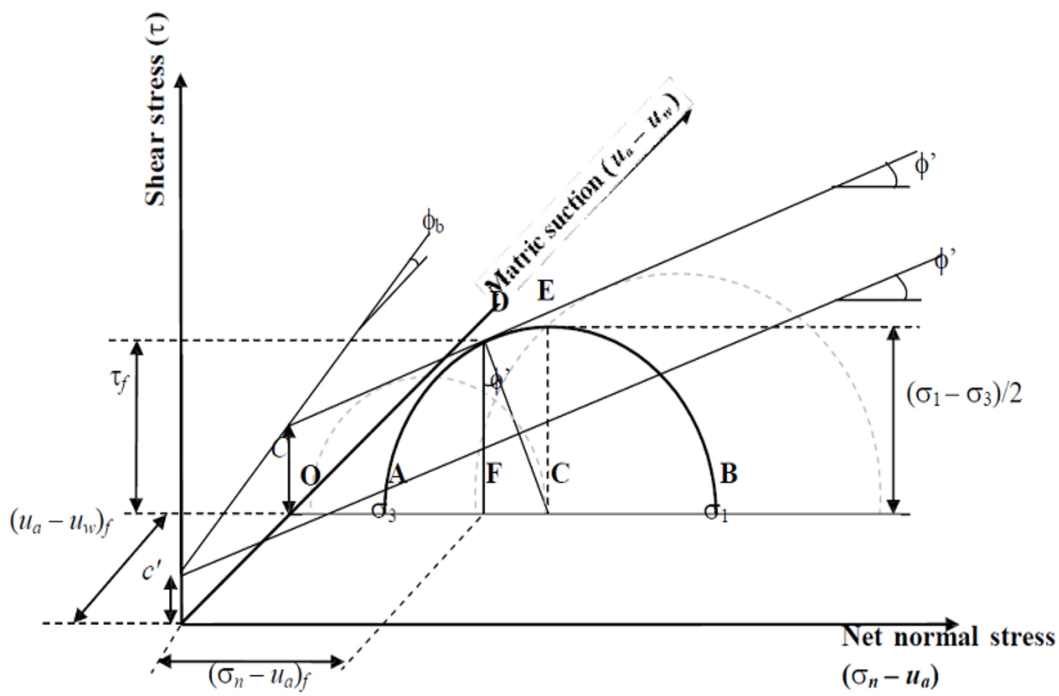

Figure 1: Extended Mohr-Coulomb failure envelope for unsaturated soils, modified after Fredlund and Rahardjo (1993)

Stability of Unsaturated Slopes

The FOS is defined as that factor by which the shear strength of the soil must be reduced in order to bring the mass of soil into a state of limitting equilibrium along a selected slip surface (Krahn, 2004). Calculations for the stability of a slope are performed by dividing the soil mass above the circular slip surface into vertical slices.

Figure 2 shows the forces acting on a slice within the sliding soil mass.

