DISCUSSION

A method for locating critical slip surfaces in slope stability analysis: Discussion[1]

Ashok K. Chugh

I have read this paper with interest since its subject matter pertains to our work in embankment dam engineering. As indicated in the paper, there are several procedures devised to locate a shear surface with the lowest factor of safety, and the author has presented one more and compared the results of his procedure with those of others; all based on the limit equilibrium method of slope stability analysis. The new results are about the same as the results previously reported by others.

In an attempt to see how the results from a continuum-mechanics-based procedure will compare with those included in the paper, I made a quick analysis of the six problems using a commercially available computer program, FLAC (Itasca 1995). Also, I made an analysis of the problems using the limit-equilibrium-based slope stability analysis procedure SSTAB2 (Chugh 1992). Results of these analyses form the basis of this discussion.

For Example 3, the values of effective internal friction angle, ϕ', given in Table 1 of the paper are different from the values in the 1996 Greco paper; in fact they are a repeat of the numbers in the unit weight, γ, column. The values given in the 1996 Greco paper were used for results included in this discussion. For the Case 2 problem, Fig. 15 of the paper was scaled to obtain the data necessary for the analysis.

In limit-equilibrium-based numerical procedures, the effectiveness of an automated search procedure depends on the successful performance of a nonlinear equation solver used to adjust trial values of factor of safety, F, and interslice force inclination, θ, to achieve a match between the computed and known values of boundary parameters at the other end of a shear surface. However, there is no assurance that the solution details associated with the critical shear surface thus found will necessarily be reasonable. These solution details are in terms of normal and shear forces at the base of slices, and interslice forces; their inclination and locations. Thus a search procedure which does not involve a criterion for an acceptable solution leaves the task of final selection of critical shear surface up to the user.

There is no uniqueness in criteria for an acceptable solution to a slope problem by limit equilibrium procedures. For the location of interslice forces, some engineers prefer the middle third of the interslice boundary on the basis of linear distribution of normal stress, while others accept a solution in which interslice forces remain within the slide mass on the basis of nonlinear distribution of normal stress. Similarly, when a soil has cohesive strength, some engineers are willing to accept a solution with tensile stresses that are consistent with the magnitude of the cohesion value, while others consider the tensile strength of the soil to be zero and introduce a crack at the upper end of a shear surface. Inclination of interslice forces affects interslice shear forces. Some computer programs check for interslice shear failures, while others do not. Relying on a computed factor of safety without checking on the acceptability of the associated solution details is a mistake and should be discouraged. It would be helpful to know the criteria the author used in his work.

Also, in limit equilibrium slope stability analysis, a search for critical shear surface should be preceded by analysis of shear surfaces of the engineers' choosing. Such practices sharpen engineers' skills to judge the path along which a sliding failure is likely, if one were to occur. Some of the shear surfaces included in the paper, especially those with long-drawn reverse curvatures at their exits, must be numerical constructs, as those geometries are unlikely to occur even in an ideal environment where the numerical model conditions could be duplicated, much less in nature. Thus, all of the slip surfaces attempted in the problems included in the paper must not have acceptable solution details. This should affect the final selection of an acceptable critical shear surface. It would be helpful to know what nonlinear procedure the author used; the slope stability computer program in which he implemented his search procedure; his experiences with their use; and if he checked the computed solutions by examining the details for each shear surface obtained and what he found. Use of eq. [9] does not necessarily preclude occurrence of an unacceptable solution to a slope stability problem in general.

Figures D1–D6 show the results of the problems using the continuum mechanics program FLAC. There are three parts to each figure: (*a*) shows the problem as modeled, (*b*) the convergence of trial factors of safety, and (*c*) the material

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A.K. Chugh. U.S. Bureau of Reclamation, P.O. Box 25007, Denver, CO 80225, U.S.A. (e-mail: ACHUGH@do.usbr.gov)

[1]Paper by Da-Yong Zhu. Canadian Geotechnical Journal, **38**: 328–337.

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Fig. D1. Example 1.

