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A cusp catastrophe model of mid–long-term landslide evolution over low latitude highlands of China

Yun Tao [a,b], Jie Cao [a,*], Jinming Hu [c], Zhicheng Dai [a]

[a] Department of Atmospheric Science, Yunnan University, Cuihu North Road 2, Kunming 650091, China
[b] Meteorological Institute of Yunnan Province, Kunming 650034, China
[c] Asian International Rivers Center, Yunnan University, Kunming 650091, China

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ABSTRACT

Based on a model describing a certain landslide case and catastrophe theory, we derived a cusp catastrophe model and corresponding inversion method to study mid–long-term landslide evolution. According to data of landslides, precipitation, and socioeconomic development from 1976 to 2008, the cusp catastrophe model describing this landslide evolution across a low-latitude highland area in China is obtained with the least squares method. Results of the model indicate that human activity determines landslide intensity. Local precipitation also impacts yearly landslide intensity to some extent, and controls the time when a strong and abrupt change in landslides occurs. During the period 1976–2008, there was an abrupt decrease of landslide intensity during 1994–1995, and an abrupt increase during 1995–1996. Since then, there have been frequent landslides in the low-latitude highland, with greater intensity. All these factors provide a scientific basis for formulating a contingency plan regarding landslide disasters.

1. Introduction

The cusp catastrophe was advanced in the 1970s (Thom, 1972; Zeeman, 1976) to depict phenomena characterized by abrupt and smooth changes, divergent and bimodal behaviors, hysteresis, and stability of structure. The major characteristics of a cusp catastrophe model are conceptualized in Fig. 1. The bottom blue and top red sheets in the figure respectively represent bimodal states before and after a certain behavior, controlled by two constraints as shown in the control panel. Bifurcation-set curves delineate the boundaries where abrupt changes of a state variable possibly occur. If constraints enter into and pass through the bifurcation set (e.g., the behavior along path B in Fig. 1), the state variable will show an abrupt jump upon encountering the edge of the pleat, even with a slight change of the constraints. If not (e.g., the behavior along path A), there is no abrupt change, i.e., the state variable shows a gradual change.

These cusp catastrophe characteristics have also been found in many geomorphic processes on the Earth's surface, such as landslides, debris flows, and river sediment transport. Therefore, the cusp catastrophe model was used by geomorphologists to explore the mechanism of these processes (e.g., Henley, 1976; Graf, 1979; Chappell, 1983; Thornes, 1983; Cui and Guan, 1993; Yi, 1995; Chau, 1998; Qin et al., 2001a,b, 2006; Li et al., 2009; Wang et al., 2011). Among these studies, more attention was paid to application of the cusp catastrophe to landslide studies. According to the mechanical model of a slip-buckling slope and the quasi-static motion process of the slope, Qin et al. (2001a) first established the expression of overall potential energy. They then determined the mechanical criterion of slope instability, and obtained a cusp catastrophe model for the slip-buckling slope. After they tested model applicability by applying their equations to the Bawang Mountain landslide, China, they suggested that the instability of a slope with given geometric and mechanical conditions depends on a certain combination of forces perpendicular and parallel to the slope surface. According to the mechanical model of a planar-slip slope, Qin et al. (2001b, 2006) obtained the overall potential energy by summing strain and potential energy components. They then presented a nonlinear cusp catastrophe model of landslides, and discussed the conditions leading to rapidly or slowly moving landslides. They found that slope instability depends mainly on the ratio of stiffness of the elasto-brittle medium to post-peak stiffness of the strain-softening medium, and that the effect of water increases material homogeneity or brittleness, thereby reducing the stiffness ratio. Long et al. (2001) obtained a standard cusp catastrophe model through variable substitution. They used the model in analysis of displacement data of the Huangci and Wolongsi landslides in China, to understand slope evolution before sliding. They also found that the nonlinear dynamic model made some satisfactory predictions. Assuming a shallow and infinitely long slope, and a slip surface made up of an elasto-brittle medium and strain-softening medium, Long et al. (2002) developed a cusp model of two control parameters with a simple law of mechanics. They found that when the slip surface is continuous and there is erosion caused by precipitation, control parameters of the slip surface may evolve such that a previously stable slope may abruptly become unstable, given a small

* Corresponding author. Tel.: +89 871 5033019; fax: +86 871 5033733.
E-mail address: caoj@ynu.edu.cn (J. Cao).