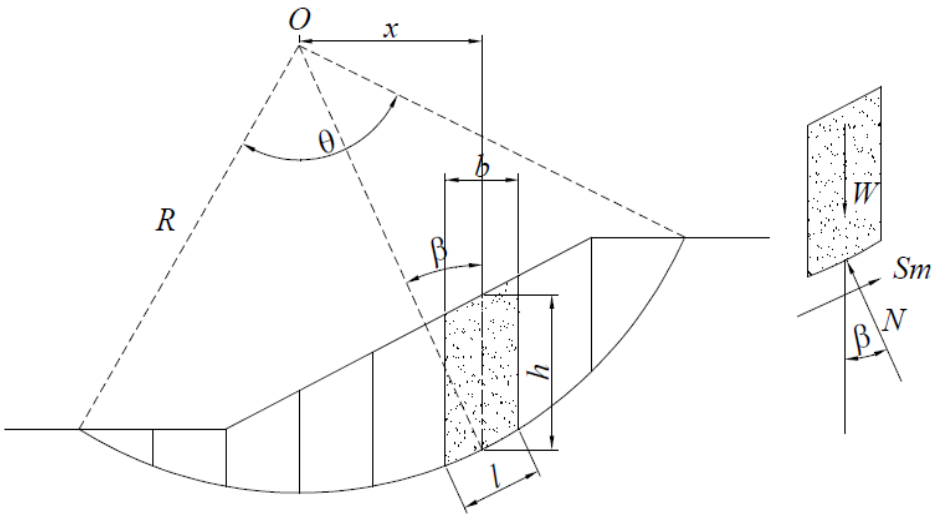

Figure 2: Forces acting on a slice through a sliding mass with a circular slip surface, modified after Fredlund and Rahardjo (1993)

The variables in Figure 2 are defined as follows:

W = the total weight of a slice (*kN)*

N = the total normal force on the base of the slice (*kN)*

Sm = the shear force mobilized on the base of each slice (*kN)*

O = the centre of orientation

x = the horizontal distance from the centreline of each slice to the centre of orientation, *O (m)*

l = the length of the each slice (*m)*

b = the width of the each slice (*m)*

h = the vertical distance from the centre of the base of each slice to the uppermost line in the geometry (*m)*

R = the radius for a circular slip surface (*m)*

β = the angle between the tangent to the centre of the base of each slice and the horizontal (*degrees)*

θ = the angle between the slip surface and a centre about which it rotates (*degrees)*

METHODOLOGY

To calculate the FOS in unsaturated soil slope, a force equation which includes matric suction must be established. The mobilized shear force at the base of a slice can then be written as (Lambe and Whitman, 1969).

$$S_m = \frac{\tau l}{F} \tag{3.1}$$

where τ is shear strength of unsaturated soil as defined previously in equation (2.1). Combining equation (2.1) and (3.1), gives,

$$S = \frac{l\,(c' + (\sigma_n - \mu_a)\tan\phi' + (\mu_a - \mu_w)\tan\phi^b)}{F} \tag{3.2}$$

Resolve Bishop vertically,

$$N\cos\alpha = W + \Delta X - S\sin\alpha$$

$$N = \frac{W + \Delta X - S\sin\alpha}{\cos\alpha}$$

$$S = \frac{(c'l + (N - \mu_a l)\tan\phi' + (\mu_a - \mu_w)\,l\tan\phi^b)}{F} \tag{3.3}$$

Substitute for N;

$$S = \frac{(c'l\cos\alpha + (W + \Delta X - S\sin\alpha - \mu_a l\cos\alpha)\tan\phi' + (\mu_a - \mu_w)\,l\cos\alpha\tan\phi^b)}{F\cos\alpha} \tag{3.4}$$

As b = width of slice = $l\cos\alpha$ and substitute $(\mu_a - \mu_w)$ which is matric suction as M and also assuming the air pore pressure is constant (atmospheric) then $\mu_a = 0$;

$$S = \frac{1}{F}\left[\left(\frac{c'b + (W + \Delta X - \mu_a b)\tan\phi' + Mb\tan\phi^b}{\cos\alpha}\right) - S\tan\alpha\tan\phi'\right] \tag{3.5}$$

Substitute $\left(1+\dfrac{\tan\alpha\tan\phi'}{F}\right)=m_\alpha$;

$$S = \frac{1}{F}\left(\frac{c'b+(W+\Delta X-\mu_a b)\tan\phi'+Mb\tan\phi^b}{\cos\,\alpha}\right)\left(\frac{1}{m_a}\right) \tag{3.6}$$

Moment of equilibrium;

$$\sum W\sin\alpha=\sum S$$

$$F = \frac{\sum\left[\left(c'b+(W+\Delta X-\mu_a b)\tan\phi'+Mb\tan\phi^b\right)\left(\dfrac{\sec\alpha}{m_a}\right)\right]}{\sum W\sin\alpha} \tag{3.7}$$

After much consideration, the final formula is as stated in equation 3.7. The element of matric suction, $(\mu_a-\mu_w)$ together with unsaturated friction angle, ϕ^b was included in the original equation of Bishop’s Simplified method (1955) of saturated soil. When suction becomes zero, it means that the soil is saturated and the equation will turn to the original equation as done by Bishop.