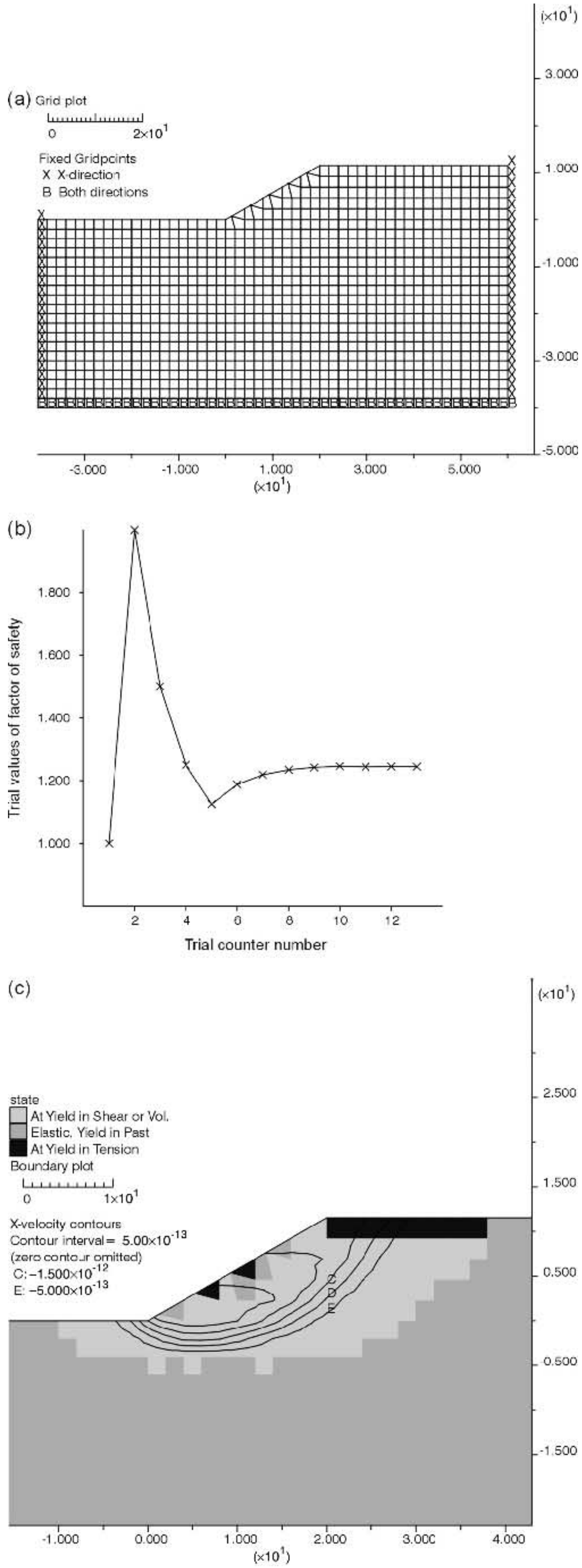


Fig. D2. Example 2.

