Appendix A3

Guidelines for slope stability analysis in risk modelling

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A3.1 Introduction

The purpose of slope stability analysis is to provide a quantitative measure of the stability of a slope or part of a slope. Traditionally, it is expressed as the factor of safety against failure of that slope, where the factor of safety is defined as the ratio of the restoring forces to the disturbing forces, such that a factor of safety greater than unity denotes stability but a factor of safety less than one denotes failure. It may be more valuable to have a measure of the probability of failure and the traditional analysis does not provide this. With modern computer power it is possible, however, to carry out a probabilistic analysis that would give a figure for the likelihood of failure.

A3.2 Soil slopes

A3.2.1 Geometry of the slope

The infinite slope analysis may often be adequate for preliminary calculations of susceptibility to secondary landslides in the downstream valley where slopes are often large and relatively uniform and edge effects are unimportant. When analysing possible breach mechanisms at a lake, however, it is important that the geometry of the slope is modelled with some accuracy. For an initial appraisal, this may be done by simple mapping techniques using hand held equipment such as a compass clinometer, Abney level, altimeter or Global Positioning System (GPS) but in cases where there is perceived to be a real threat or where remedial measures are under consideration then a topographic survey is justified. It may be that the location of a potential breach is not known or is ambiguous and thus several sections are likely to be modelled for a single moraine dam.

A3.2.2 Geological conditions

Modelling of the geological conditions will often need to be based upon surface expression of the underlying geology and significant interpolation will need to be relied upon. Often a simplified model will be the result. It may be that there will be information on conditions at depth from geophysics or more rarely from drilling. In particular geophysics may provide information on the presence or absence of buried ice in a moraine dam. This allows a variety of scenarios to be modelled. The contemporary situation can be simulated simply by modelling the ice as a stratum, perhaps with high cohesion but low friction. It may be more valuable to model the situation that would exist when the ice had wholly or partially melted, by subtracting all or part of the ice thickness from the topography. Clearly, this may lead to some degree of topographic inversion and the critical cross-section under such circumstances may be different from any of those suspected under contemporary conditions.

A3.2.3 Soil parameters

Assigning shear strength and other parameters to soil strata is likely to be problematical as it is impractical to collect and transport samples that are large enough to be representative. In addition, commercially available test apparatus is too small to obtain representative results from boulder-rich moraine sediments. Valuable work has, however, been done by taking and testing small samples in small apparatus and, presumably, obtaining lower bound parameters. These results have shown a remarkable correspondence with parameters obtained from back analysis. Back analysis is probably the most practical method of obtaining credible strength parameters for coarse soils. This involves careful mapping of slopes in similar materials that are deemed to be close to failure followed by analysis to discover what parameters could give rise to a factor of safety close to unity in such a situation. This requires a great deal of caution since other factors come into play in the overall stability, for example groundwater conditions, which may be quite different in the back analysed slope from the slope that one is attempting to model. In dry conditions, for example, negative pore water pressures may allow a slope temporarily to stand at a much steeper gradient than the shear strength of the soil would suggest. Other factors that may need to be considered include the history of landsliding in the area; for example if the slope is subject to the re-activation of an old landslide then it may be necessary to use reduced or residual parameters.

A3.2.4 Groundwater conditions

Groundwater conditions form an important part of the model. Once again it is likely that much of the information will come from the mapping of surface expressions such as streams or springs. At least in the case of moraine dams the level of the lake provides good information on the location of the piezometric surface at one end of the section, unless of course the lake may be perched. As discussed above, valuable information may be obtained from geophysics, or more rarely from boreholes. It is unlikely to be considered practical to install and monitor piezometers except in the most accessible of situations.

A3.2.5 The calculations

It is simply not practical to consider carrying out the calculations by hand. Modern computers can carry out many thousands of sophisticated calculations in much less time than it would take even the most skilled practitioner to perform one rudimentary calculation. In many ways the key is to carry out a wide variety of calculations, varying soil parameters, groundwater conditions, topographical cross-sections, analysis method and the location and nature of the failure surface, to ensure that the critical situation is modelled. This is only practical using up-to-date computers and software. Most modern software produces accurate results provided that it is used correctly (Figure A3.1). Differences seem to be in ease or speed of use, quality of presentation and degrees of sophistication in terms of the analysis methods and ways of defining the failure surface. It is important to have the possibility of defining the failure as either circular, as one would expect in unstratified, essentially granular material; or non-circular as may be expected where there is definite structure or a weaker layer within the slope. The differences between the results produced by the various analysis methods within each of the circular or non-circular categories are generally small compared to the assumptions already made in the analysis.