RESULTS AND DISCUSSION

Figure 3 show method of slices: division of sliding mass into slices and forces acting on a typical slice.

Chowdhury *et al* (2010) have pointed out that, the major difference between Bishop’s Simplified method (1955) with Fellenius’s method (1936) is that in considering the vertical equilibrium of any slices, there is no need to account for the horizontal components of the inter-slice forces. The resolution of forces takes place in vertical direction instead direction normal to the arc. Meaning that, with Bishop’s Simplified method (1955) of slices, the side forces E acting on the sides of the slices will not enter into the analysis. It is assumed that the shear side forces X may be neglected without introducing serious error into the analysis.

Figure 4 shows the detail of slope geometry with slip surface and location of slices by Ishak (2014). Ishak (2014) used this detail geometry in his research to calculate slope stabilization using Fellenius’s method (1936) equation for unsaturated soil which had been modified by Rees and Ali (2012).

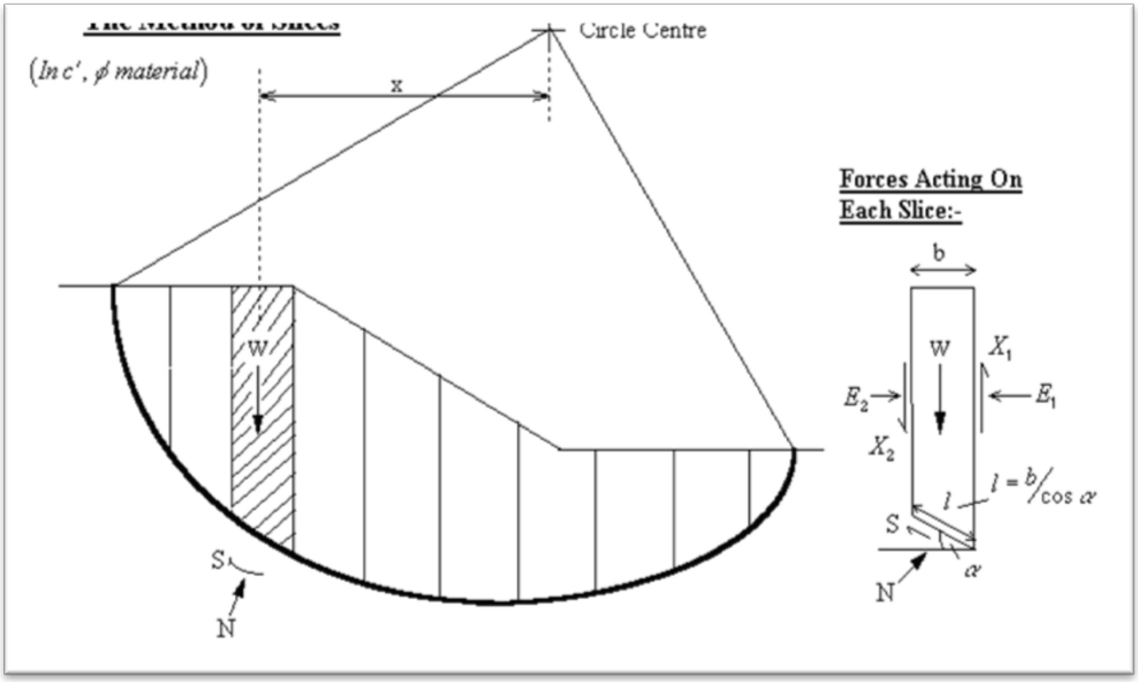

Figure 3: Method of slices: Division of sliding mass into slices and forces acting on a typical slice

