27 May 2010, 4:30 pm - 6:20 pm

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

SEISMIC SLOPE STABILITY OF REACTIVATED LANDSLIDES - A PERFORMANCE BASED ANALYSIS

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ABSTRACT

The purpose of this study is to identify and analyze the differences between the various methods of slope stability analysis with respect to the height of the water table, and earthquake excitation. This was achieved through analysis of a cross section of the 2005 Bluebird Canyon Landslide in Laguna Beach, California. The profile was analyzed with the slope stability analysis software Rocscience Slide, using eight different methods, varying the water table in two meter increments and the seismic coefficient in increments of one tenth. A total of 15 different water tables were used with 10 different seismic loadings, yielding a relatively large set of data. Additionally, spreadsheets were constructed for analysis using Bishop's Simplified Method with the pseudo static approach for seismic loading. While all of the methods yielded results for the tests with no seismic excitation, the number of methods yielding results diminished as the seismic coefficient increased. The only two methods that gave results for all loading conditions were the Army Corp #2 method and the Ordinary Method of Slice. In general, the Army Corp #2 method gave the least conservative results, while the Ordinary Method of Slice gave the most conservative results. This was true for almost all loading conditions and water tables. Another trend was Bishop's Simplified Method giving nearly identical results to the Jambu Corrected method, and the spreadsheet results being nearly the same as the Jambu Simplified method. As expected, lowering the water table increased the safety factor for nearly all the methods. This beneficial effect was found to diminish as the water table lowered, and as the seismic coefficient increased. The incremental effect of lowering the water table on the safety factor was found to be nearly the same for all cases except the Army Corp #2 method. In this case, lower safety factors were obtained for lowering the water table in the presence of seismic excitation. As the seismic coefficient increased, the beneficial effect of lowering the water table decreased. The effect that the seismic coefficient had on safety factor also decreased with an increase in the coefficient. Furthermore, it was found that for lower water tables, the effect that the seismic coefficient has on safety factor is relatively large, while the effect is small for full or nearly full water tables. This was found to be true for all cases except the Army Corp #2 method.

INTRODUCTION

The stability of a slope can be expressed in terms of the driving moments and resisting moments, or simply a safety factor. The driving moment is due to the slopes natural tendency to slide under its own weight. The resisting moment is provided by the shear strength of the soil. For analysis, a sliding surface is assumed, and checked for stability. This is done for several sliding surfaces until the surface with the lowest safety factor is found. This surface is the critical sliding surface, and its safety factor defines the stability of the slope.

The problem of stability in slopes is statically indeterminate, meaning there are more unknowns than the three equations provided by statics. For this reason, assumptions are made to make the problem statically determinate. Various methods are available to analyze the stability of slopes, and different methods make different assumptions. The assumptions vary from the shape of the sliding surface, to the inclination of interslice forces.

The methods can be generalized into two categories. There are methods which analyze the sliding mass as a whole, while the rest divide up the slope into slices. In general, the methods will satisfy one, two or all three of the equations of static equilibrium. While they will not be used in calculations, a brief summary of the methods that assume the sliding mass as a whole will be presented here. The methods that are commonly used for the slope stability analysis are explained in detail by Duncan and Wright (2005).

INFINITE SLOPE

This procedure assumes that the slope extends indefinitely in both directions of the sliding surface. This assumption provides equal, opposite, and collinear interslice forces, which cancel each other out. The problem is then statically determinate. The normal and shear force can be solved for using a force polygon, or simply summing the forces in the horizontal and vertical direction. The safety factor can then be expressed in terms of the shear strength and the shear stress.

LOG SPIRAL

The log spiral procedure assumes that the sliding surface is the shape of a log spiral, making the problem statically determinate. Moments of the resisting and driving forces (shear stress, normal force and weight) are taken about the center of the spiral. The factor of safety can be solved for directly in this manner. This method also explicitly satisfies force equilibrium (Duncan and Wright, 2005), so the results are relatively accurate.

SWEDISH CIRCLE ($\Phi = 0$) METHOD

This method assumes a circular slip surface, and that the internal angle of friction of the soil is zero. Because of this, the resisting force can be expressed simply in terms of cohesion and the arc length of the circle. Moment is taken at the center of the circle; the moment arm for the resisting force is simply the radius of the circle. The driving force is expressed in terms of the weight, and the perpendicular distance from the center of the circle to the center of gravity of the sliding mass.

The alternative way to perform analysis is to divide the slope into slices, and consider the forces on each individual slice. To make the problem statically determinate, the stresses between the slices must be assumed. Methods involving slices differ in the assumption of interslice forces.

ORDINARY METHOD OF SLICES

The ordinary method of slices neglects interslice forces, and assumes a circular slip surface. In this manner, the forces for each individual slice can be found, and the moment is taken about the center of the circle. The factor of safety can then be solved for directly. This method satisfies moment equilibrium but not force equilibrium. It is not recommended to use the ordinary method of slices with seismic loading, as the results are relatively inaccurate (Duncan and Wright, 2005). The Ordinary Method of Slices is rarely used in practice, because it is too conservative (Das, 2006).

