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Pore pressure effect on slope stability assessment

Kelvin Lim[1], An-Jui Li[1] and Mark Cassidy[2]

[1]School of Engineering, Deakin University, 75 Pigdons Road, Waurn Ponds, VIC 3217, Australia; PH (613) 5227 2998; email: kkwl@deakin.edu.au, a.li@deakin.edu.au
[2]Centre for Offshore Foundation Systems, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia; PH (613) 6488 3732; email: mark.cassidy@uwa.edu.au

ABSTRACT

Slope stability assessment has been an integral problem for geotechnical engineering all these years. While stability of slopes is affected by various factors, pore pressure is one of the common natural elements that influence slope stability analysis. This paper studies the effect of pore pressure on slope stability assessment by using Limit Equilibrium Method (LEM). The results will be compared to the solutions of Hoek and Bray charts. In this study, slopes with different levels of water table corresponding to those of Hoek and Bray charts are investigated. It's interesting to observe that the results obtained from the Hoek and Bray charts yielded different factor of safety compare to those in the study here-in. In fact, the different between the factors of safety could be up to 30%. Hence this issue should be taken into consideration during slope design.

Keywords: Landslide, Limit equilibrium, water

1 INTRODUCTION

Traditionally, slope stability assessment has been performed using the conventional limit equilibrium method (LEM) due to its simplicity. In fact, this is usually achieved by satisfying moment/force equilibrium and the factor of safety can typically be obtained by calculating the amount of available shear strength to resist the mobilized sliding shear stress. Apart from the LEM, many other methods have also been developed to tackle slope stability problems. Some of which are able to consider displacement (finite element method) (Griffiths and Lane 1999; Manzari and Nour 2000) or even bracket the true solutions to within a range by using the upper and lower bound finite element limit analysis method (Michalowski 2002; Chen et al. 2003; Chen et al. 2005). Therefore, depending on the purpose and required accuracy of the slope being investigated, the appropriate methods can be utilized. Despite of the well-known limitations of the LEM, it still remains the most popular method due to its ability to produce quick solutions.

In geotechnical engineering, slope stability problems include natural slopes, fill slopes (such as embankment, earth dams and levees) or cut slopes. While these are the physical geometry and properties that influence the stability of slopes, some other factors such as external forces (earthquake, pore pressure and others) are also significant when investigating slope stability problems. With respect to these different factors affecting slope stability, some researchers (Duncan 2000; Cassidy et al. 2008; Li et al. 2012) have even performed reliability assessments for their respective slope stability study to account for uncertainties in design.

Chart solutions within the field of slope stability investigation can be found way back when Taylor (1937) first introduced it in his study. It was found to be a convenient tool and can since be found in studies utilizing the LEM (Gens et al. 1988; Baker et al. 2006) and limit analysis method (Michalowski 2002; Kumar and Samui 2006; Michalowski 2010). However, the application of stability charts utilizing finite element method is fairly limited largely due to the high computational time required by the method.

Therefore, based on the pre-existing Hoek and Bray charts, this paper will investigate the effect of pore pressure on slope stability assessment by using the ever so conventional limit equilibrium method. In this study, slopes with different levels of water table are considered according to the Hoek and Bray charts. As such the results obtained from this study are also compared to that of the Hoek and Bray study.

2 PREVIOUS STUDY

2.1 Chart solutions

As previously mentioned, many methods have been developed to investigate the different kinds of slope stability problems. Hence, utilizing these methods, slope stability charts have been developed and produced. The stability charts are known to be convenient tools for geotechnical engineers for preliminary design of slopes (Gens et al. 1988; Michalowski 2002; Li et al. 2009). As a matter of fact, different charts have been produced for different type of slopes (Gens et al. 1988; Yu et al. 1998; Kumar and Samui 2006; Li et al. 2009, 2010; Michalowski 2010; Qian et al. 2014). Then, similarly to Hoek and Bray charts, some of the chart solutions also incorporated the different natural forces such as pore water pressure as well as seismic force (Kim et al. 1999; Michalowski 2002; Loukidis et al. 2003; Baker et al. 2006).