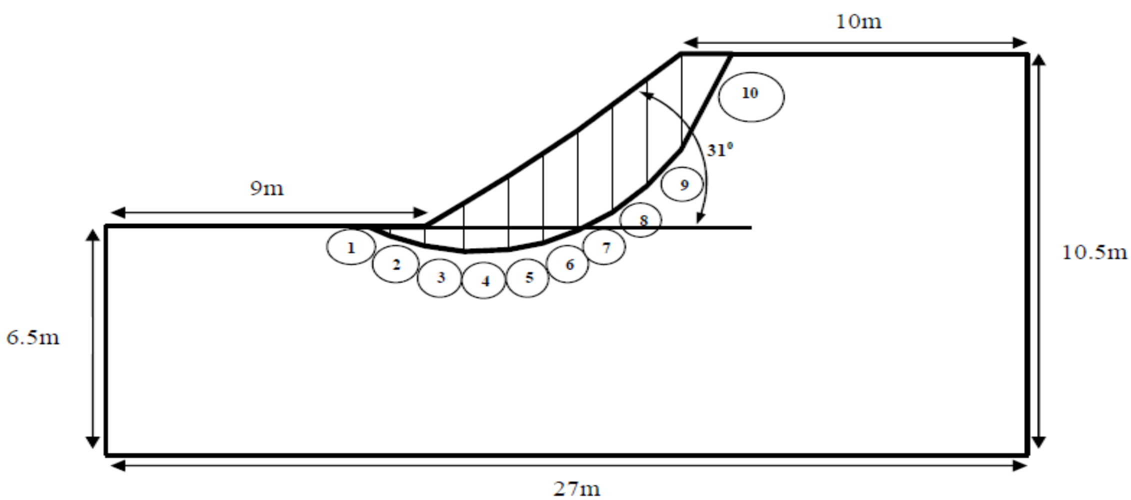

Figure 4: Detail slope geometry with slip surface and location of slices

(Ishak, 2014)

The experimental values of shear strength with ϕ^b angle of tropical residual soil suggested by Ishak (2014) is as shown in table 1. In this study, three suction values were used (0 kPa, 20 kPa and 40 kPa) for FOS values on slope. Table 2 show the calculations of Bishop's Simplified method (1955) with 0 kPa suction.

Table 1: Experimental values of shear strength with ϕ^b angle of tropical residual soil

Researcher	Location	c' (kPa)	ϕ' (°)	ϕ^b (°)
Ishak (2014)	Faculty of Electrical Engineering, UTM	9	23	20

Ishak (2014) suggested that the type of soil in faculty of electrical engineering, UTM is sandy silt with cohesion value, c is 9 kPa, friction angle, ϕ' is 23°, and saturated friction angle, ϕ^b is 20°.

Table 2: Calculations of Bishop's Simplified method (1955) with 0 kPa suction (values for *z*,*b*,*W*, and α are suggested by Ishak, 2014)

Slice No.	*z* (cm)	*b* (m)	*W* (kN)	*α* (°)	*sin α*	*c'b* (1)	*Wtanϕ'* (2)	*Ψbtanϕ^b* (3)	*W sin α* (kN) (5)	*assumed FS=1.5* (4)-1	*assumed FS=2.0* (4)-2
1	12.876	0.62481	1.5	-21.199	-0.362	5.62	0.637	0	-0.543	7.539	7.313
2	39.42	1	7.5	-15.04	-0.259	9	0.424	0	-1.943	10.561	10.348
3	92.1	1.18	20.6	-7.005	-0.122	10.62	8.734	0	-2.513	20.202	20.022
4	165.01	1.3	40.8	1.9909	0.035	11.7	17.299	0	1.428	28.734	28.804
5	218.51	1.01	41.9	10.4	0.181	9.09	17.766	0	7.584	25.956	26.281
6	253.06	1.01	48.6	17.944	0.308	9.09	20.606	0	14.969	28.594	30.193
7	276.34	1.0067	52.9	25.819	0.436	9.06	22.429	0	23.064	30.768	31.723
8	285.68	1.0067	54.6	34.259	0.563	9.06	23.15	0	30.740	32.674	34.049
9	272.04	1.0067	52	43.691	0.691	9.06	22.048	0	35.932	33.866	35.769
10	153.11	1.498	43.6	59.41	0.861	13.48	18.486	0	37.540	42.480	46.221
Total									146.258	261.374	270.722

$$FOS_1 = \frac{261.374}{146.258} = 1.79$$

$$FOS_2 = \frac{270.722}{146.258} = 1.85$$

Figure 5 shows the graph of Bishop's Simplified method (1955) with 0 kPa suction.

