Geomorphology 223 (2014) 20–32

Contents lists available at ScienceDirect

Geomorphology

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

Evolution of a large landslide in the High Himalaya of central Nepal during the last half-century

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ARTICLE INFO

Article history:
Received 8 January 2014
Received in revised form 5 June 2014
Accepted 9 June 2014
Available online 26 June 2014

Keywords:
Landslide
Erosion rates
Remote sensing imagery
SPOT images
Digital elevation model
Himalayas

ABSTRACT

Episodic and catastrophic landslides are considered to be one of the main sources of sediment in the steep, mountainous landscapes of the Himalayas. However, the evolution of a single landslide through time and its contribution to erosional processes remain poorly constrained. In this study, we focus on a single, large (0.5 km^2) landslide in a small catchment on the southern flank of the Annapurnas in Nepal (the Khudi valley) in order to quantify its importance in the overall erosion of this steep Himalayan catchment.

The evolution of the Saituti landslide has been continuously monitored by remote sensing for the past 46 years. During that period, the Saituti landslide displayed sustained activity, such that the area of the landslide scar increased by a factor of 4. This retrogressive failure, a consequence of several sporadic flank and crown collapses, has not been continuous. Rather, acceleration phases have alternated with more quiescent periods. Simultaneously, the upper edge moved upward by 900 m. Based on field evidence from recent activity (such as scarps and open tension cracks above the landslide) and on an analysis of slope angles, at least the next 500 m is expected to fail.

Volume losses within the landslide were estimated from differences between digital elevation models (DEMs) and from changes in landslide area, using a calibrated power law relationship between landslide area and volume. Corresponding landslide-induced erosion rates at the scale of the whole Khudi catchment were found to be 2.6 ± 0.9 mm/y for the past half-century. Those rates are similar to denudation rates obtained from sediment load measurements between 1999 and 2004. Those results, along with the lack of other major landslides in the valley for the last 46 years, suggest that the Saituti landslide plays a dominant role in the modern erosion of the High Himalayan Khudi catchment for the last years and possibly for the past few decades.

We propose that continuous and sustained activity of a few major landslides over the past few decades might represent a significant contribution to the erosion of the High Himalayan range. This long-lasting, landslide-induced erosion should be taken into account when interpreting suspended load measurements, results from provenance analysis, or cosmogenic nuclides in river sand. Such processes should also be included in landscape evolution models when annual to secular problems are explored.

1. Introduction

The production of mountainous landscapes and continental relief is the result of competition between tectonic and erosional processes. In response to the creation of topography (via thrusting, crustal thickening, or any other source of rock uplift), fluvial, glacial, and hillslope denudation processes erode topography, leading to rock exhumation and sediment redistribution under lithological and climatic controls.

When trying to better document the links between climate, tectonic, and erosional processes and the role of controlling factors in mountain range evolution, quantifying the influence of each erosion process in a given environment is fundamental. In mountainous landscapes, fluvial processes and the response of the fluvial network to tectonic forcing have received a large amount of attention (e.g., Seeber and Gornitz, 1983; Lavé and Avouac, 2001; Whipple and Tucker, 2002; Sklar and Dietrich, 2006; Lague, 2010). Comparatively, hillslope response has received significantly less attention, partly owing to research showing that hillslope topography is much less sensitive to tectonic forcing in active mountain belts because it attains critical inclination (e.g., Burbank et al., 1996).

In active tectonic and erosional settings, landslides are generally considered the dominant hillslope process that permits rapid hillslope adjustment to hillslope base level lowering. A landslide is defined as the movement of a mass of rock, debris, or soil down a slope (Cruden, 1991) and includes sediment transfer over highly variable distances at mean rates that can vary from very slow (cm/y) to extremely rapid (tens of m/s). Landslide triggering is primarily controlled by a stability or safety criterion, which depends on material strength loss (e.g., Larsen et al., 2010), precipitation (Iverson, 2000) through pore pressure

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http://dx.doi.org/10.1016/j.geomorph.2014.06.021
0169-555X/

and water table height, or seismic shaking (e.g., Keefer, 1984). Because the internal angle of friction appears constant for most fractured rocks (Byerlee, 1978) and, in theory, might induce a nearly uniform hillslope angle in steep mountains, the links between landslides and landscape development in active orogenic belts have often been neglected in quantitative geomorphological models (e.g., Densmore et al., 1998). A few works suggested the existence of a threshold hillslope rapidly adjusting to changes in incision rates (Schmidt and Montgomery, 1995; Burbank et al., 1996). In addition, those models explore factors contributing to slope failure at the slope scale with limited consideration of the temporal evolution of processes. Landslides are supposed to occur along the steepest slopes (Densmore et al., 1998) either instantaneously or according to a probability function of occurrence that depends on the time elapsed since the last landsliding event at a given point (Champel et al., 2002).

Recent observations, however, challenge such simplified models: the threshold angle may be strongly dependant on climate (Gabet et al., 2004b) or on lithology (Hurst et al., 2013), even within a few kilometers distance. Soil production seems to increase with increasing landslide-induced erosion, inducing a smooth transition from soil to bedrock landscapes, hence a smooth change in landslide nature (Heimsath et al., 2012). Moreover, slope failures may have different consequences on catchment morphology and the size of the drainage basin or on the fluvial morphology, in particular on the grain size distribution of material brought to the fluvial network (Howard, 1998; Korup et al., 2010). This fosters the need to investigate more precisely landslides dynamics and their effects on landscape evolution in depth. One major scientific challenge stands in the way of quantifying the effects of such dramatically variable processes (soil slip, rockfall, or deep-seated deformations).