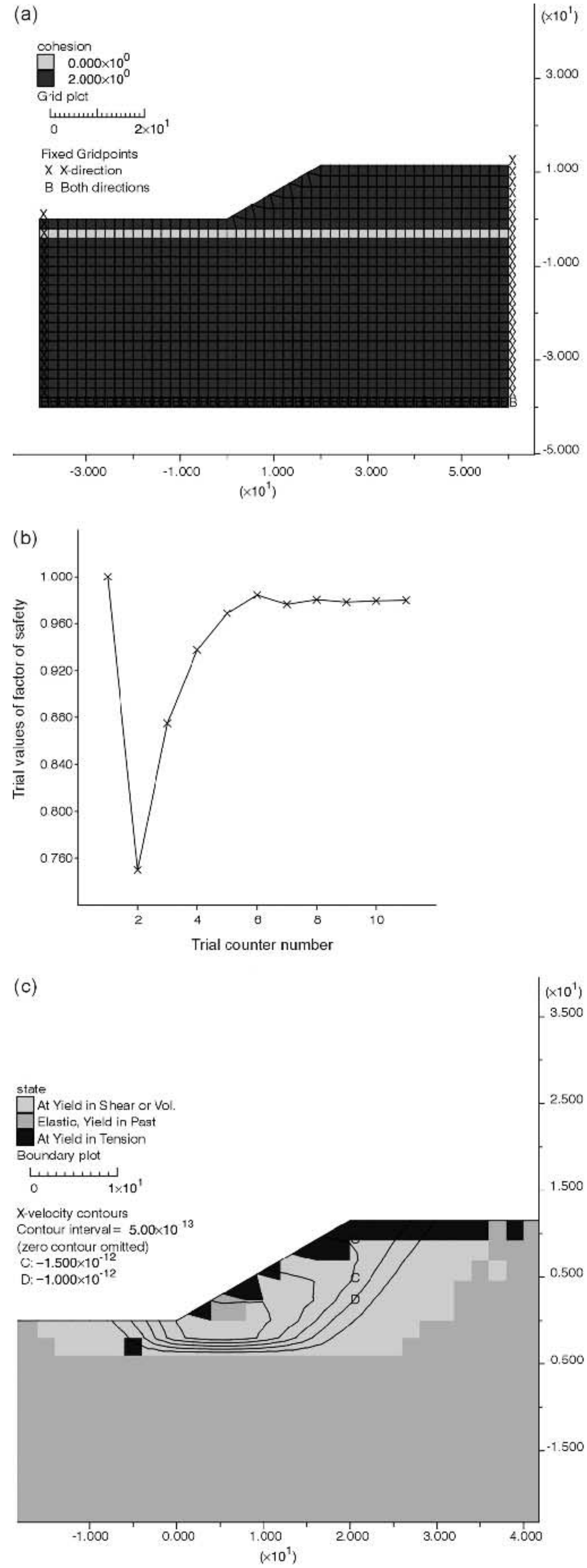
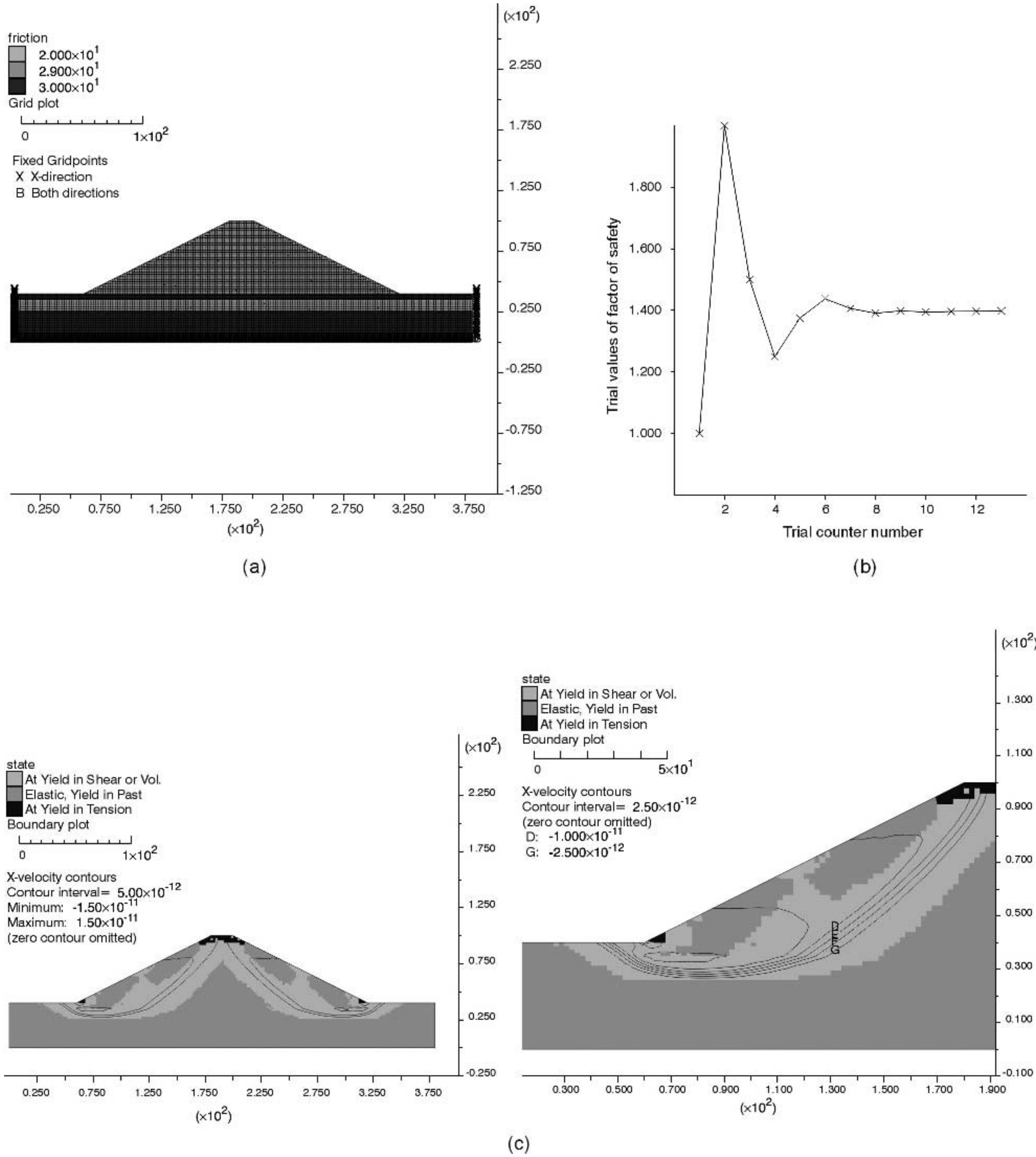