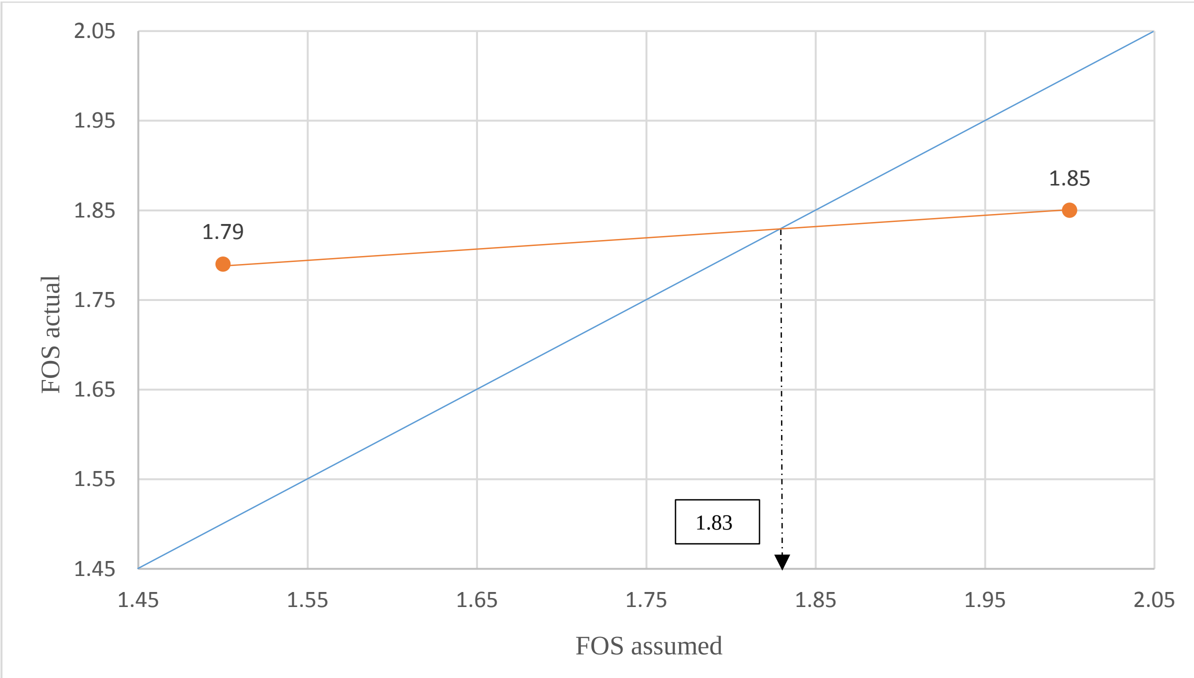

Figure 5: Graph of Bishop's Simplified method (1955) with 0 kPa suction

The graph indicates that the actual FOS value for Bishop (1955) with 0 kPa suction is 1.83. Since the FOS is greater than 1, therefore it is safe. Table 3 show the percentage differences of FOS between Bishop's Simplified method (1955) with Fellenius's method (1936) of 0 kPa suction.

Table 3: Differences of FOS value with 0 kPa suction

Type of Analysis	FOS	Percentage Difference (%)
Fellenius's method (1936) (Ishak, 2014)	1.70	0
Bishop's Simplified method (1955)	1.83	7.65

The results suggest that, calculation by using Bishop's Simplified method (1955) gave higher FOS value compare to ordinary Fellenius's method (1936) by 7.65 % for 0 kPa suction. Table 4 shows the calculations of Bishop's Simplified method (1955) with 20 kPa suction.