While different charts were produced in the recent years, it is worthwhile to note that the charts were produced utilizing the different available methods in slope stability analysis. For example utilizing the limit equilibrium method (LEM), Taylor (1937) was one of the first researchers to produce a set of stability charts for purely cohesive soil. Then, in order to investigate the boundary effects on the stability of slope, Gens et al. (1988) perform a 3D analysis and produced a set of stability charts on the similar soil profile (purely cohesive soil). Apart from that, Baker et al. (2006) and Leshchinsky and San (1994) in recent years also produced chart solutions for their investigation and incorporated pseudo static effect on the stability of slope.

Based on the limit theorem, various chart solutions have also been produced. In his study, Michalowski (1997, 2002, 2010) has notably investigated the stability of slope considering various factors such as reinforcement, pore pressure as well as seismic effect. It is to be understood that these different studies have all incorporated chart solutions within them. On the other hand, Kumar and Samui (2006) also produced a set of stability charts for their study on stability of layered soil slopes. In addition to that, (Viratjandr and Michalowski 2006) have also utilized the limit analysis method to investigate the stability of submerged slopes subjected to water drawdown and produced a set of stability charts for the study. It is however worthwhile to be noted that these charts were produced using only the upper bound limit analysis method. This is due to the fact that, constructing the statically admissible stress field (lower bound) is very complex and difficult.

In light of these limitations, another stream of researchers (Lyamin and Sloan 2002a, b; Krabbenhoft et al. 2005) developed the upper and lower bound finite element limit theorem to solve various geotechnical engineering problems. In fact, according to (Sloan 2013), these limit theorem can be applied on various geotechnical engineering problems such as bearing capacity (Shiau et al. 2003; Shiau et al. 2011), trench stability (Li et al. 2014) and not only slope stability problems. Then, specifically for slope stability problems, various chart solutions were produced including those by Kim et al. (1999), Li et al. (2009, 2010), Loukidis et al. (2003), (Qian et al. 2014) and Yu et al. (1998). It is to be noted that while Loukidis et al. (2003) considered seismic force in their study, Kim et al. (1999) incorporated pore water pressures in theirs.

Thus, from above, it can be seen that charts solutions have gain much popularity in the recent years, as they continue to gain the interests and attention from the various researchers. In fact, it can also be seen that utilizing the different available methods in slope stability problems, different chart solutions have been produced considering the different natural factors such as pore water pressure. Having said that, it is also interesting to compare the results obtained using the stability charts as well as those obtained from the more conventional limit equilibrium method. Therefore, this paper aims to use the limit equilibrium method to investigate the stability of slope under the effect of pore water pressure and for comparison, the results obtained will be compared to those obtained using the Hoek and Bray's charts.

3 PROBLEM DEFINITION

Figure 1 shows the typical slope configuration constructed using the LEM (SLIDE 6.0) program in this study. A range of slope angle (β) = 56°, 45° and 30° is investigated in the study herein. As the main purpose of this study is to investigate the effect of pore pressure on slope stability assessment, different water levels within the slopes are studied. It should be noted that, the different water level investigated is based on that of the Hoek and Bray, as shown in Figure 2. The charts being used in this paper corresponding to the water level are also displayed in Figure 3. Figure 4 is an example for which the water level is at 4 times (4X) slope height behind toe of slope. Similar to Figure 4, other water levels investigated for slope of β = 56° include fully drained and saturated slope as well as slopes with surface water 2 times (2X) and 8 times (8X) slope height behind toe of slopes. For the case of β = 45°, water level investigated were 2 times and 8 times slope height behind toe of slopes. Finally for the case of β = 30°, water level investigated were 2 times and 8 times slope height behind toe of slopes. It should be noted that unlike the assumption made by Hoek and Bray (1981), tension crack is not considered herein.