A3.2.6 Factors of safety

As discussed above, a factor of safety equal to one indicates that the slope is at the limit of stability. Strictly, a factor of safety below unity should not occur, since the slope should have already failed. In practice it may indicate that some factor not taken into account may be allowing the slope to remain temporarily or permanently stable. Such factors may include cementation or soil suction (the latter at least is likely to lead only to temporary stability until the slope becomes wet) or it may be that one or more of the assumptions is over-pessimistic. A factor of safety above unity indicates that the slope is stable, even if only marginally so. Given the scale of the uncertainties outlined above it is clear that it would be unwise to rely upon a factor of safety that only marginally exceeds one. The question remains then as to what factor of safety is acceptable.

Different factors of safety are generally deemed acceptable in different situations. Where the analysis is simple and the parameters and conditions well known or perhaps the slope is known to have remained stable for many years, then a factor of safety just above one may be acceptable. Where there are many unknowns and the consequences of failure are great then a much higher figure will be required. For example, when a reasonable amount of testing has been carried out and the consequences of failure are likely to be damage to property then a figure such as 1.3 is often deemed an acceptable factor of safety. Where failure is likely to lead to loss of human life then 1.5 is likely to be preferred. In a situation where the soil parameters and groundwater conditions, for example, are poorly known and where failure may result in widespread loss of life, then it may be necessary to consider 1.7 to be the lowest acceptable factor of safety. It could be that a lower factor of safety is considered acceptable some of the downstream areas, perhaps away from habitation, than at the lake itself.

A3.2.7 Probabilistic analysis

In a situation such as this, where some or all of the conditions have a degree of uncertainty, it can be very helpful to carry out a probabilistic analysis. In such a case a range of scenarios can be put into the analysis. For example, the shear strength parameters of the soil can be specified so that they may fall between certain limits and that the piezometric surface may, in the same way, vary within a given range. The computer then carries out a large number of calculations by Monte Carlo trial or other statistical method. The result of the analysis then provides not only the most probable factor of safety but also the probability of the factor of safety falling below any given figure, for example, one.