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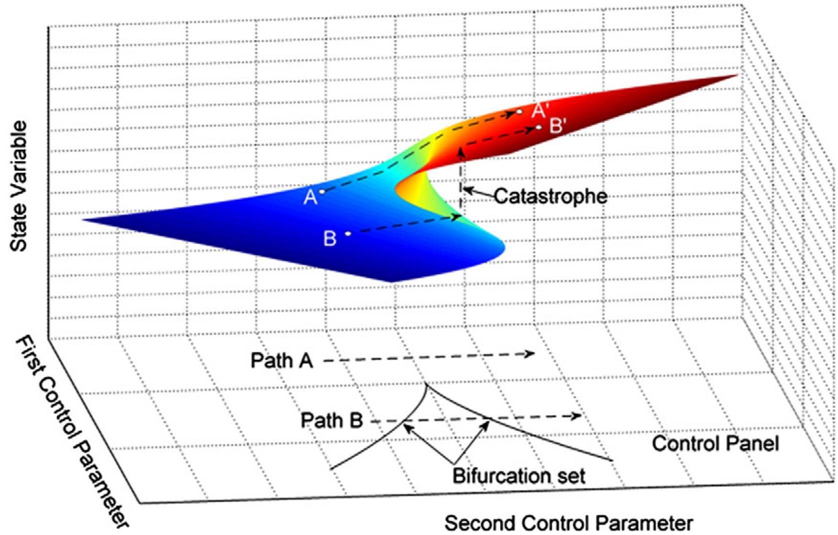

Fig. 1. Conceptual model of cusp catastrophe.

perturbation. According to the cusp catastrophe, Li et al. (2009) established a nonlinear dynamic model for simulation of landslide forecasting. According to a landslide case study and taking into account thickness of the sliding body, they suggested that periodic precipitation and reservoir level fluctuation are the main factors leading to step-like changes in the curve of monitoring displacement.

Low-latitude highlands are found south of 30° latitude, where average altitude usually exceeds 1500 m above sea level. In China, these areas include Yunnan, southern Sichuan, and western Guizhou and Guangxi provinces (Fig. 2). In these areas, environmental and geologic backgrounds such as undulant terrain, strong tectonic movement, weak geologic structures, and fragmented rocks provide favorable conditions for landslides (Tang et al., 1995; Tang and Zhu, 2003). Highly concentrated precipitation and frequent rainstorms in the rainy season favor the triggering of landslides (Qin et al., 1997; Liu et al., 2011). Landslides and debris flows occur widely and frequently in the highlands, causing great losses of life and properties. For example, in 1986, 1989 and 1990, the death toll from landslide disasters in the highlands exceeded 200 per year, and their direct economic loss reached 0.3 billion RMB (Wen and Liu, 2006). Furthermore, a landslide disaster during October 24 and November 2, 2008 affected 1.07 million people, with 83 people dead or missing, and direct economic loss of 0.59 billion RMB (www.gov.cn/jrzg/2008-11/04/content_1139616.htm).

Since landslide disasters seriously threaten the life and properties of local people and restrict regional socioeconomic development, landslide evolution in the highlands has been studied to satisfy the increasingly urgent demand for disaster mitigation and control (e.g., Tang et al., 1995; Tang and Zhu, 2003). Tao et al. (2005) indicated that a rainstorm on the previous day was the principal direct meteorological condition for landslides and debris flows in Dehong Prefecture on July 5, 2004, in addition to geologic and geomorphologic conditions. Duan et al. (2007) investigated the relationship of landslides and debris flows with precipitation in Yunnan Province under different geologic and geomorphologic conditions. They found a close relationship of the landslides and debris flows with antecedent cumulative precipitation. The critical precipitation for the landslides and debris flows changes with the aforesaid conditions. In a study on mid–long-term landslide and debris flow evolution in the low latitude highlands, Tang and Zhu (2003) defined an area index of this evolution, finding that the area with landslides and debris flows tended to enlarge over their research period. The active period was mainly from the early 1980s to mid-1990s, which was intimately associated with precipitation. Tao et al. (2009) indicated the interannual variability of landslides and debris flows in Yunnan. The

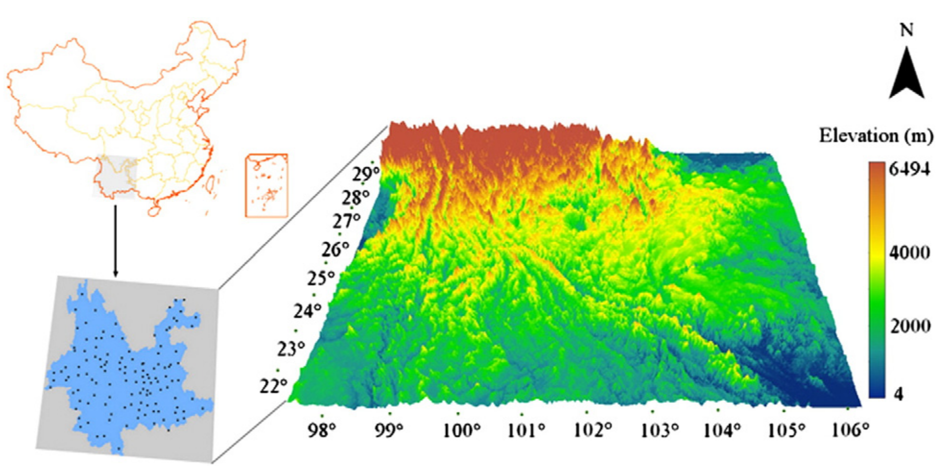

Fig. 2. Low-latitude highlands of China. Rainfall stations are denoted by black dots.