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

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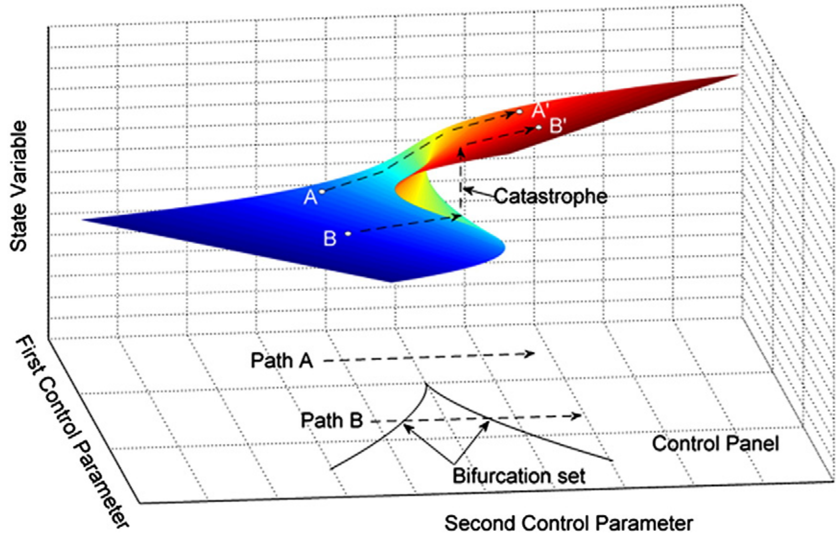

Fig. 1. Conceptual model of cusp catastrophe.

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

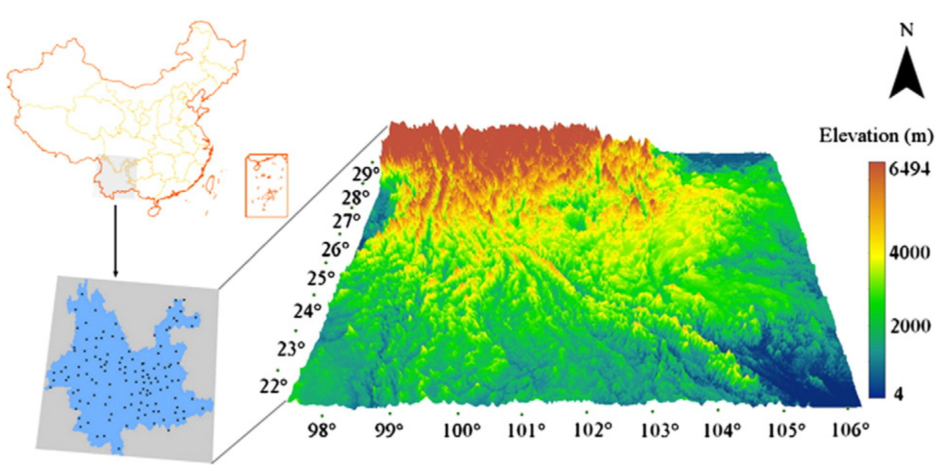

Fig. 2. Low-latitude highlands of China. Rainfall stations are denoted by black dots.

frequency of landslide/debris flow hazards is strongly related to annual precipitation and the annual number of rainstorm and heavy rain events. In other words, atmospheric circulation anomalies strongly influence the frequency of landslide/debris flow hazards.

From the aforementioned review, we found that the majority of studies focused on certain short-term cases. Therefore, the mid–long-term landslide evolution in the low latitude highlands of China still remains unclear. This motivated our exploration of landslide evolution. The mechanical model of planar-slip slope instability developed by Qin et al. (2001b) includes two constraints: one is directly related to geologic and geomorphologic conditions, and the other indirectly to rainfall. Because both represent the major controlling factors of landslides, we adopted this model and cusp catastrophe theory to study the mid–long-term landslide evolution. Based on the model of Qin et al. (2001b), the governing equations describing landslide evolution and a corresponding data retrieval method are developed in Section 2. Section 3 describes the mechanism of the evolution and the impacts of human activity and precipitation on it. Section 4 gives discussion and conclusions.