BISHOP’S SIMPLIFIED

In Bishop’s procedure, the forces between the slices are assumed to be horizontal. The forces on the slices are found using equilibrium of vertical forces. The factor of safety is then expressed by summing the resisting and driving moments due to these forces. While in the previous methods discussed the factor of safety could be solved for directly, Bishop’s method requires an assumed factor of safety before calculating it. Thus, iteration is required to solve the problem. Since the procedure largely neglects horizontal equilibrium, it should be used with caution when performing analysis with seismic loads. In contrast, this procedure has comparable results to those with complete force equilibrium (Duncan and Wright, 2005).

JAMBU’S METHODS

This procedure assumes that the interslice forces are horizontal. This method does not assume that the slip surface is circular, and only satisfies force equilibrium. This method often gives factors of safety lower than those given by more involved procedures (Duncan and Wright, 2005), so a correction factor is often applied. When the correction is applied, the procedure is called Jambu Corrected.

SPENCER

Spencer’s procedure is a complete equilibrium procedure. It satisfies all equations of static equilibrium, and is based on the assumption that the interslice forces are parallel. It also assumes that the normal force acts at the center of the slice, which has negligible effect on the accuracy of the procedure (Duncan and Wright, 2005). The slip surfaces are assumed to be noncircular, and the solution using this method is a trial and error procedure to find the inclination of the interslice forces, and the factor of safety.

ARMY CORP OF ENGINEERS’

The U.S. Army Corps of Engineers’ modified Swedish Method assumes that the interslice forces act an inclination parallel to the average slope of the embankment. Variations on this procedure include taking the average inclination of the entire slope, or using the slopes of the individual slices separately. This method satisfies force equilibrium, but not complete equilibrium. It produces results that are consistently higher than procedures of complete equilibrium.

MORGENSTERN AND PRICE

The Morgenstern and Price procedure achieves a statically determinate solution by assuming that the shear force on the slices is related to the normal force by a function and a scaling factor. The assumptions about the location of the normal force vary, but all techniques solve for the same unknowns. When the function is assumed to be constant, the procedure yields almost identical results to those obtained with Spencer's procedure.

IMPACT OF VARIATION OF WATER TABLE ON SLOPE STABILITY

In general, an increase in the height of the water table will adversely affect the factor of safety. It is of interest to know how the different methods will incrementally change with variation of the water table.

IMPACT OF VARIATION SEISMIC EXCITATION ON SLOPE STABILITY

It is also of interest to know how seismic excitation will affect the results for the different methods of analysis. While some methods of slope stability analysis are not particularly recommended for seismic use, all of the methods of slices discussed will be examined using a pseudo-static approach. In this approach, the seismic force is assumed to be proportional to weight.

METHODOLOGY OF THIS STUDY

A profile of the 2005 Bluebird Canyon Landslide (Richter and Trigg, 2008) was obtained to use as an arbitrary, typical slope subject to failure. The profile is shown in figure 1.

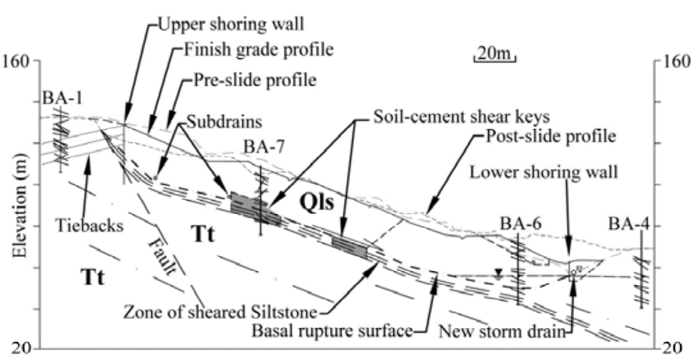


Figure 1 2005 Bluebird Canyon Landslide profile and sliding surface (Source: Richter and Trigg (2008), GeoCongress2008)

This cross section was imported into AutoCAD, and scaled appropriately using the scale on the image. The profile was then divided into 5 meter vertical sections and into smaller increments where anomalies in the profile occurred. The pre-sliding ground surface was then traced over the image in these increments. The sliding surface was traced in a similar manner. Figure 2 shows the AutoCAD model of the profile.

The construction of these lines, along with the vertical lines that divided the profile into sections, provided the coordinates of the ground and sliding surfaces. These coordinates were then input into a Microsoft Excel worksheet.

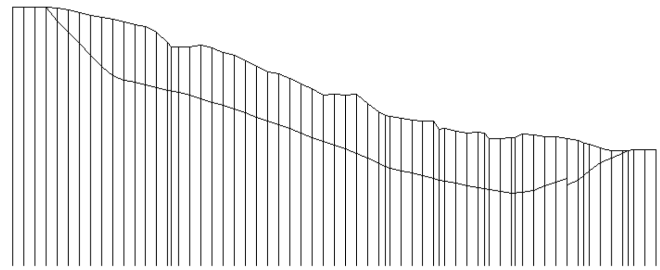


Figure 2 Vertical lines separate the slices; their lengths specify coordinates

Several versions of the same profile were constructed, varying the height of the water table. The water table was set at the top of the surface, and lowered in two meter increments for each set of data until the dry condition was reached. Tests were given a designation relating to the position of the water table. The test designation WT-0 means that the water table is zero meters from the ground surface. The tests were also distinguished by the parameter H_{wt}, which is this distance. This parameter will be referred to as the maximum dry height of slice. Figure 3 shows this nomenclature on a slope profile.