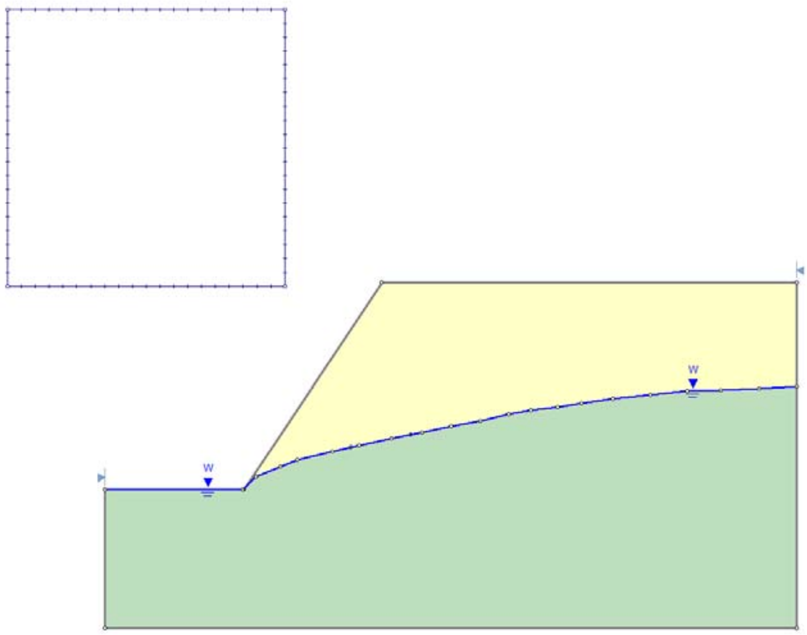


Figure 1. Physical slope geometry and groundwater level

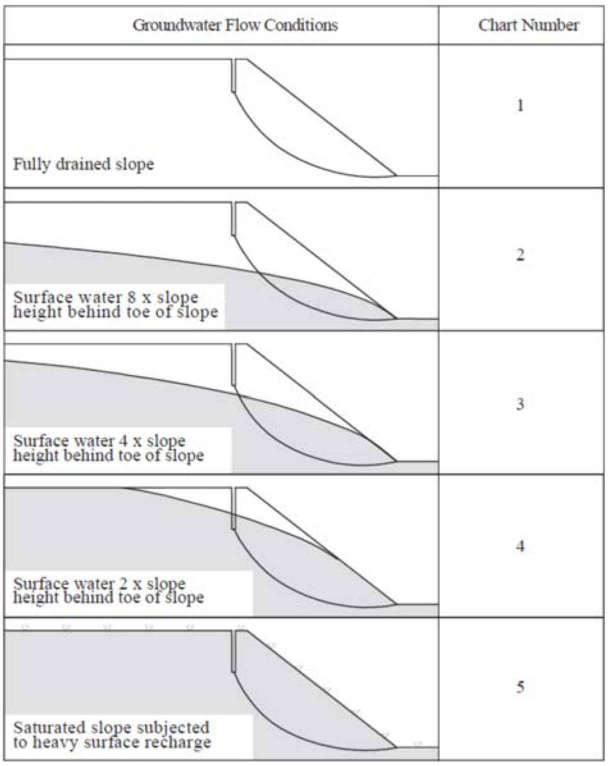
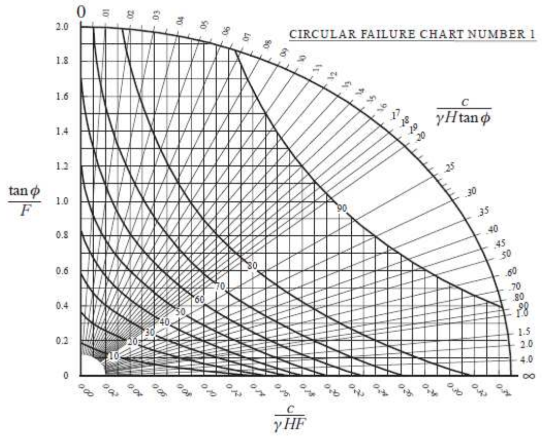
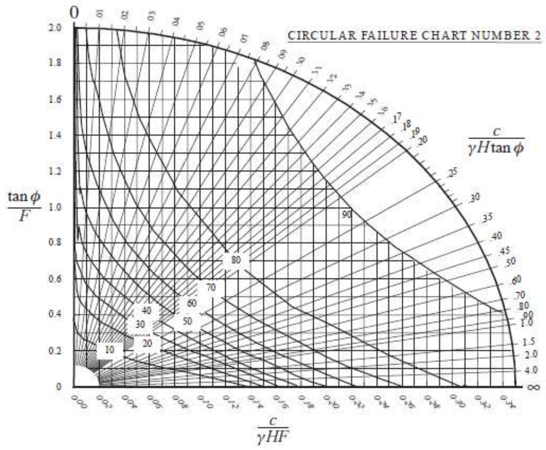