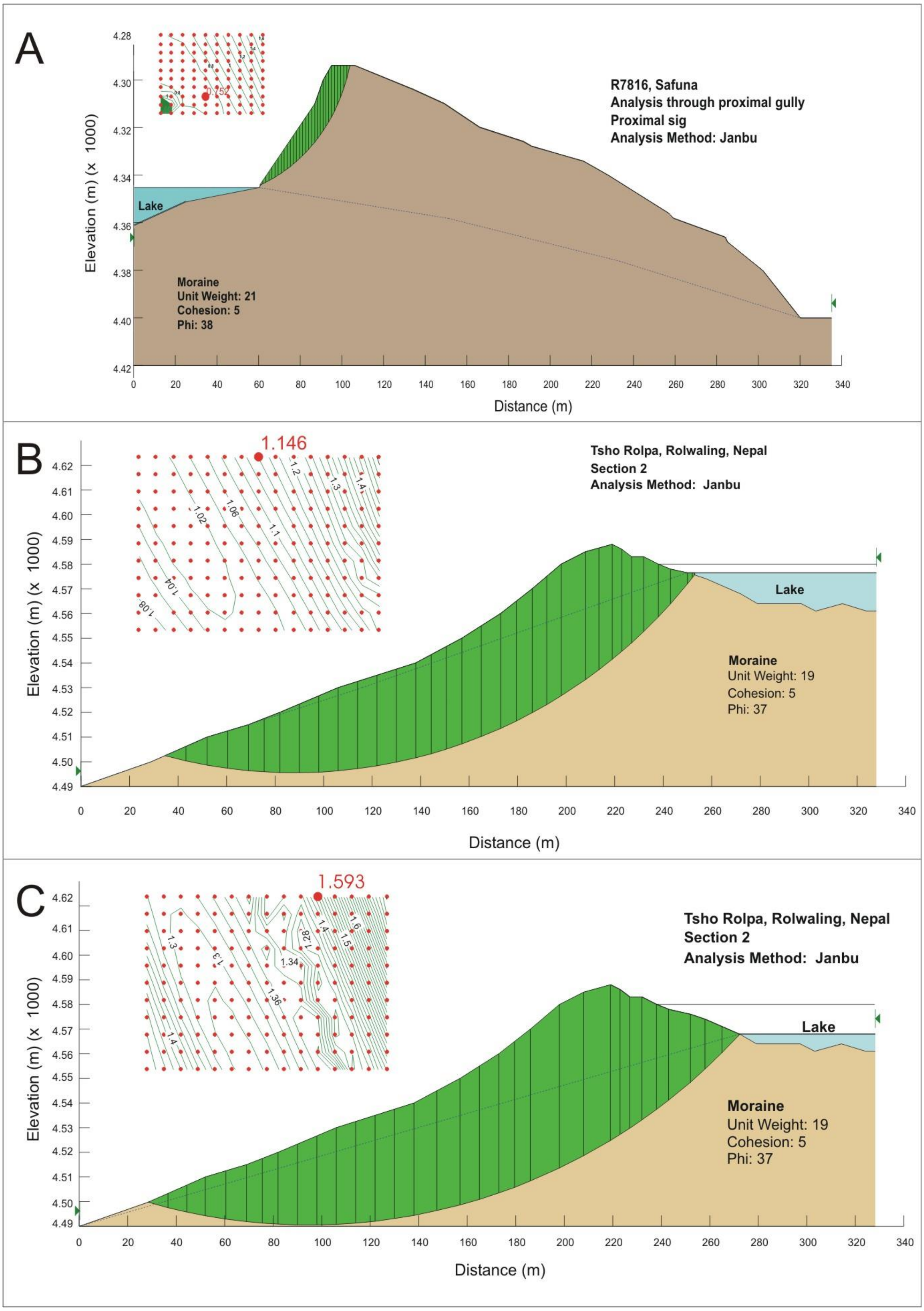

Fig. A3.1: Example outputs from Slope/W slope stability modelling software: (A) application to moraine stability assessment, Laguna Safuna, Peru; (B) and (C) to determine level of lake drawdown required to achieve satisfactory factor of safety, Tsho Rolpa, Nepal.

A3.3 Rock slopes

A3.3.1 General

Failures in rock slopes, unless they are completely weathered, are much more likely to be controlled by discontinuities and much less dependent on the intact strength of the geological material. For this reason the nature and orientation of discontinuities and their relationship to the orientation of the face are of primary importance. In the case of completely weathered materials it may be appropriate to incorporate some of the techniques discussed above in relation to soils.

A3.3.2 Geometry of the slope and discontinuities

As discussed above, the geometry of the slope can be obtained either by the use of hand held equipment or by topographic survey. Some of the steeper or more extensive faces are likely to be completely inaccessible to surveying equipment. Where detailed information is required, such as during remedial works, it would be possible to carry out a photogrammetric survey but usually it will be sufficient to make a visual assessment of angles and azimuths from compass clinometer and/or Abney level readings. Similarly, the orientations of principal discontinuities or discontinuity sets can be measured using hand held equipment, if necessary from a remote location. Care must also be exercised to ensure that persistent but less frequent discontinuities are not omitted at this stage.

A3.3.3 Shear strength

The next most important factor in analysing the stability of a rock slope is the shear strength of the potential failure surface. Except in the cases of some completely weathered rock masses this is unlikely to be the shear strength of the intact rock material but rather the shear strength across a discontinuity plane or a series of discontinuities. This will depend not only upon the friction angle of the two rock surfaces in contact but also upon the roughness and undulations of the surfaces, the degree of openness, the shear strength of any cementation or infill to the discontinuity and upon the presence of water. The shear strength across a discontinuity plane can be modelled by testing in a laboratory or portable shear test apparatus and this would not require unreasonably large samples as discussed above in relation to soils. It is important, however, that the test models the discontinuity accurately in terms of its infill, cementation, roughness, *etc.* It is also possible to carry out simple tilt tests on site with very little apparatus and these can give a first approximation of the friction angle across uncemented discontinuities. Given the degree of variation in the nature of discontinuities and within a single discontinuity, it may be considered that recourse to published figures provides a useful estimate of shear strength.

A3.3.4 Pore pressures

The shear strength in rocks may be reduced significantly in the presence of water by the reduction in normal stress across the failure surface. In terms of the stability of slopes in competent rocks, the presence of a small volume of water trapped within the rock mass at high pressure is more important than a large volume of water discharging from a free draining aquifer. It is important, therefore, during the mapping stage, that attention is paid to springs and seepages in the rock mass.

A3.3.5 Graphical analysis

Unlike soil slopes, the experienced eye can make useful stability assessments rapidly while on site insofar as the relationship between the orientation of discontinuities and the slope face can be observed. Care should be exercised, however, since without a systematic exercise of data gathering and analysis, the observer may simply reinforce his own prejudices. It is also difficult to predict wedge failures in particular without plotting the results on a stereonet. In this method, a large number of discontinuity orientations are plotted in stereographic projection together with the orientation or orientations of the slope face. The discontinuity data are usually contoured to produce a density plot of orientations. Both plotting and contouring can be done by computer but are possible by hand with little loss of accuracy, if rather more slowly. From the contoured plot it is relatively straightforward to assess graphically the possibility of planar, toppling or simple wedge failures. In the case of more complex wedge failures, or where modelling of pore water pressures is necessary, it is normal to resort to one of the specialist software packages.