2. Methods

2.1. Governing equation

Assuming that the sliding surface with obliquity β is an inhomogeneous intercalation composed of only two kinds of media with different mechanical features, and the rock mass above a sliding surface is a rigid body (Fig. 3), a nonlinear catastrophe model of planar-slip slope instability derived by Qin et al. (2001b) is as follows:

$$\frac{2G_s l_s u_1 e^{-2}}{3h}\left(\frac{u-u_1}{u_1}\right)^3+\frac{G_s l_s u_1 e^{-2}}{h}\left(\frac{G_e l_e e^2}{G_s l_s}-1\right)\left(\frac{u-u_1}{u_1}\right)+\frac{2G_s l_s u_1 e^{-2}}{3h}\left(1+\frac{G_e l_e e^2}{G_s l_s}\right)-mgh\sin\beta=0 \quad (1)$$

where G_s is the initial shear modulus; G_e is the shear modulus; u is creeping displacement; u_0 is the displacement value at peak stress and $u_1=2u_0$; l_s and l_e are lengths of the sliding surface for the strain-softening medium and elasto-brittle medium, respectively; H, h, β and mg (g is acceleration of gravity) are vertical height of rock mass, layer thickness of the intercalation, dip angle of the sliding surface, and weight of the rock mass, respectively; and e is the exponential function.

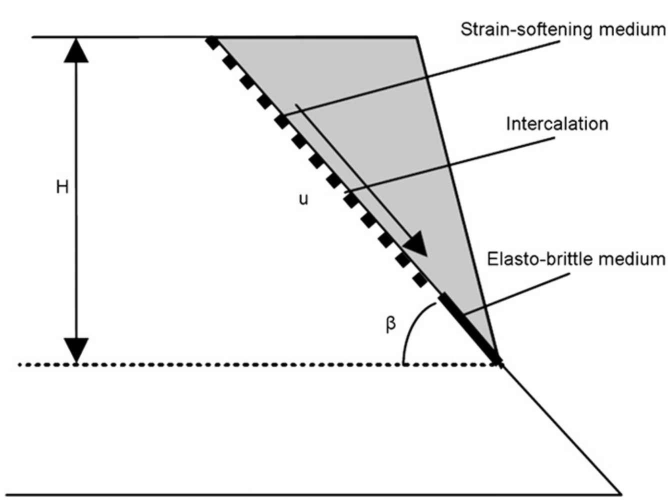

Fig. 3. Mechanical model of a planar-slip slope.

Given $a=\frac{2G_s l_s u_1 e^{-2}}{3h}$, $b=\frac{G_s l_s u_1 e^{-2}}{h}\left(\frac{G_e l_e e^2}{G_s l_s}-1\right)$, $c=\frac{2G_s l_s u_1 e^{-2}}{3h}\left(1+\frac{G_e l_e e^2}{G_s l_s}\right)$, $\xi=-mgh\sin\beta$, $x=\left(\frac{u-u_1}{u_1}\right)$, one has:

$$ax^3+bx+c+\xi=0 \quad (2)$$

Further, given the landslide displacement index (LDI, shortened as P) that is proportional to displacement x, the potential function of LDI ($=P$) is expressed as:

$$V(P,a,b)=\frac{1}{4}aP^4+\frac{1}{2}bP^2+cP+\xi P \quad (3)$$

Van Beek (2002) and Tang and Zhu (2003) indicated that human activities in the highland area affecting landslides include: infrastructure construction projects such as roads and canals; nonferrous metal mining which directly weakens the strength of rock and soil through changing physical characteristics of the slope; deforestation especially the disappearance of tree roots, which decreases rock and soil cohesion of the slope; and house building which heaps additional soil and rock on a slope, increasing its weight. Recently, Crozier (2010) came to a similar conclusion regarding the detrimental impact of human activity on landslides. Since both parameter b in Eq. (3) and local human activity are related to change in environmental geological conditions, we propose a function between b and local human activity:

