Engineering Geology 189 (2015) 17–31

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

The role of the lithological setting on the landslide pattern and distribution

Cristina Henriques [a,*], José Luís Zêzere [a], Fernando Marques [b]

[a] Riskam, Centre for Geographical Studies, Institute of Geography and Spatial Planning, Universidade de Lisboa, Edifício da Faculdade de Letras, Alameda da Universidade, 1600-214 Lisboa, Portugal
[b] Universidade de Lisboa, Faculdade de Ciências, Centro de Geologia e Departamento de Geologia, Campo Grande, edifício C6, 3° piso, 1749-016 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 11 June 2014
Received in revised form 21 January 2015
Accepted 27 January 2015
Available online 11 February 2015

Keywords:
Landslides
Lithology
Predisposition
Validation

ABSTRACT

In landslide susceptibility mapping studies, the quality of whole inputs such as geological setting and DEM derivatives should be as high as possible. Given the strong relationship between landslide occurrences and geology the use of a detailed lithological map is certainly an alternative preferable to the most commonly available rough geological map. Therefore, this study focuses on this reality and proposes a procedure for improving the available geological map in a study area located 90 km North of Lisbon.

Based on a 1:50,000 scaled official geological map and according to the litho-stratigraphic characteristics, the map improvement was performed using the interpretation of aerial photographs by stereoscopic analysis and further field validation.

In order to assess the relevance of the lithological improvement regarding the relationships with landslide distribution, a comparison was performed between the results obtained with the official lithological map and the improved detailed lithological map using the Conditional Probability (CP), the Accountability (ACC) and Reliability (RLB) indexes. A landslide inventory, including shallow and deep-seated landslides, was prepared for the study area and landslides were overlapped with both lithological maps. The ACC and RLB indexes obtained with the detailed geological map are higher than equivalent features obtained with the official lithological map. From these procedures it was possible to conclude that the detailed lithological map has a better discriminating power than the official lithological map, enabling a better quality of the landslide susceptibility analysis with the separation of the relevant lithological classes.

1. Introduction

According to Wu and Qiao (2009), who improved the original concept by Terzaghi (1950), the factors affecting the development of landslides can be classified as external and internal. External factors include rainfall, earthquakes and anthropic actions that act as occasional triggering factors. Internal factors include lithology, slope angle, slope aspect, and slope profile and are related to the predisposing factors which are static and inherent to the terrain (Wu and Qiao, 2009).

Numerous studies indicate that landslides are greatly conditioned by the lithological properties of the land surface (e.g., Carrara et al., 1991; Anbalagan, 1992; Mejia-Navarro and Wohl, 1994; Mejia-Navarro and Garcia, 1996; Pachauri et al., 1998; Luzi and Pergalani, 1999; Dai and Lee, 2001; Duman et al., 2006; Hammond, 2007; Yalcin, 2008; Boboc et al., 2012; Ercanoğlu and Temiz, 2011; Nefeslioglu et al., 2012; Das et al., 2013). As an accepted rule, the geologic/lithologic theme is one of the landslide predisposing factors considered in any landslide susceptibility assessment using data-driven methods (e.g., Guzzetti et al., 1996; Van Westen et al., 2006; Blahut et al., 2010).

Typically, the lithologic data used in landslide susceptibility models are generally obtained from available official geological maps, having an intermediate scale such as 1:25,000 or 1:50,000, which are usually made following a litho-stratigraphic perspective. Such rough data may not be appropriate for landslide susceptibility assessment when the lithological controls on landslide are dominant. However, the advantage of lithological data converted directly from official geologic maps is related to the possibility to obtain such data in digital format at a low cost.

A more detailed lithological map has great importance in providing data for landslide susceptibility mapping, since different lithological units may have different landslide susceptibility weights. For this reason, it is essential to group the lithologic units according to their physical (geotechnical) properties (Carrara et al., 1991; Anbalagan, 1992; Mejia-Navarro and Wohl, 1994; Mejia-Navarro and Garcia, 1996; Pachauri et al., 1998; Luzi and Pergalani, 1999; Dai and Lee, 2001; Duman et al., 2006; Hammond, 2007; Yalcin, 2008).

According to Varnes (1984) the simplest type of geological map must show conventional geologic formations, and contain explanatory notes or tabular text about the propensity to slope instability of the geologic units. But in a more purposeful assessment aimed to obtain more refined lithological data, the geological units should be grouped or split by sub-lithology, not necessarily preserving stratigraphic order, and ranked according to the observed or inferred slope stability.

* Corresponding author.
E-mail addresses: cristina.s.henriques@gmail.com (C. Henriques), zezere@campus.ul.pt (J.L. Zêzere), fsmarques@fc.ul.pt (F. Marques).

http://dx.doi.org/10.1016/j.enggeo.2015.01.025
0013-7952/

Critical and detailed lithological interpretations have also implications in other fields such as engineering. Detailed lithological maps are a valuable tool to make better design decisions or, after failure, to evaluate causes and errors in an engineering model (Hammond, 2007).

In landslide susceptibility mapping studies, the quality of whole inputs such as geological settings and DEM derivatives, should be as high as possible. Given the strong relationship between landslide occurrence and geology the use of a detailed lithological map is certainly an alternative preferable to the most commonly available rough geological map. Therefore, this study focuses on this reality and proposes a sample procedure for improving the available geological map.

The aim of this paper is to demonstrate how the improvements on the lithological data can help to produce better results on the lithological data, which may be used to assess landslide susceptibility. Thereby, in this work, a detailed lithological map scaled as 1:10,000 was produced in order to support the landslide susceptibility assessment. The improvements on the detailed lithological theme are evaluated in terms of landslide distribution by comparing with the official lithological map.