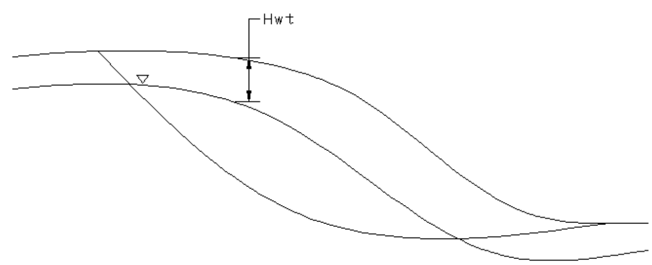


Figure 3 Nomenclature for max dry height of slice

The coordinates of each of these profiles were input into "Rocscience – Slide". A total of 14 different versions of the same profile were imported into this software. For each version, ten different seismic loadings were applied, and each of these versions was then saved in a separate file. The software provides pseudo static approach for seismic excitation, and the coefficient was varied from 0.1 to 2.0. Analysis was performed for each of these profiles, using several different methods. The factor of safety was obtained for each profile, and each method. A total of 140 conditions were used in analysis. The methods used were; Ordinary Method of Slices, Bishop Simplified, Jambu Simplified, Jambu Corrected, Spencer, Morgenstern and Price, and two Army Corp methods.

In addition the slices were analyzed using Bishop's Simplified Method using Microsoft Excel. The equations used were obtained from "Soil Strength and Slope Stability" by Duncan and Wright (2005), and included a seismic term using a pseudo static approach. For each water table, a separate spreadsheet was constructed.

After factors of safety were obtained for all conditions, tables were populated for each coefficient of seismic excitation. The factor of safety was then plotted against the height of the water table for each seismic coefficient, yielding a total of ten graphs with each of the eight methods superimposed on the graphs. Additionally, the incremental change in safety factor with the incremental change in water table was then plotted to analyze how each method varied with the change in water table.

When available, the factor of safety was plotted against the height of the water table using the seismic coefficients as contours, as to observe the effect of the water table and seismic excitation against the safety factor.

RESULTS

The results for the profiles analyzed without seismic loading are plotted in figure 4.

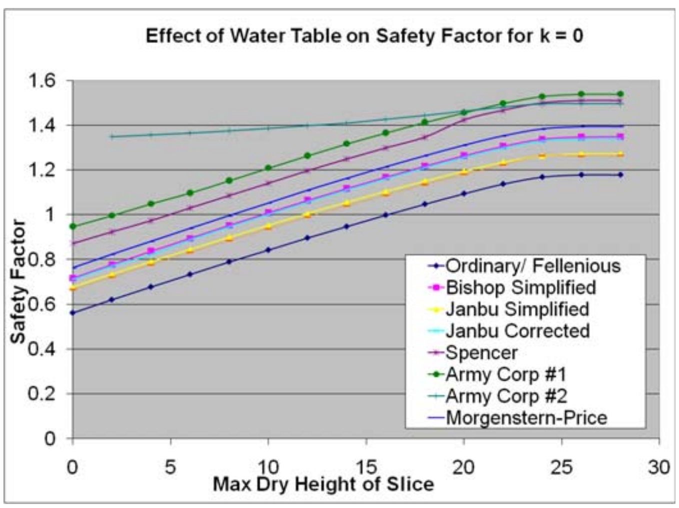


Figure 4 Nine methods of slope stability analysis plotted against water table

It can be seen from figure 4 that for no seismic loading, the Ordinary Method of Slices gave the most conservative factor of safety. From highest to lowest, all of the methods maintained their position with respect to each other when the water table increased, with the exception of the Army Corp Method #2. This method gave more conservative results than the Army Corp #1 method and Spencer's Method as the slope approached the dry condition.

As the height of the dry slice increased to the full height of the slice, the safety factor leveled off. This is due to the fact that as the water table decreased, some of the slices became completely dry; while some were still partially submerged, meaning the tests approached the dry condition in a non-uniform manner.

Bishop simplified procedure gave nearly the same results as the Jambu Corrected procedure. Additionally, the Bishop Seismic procedure from the spreadsheet analysis gave nearly the same results as Jambu Simplified. It is interesting to note that both Bishop's Simplified procedure and the Jambu Simplified procedure make the same assumption that interslice forces are horizontal. They differ in the assumption of the shape of the slip surface, and the equilibrium equations they satisfy. Figure 5 shows the variation of the slope of the curves in figure 4 with the maximum dry height of the slices.