$$b=f_1(I_{\mathrm{human}}) \quad (4)$$

where I_{human} is an index of local human activity. Further, because local precipitation triggers landslides through increasing slope weight and weakening soil and rock strength, we also propose a function between parameter $c+\xi$ and precipitation, namely,

$$c+\xi=f_2(I_{\mathrm{rain}}) \quad (5)$$

where I_{rain} is an index of local precipitation.

Making a Taylor series expansion with respect to I_{human} for Eq. (4) at $I_{\mathrm{human}}=0$, and I_{rain} for Eq. (5) at $I_{\mathrm{rain}}=0$, truncating those beyond the linear terms, one readily obtains:

$$b=f_1(I_{\mathrm{human}}=0)+f_1'(I_{\mathrm{human}}=0)I_{\mathrm{human}}+\mathrm{R}_1=\mathrm{B}_0+\mathrm{B}_1 I_{\mathrm{human}} \quad (6)$$

and

$$c+\xi=f_2(I_{\mathrm{rain}}=0)+f_2'(I_{\mathrm{rain}}=0)I_{\mathrm{rain}}+\mathrm{R}_2=\mathrm{A}_0+\mathrm{A}_1 I_{\mathrm{rain}} \quad (7)$$

where A_0, A_1, B_0, B_1, R_1 and R_2 are constants.

Substituting Eqs. (6) and (7) into Eq. (3) yields:

$$V(P,a,b)=\frac{1}{4}aP^4+\frac{1}{2}(\mathrm{B}_0+\mathrm{B}_1 I_{\mathrm{human}})P^2+\mathrm{A}_1 I_{\mathrm{rain}}P+\mathrm{A}_0 P \quad (8)$$

Since there is a relation between the potential function V and the state variable as:

$$\frac{\partial P}{\partial t}=-\frac{\partial V}{\partial P} \quad (9)$$

we can study mid–long-term landslide evolution in the highlands with the following:

$$\frac{\partial P}{\partial t}=-\frac{\partial V}{\partial P}=-\left[aP^3+B_1 I_{\mathrm{human}}P+B_0 P+A_1 I_{\mathrm{rain}}+A_0\right] \quad (10)$$

2.2. Retrieval method for governing equation

Because the time interval of observational data is 1 year ($\Delta t = 1$), Eq. (10) should be discretized to retrieve corresponding parameters. The discretized form of this equation is:

$$P(t+1) = -\left[aP^3(t) + B_1 I_{human}(t)P(t) + (B_0 - 1)P(t) + A_1 I_{rain}(t) + A_0\right] \quad (11)$$

The matrix form is

$$\mathbf{P} = \mathbf{LX} \quad (12)$$

where

$$\mathbf{P} = [P(2) \quad P(3) \quad \dots \quad P(n)], \quad (13)$$

$$\mathbf{X} = \begin{bmatrix} P^3(1) & P^3(2) & \cdots & P^3(n-1) \\ I_{human}(1)P(1) & I_{human}(2)P(2) & \cdots & I_{human}(n-1)P(n-1) \\ P(1) & P(2) & \cdots & P(n-1) \\ I_{rain}(1) & I_{rain}(2) & \cdots & I_{rain}(n-1) \\ 1 & 1 & \cdots & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{P}^3 \\ \mathbf{I}_{human}\mathbf{P} \\ \mathbf{P} \\ \mathbf{I}_{rain} \\ 1 \end{bmatrix} \quad (14)$$

$$\mathbf{L} = -[a \quad B_1 \quad B_0 - 1 \quad A_1 \quad A_0] \quad (15)$$

and n is the sample number. Since $n >> 5$, the parameters in $\mathbf{L}$ of Eq. (15) are determined by the least squares method.