Table 4: Calculations of Bishop's Simplified method (1955) with 20 kPa suction (values for *z*,*b*,*W*, and α are suggested by Ishak, 2014)

Slice No.	*z* *(cm)*	*b* *(m)*	*W* *(kN)*	*α* *(°)*	*sin α*	*c'b* *(1)*	*Wtanϕ'* *(2)*	*Ψbtanϕ^b* *(3)*	*W sin α* *(kN)* *(5)*	*assumed FS=2.5* *(4)-1*	*assumed FS=2.4* *(4)-2*
1	12.876	0.62481	1.5	-21.199	-0.362	5.62	0.637	4.549	-0.543	12.405	12.449
2	39.42	1	7.5	-15.04	-0.259	9	0.424	7.28	-1.943	18.124	18.157
3	92.1	1.18	20.6	-7.005	-0.122	10.62	8.734	8.590	-2.513	28.755	28.782
4	165.01	1.3	40.8	1.9909	0.035	11.7	17.299	9.464	1.428	38.271	38.232
5	218.51	1.01	41.9	10.4	0.181	9.09	17.766	7.353	7.584	34.072	33.696
6	253.06	1.01	48.6	17.944	0.308	9.09	20.606	7.353	14.969	36.091	33.344
7	276.34	1.0067	52.9	25.819	0.436	9.06	22.429	7.329	23.064	39.866	39.711
8	285.68	1.0067	54.6	34.259	0.563	9.06	23.15	7.329	30.740	42.900	42.702
9	272.04	1.0067	52	43.691	0.691	9.06	22.048	7.329	35.932	45.740	45.471
10	153.11	1.498	43.6	59.41	0.861	13.48	18.486	10.905	37.540	65.464	64.864
Total									146.258	361.678	357.408

$$\mathrm{FOS}_1 = \frac{361.678}{146.258} = 2.47$$

$$\mathrm{FOS}_2 = \frac{357.408}{146.258} = 2.44$$

Figure 6 shows the graph of Bishop's Simplified method (1955) with 20 kPa suction.

