Practical reliability approach to urban slope stability

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1 INTRODUCTION

1.1 Slope stability, triggering factors and uncertainties

In many urban areas of the world, the problems of slope stability are numerous and varied, ranging from first-time failures to reactivated landslides and from minor, localized slope movements to catastrophic events. There are many challenges in the accurate assessment of slope reliability on the one hand and landslide susceptibility on the other. Short-term goals include the identification of recent slope failures and areas of low or marginal stability, performing site-specific analyses, so that remediation or preventive slope management can be carried out effectively. Long-term goals include investigating the variability of important influencing factors, assessing local and regional uncertainties and carrying out required analyses in order to minimize slope failure hazards, mitigate associated risks and plan future development on a rational basis. There are a variety of factors, topographical, geological, geotechnical and environmental, which control the occurrence of slope failures. It is also important to consider the main triggering factors in a region such as the occurrence of excessive rainfall or an earthquake. The quantity and quality of detailed and accurate data are often limited by financial and other constraints. A brief reference is made in the next section to regional assessments of urban slope stability. Such assessments may be subject to even greater uncertainty than site-specific assessments.

1.2 Progressive failure, peak and residual shear strength

It is essential to understand the basic causes and mechanisms of slope failures which are caused by decreased shear strength and increased pore water pressure. Progressive failure is often a consequence of the strain-softening mechanical behavior of soil and rock. Peak shear strength along a slip surface is usually considered to be applicable to slope analysis of potential first-time slope failures. On the other hand, residual shear strength is applicable to the analysis concerning the potential reactivation of existing landslides. However, in many instances processes of progressive failure are important and it is often necessary or useful to consider the role of strain-softening in slope stability assessments either on a deterministic or probabilistic basis. With increasing strain or increasing relative deformation along any surface, the shear strength may decrease from its peak value, the extent of decrease depending on the type of soil and the extent of strain or deformation.

The average shear strength along a potential slip surface may be at its peak value or at its residual value or at a value in between. The term ‘Residual Factor’ may be defined as the proportion of average shear strength decrease from a peak value to a resi-
There may be more than three significant random variables. For example, if there is considerable uncertainty with regard to the extent of progressive failure at a site, it may be important to include the residual factor $R$ as a random variable in addition to peak and residual shear strength parameters. It would be a random variable with values between 0 and 1. With peak and residual shear strength parameters, the number of random variables would increase to 6 including pore pressure ratio and residual factor.

Using the appropriate performance function applicable to the identified failure mechanism and the assumed shape of a potential slip surface and taking into consideration all the important random variables, the probability moments of $F$ may be calculated using well known methods and techniques.

A number of applications of slope reliability analysis have been discussed in some detail with several numerical examples in Chapters 3 and 10 of Chowdhury et al (2010).

1.4 Main objective of this paper

As discussed briefly below, regional studies require a different perspective and considerable information and data on a regional scale. Often adequate attention has not been given to incorporating both spatial and temporal uncertainties in assessments of slope stability and reliability. Similarities and differences between site-specific and regional studies require further exploration.

A practical approach to urban slope reliability requires the establishment of a linkage between the results of regional studies on the one hand and those of site-specific assessments on the other. In this paper an innovative approach is introduced to show that a regional hazard study can be interpreted in terms of reliability of each hazard zone. Consequently, mean factors of safety associated with each hazard zone can be estimated. Thus a GIS-based regional study developed on the basis of various data-sets is interpreted in terms of traditional performance indicators with which geotechnical engineers are familiar. This approach has allowed a further validation of a comprehensive regional study for an urban region in Australia. Further reference to this study is made in Section 3 below.

2 REGIONAL SLOPE STABILITY ASSESSMENTS

2.1 Basic requirements

Regional slope stability studies are often carried out within the framework of a Geographical Information System (GIS) and are facilitated by the preparation of relevant data-sets relating to the main influencing factors such as geology, topography, drainage characteristics and by developing a comprehensive inventory of existing landslides.
velopment of a digital elevation model (DEM) facilitates GIS based modeling of landslide susceptibility, hazard and risk within a GIS framework. Regional slope stability and hazard studies facilitate the development of effective landslide risk management strategies in an urban area.

2.2 Landslide Inventory

Identifying the location of existing landslides is just the beginning of a systematic and sustained process with the aim of developing a comprehensive landslide inventory. Among other features, it should include the nature, size, mechanism, triggering factors and date of occurrence of existing landslides. While some old landslide areas may be dormant, others may be reactivated by one or more regional triggering factors such as heavy rainfall and earthquakes.