Beyond its potential contribution to landscape evolution, which deserves to be evaluated and accounted for in geomorphological models, understanding the evolution of landslides has a major social impact. Landslides cause enormous human and material losses (estimated at more than $7 billion per year by the 2nd World Landslides Forum in 2011; ISPRA Press Release) and represent a major natural hazard for millions of people living on steep and unstable slopes. In many countries, the disastrous effects of landslides can outweigh the consequences of other natural disasters, such as earthquakes and floods (Schuster and Fleming, 1986; Alexander, 1989; Guzzetti et al., 1999).

The Himalaya is one of the youngest and most active mountain ranges on Earth. Intense erosion arises from tectonic activity in the central Himalaya and adjacent monsoon rainfall. Previous studies (Shroder, 1998; Shroder and Bishop, 1998; Barnard et al., 2006; Dahal and Hasegawa, 2008) showed that slope failure is the major erosion process in unglaciated regions of the Himalayas. In particular, a special emphasis has been given to giant, late Quaternary rockslides (Weidinger et al., 1996; Weidinger, 2006; Dortch et al., 2009). However, compared to other landslide-prone regions of the world (such as Japan or Italy), the survey of active Himalayan landslides, despite their importance, remains limited. If landslides are the main erosion process on the steep Himalayan slopes, their mid-term evolution needs to be more thoroughly documented and their contribution to the total erosion still needs to be quantified.

In this study, we monitored a single, large landslide in a small catchment of the central High Himalayas, the Khudi catchment (Fig. 1). By comparing satellite and aerial images over 46 years, the evolution of the scar area can be calculated and volumes of exported sediment can be estimated. Then, equivalent erosion rates, i.e., erosion rates caused by landsliding, can be compared to catchment-scale total erosion rates obtained by independent methods (Gabet et al., 2004a, 2008). Finally, we discuss possible future propagation and/or stabilization processes by comparing the Khudi landslide with a slide in a neighboring catchment that presents similar features, but that has mostly been inactive during past decades.

2. Study setting

2.1. Geological and geomorphologic setting

The Himalayas are the result of the collision between India and Eurasia initiated 50 Ma ago (Patriat and Achache, 1984). The range

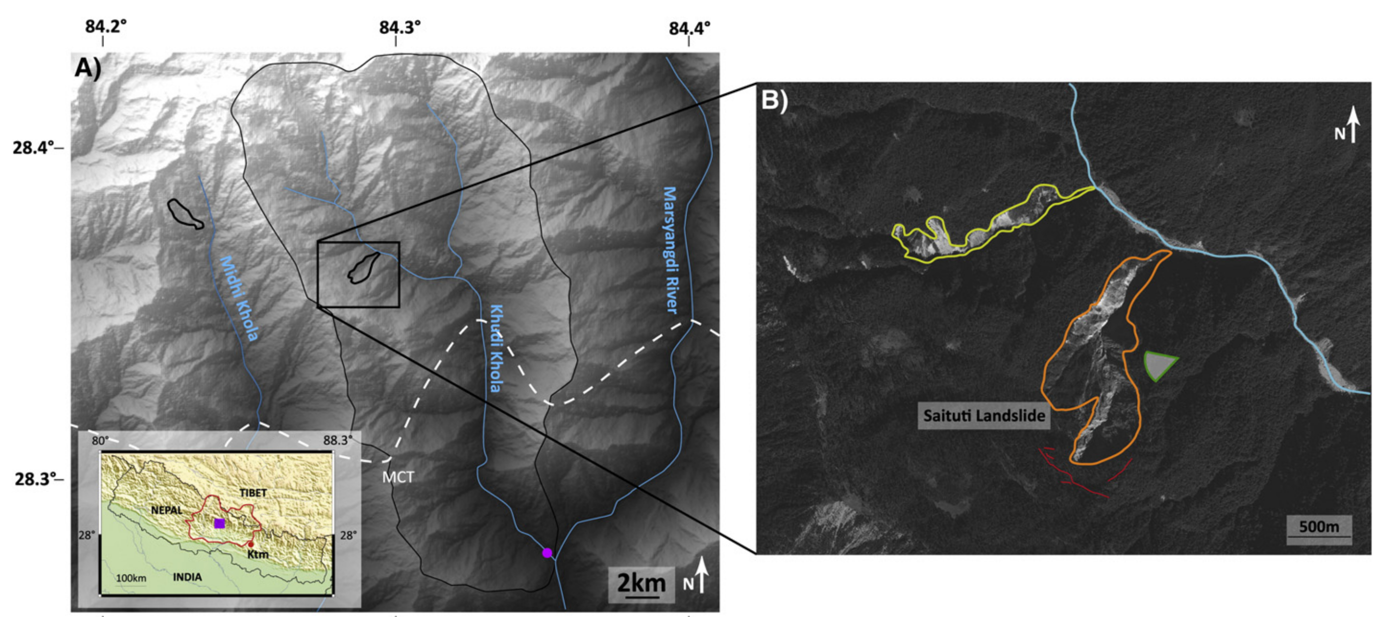

Fig. 1. Geographic setting. (A) In inset, topographic map of the Nepalese Himalayas and location of the study area (in purple) and of the whole Narayani catchment (red line). The main picture displays a shaded topography (derived from a 20-m Spot-DEM) of the Khudi catchment area in central Nepal. The Khudi catchment is delimited in black. The approximate trace of the Main Central Thrust, represented in white, separates black shales of the lesser Himalaya series in the south from quartzo-pelitic gneisses of the High Himalayan series in the north. Sediment sampling point from Gabet et al. (2004a, 2004b) is represented by the purple circle. (B) Zoom on the landslide areas. The two main Khudi landslide areas are delimited in orange (Saituti) and light green (Phorne), whereas the Midhi landslide, observed in an adjacent valley, is represented in (A).