Ecological Engineering 106 (2017) 609–619

Contents lists available at ScienceDirect

Ecological Engineering

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

Research Paper

A 3D model applied to analyze the mechanical stability of real-world forested hillslopes prone to landslides

André Guy Tranquille Temgoua [a,*], Nomessi K. Kokutse [b], Zanin Kavazović [c], Martin Richard [d]

[a] University of Ottawa, 120 University, Department of Earth Sciences, Ottawa, ON, Canada
[b] Procenvi Inc., 939 rue Chapman, L'Ancienne-Lorette, G2E 3Z4, Québec (Québec), Canada
[c] Khalifa University of Science and Technology, Department of Applied Mathematics and Sciences, P.O. Box 127788, Abu Dhabi, United Arab Emirates
[d] Memorial University of Newfoundland, Morrissey Road, A1B 3X5, Department of Civil Engineering, St. John's, NL, Canada

ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form 18 June 2017
Accepted 20 June 2017
Available online 4 July 2017

Keywords:
Hillslope stability
Landslide
3D finite element model
Ecological engineering

ABSTRACT

This paper is dedicated to a numerical simulation using a 3D model applied to analyze a hillslope's stability in an ecological area in Togo. The 3D model is applied to two natural slopes prone to landslides located in Atakora mountains. The slopes are covered by a randomly distributed heterogeneous vegetation. There were four species of timber and one species of firewood present on the studied sites. Samples of soil and root systems were collected and tested in the laboratory in order to determine their properties which were then used as entry parameters for the 3D numerical model. The study examines the influence of natural forest stands and the morphology of the root system on slope's stability. It was noticed that, close to the tree's trunk, the additional cohesion due to the presence of the roots had a significant influence on the improvement of the slope's stability. Moreover, the depth of the root system as well as spatial repartition and the density of trees on a given site have a major impact on the stability of a hillslope. The model proposed here can be used as a decision-making tool in elaboration of forest management plans and strategies.

1. Introduction

Understanding of interactions between forest plantations and hillslope's stability requires an interconnection between both experimental and modelization approaches. Traditionally, the models proposed by pioneers of the stability analysis were two-dimensional. As a consequence, they do not always allow an explicit integration of parameters characterizing a structure of the forest stands. Hence their limitation to analyze complex configurations. In the last decade, several researchers have proposed innovative models (Kokutse et al., 2006; Stokes et al., 2009; Thomas and Pollen-Bankhead, 2010; Ji et al., 2012; Vergani et al., 2014; Veylon et al., 2015; Schwarz et al., 2015; Temgoua et al., 2016). However, a more comprehensive study in sub-Saharian Africa proves to be challenging as the field data are generally difficult to obtain. There are numerous landslides documented in several forest sites in Togo. Amongst those, there was a landslide whose zone of failure was 160 m long and 28 m wide with an average depth of 1.4 m. This landslide caused a partial destruction of a close-by village (Kokutse, 2003).

Current study is based on a stability analysis conducted using parameters of non-Equestrian forest stands. The ecological zone studied here (Togo – Western Africa) is characterized by a randomly distributed heterogeneous vegetation (Hall and Swaine, 1981; White, 1986; Kokou, 1998; Kokou et al., 1999a, 1999b, 2005). In Togo, Atakora is a chain of mountains dividing the country on a south-west to nord-est axis. This ecological zone is covered by semi-deciduous forests (Ern, 1979; Akpagana, 1989; Kokou et al., 1999a, 1999b; Adjossou, 2009; Adjonou et al., 2013, 2014). Moreover, in this zone, hillslopes are known to be unstable and prone to landslides. Their occurrence has increased in recent years as a consequence of an accelerated deforestation which now is even affecting protected areas (Adjonou et al., 2011; Adou Yao et al., 2011; Kokou et al., 2012). Efforts of rehabilitation of these vulnerable forest areas, especially those with steep slopes, have been undertaken by forest protection services in order to restore vegetal coverage and protect the soil (Kokou et al., 2010; Kokou et al., 2012). In the ecological zone studied here, forest stands are mixed with a very irregular spatial distribution and they are situated on steep slopes (Kokou et al., 2005; Ajoussou, 2009; Adjonou et al.,

* Corresponding author.
E-mail address: atemgoua@uottawa.ca (A.G.T. Temgoua).

http://dx.doi.org/10.1016/j.ecoleng.2017.06.043
0925-8574/

2013; 2014). Stability analysis of these slopes covered by irregular stands requires a 3D simulation model of a slope. A general objective of this paper is to use examples of the two natural sites in Togo to assess slope's stability in the case of a hillslope with a randomly distributed heterogeneous vegetation. Taking into consideration a very irregular spatial distribution of individual trees composing the forest stands, this study also has two specific objectives. First, collect the data relative to the hillslopes covered by a randomly distributed heterogeneous vegetation. This allows to provide numerical values for the parameters required to run a 3D numerical model able to assess slope's stability. Second, identify elements of the spatial distribution of the stands that influence slope's stability.