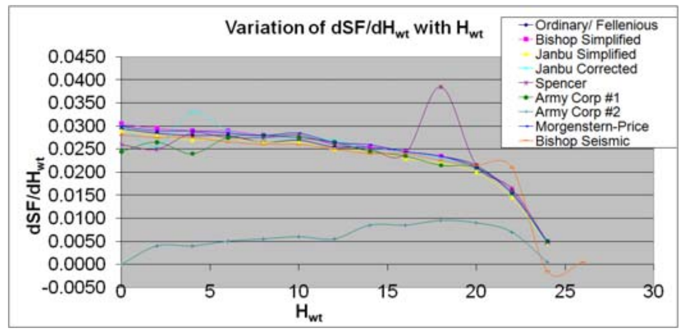


Figure 5 The variation of slope of the curves in figure 4

Bishop's Simplified Method and the Morgenstern-Price method had the highest incremental increase in safety factor with a decrease in water table, and were nearly exactly the same. Overall all of the methods gave roughly the same incremental increase in safety factor. The averages were taken over the first 8 decreases in the water table.

It can also be seen in figure 5 that the Army Corp #2 Method had the lowest incremental increase in safety factor. This means that the safety factor is only slightly affected by the water table when using the Army Corp #2 method.

An overall trend in all of the methods is the decrease in incremental increase of safety factor with the lowering of the water table. This means that the further the water table is lowered, the less effect it will have on the safety factor. This is especially true when the water table is near the sliding surface, since only some of the slices are still submerged in this condition.

Figure 6 shows the results for the first seismic loading, with a coefficient of 0.1.

This test set of data yielded similar results with respect the order of highest to lowest safety factors. A notable difference is the fact that the safety factor for the Army Corp #2 Method decreased with the lowering of the water table, while all the other methods increased.

For this test, Army Corp #1 and Spencer's procedure slowly converged with the lowering of the water table, and intersected at a dry height of approximately twenty meters. Another trend seen in this test as well as the previous test is Bishop's Simplified method and the Jambu Corrected method yielded nearly identical results.

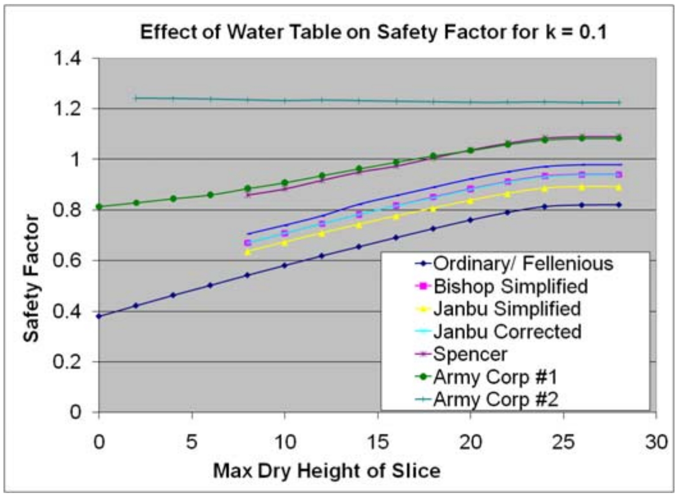


Figure 6 Variation of safety factor with max dry slice height

The spreadsheet values for the safety factor were not used in this test. It was found that for any seismic coefficient, there were multiple solutions to the equation for the factor of safety. It is for this reason the data will not be included for any of the seismic loadings.

Figure 7 shows the variation of incremental increase in safety factor with decrease in water table.

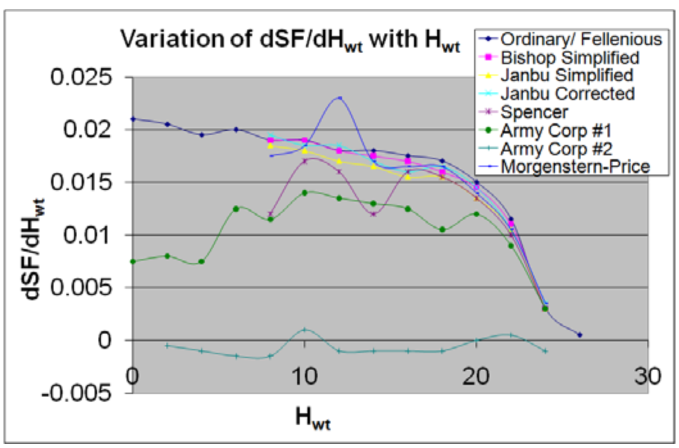


Figure 7 The variation of slopes of figure 6

Again Bishop's Simplified Method and the Morgenstern-Price method had the highest incremental increase with decrease in water table. Almost all methods decrease in incremental increase of safety factor with the lowering of the water table, as in the case with no seismic excitation. When compared to figure 5, it can be noted that the effect of lowering the water table on safety factor is less in the presence of seismic excitation.

Figure 8 shows the results for a seismic coefficient of 0.2.

It should be noted at this point, the some of the methods used did not yield results for all of the conditions. For this seismic loading, all of the tests gave results for a low water table, while only a few of the test gave results for a full or nearly full water table. Again, Bishop Simplified and Jambu Corrected gave nearly identical results.

The order of the least to most conservative safety factor remained, with the exception of the Spencer method yielding a higher result than the Army Corp #2 method. It should also be noted that while most of the methods have a similar upward trend, the two Army Corp methods are the only two methods with aberrant slopes.

