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A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping

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Abstract

In this paper, a multi-method approach for the assessment of the stability of natural slopes and landslide hazard mapping applied to the Dakar coastal region is presented. This approach is based on the effective combination of geotechnical field and laboratory works, of GIS, and of mechanical (deterministic and numerical) stability analysis. By using this approach, valuable results were gained regarding instability factors, landslide kinematics, simulation of slope failure and coastal erosion. This led to a thorough assessment and strong reduction in the subjectivity of the slope stability and hazard assessment and to the development of an objective landslide danger map of the SW coast of Dakar. Analysis of the results shows that the slides were influenced by the geotechnical properties of the soil, the weathering, the hydrogeological situation, and the erosion by waves. The landslide susceptibility assessment based on this methodological approach has allowed for an appropriate and adequate consideration of the multiple factors affecting the stability and the optimization of planning and investment for land development in the city.

Keywords: Landslide; GIS; Hazard assessment; Numerical modeling; Dakar; Stability; Multi-method approach

1. Introduction

Rapid urbanization and population growth in Dakar are placing increasing development pressures on the available space and, as the more favourable areas are occupied, marginal land such as that on or adjacent to coastal slopes is being developed. The coastal areas were avoided in the past because of their exposure to natural hazards such as landslides and erosion of the cliffs. Thus, in the context of increasing demands from the population of Dakar for protection against natural catastrophes, particularly coastal landslides, landslide danger mapping is a valuable assistance tool in decision making. However, it is well known that landslides are often the result of the temporal conjunction of several factors. According to Dai and Lee (2001), these factors can be regrouped into: (i) the quasi-static variables, which contribute to landslide susceptibility, such as geology, slope characteristics (gradient, slope aspect, elevation, etc.), geotechnical properties, and long-term drainage patterns, etc.; and (ii) the dynamic variables, which tend to trigger landslides in an area of a given landslide susceptibility, such as rainfall and earthquakes (Wu and Sidle, 1995; Atkinson and Massari, 1998). However, these instability factors are sometimes unknown or cannot be cost-effectively determined over large areas. Based on the facts mentioned above, it can be affirmed that the stability assessment of natural

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slopes, particularly coastal cliffs, the analysis of the causes of slope failures, and the evaluation of the landslide hazards are very delicate and complex. Additionally, in the case of a sufficiently large study region, individual studies for all slopes present at the study area may not appear feasible and are not economical.

Different techniques or tools may be adopted with various approaches for determining potentially unstable areas or landslide hazard assessment. These techniques can be divided into three groups: expert evaluation, statistical methods, and mechanical approach (Leroi, 1997; etc.).

Expert evaluation is the most widely used approach for landslide hazard evaluation (Nash, 1987; Anbalagan, 1992; Fall et al., 1996; Evans et al., 1997; Leroi, 1997; Atkinson and Massari, 1998; Guzzetti et al., 1999; etc.). The expert evaluation can include landslide inventory mapping and/or heuristic approaches. Landslide inventory maps can be used as an elementary form of susceptibility map because they emphasize the position and dimension of recorded landslides (Dai and Lee, 2001; Dai et al., 2002). In the heuristic methods, the opinion is used to estimate and/or classify the landslide hazards based on quasi-static variables only (Fall, 2000; Dai and Lee, 2001). The main criticism of the methodology of expert evaluation is the subjectivity in the decision making (Westen Van et al., 1997; Leroi, 1997; Fall, 2000), because the landslide hazard maps produced by different researchers according to expert evaluation can be very different (Carrara et al., 1992). However, it is evident that the approach based on expert evaluation will remain the most widely used and the most versatile, but improvement is required. This means it will be necessary to rely on more sophisticated techniques for landslide hazard or susceptibility evaluation (statistical methods, mechanical methods, etc.) and on state-of-the-art geographical data management tools, in order to be integrated into the overall methodology of landslide danger or hazards mapping.

Statistical methods were developed to overcome the relatively high level of subjectivity related to expert evaluation. They involve the statistical determination of the combinations of variables that have caused past instability processes (Dai and Lee, 2001). Quantitative or semi-quantitative estimates are then performed for areas not affected by landslides, but where the same conditions exist (Dai and Lee, 2001). Several works (Bernknopf et al., 1988; Yin and Yan, 1988; Carrara et al., 1991; Carrara and Guzzetti, 1995; Atkinson and Massari, 1998; etc.) have applied both simple and multivariate statistical methods to evaluate the landslide hazards successfully. However, the most serious drawback of the use of statistical methods is the collection of data over large areas and sometimes over large time periods regarding landslide distribution and factors. It could be very problematic to carry out this data gathering at acceptable costs (Westen Van et al., 1997). A further potential source of error, which is common to all statistical methods, is the quality and detail of the landslide frequency or factors data on which the correlations are based. Thus, the results are largely dependent on the quality of the data.

Mechanical approaches allow the evaluation and analysis of the stability state of the slopes using deterministic methods (e.g. limit equilibrium methods) and/or numerical methods (e.g. continuum or discontinuous modeling). Deterministic or numerical stability slope models have been successfully used for many years to evaluate landslide hazards (Ward et al., 1981; Nash, 1987; Terlien et al., 1995; Atkinson and Massari, 1998; Fall and Azzam, 2001a,b; etc.). The advantage of the application of mechanical models (deterministic or numerical models) in landslide hazard assessment is that these models are physically sound. With these models it is possible to quantify the stability of the slopes by a safety factor (Westen Van et al., 1997). Additionally, today, the development of several high-quality constitutive models for geomaterials and numerical codes combined with an increasing computer performance, allow us to predict, simulate and evaluate the behaviour or stability of any slopes submitted to different instability factors with relatively good accuracy. The results derived from stability analysis based on mechanical models can also be directly used by engineers in the design of infrastructural or remedial works. However, due to the high spatial variability of the geotechnical parameters (input data of the mechanical models) and the laborious methods involved in acquiring these data, an acceptable approximation of the values is practically only attainable at the level of site investigation, which implies a serious limitation of these models in large area stability hazard zoning at a reasonable cost/benefit ratio (Westen Van et al., 1997). Hence, in landslide susceptibility or hazard assessment of large areas, the mechanical methods should only be applied to study the stability of slopes, which cannot be determined with sufficient accuracy with the other methods of landslide hazard assessment.

The review of the different methods for slope stability assessment or landslide hazards presented above has shown that all existing approaches for landslide susceptibility or hazards assessment present advantages and disadvantages. The successful use of one method or another strongly depends on many factors such as the