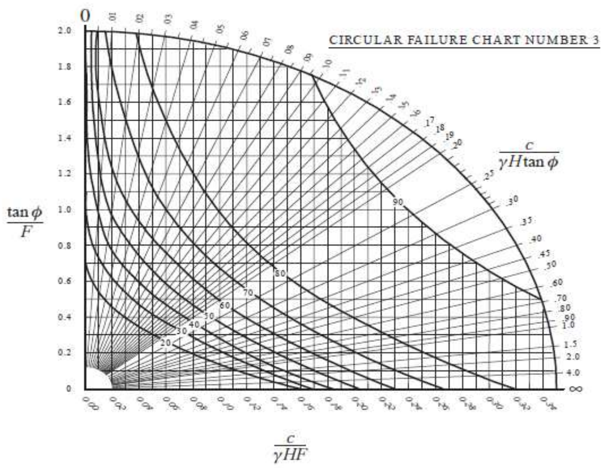
Figure 2. Groundwater level witihin the slope adapted from Hoek and Bray (1981)



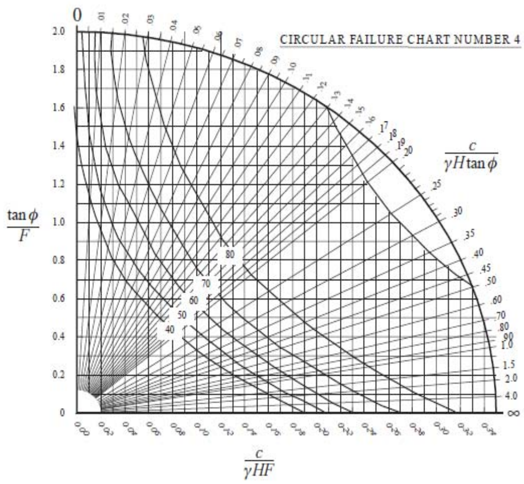
(a) Fully drained slope



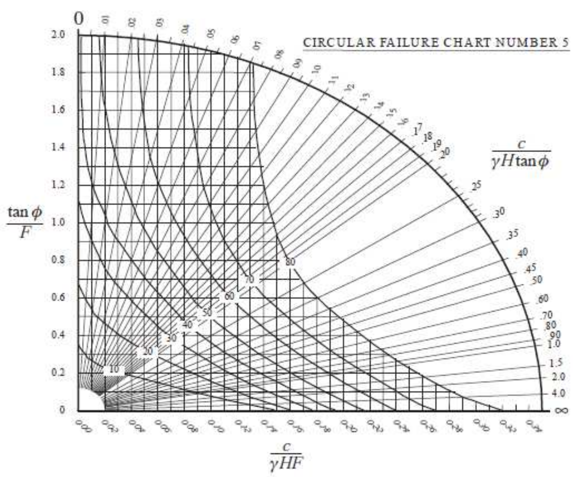
(b) 8x slope height behind toe of slope



(c) 4x slope height behind toe of slope



(d) 2x slope height behind toe of slope



(e) Fully saturated slope

Figure 3. Chart solutions for corresponding level of water table adapted from Hoek and Bray (1981)

4 RESULTS AND DISCUSSION

Table 1 and Table 2 shows the results for β = 56°, 45° and 30° with the corresponding water table level. It is to be noted that the values obtained from Table 1 are the calculated values from the program SLIDE 6.0 while that from Table 2 are the values obtained from the Hoek and Bray charts. Corresponding to each of the parameters (tan*ϕ/F* and *c/γHF*) in Table 2, the differences in factor of safety between the chart solutions and the LEM (SLIDE 6.0) have been shown.