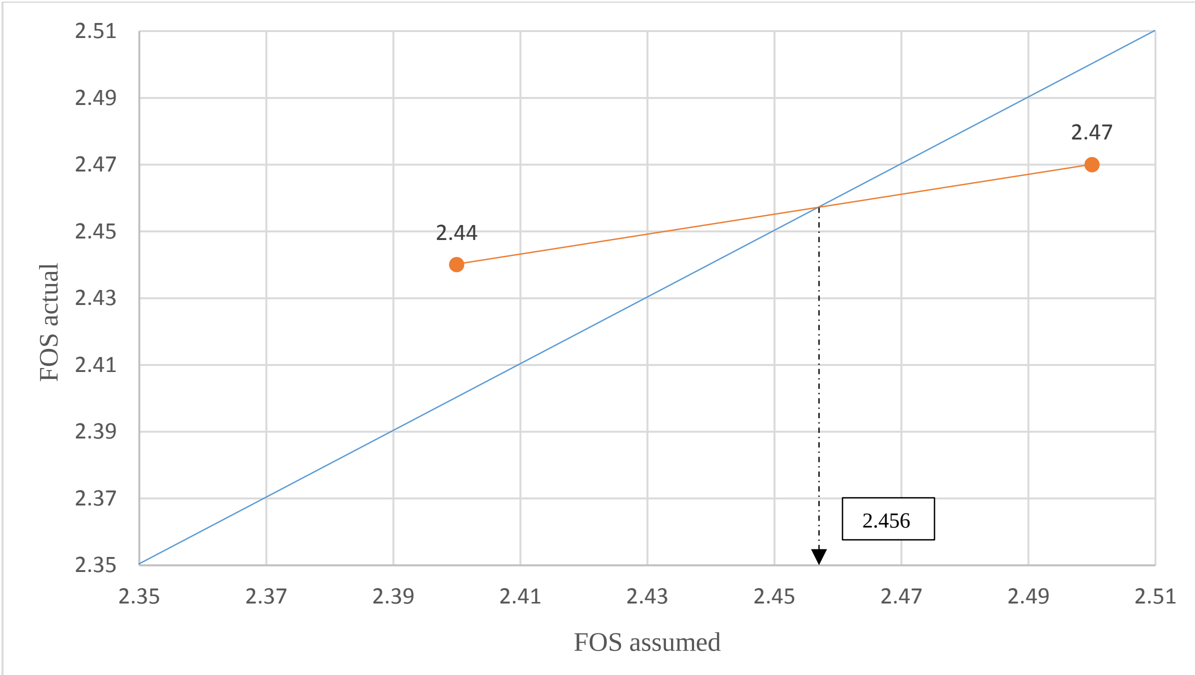

Figure 6: Graph of Bishop's Simplified method (1955) with 20 kPa suction

The graph indicates that, the actual FOS value for Bishop (1955) with 20 kPa suction is 2.456. Since the FOS is greater than 1, therefore it is safe. Table 5 show the percentage differences of FOS between Bishop's Simplified method (1955) with Fellenius's method (1936) of 20 kPa suction.

Table 5: Differences of FOS value with 20 kPa suction

Type of Analysis	FOS	Percentage Difference (%)
Fellenius's method (1936) (Ishak, 2014)	2.34292	0
Bishop's Simplified method (1955)	2.456	4.83

The results indicate that, calculation by using Bishop's Simplified method (1955) gave higher FOS value compare to ordinary Fellenius's method (1936) by 4.83 % for 20 kPa suction. Table 6 show the calculations of Bishop's Simplified method (1955) with 40 kPa suction.

Table 6: Calculations of Bishop's Simplified method (1955) with 40 kPa suction (values for z,b,W, and α are suggested from Ishak, 2014)

Slice No.	*z* *(cm)*	*b* *(m)*	*W* *(kN)*	*α* *(°)*	*sin α*	*c'b* (1)	*Wtanϕ'* (2)	*Ψbtanϕ^b* (3)	*W sin α* *(kN)* (5)	*assumed FS=3.5* (4)-1	*assumed FS=3.1* (4)-2
1	12.876	0.62481	1.5	-21.199	-0.362	5.62	0.637	9.096	-0.543	17.280	17.395
2	39.42	1	7.5	-15.04	-0.259	9	0.424	14.559	-1.943	25.670	25.782
3	92.1	1.18	20.6	-7.005	-0.122	10.62	8.734	17.179	-2.513	37.365	37.446
4	165.01	1.3	40.8	1.9909	0.035	11.7	17.299	18.926	1.428	47.753	47.733
5	218.51	1.01	41.9	10.4	0.181	9.09	17.766	14.704	7.584	41.334	41.228
6	253.06	1.01	48.6	17.944	0.308	9.09	20.606	14.704	14.969	44.906	44.666
7	276.34	1.0067	52.9	25.819	0.436	9.06	22.429	14.656	23.064	48.421	48.083
8	285.68	1.0067	54.6	34.259	0.563	9.06	23.15	14.656	30.740	52.378	51.881
9	272.04	1.0067	52	43.691	0.691	9.06	22.048	14.656	35.932	56.719	55.649
10	153.11	1.498	43.6	59.41	0.861	13.48	18.486	21.809	37.540	87.682	85.825
Total									146.258	459.508	455.688

$$\text{FOS}_1 = \frac{459.508}{146.258} = 3.14$$

$$\text{FOS}_1 = \frac{455.688}{146.258} = 3.12$$

Figure 7 indicates the graph of Bishop's Simplified method (1955) with 40 kPa suction.