3. Results

3.1. Retrieved catastrophe model for low-latitude highlands

Data from Yunnan were used, because it is at the core of the highland area. These data include landslides, normalized total precipitation I_{rain}, cultivated area, miles of roads, hydropower capacity, population, and nonferrous metal output (Yunnan Bureau of Statistics, 1990–2009; Committee of Yunnan Yearbook for Disaster Reduction, 1997–2009; Yunnan Disaster Prevention Association, 1999; Tang and Zhu, 2003; Tao et al., 2005). The research period is from 1976 to 2008. The number of landslides in each year was counted. Since most landslides in the highlands occur suddenly on unstable slopes with very complex geological conditions, the displacement of each landslide cannot be measured with precision. Additionally, because the spatiotemporal scales in this study are much larger, we neglected the displacement of each landslide. The sum of yearly landslide numbers was used as LDI ($= P$). The normalized precipitation summed over the research domain was used as I_{rain}. The first principal component was extracted from cultivated area, road miles, hydropower capacity, population and nonferrous metal output using principal component analysis. Since the first component explained 91.9% of total variance of the five variables reflecting local human activity, the component was used as I_{human} (Fig. 4).

Substituting normalized $P(t)$, $I_{rain}(t)$ and $I_{human}(t)$ into Eq. (11), in which $t = 1976, 1977 \dots 2008$, the parameters in this equation were obtained using the least squares method. The obtained model is:

$$P(t+1) = -0.207P^3(t) + 0.120 I_{human}(t)P(t) + 1.390P(t) + 0.249 I_{rain}(t) + 0.268 \quad (16)$$

Fig. 4 shows that the fitted value successfully represents the observed LDI evolution. Indeed, the multiple correlation coefficient (0.78) of Eq. (16) passes the significance test at the 99.9% confidence level. Eq. (16) shows that human activity and precipitation are

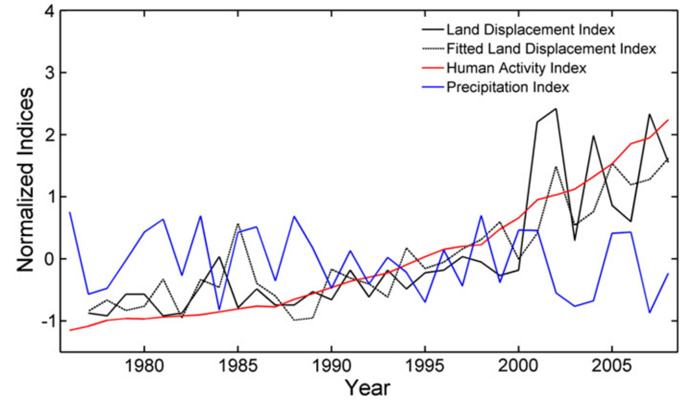

Fig. 4. Evolution of landslide displacement, human activity and precipitation indices in low-latitude highland.

proportional to LDI, in agreement with previous research results (Van Beek, 2002; Duan et al., 2007; Wang et al., 2008; Zhang et al., 2008; Tao et al., 2009; Crozier, 2010). Therefore, Eq. (16) has a physical meaning and can be used to study mid–long-term landslide evolution in the highland area.

3.2. Mechanism of mid–long-term landslide evolution

When the landslide attains equilibrium, the surface composed of all equilibrium points can be derived from Eq. (16) as:

$$0.207P^3 - (0.120 I_{human} + 0.390)P - (0.249 I_{rain} + 0.268) = 0 \quad (17)$$

The cusp catastrophe described by the equilibrium surface containing two pleats is presented in Fig. 5, in which the two horizontal axes are related to the control parameters I_{human} and I_{rain}, and the vertical axis to the state variable P. The behavior of P on the equilibrium surface has gradual or abrupt change along the equilibrium sheet. If the point moves continuously up the equilibrium sheet along path A, there will be a gradual increase in the value of P with a continuous increase of rainfall. If the point moves along path B, P will have an abrupt jump to the higher equilibrium sheet even with a slight change in rainfall, because it encounters the edge of the pleat. A control panel is the surface denoted by the human activity and rainfall effects, or the projection of a three-dimensional equilibrium surface in the two-dimensional control space. The curve called the singularity set marks the edges of the pleat on the equilibrium surface, where