Our study is focused on two sites located in the southern part of the ecological zone. This analysis complements studies on the flora conducted in the same area (Akpagana and Guelly, 1994), studies on distribution of forest stands (Kokou et al., 1999a, 1999b), Riparian forests (Adjossou, 2009), analysis of local trees' overload (Dety, 2005) and spatial and time evolution of the forest cover (Kokou et al., 2005; Adjonou et al., 2013, 2014). A use of numerical tools and 3D modelization in eco-engineering represents a modern approach in analyzing stability of a large variety of forest stands' configurations (Stokes et al., 2009; Genet et al., 2010; Mao et al., 2013; Kokutse et al., 2015; Temgoua et al., 2016). In this study, this modern approach is applied to the steep slopes covered by randomly distributed heterogeneous vegetation.

2. Materials and methods

2.1. Description of the studied sites

The two studied sites were chosen in the southern part of the ecological zone (Fig. 1). This ecological zone is one of the five official

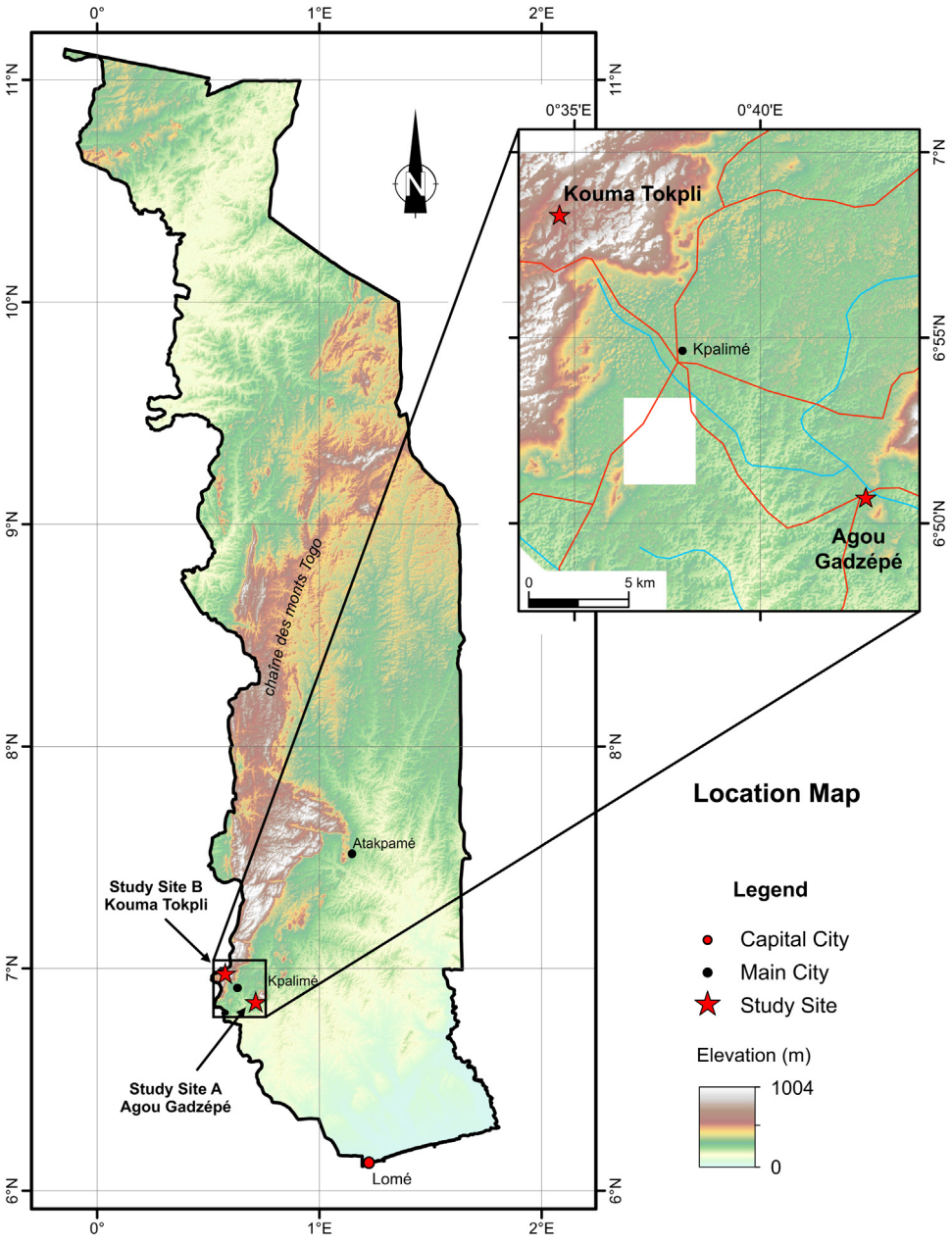

Fig. 1. Location of study sites.
Source of the digital elevation model: http://gdex.cr.usgs.gov/gdex/.