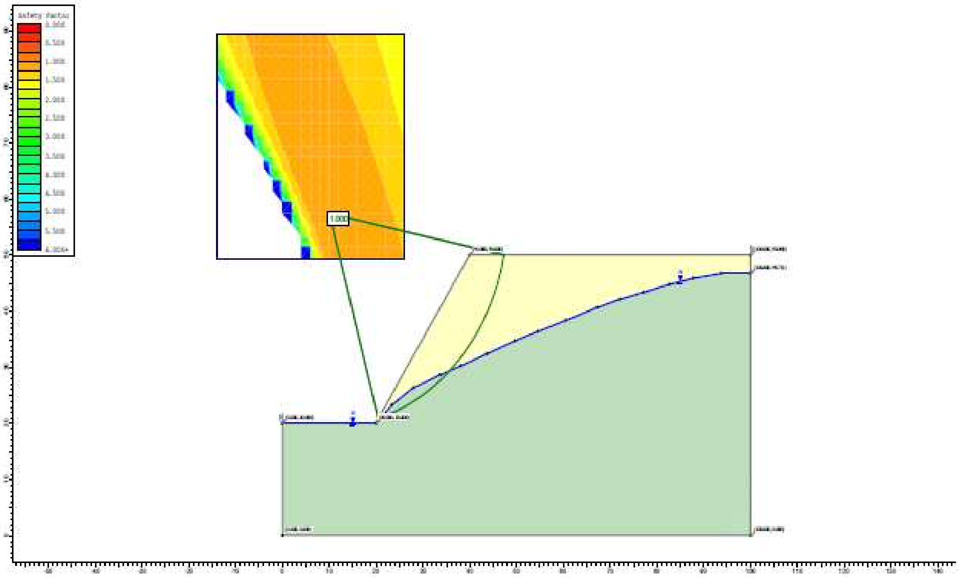


Figure 4. Example of the slope, β = 56° with water level of 4X slope height behind toe of slope

Table 1: Results from LEM for β = 56°, 45° and 30°

Slope Angle	Water Table		LEM results			
		Trial #	*F*	*ϕ′*	tan*ϕ′*	*c/γH*tan*ϕ’*
56	Fully Drained	1	1.01	20	0.36	0.24
		2	1	45	1	0.01
	2X	1	0.997	20	0.36	0.32
		2	0.998	37.5	0.77	0.04
		3	0.991	47	1.07	0.02
	4X	1	1.009	20	0.36	0.24
		2	1.008	25	0.47	0.15
	8X	1	0.996	5	0.09	0.33
		2	1	10	0.18	0.41
		3	1.004	15	0.27	0.75
		4	1	17	0.31	1.79
	Saturated	1	1	15	0.27	0.62
		2	1	30	0.58	0.26
		3	1	45	1.00	0.04
		4	0.997	45	1.00	0.07
45	2X	1	0.999	15	0.27	0.47
		2	1.003	20	0.36	0.26
		3	0.999	30	0.58	0.09
		4	0.998	40	0.84	0.05
	8X	1	1.007	5	0.09	1.78
		2	1.002	10	0.18	0.84
		3	0.999	20	0.36	0.17
		4	1.004	25	0.47	0.09
30	2X	1	0.991	15	0.27	0.17
		2	1.004	20	0.36	0.07
		3	1.001	25	0.47	0.02
	8X	1	0.995	15	0.27	0.21
		2	1.002	20	0.36	0.07
		3	1.007	25	0.47	0.02

It can clearly be seen that for the case of β = 56°, while minor differences with a maximum of 4% are observed when the slope is fully drained, the same can't be said when the slope is fully saturated. This is because when the slope is fully saturated, the differences between the factor of safety obtained from the LEM and Hoek and Bray can be up to 20% (overestimation) and 16% (underestimation). Apart from that, the difference between the factors of safety can be observed to be up to 10% for other cases (4 times and 8 times slope height behind toe of slopes).