2.3 Qualitative and quantitative assessments

Depending on the aims and objectives of a regional study, assessments of landslide susceptibility and hazard may vary in scope from primarily qualitative in cases where data are of limited range and quality to increasingly quantitative in cases where the extent of data is comprehensive with good quality control. For urbanized regions, a quantitative study must be considered essential.

Two different approaches for quantitative assessment may be mentioned here.

One approach is to use a geotechnical model such as the ‘infinite slope’ model within a GIS framework. The local factor of safety at each pixel would be calculated based on the available data sets and facilitated partly by the digital elevation model. Thus ‘susceptibility zones’ or ‘hazard zones’ may be identified, each zone associated with an estimated range of factor of safety values. The zone with the highest factor of safety range would indicate the lowest hazard zone while the zone with the lowest estimated factor of safety range would indicate the highest hazard zone. Other zones would, of course, lie in between these extreme zones. This approach may be developed further to calculate associated probabilities of failure pertaining to different hazard zones.

The second approach is based on analysis and synthesis of comprehensive data-sets pertaining to important influencing factors and taking into consideration all the known landslides in the region. The process identifies those combinations of different influencing factors which characterize existing landslides. The results of these analyses are then extended to the entire region. This enables the delineation of zones of different future landsliding potential within the whole area.

One comprehensive study of this type has been discussed in some detail in Chapter 11 of Chowd-hury et al (2010). This study was made for the Greater Wollongong region, New South Wales, Australia by the University of Wollongong (UOW) Landslide Research Team (LRT)

3 THE WOLLONGONG REGIONAL LANDSLIDE STUDY

3.1 The susceptibility model area and the data-sets

The area chosen within the Wollongong Region for modeling landslide susceptibility (Susceptibility Model Area) is 188 square km in extent and contains 426 Slide category landslides.

The data sets used for this study include:
1. Geology (mapped geological formations,21 variables)
2. Vegetation (mapped vegetation categories,15 variables)
3. Slope inclination (continuous floating point distribution)
4. Slope aspect (continuous floating point distribution)
5. Terrain units (buffered water courses, spur lines and other intermediate slopes)
6. Curvature (continuous floating point distribution)
7. Profile curvature (continuous floating point distribution)
8. Plan curvature (continuous floating point distribution)
9. Flow accumulation (continuous integer), and
10. Wetness index (continuous floating point distribution)

3.2 Landslide inventory

The landslide inventory for this study has been developed over a fifteen year period and comprises a relational MS Access and ESRI ArcGIS Geodatabase with 75 available fields of information for each landslide site. It contains information on a total of 614 landslides (Falls, Flows,Slides) including 480 slides. Amongst the 426 landslides within the Susceptibility Model Area, landslide volumes have been calculated for 378 of these sites. The average volume is 21800 m³ and the maximum 720,000 m³.

3.3 Knowledge-based approach based on Data Mining model

The specific knowledge-based approach used for analysis and synthesis of the data sets for this study is the Data Mining (DM) process or model. The DM learning process is facilitated by the software “See 5” which is a fully developed application of “C4.5” (Quinlan,1993). The DM learning process helps extract patterns from the databases related to the study. Known landslide areas are used for one half of the
model training, the other half comprising randomly selected points from within the model area but outside the known landslide boundaries. Several rules are generated during the process of modeling. Rules which indicate potential landsliding are assigned positive confidence values and those which indicate potential stability (no-landsliding) are assigned negative confidence values. The rule set is then reapplied within the GIS software using the ESRI Model Builder extension to produce the susceptibility grid. The complete process of susceptibility and hazard zoning is described in Flentje (2009) and in Chapter 11 of Chowdhury et al (2010).

3.4 Susceptibility and Hazard zoning

On the basis of the analysis and synthesis using the knowledge-based approach, it has been possible to demarcate zones of susceptibility and hazard into four categories:

1. Very Low Susceptibility (or Hazard) of landsliding (VL)
2. Low Susceptibility (or Hazard) of landsliding (L)
3. Moderate Susceptibility (or Hazard) of landsliding (M), and
4. High Susceptibility (or Hazard) of landsliding (H)

A segment of the landslide hazard map is reproduced as Fig 1 below.

Relative likelihoods of failure in different zones, estimated from the proportion of total landslides which occurred in each zone over a period of 126 years are presented in Table 1 below. This is only a part of the full table presented as Table 11.3 in Chowdhury et al (2010).