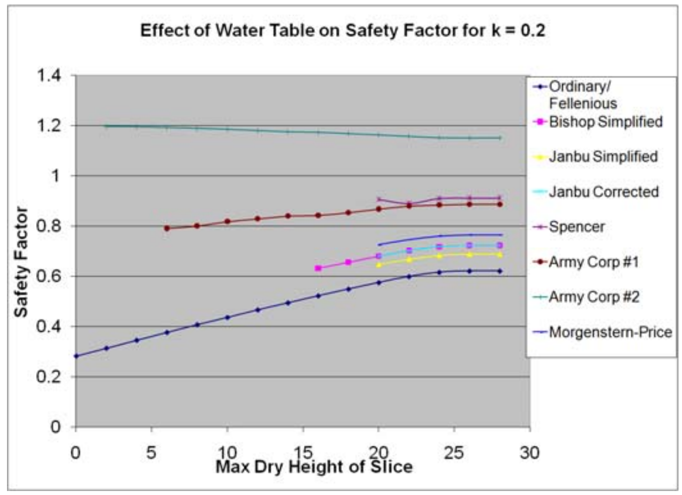


Figure 8 Results for a seismic coefficient of 0.2.

The variation of incremental increase in safety factor with decrease in water table is presented in figure 9.

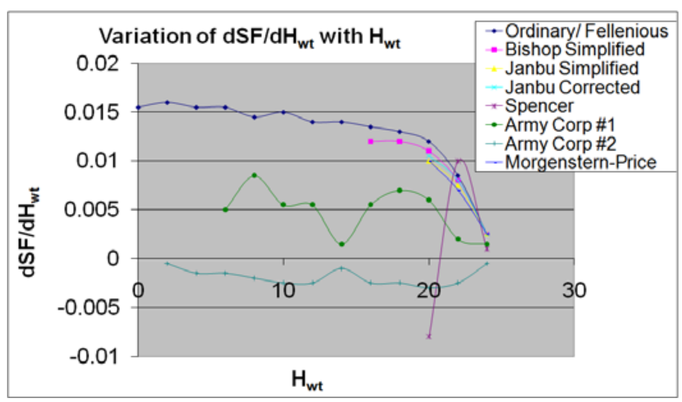


Figure 9 Incremental variation of safety factor with water table.

From this figure, some of the same conclusions can be drawn as before, confirming the trends previously discussed. Again, the effect of lowering the water table has on safety factor decreases with an increase in seismic load. This effect also decreases as the height of the water table decreases. It follows that lowering the water table will have a beneficial effect on safety factor, but that beneficial effect decreases with an increase in seismic load. The beneficial effect of lowering the water table will also decrease the more the water table is lowered.

Figure 10 shows the results for a seismic coefficient of 0.3.

At this point, the slopes of the curves will not be discussed in depth as in the previous tests, as the results for higher seismic coefficients yielded curves for only a few methods. The difference in the slope of these curves can clearly be seen from figure 8. Again, lowering the water table had a negative effect on the factor of safety for the Army Corp #2 method, while the Ordinary Method benefited. The army Corp #1 method gave only a few results; the safety factor slowly increased as the water table decreased. It should be noted by now that the Army Corp #2 Method gives consistently conservative results with respect to the other methods.

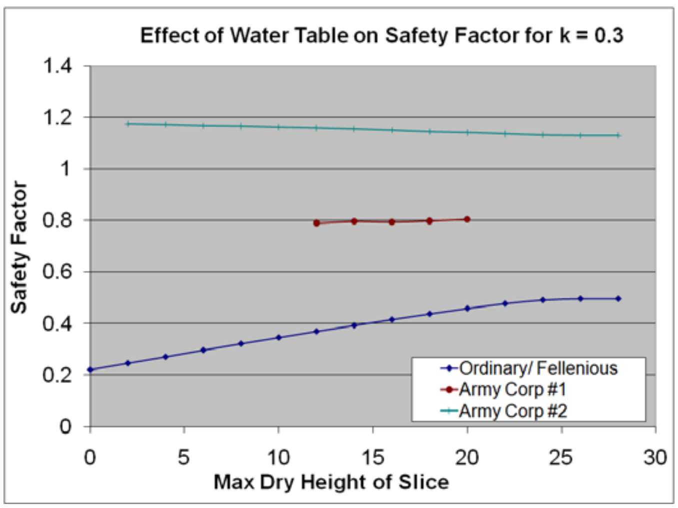


Figure 10 Variation of safety factor with water table.

As in the previous tests, with each increase in the seismic coefficient, the effect of lowering the water table has on the safety factor decreases for each method. The effect of the seismic coefficient on safety factor will be discussed in depth later.

The results for the seismic loading coefficient of 0.4 are plotted in figure 11.

The ordinary Method ranged over smaller values of the safety factor, continuing the trend for these tests. As in the previous conditions, decreasing the height of the water table increased the safety factor for the Ordinary Method, and decreased the safety factor for the Army Corp #2 Method. The results for the Army Corp #1 method lied between to two values as in the previous tests.

Figure 12 shows the results for the seismic coefficient of 0.5. At this point, the only two methods which gave results were the Ordinary Method, and the Army Corp #2 method.
As can be seen from the figure, the range of safety factors was even less than the previous test. Again, for any decrease in water table, the Ordinary Method gave higher safety factors, while the Army Corp #2 Method gave lower results.