Regional lithological criteria that should be used in evaluating landslides are reviewed below and their importance assessed. Thus, based on the pre-existing official geological map and according to the lithological and stratigraphic characteristics, the map improvements were made using the interpretation of aerial photographs by stereoscopic analysis and systematic field work.

The assessment of the lithological mapping improvement was made by using two groups of landslide inventories which were defined according to the depth of the slip surface, the merged shallow and deep-seated landslide inventories. Thereby, the main specific objectives of the study are: (i) to produce a detailed lithological map using stereoscopic interpretation of aerial photographs and field work for validation; (ii) to assess the spatial distribution of shallow and deep-seated landslides both on the official and the detailed lithological maps; (iii) to establish a comparison analysis between the available official lithological map and the improved detailed lithological map, the Conditional Probability (CP) and the Accountability (ACC) and Reliability (RLB) methods were considered; and (iv) to determine how the improvements on the lithological data can help to produce better results in the landslide susceptibility evaluation.

2. Study area

2.1. Geomorphology and geology

The study area is composed of the upper section of three hydrographic basins, named Arnoia (105 km^2), Tornada (68.9 km^2) and Alfeizerão (102 km^2), located 90 km North of Lisbon, which were selected due to their geological and geomorphological features (Fig. 1) and due to the relevant slope instability.

From the geomorphologic point of view, the three sub-catchments, of Alfeizerão, Tornada and Arnoia are located in a dissected old quaternary coastal plateau which cuts an evident syncline structure in the basement that is mainly composed by upper Jurassic sandstones and claystones (Fig. 2).

The geological structure and the lithology of the study area explain the morphology and, thus, the altitude variations along the study area. The average altitude is about 114 m. The SE part of the territory, where the higher resistance dolerite rock outcrop has the higher reliefs including the Todo-Mundo Hill (262.4 m).

The official lithological map includes ten geological units from Middle Jurassic to Quaternary (Table 1). The oldest materials from middle to upper Jurassic are located on both western and eastern flanks of the study area and correspond to the Oxfordian limestones and marls, which together occupy 0.53% of the study area. The Tithonian limestones and claystones are located on the southern part of the study area occupying 0.41% of the study area. The northwest site of the study area is the upper Jurassic (lower Kimmeridgian) marls, sandstones and claystones which occupy only 0.04% of the study area. Moreover, the most recent geological units include Miocene sandstones, claystones and limestones, Pliocene sands and Holocene alluvium. Miocene sandstones, claystones and limestones areas are the smallest in the study area (0.02% of the total). Sand deposits correspond to 0.66% of the total area.

Magmatic rocks, essentially dolerite, occurs as a WNW–ESE trending dyke and as a volcanic neck located on the southern part of the study area, at Todo-Mundo Hill, corresponding to 1.15% of the total study area. In dolerite rock areas the slopes are regular, long and rectilinear, with a relatively high relief that locally exceeds 200 m.

It is noteworthy that the study area is mostly dominated by sandstone and claystone complexes dated from the upper Jurassic, Cretaceous and Tertiary which correspond to 90.15% of the total study area and does not contain any lithological subdivision in the official geological map (Table 1 and Fig. 2). This fact was the main problem/stimulus to produce a more detailed mapping for such significant portion of the study area, mainly by interpretation of aerial photographs. The central part of the lithological map, located between the oldest lithological complexes of the study area, is mainly occupied by the upper Jurassic sandstones and claystones that form a large outcrop area (87.88% of the total). Sandstone and claystone complexes from Cretaceous and Tertiary are located respectively on the south and southeast part of territory corresponding to 2.27% of the total study area.

2.2. Landslide inventory

The study of the relationship between a landslide predisposing factor, such as lithology and the distribution and pattern of landslides, provides the basis for obtaining the weight of each lithological class taking into account the type of landslide. Thereby, we built a landslide inventory, which was obtained by interpretation of orthophotomaps dated form 2004 and subsequent field work for validation (Fig. 3 and Table 2). Only the area of the landslide depletion zone was studied, because otherwise it would not be possible to estimate the weight of each lithological class in order to assess propensity to landslide initiation.

Furthermore, the present study aims to evaluate quantitatively the relevance of the lithological improvement considering the depth of the slope failures, the merged shallow and deep-seated landslides. The descriptive statistics of the landslides inventoried in the study area are summarized in Table 2. The most prevalent type of landslides registered in the study area is the deep-seated rotational slides (126) which correspond also to the type of landslides with highest spatial density (0.457 n/km^2) and to the highest mean landslide area (0.229 ha). Conversely, the less frequent landslides are the deep-seated translational slides (2), which correspond also to the lowest spatial landslide density (0.007 n/km^2) and the lowest mean landslide area (0.019 ha). Moreover, there are 71 shallow rotational slides with a landslide density of 0.257 n/km^2 and a mean landslide area of 0.061 ha. Less frequent than the previous is the shallow translational slides with 46 occurrences, a landslide density of 0.167 n/km^2 and a mean landslide area of 0.028 ha.

3. Material and methods

The detailed lithological or litho-stratigraphic map scaled at 1:10,000 was produced by interpretation of stereoscopic aerial photographs dated from 1958 with a 1:26,000 nominal scale. These aerial photographs were chosen because they are the oldest aerial photographs that cover completely the whole study area. In addition, they denote fewer alteration of the study area, due to less intense human occupation and activity, which naturally enables better observation of the structural and geological settings.

The interpretation of stereoscopic aerial photographs and the subsequent drawing of the new lithological boundaries were done in an automatic setting system. The georeferenced stereo pair aerial photographs