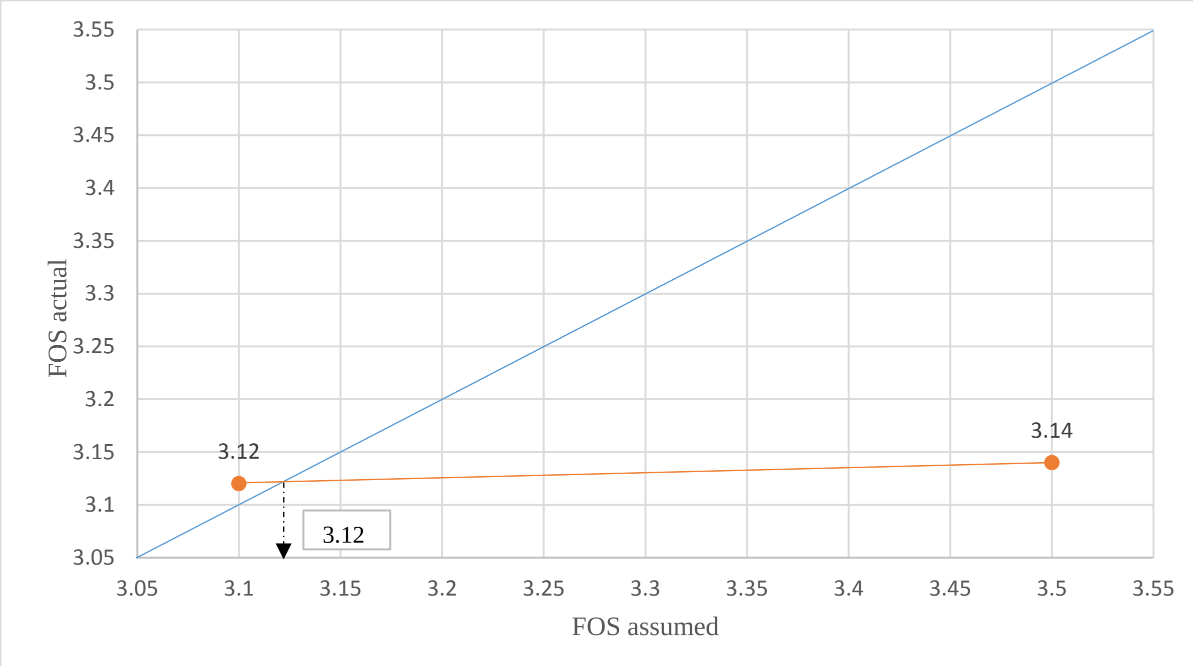

Figure 7: Graph of Bishop's Simplified method (1955) with 40 kPa suction

The graph shows the actual FOS value for Bishop (1955) with 40 kPa suction is 3.12. Since the FOS is greater than 1, therefore it is safe. Table 7 suggested the percentage differences of FOS between Bishop's Simplified method (1955) with Fellenius's method (1936) of 40 kPa suction.

Table 7: Differences of FOS value with 40 kPa suction

Type of Analysis	FOS	Percentage Difference (%)
Fellenius's method (1936) Ishak (2014)	2.9882	0
Bishop's Simplified method (1955)	3.12	4.41

From the results, calculation by using Bishop's Simplified method (1955) gave higher FOS value compare to ordinary Fellenius's method (1936) by 4.41 % for 40 kPa suction. Clearly, these three comparisons show that more accurate FOS value for slope stabilization can be obtained by calculating using Bishop's Simplified method (1955) compare to Fellenius (1936). Also, as the FOS value was greater than 1, therefore, the slope was in safe condition.

CONCLUSION

It can be concluded that, Bishop's Simplified method (1955) gave higher and more accurate FOS value compare to Fellenius's method (1936) for slope stabilization.

The results indicate that, there is more than 7 % differences in FOS when calculated using Bishop (1955) instead of Fellenius (1936) for 0 kPa suction. Bishop (1955) also gave more than 4% differences of FOS value compare to Fellenius (1936) when applying both 20 kPa and 40 kPa suction values.

The analysis of Bishop's simplified method (1955) was carried out in term of stresses instead of forces which were used in Fellenius (1936). The major difference between these two methods is that, in Bishop (1955), the resolution of forces takes place in the vertical direction instead the direction normal to the arc.

Meaning that, the side forces E of Bishop acting on the sides of the slices will not enter into the analysis. The reason for the relative accuracy of the Bishop (1955) is that in considering only the vertical equilibrium of any slice, there is no need to account for the horizontal components of the inter-slice forces (Chowdhury *et al.*, 2010).

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