Figure13 shows the results for a seismic loading of 0.6.

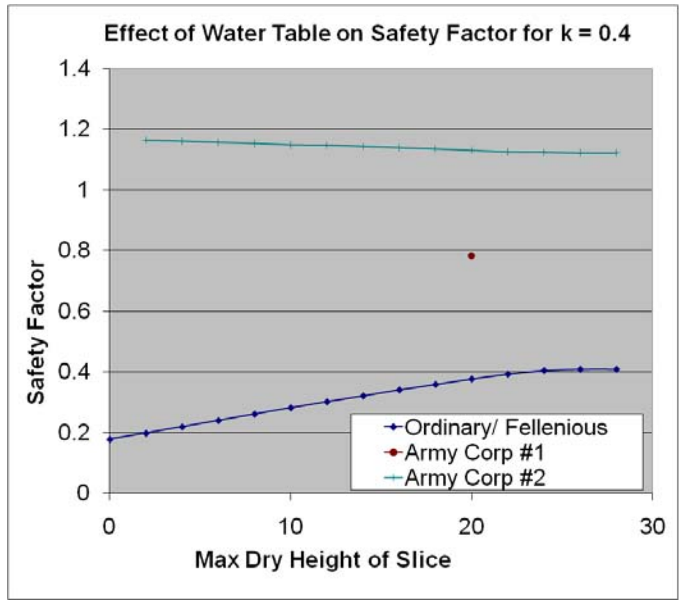


Figure 11 Variation of safety factor with water table for k =0.4.

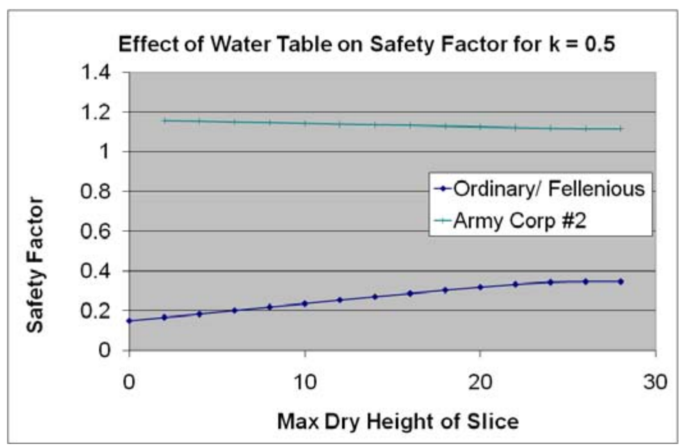


Figure 12 Variation of safety factor with water table for k =0.5.

It can be seen from figure 13 that the range of values continued to decrease with an increase in seismic loading.

The same trends relating to the decrease in water table can be observed as in the previous tests.

Figure 14 shows the results for a seismic coefficient of 0.7, 0.8, and 0.9.

It should be noted at this point that while the ordinary method continued to give visibly lower values for safety factor with an increase in seismic loading, the Army Corp # 2 method gave roughly the same values. The same trends are seen for a decrease in water table as the previous tests.

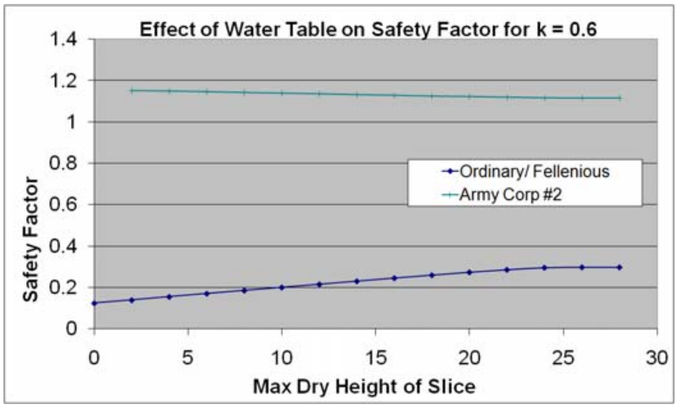


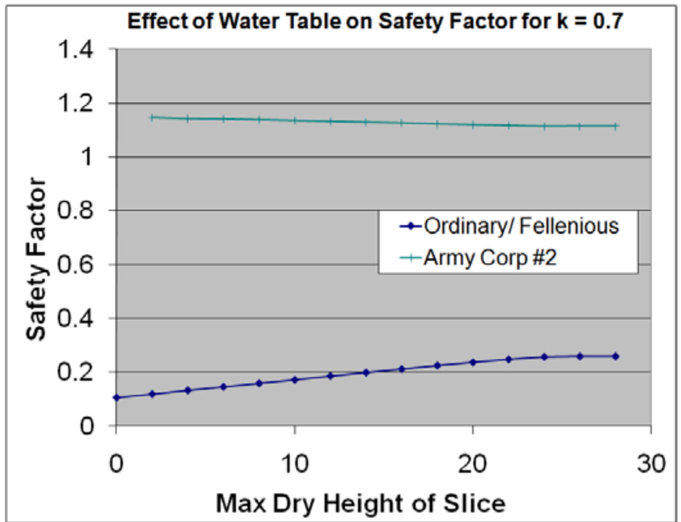
Figure 13 Results for a seismic coefficient of 0.6.