Table 2: Comparison of factors of safety obtained from LEM and Hoek and Bray's chart

Slope Angle	Water Table	LEM results					
		$\tan\phi'/F$	F_1	% in F difference	$c/\gamma HF$	F_2	% in F difference
56	Fully Drained	0.36	1.00	-0.73	0.09	1.05	3.54
		1.03	0.97	-3.01	0.01	1.00	-0.03
	2X	0.36	1.01	1.69	0.11	1.04	4.80
		0.79	0.97	-2.43	0.03	0.98	-1.76
		1.03	1.05	5.57	0.02	1.02	2.56
	4X	0.41	0.88	-12.45	0.10	0.89	-12.25
		0.51	0.92	-9.11	0.08	0.88	-12.21
	8X	0.10	0.92	-7.54	0.17	0.93	-6.26
		0.20	0.89	-10.95	0.14	0.93	-7.07
		0.28	0.95	-5.36	0.12	0.94	-6.22
		0.34	0.89	-10.61	0.11	0.93	-6.62
	Saturated	0.28	0.95	-4.64	0.16	1.03	3.13
		0.49	1.18	17.59	0.12	1.20	19.92
		1.19	0.84	-15.61	0.05	0.86	-14.35
		0.92	1.08	8.67	0.07	1.04	4.72
45	2X	0.27	0.99	-1.03	0.11	1.09	9.57
		0.35	1.05	4.58	0.09	1.08	7.84
		0.52	1.10	10.50	0.05	1.10	9.90
		0.67	1.24	24.74	0.03	1.23	23.32
	8X	0.09	0.97	-3.47	0.16	0.93	-7.78
		0.18	0.96	-3.84	0.14	1.09	8.80
		0.41	0.89	-11.35	0.07	0.85	-14.88
		0.53	0.88	-12.70	0.05	0.84	-16.37
30	2X	0.29	0.93	-6.44	0.05	0.94	-5.18
		0.43	0.85	-15.30	0.03	0.86	-14.07
		0.57	0.82	-18.56	0.01	0.85	-15.05
	8X	0.39	0.70	-30.05	0.07	0.76	-23.13
		0.51	0.71	-29.05	0.03	0.73	-26.72
		0.39	1.20	19.35	0.01	0.87	-13.25

In fact, similar trend (difference) can be observed for a lower slope angles. For the case where β = 45° and water level of 2 times slope height behind toe of slope, majority of the factors of safety obtained from the Hoek and Bray charts are overestimated. As a matter of fact, using the Hoek and Bray chart can overestimate the factor of safety by as much as 25%. However, when the water level is at 8 times slope height behind toe of slope, the total opposite is true where the majority of factors of safety obtained from the Hoek and Bray charts are underestimated.

Having said that, a more uniform trend can be observed for the case where β = 30°. To further support this statement, reference to Table 2 is to be made as it can be seen that compared to the results from the LEM, now the majority of the factors of safety obtained from Hoek and Bray charts are underestimated regardless of the water level being at 2 times or 8 times slope height behind the toe of slopes. In fact, the underestimated factor of safety is shown to differ by as much as 30%. The reason could be due to the tension crack that is not taken into account in this study.

Despite efforts being made, it can be concluded that no apparent relations between the water level and difference in the factors of safety can be made. Apparently, the only relation observed here is when the water level is 8 times slope height behind the toe of slope in which the increase in slope angle leads to an increase in the difference between the factors of safety from Hoek and Bray and that of the LEM.

Therefore, from the results presented herein, this clearly shows that, when using Hoek and Bray charts for solving slope stability problems, cautions have to be made due to the major differences compared to the results obtained through the use of the LEM.

5 CONCLUSION

This paper investigated the effect of pore water pressure on slope stability assessment using the conventional limit equilibrium method. The obtained results (factors of safety) are compared against the pre-existing Hoek and Bray stability charts. The results obtained show that using Hoek and Bray charts for slope designs would lead to over- or underestimation of the factor of safety by as much as 30%. Therefore, with the distinct differences from the two methods, this shows that pore water pressure is a significant influence in slope stability assessment and as a result careful consideration and precautions should be taken for slope designs involving pore water pressure. Apart from that, unlike in Hoek and Bray’s study, this investigation has not taken into consideration the effects of tension crack which may results in the difference of factors of safety obtained by this study and Hoek and Bray.

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