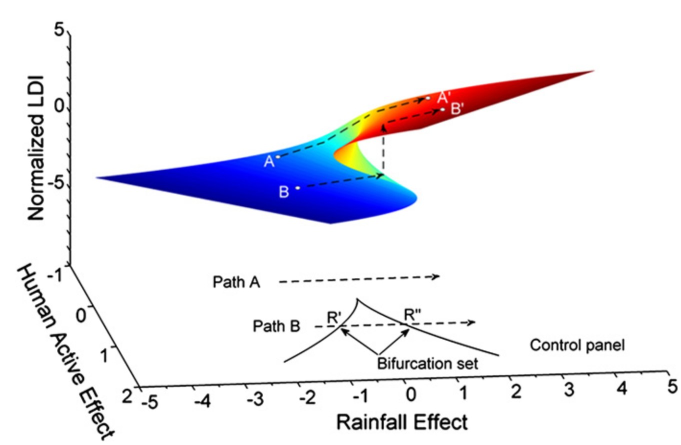

Fig. 5. Cusp catastrophe model describing mid–long-term landslide displacement evolution in low-latitude highland area.

the lower and higher sheets fold over to construct the middle sheet. The singularity set was determined from:

$$-0.621P^2 + (0.120I_{\text{human}} + 0.390) = 0 \quad (18)$$

By combining Eqs. (17) and (18) and eliminating P, the bifurcation set is obtained as:

$$4\left(-\frac{0.120I_{\text{human}} + 0.390}{0.207}\right)^3 + 27\left(-\frac{0.249I_{\text{rain}} + 0.268}{0.207}\right)^2 = 0 \quad (19)$$

The set determines the thresholds at which abrupt changes appear. If the control point stays outside the bifurcation set, P changes smoothly with the variation of the two control parameters. If the point determined by the two control parameters enters into the bifurcation set but does not pass through that set, the abrupt change of P will not take place. However, if the control point crosses the bifurcation set, an abrupt change of P is inevitable.

Combining Eqs. (16), (17) and (18) with the mid–long-term landslide evolution in the highlands, the corresponding mechanism was obtained as follows. For $(0.120I_{\text{human}} + 0.390) < 0$, i.e., relatively weak human activity, Eq. (17) has only one root, and P gradually increases or decreases with continuous variation of local precipitation. This type of gradual LDI evolution corresponds to the motion along path A in Fig. 5. However, for $(0.120I_{\text{human}} + 0.390) > 0$, i.e., relatively high human activity, Eq. (17) has three roots inside the area delimited by the bifurcation set. P jumps discontinuously from low to high values, with local precipitation increasing continuously from a negative to positive anomaly, crossing point R'' on the right bifurcation curve in Fig. 5. This type of abrupt LDI evolution corresponds to shifting along path B in Fig. 5. To clarify the two types of LDI evolution, we further analyzed this evolution before 1993 and after 1994 with real numbers, because the value of $(0.120I_{\text{human}} + 0.390)$ was <0 before 1993, but >0 after 1994.

Table 1 shows differences in the average and standard deviation of rainfall in Yunnan between the two periods were only 4 and 0.5 mm, respectively, but LDI evolution was significantly different. During 1977–1993, normalized I_{human} was -0.79, i.e., human activity was relatively low, LDI caused by per unit rainfall was smaller, and LDI standard deviation was 6. However, during 1994–2008, normalized I_{human} reached 0.84, i.e., human activity was relatively high, LDI caused by per unit rainfall was larger, and LDI standard deviation reached 25. The mean value and variable amplitude of LDI under the condition $(0.120I_{\text{human}} + 0.390) < 0$ were smaller than those under the condition $(0.120I_{\text{human}} + 0.390) > 0$. This suggests that the abrupt LDI evolution along path B is very different from the gradual LDI evolution along path A.