Fig. D3. Example 3.



state at the onset of slope instability, and the contours of velocity in the horizontal direction at the onset of slope instability. In these calculations, in addition to the material properties given in the paper, the elastic constants of bulk and shear modulus were assigned values of 2×10^{10} and 1×10^{10}, respectively; the tensile strength was specified to be zero; and the dilation angle was set equal to the friction angle. The units for the values assigned to elastic constants were the same as those of the cohesion values used. In the results of FLAC calculations, the potential slip surface is along the path of velocity discontinuity, which in Figs. D1–D6 can be taken as the velocity contour of lowest value. Table D1 summarizes the converged values of factor of safety for the sample problems. In general, the location of the slip surfaces shown in Figs. D1–D5 are in general agreement with the ones shown in the paper. For the first five problems, the corresponding factor of safety values are close to those obtained using the limit-equilibrium-based procedures and given in the paper, but they are not necessarily the same. The differences in results are likely due to differences in the methods of analyses, and (or) unacceptable solution details for the critical shear surfaces reported in the paper.

Fig. D4. Example 4.

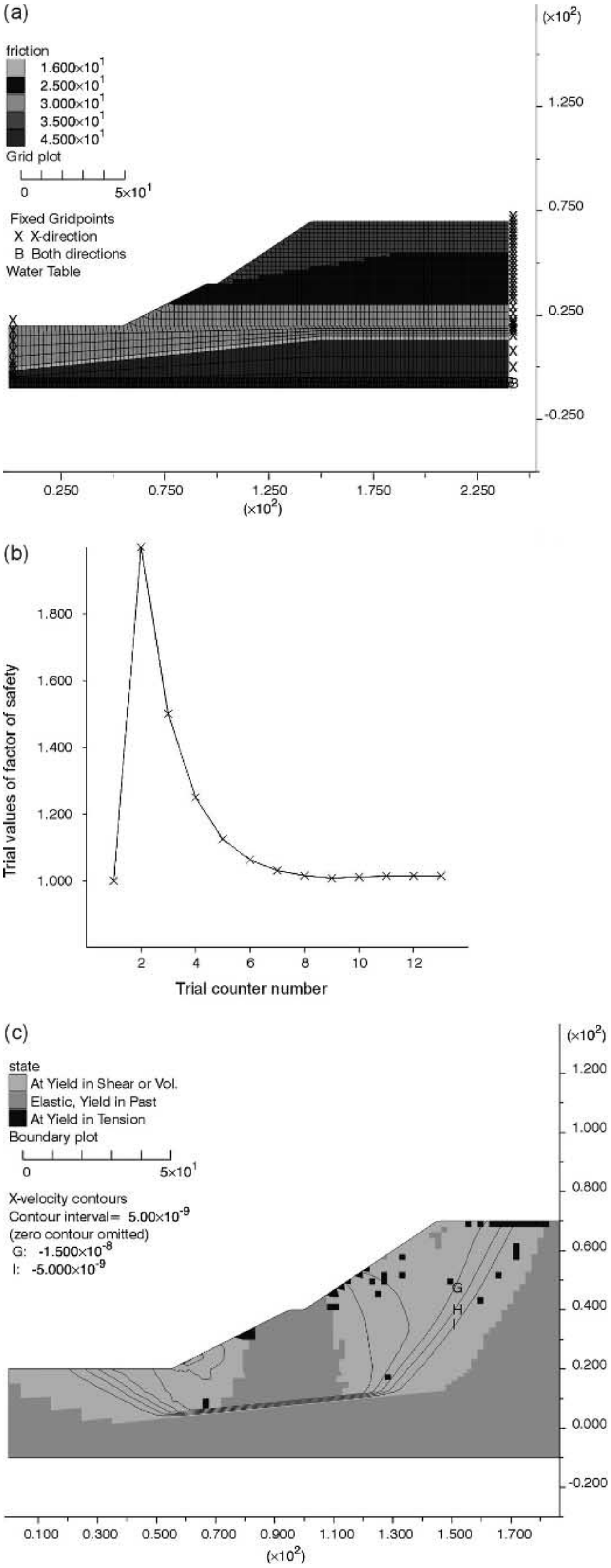
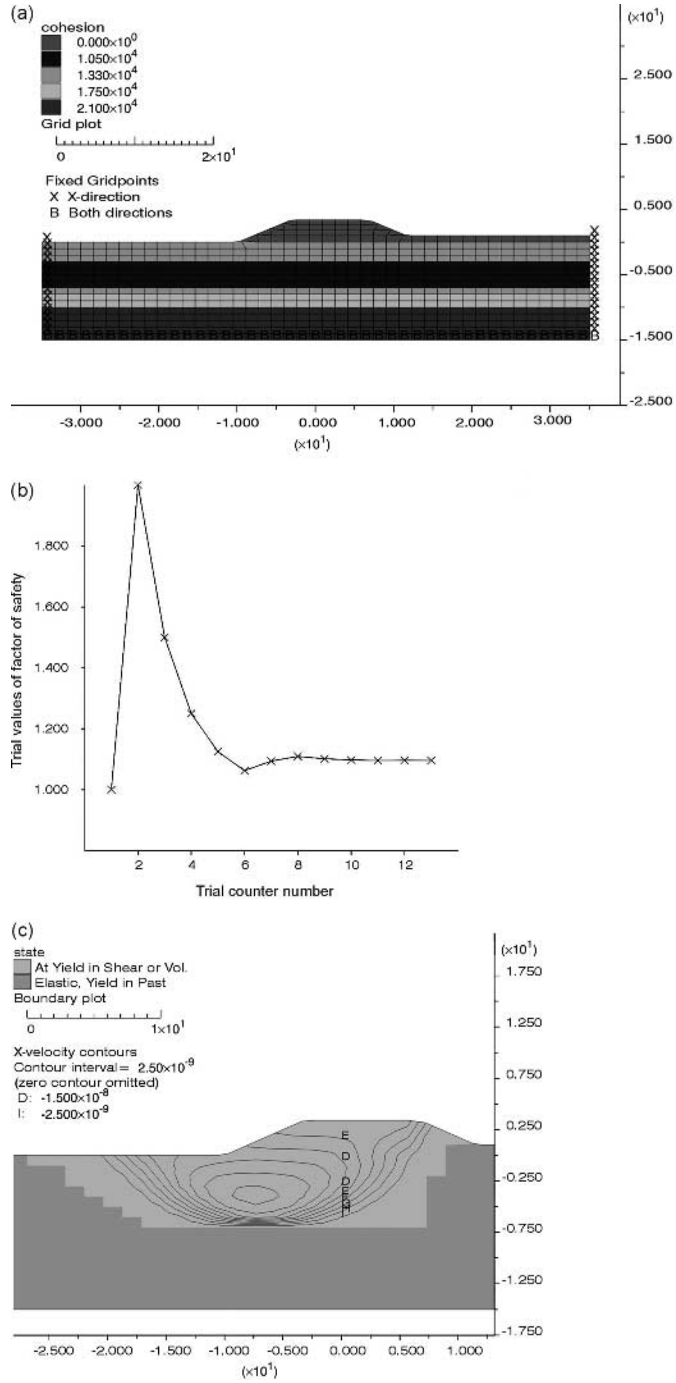
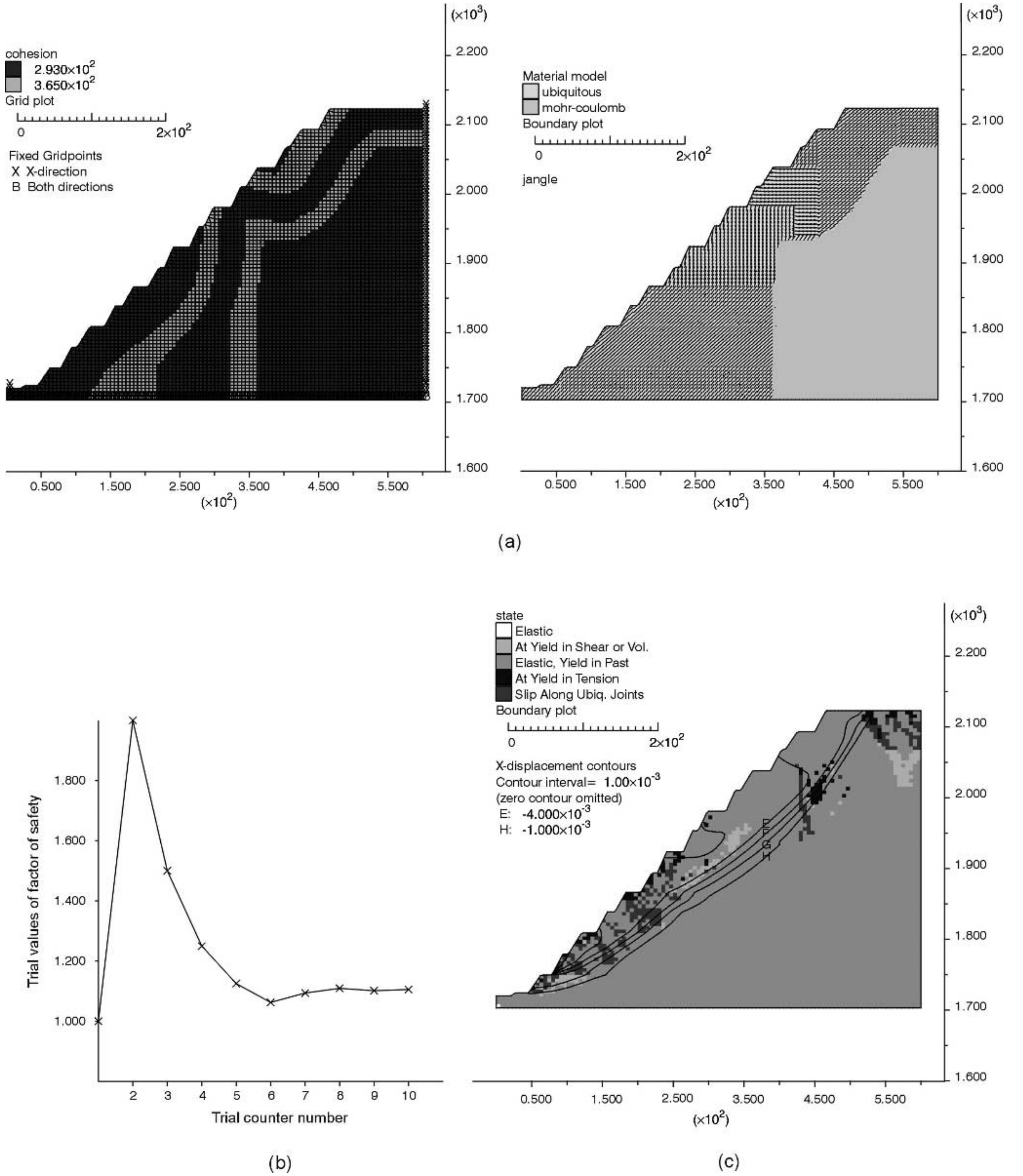