<table>
<thead>
<tr>
<th>Hazard Zone Description</th>
<th>Failure Likelihood</th>
<th>Reliability Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>$7.36 \times 10^{-3}$</td>
<td>2.44</td>
</tr>
<tr>
<td>Low</td>
<td>$6.46 \times 10^{-2}$</td>
<td>1.51</td>
</tr>
<tr>
<td>Moderate</td>
<td>$3.12 \times 10^{-1}$</td>
<td>0.49</td>
</tr>
<tr>
<td>High</td>
<td>$6.16 \times 10^{-1}$</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

4 ESTIMATED RELIABILITY INDICES AND FACTORS OF SAFETY

Assuming that the factor of safety has a normal distribution, the reliability index was calculated for each zone based on the associated failure likelihood which is interpreted as the probability of failure.

These results are presented in the last column of Table 1.

Assuming that the coefficient of variation of the factor of safety is 10%, the typical values of mean factor of safety for each zone are shown in Table 2.

Table 2. Typical mean value of Factor of Safety F for each Hazard Zone considering coefficient of variation to be 10%.

<table>
<thead>
<tr>
<th>Hazard Zone Description</th>
<th>Reliability Index</th>
<th>Mean of F ($V_F = 10%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>2.44</td>
<td>1.32</td>
</tr>
<tr>
<td>Low</td>
<td>1.51</td>
<td>1.18</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.49</td>
<td>1.05</td>
</tr>
<tr>
<td>High</td>
<td>-0.3</td>
<td>0.97</td>
</tr>
</tbody>
</table>

The results were also obtained for other values of the coefficient of variation of the factor of safety (5%, 10%, 15% and 20%). These results are shown in Table 3.

Table 3. Typical mean Factor of Safety with different values of coefficient of variation

<table>
<thead>
<tr>
<th>$V_F%$</th>
<th>Mean of F for different Hazard Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>Low</td>
</tr>
<tr>
<td>5</td>
<td>1.14</td>
</tr>
<tr>
<td>10</td>
<td>1.32</td>
</tr>
<tr>
<td>15</td>
<td>1.57</td>
</tr>
<tr>
<td>20</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Most of the landslides have occurred during very high rainfall events. It is reasonable to assume that most failures are associated with a pore water pressure ratio of about 0.5 (full seepage condition in a natural slope). Assuming that the ‘infinite slope’

model applies to most natural slopes and that cohesion intercept is close to zero, the values of factor of safety can be calculated for other values of the pore pressure ratio (0.2, 0.3, and 0.4) for any assumed value of the slope inclination. The results shown below in

Figure 1. Segment of Landslide Inventory and Susceptibility Zoning Map, Wollongong Local Government Area, New South Wales, Australia.
Table 4 are for a slope with an inclination of 12 degrees for pore pressure ratios in the range 0.2-0.5.

<table>
<thead>
<tr>
<th>Pore water pressure ratio</th>
<th>Mean of F for different Hazard Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td>0.5</td>
<td>1.32</td>
</tr>
<tr>
<td>0.4</td>
<td>1.61</td>
</tr>
<tr>
<td>0.3</td>
<td>1.90</td>
</tr>
<tr>
<td>0.2</td>
<td>2.19</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

5.1 Summary of what has been achieved so far

In this paper an innovative approach has been presented for interpreting the results of a regional landslide susceptibility study. Based on the assessed values of slope failure susceptibility in a regional study, estimates have been made of the reliability index values for each hazard zone. The results are reasonable and credible and provide further validation of the comprehensive regional study. This approach is a practical application of reliability analysis within a probabilistic framework. In fact it demonstrates that the reliability process can be usefully applied in reverse and that the results of a quantitative regional study can be presented in terms of performance indicators used in a conventional site-specific studies, deterministic and probabilistic.

5.2 Future Extension

So far the results have only been obtained as a typical F value or a set of F values referring to each hazard zone. However, taking into consideration the spatial variation of slope angle, shear strength and other factors, this approach can be further developed in order to facilitate the calculation of factors of safety at individual location within the whole area. This can be done effectively after validating the initial results for each zone with respect to a few well-documented case studies of site-specific analysis.

Having achieved estimates of the spatial variation of local factor of safety throughout the region, it is also feasible to estimate the variation of local probability of failure throughout the region.

Finally, this approach would also prove useful in scenario modelling for changed climatic conditions in the future.

As reliable data concerning future fluctuations in pore pressure become available, failure susceptibility under those conditions can be modelled. Assessments can also be made concerning the potential for catastrophic slope failures under those changed conditions.

6 REFERENCES.