Since the two pleat edges corresponding to the two curves of the bifurcation set do not coincide, LDI cannot return to low values even though precipitation decreases to the point R'', where the abrupt increase of LDI occurs (Fig. 5). Only if precipitation decreases across the negative anomaly point R' on the left bifurcation curve, LDI can abruptly decrease from high to low values.

To distinguish more nonlinear characteristics of the mid–long-term landslide evolution, the point $\left(\frac{0.120I_{\text{human}}(t)+0.390}{0.207}, \frac{0.249I_{\text{rain}}(t)+0.268}{0.207}\right)$ was drawn for each year on the control panel, where the vertical axis is the precipitation effect and horizontal axis the human activity effect (Fig. 6). Before 1991, $(0.120I_{\text{human}} + 0.390) < 0$ and environmental geology conditions were less damaged by (relatively weak) human activity, and highland landslide evolution was in the area of gradual change. LDI changed smoothly with precipitation. Since the early 1990s, the value of $(0.120I_{\text{human}} + 0.390)$ has changed from negative to positive, indicating that human activity caused landslide evolution to move into the abrupt change area, by significantly destroying the environmental geology conditions. The landslides became more sensitive to precipitation, i.e., a gradual precipitation change caused abrupt LDI change. Fig. 6 indicates that LDI had two abrupt changes after 1990: an abrupt decrease during 1994–1995 associated with rainfall decrease, and an abrupt increase during 1995–1996 associated with rainfall increase. With human activity increase after 1996, the environmental geology conditions worsened during the research period. This caused LDI to remain high. Because the change of control parameters did not cross the critical value, i.e., the blue bifurcation curve in Fig. 6, landslide displacement in the highland was comparatively large.

Table 1
Difference between abrupt and gradual LDI evolutions.

Period	Normalized I_{human}	Average rainfall (mm)	Standard deviation of rainfall (mm)	Average LDI	Standard deviation of LDI
1977–1993	−0.79	90	7.5	14	6
1994–2008	0.84	94	7.0	44	25

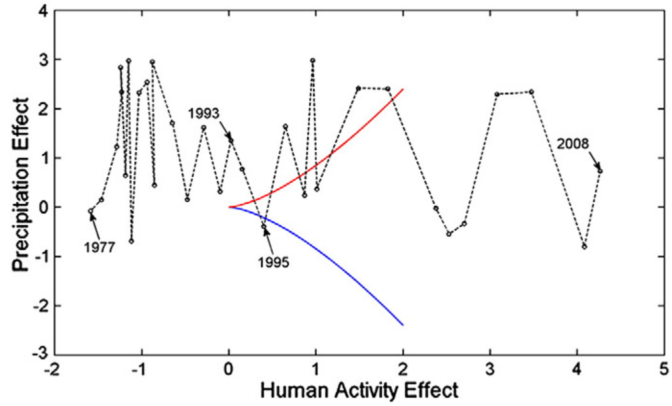

Fig. 6. Mid–long-term landslide displacement evolution in low-latitude highland area, projected on control panel.

3.3. Mann–Kendall analysis of LDI

To verify reliability of the above catastrophe analysis results, we detected the abrupt change point in the LDI ($=P$) series with the Mann–Kendall method (Goossens and Berger, 1986). Fig. 7 shows that there was a significant increasing trend of LDI after the mid-1980s, and the blue and red lines crossed each other in 1995, indicating that