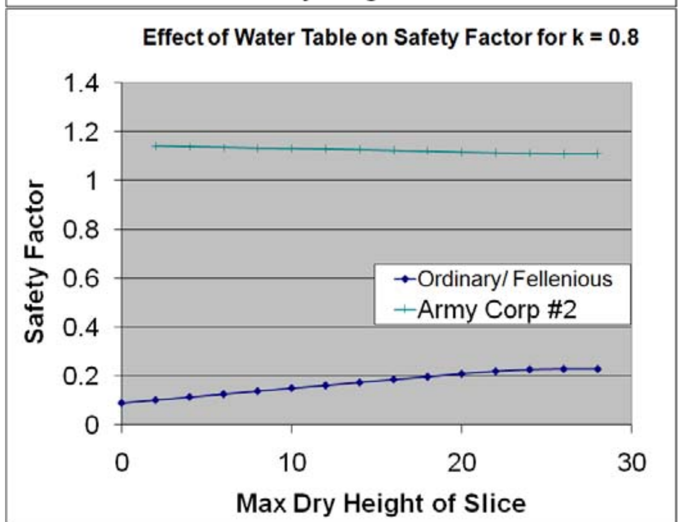
The remaining results will be presented in a manner which best illustrates the effect of seismic loading on safety factor, and how it varies with water table. A plot of the Army Corp #2 method is shown in figure 15. The height of the water table is plotted against the safety factor for various values of k.

The results show that decreasing the height of the water table had a positive effect on the safety factor for the condition with no loading; it negatively affected the safety factor for the conditions with seismic loading. It can also be seen that increasing the seismic coefficient had a diminishing effect on the factor of safety as the coefficient increased, asymptotically approaching a value of approximately 1.1. It will be shown in the following discussions that the trends for this method do not apply to the other methods.

Figure 16 shows the variation of water table with the factor of safety given by the Ordinary Method of Slices, with the seismic coefficients plotted as contours.

It can be seen in this graph that the effect of decreasing the water table has on increasing the safety factor diminishes as the water table decreases. This effect also decreases with an increase in the seismic coefficient. Thus it can be concluded that when the seismic coefficient is increased, the effect of lowering the water table on the safety factor decreases. One can also conclude from figure 15 that for a full water table, the effect of using different seismic coefficients is relatively small, while the dry condition yields relatively large differences.





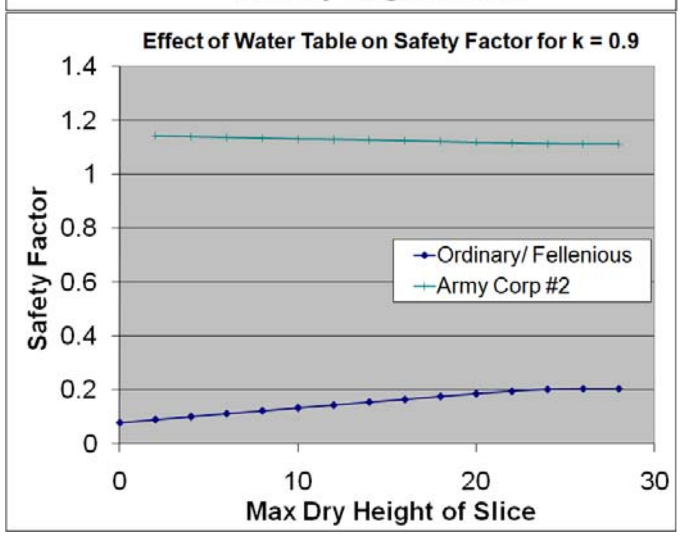


Figure 14 Results for a seismic coefficient of 0.7, 0.9, and 0.9.

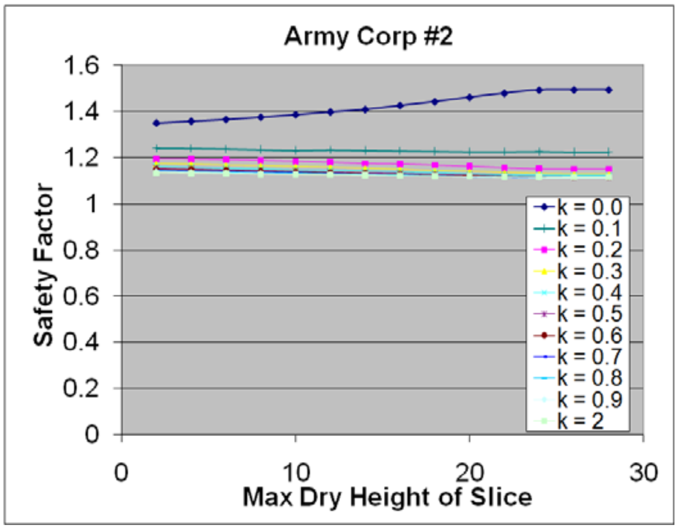


Figure 15 Safety Factor vs. Max Dry height of slice for the Army Corp #2 method.