Fig. D5. Case 1.



For the sixth problem, however, the differences in the factor of safety by the two methods are significant. It is quite possible that the problem modeled in FLAC is not the same problem as the author had modeled. Also, due to lack of information, no ground water or pseudostatic earthquake was included in the FLAC model. The problem details modeled in FLAC and the results obtained are shown in Fig. D6. These results are interpreted to say the following: (*i*) if the rock instability were to occur, it is likely to be in the lower exposed layer 1; and (*ii*) only if the lower exposed layer 1 was held in place, a slip surface similar to the one given in

Fig. D6. Case 2.



the paper can occur. It would be helpful if the author could point out the differences in the two problem definitions since he has an intimate knowledge of the field conditions and his numerical modeling of them. In general, for complex situations such as this Case 2 problem, realistic use of continuum-mechanics-based solution procedures should be most effective and advantageous.

In the computer program SSTAB2, the problem solving strategy is through the use of recursive relations for the force and moment equilibrium for each slice; the nonlinear equa-

Table D1. Comparison of results.

	Author's results		FLAC results	SSTAB2 results	
Problem	Fs	θ	Fs	Fs	θ°
Example 1	1.022	0	1.245	1.053	19.65
Example 2	0.794	0	0.980	0.761	8.91
Example 3	1.395	f(*x*) = 1; λ = ?	1.398	1.430	18.06
Example 4	1.016	f(*x*) = 1; λ = ?	1.015	1.026	12.74
Case 1	0.947	f(*x*) = half sine; λ = ?	1.096	0.960	3.15
Case 2	1.304	f(*x*) = 1; λ = ?	1.101	Procedure not applicable	

Note: Question mark (?) indicates information not given in the original paper.

tion solver used to simultaneously adjust trial values of factor of safety and interslice force inclination is RQNWT, which is a proprietary software of Boeing Aircraft Company. The automated search scheme is for circular shear surfaces only and implements Spencer's assumption of constant interslice force inclination. The SSTAB2 program is not designed for rock slopes with the attributes of Problem 6; therefore, it was not analyzed. Table D1 shows the results for the first five problems using SSTAB2. It should be noted that all of the solutions obtained by the SSTAB2 search and included in Table D1 did not necessarily meet our requirements of being an acceptable solution. They are included here only for comparison purposes. No attempt was made to investigate their effects on the computed factor of safety. Details of these results can be obtained from the writer by request. They are not included here to conserve space.

In our work, we generally report factors of safety to two significant figures. Only for comparison purposes, extra significant figures are included in this write-up.

References

Itasca. 1995. FLAC – Fast Lagrangian Analysis of Continua. Itasca Consulting Group, Minneapolis, Minn.

Chugh, A.K. 1992. SSTAB2 – Slope Stability Analysis Program, U.S. Bureau of Reclamation, Denver, Colo.