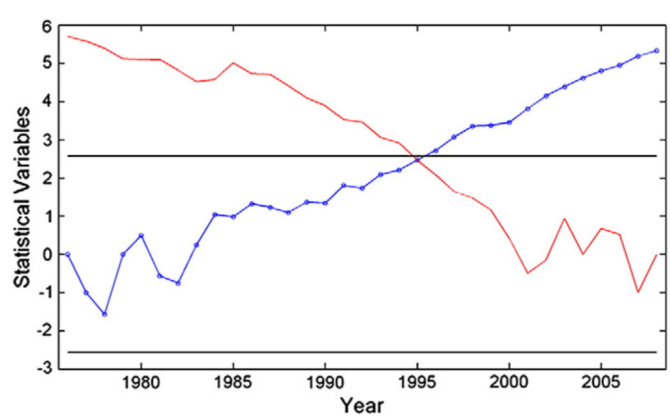

Fig. 7. Detection result of abrupt change point in landslide displacement index series. Black solid lines denote critical value passing significance test at 99% confidence level.

the LDI increase of 1995–1996 was abrupt. The Mann–Kendall results agree with those in Section 3.2, indicating the reliability of results from catastrophe theory.

4. Discussion and conclusions

Based on previous research on landslides and catastrophe theory, a cusp catastrophe model was developed to study mid–long-term landslide evolution. The cusp catastrophe model includes two control parameters: one for human activity and the other for precipitation. Human activity determines whether a landslide occurs abruptly or gradually, through changing environmental geology conditions. Local precipitation also influences landslide intensity to some extent, and controls when a landslide occurs through increasing the weight of rock and soil.

Parameters in the cusp catastrophe model were obtained by the least squares method and corresponding data from the low-latitude highland region of China. The obtained cusp catastrophe model has five classical features: sudden transitions, hysteresis, bimodality, inaccessibility, and divergence (Zeeman, 1976). Before the 1990s, landslide evolution was limited to the unimodal area because of relatively weak human activity, so that only rainfall change caused the gradual change in LDI (landslide displacement index). After the early 1990s, human activity in the area greatly increased. This caused landslide evolution to enter into an area in which the bimodal state may be encountered, so that rainfall change can trigger sudden transitions of LDI with a large margin. Over the period 1976–2008, there was an abrupt decrease of LDI during 1994–1995, and an abrupt increase during 1995–1996. Since then, LDI in the area has remained relatively high, indicating frequent landslide occurrence. The abrupt change during 1995–1996 was detected with the Mann–Kendall method, which agreed with the catastrophe model output, suggesting that the cusp catastrophe model describing the mid–long-term landslide-area evolution is reasonable and reliable. We can thus adopt this model to decipher the effect of human activity and climate change on landslide activity.

The cusp catastrophe model also provided a treatment method for landslides in the low-latitude highlands. During the research period, human activity consistently aggravated environmental geology conditions, which pushed landslide activity into the area of abrupt change. If these conditions stabilize and do not worsen further with human activity, the grave status of landslide activity will not improve, that is, even a precipitation decrease will not significantly reduce this activity because of the hysteresis effect. If the environmental geology conditions improve significantly with a reduction in destructive human activities, via landslide control measures (e.g., bolt supports, nets sprayed with concrete, and retaining walls at the foot of mountains) and forest vegetation recovery, landslide activity may return to the area of gradual change. With such amelioration, precipitation conditions will cause a gradual change of landslide activity in the highlands; a precipitation decrease would immediately reduce landslide activity, because the hysteresis effect would vanish. In conclusion, our method can provide a new way to predict landslide occurrence on the interannual timescale, by connecting landslide evolution to human activity and climate change.

There are limitations of the cusp catastrophe model, including the designation of control factors, definition of potential, qualitative nature of the theory, and its generality (e.g., Graf, 1979). If we can overcome these limitations, however, the cusp catastrophe model has great value in the study of geomorphic processes at Earth's surface. The results here suggest that as long as the cusp catastrophe model is derived from a mechanical model, the corresponding control factors and potential function will have clear physical meaning. Additionally, the model obtained from observational data permits quantitative study of the mechanism of mid–long-term landslide evolution. Therefore, the cusp catastrophe model developed here can be generally applied to the study of mid–long-term landslide evolution with catastrophe features.

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