Furthermore, it can be seen that the effect of seismic coefficient on the safety factor decreases as the seismic coefficient increases. Examining the dry condition when k varies from 0 to 1, the safety factor varies by roughly unity. When k varies from 1 to 2 for this condition, the safety factor varies by approximately one tenth. Thus the difference between using 0.1 and 0.2 may be relatively large while the difference between using 0.8 and 0.9 may be relatively small. It should be noted that this difference is especially large for the dry condition.

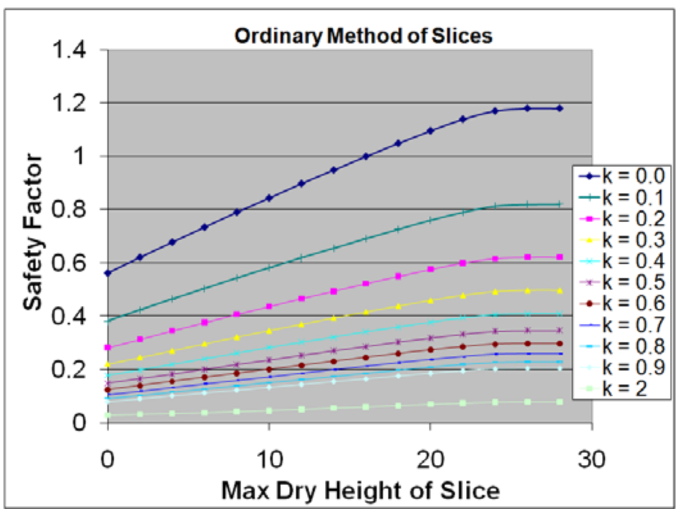


Figure 16 Safety Factor vs. Max Dry height of slice for the Ordinary Method. Values of k are plotted as contours.

It can be shown that the trends discussed above apply to all of the methods of analysis, with the exception of the two Army Corp methods as shown in figure 17.

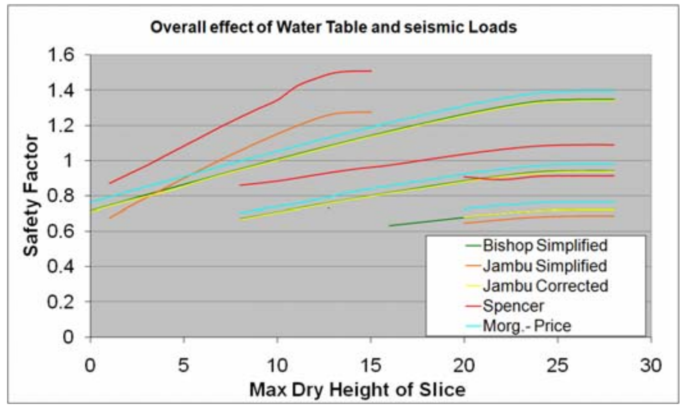


Figure 17 A plot of several methods for each seismic coefficient

When each set of contours is considered separately, the trends seen in the Ordinary Method of Slices also apply to all of the other methods, with the exception of the two Army Corp methods.

RECAPITUALTION

GENERAL TRENDS

The general trends of the results can be summarized in the following manner:

1. The Army Corp #2 method almost always gave the least conservative results.
2. The Ordinary Method almost always gave the most conservative results.
3. Bishop's Simplified Method gave nearly identical results to Jambu Corrected.
4. As the seismic coefficient increased, only a few of the methods gave results at all. The only methods that yielded results for coefficients higher than 0.5 were Army Corp #2 and the Ordinary Method.

WATER TABLE

Trends relating to the water table can be summarized as follows:

1. In general, a lowering of the water table increased the safety factor. This was true for all cases except the Army Corp #2 method, which gave lower safety factors for lowering the water table in the case of seismic excitation.
2. The effect of lowering the water table has on safety factor diminishes as the water table gets lower.
3. This effect also diminishes when the seismic coefficient is increased.
4. The incremental increase in safety factor with the incremental decrease in water table was roughly the same for all methods except the Army Corp #2 method.

SEISMIC EXCITATION

The trends relating to seismic excitation can be summarized as follows:

1. Not all methods yielded results for higher coefficients of excitation (i.e. greater than 0.5).
2. In general, as the seismic coefficient increased, the beneficial effect of lowering the water table decreased.
3. As the seismic coefficient increased, the effect that it had on the safety factor decreased. Thus, the factor of safety is relatively sensitive to changes when k is small.
4. For a full water table, the effect of using different seismic coefficients is relatively small, while the dry condition yields relatively large differences.

DISCUSSION

While the pseudo static approach may be utilized with many methods, it may not be completely representative of the actual conditions present in the slope. If the water table is relatively high, pore water pressure can develop due to dynamic loading and yield unconservative results for the stability of the slope (State Minding and Geology Board, 1997).

The pseudo static method also ignores the dynamic strength of the soil. The use of the static strength is often implemented, and is generally conservative in partially saturated conditions (State Minding and Geology Board, 1997). In the presence of liquefaction hazards, post-liquefaction residual strengths should be used as the strength of the soil (ASCE 2002).

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