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Human vulnerability to quick shallow landslides along road: fleeing process and modeling

Abstract Throughout the history, many lives have been lost due to landslides. Understanding the process of human flight during landslide events is important in assessing the risks posed by future landslides. This study proposes a model for simulating human flight from a quick shallow landslide along a road, quantifies the flight success rate, and identifies the crucial variables that impact flight efficiency. A questionnaire survey was undertaken along a stretch of highway near Yingxiu, China to collect information regarding human responses and behavior in the face of landslide events. The factors influencing human flight are classified into factors related to the evacuees, the landslide intensity, and the flight path. Subsequently, a flight model is proposed to simulate the movements of people randomly located along a road threatened by landslides. Various components of "available time" and "demand time" for escaping from the landslide affected area are treated as random variables. Based on this model, probability analysis is conducted to estimate the flight success rates of the people at risk when fleeing from landslides of various intensities. Sensitivity analysis shows that the pre-failure time and the response time are the most important factors in the flight process. Finally, comparison between the flight success rates from two existing methods and those from the new model is made.

Keywords Landslides · Slopes · Landslide risk · Risk analysis · Human vulnerability

Introduction

Landslides occur with a great destructive power and often lead to the loss of human lives. Risk evaluation for landslides in densely populated urban areas is currently one of the most important disaster mitigation tasks throughout the world (Sassa et al. 2004). Landslide risk is the product of the probability of occurrence of a specific landslide, vulnerability, and elements at risk (Fell 1994; Fell et al. 2008). Vulnerability to a landslide is defined as the level of potential damage or the degree of loss of a given element subjected to the landslide of a given intensity (e.g., Fell 1994; Leone et al. 1996; Dai et al. 2002). Various approaches to estimating the human vulnerability have been discussed qualitatively and quantitatively. Leone et al. (1996) proposed a vulnerability matrix method based on historic records. With this method, the vulnerability of people inside buildings depends on the characteristics of the landslide and the technical resistance of the building. Bell and Glade (2004) determined the vulnerability of building structures based on their resistance to debris flows and rock falls of different magnitudes. Vulnerability of persons in buildings was further assessed with regard to landslide process, landslide magnitude, and building type. Wong and Ko (2006) and Wong et al. (1997) proposed vulnerability factors for toe and crest facilities threatened by landslides. Uzielli et al. (2008) presented a scenario-based method for quantifying the vulnerability of the built environment to landslides. Lacasse et al. (2012), Lacasse and Nadim (2011), and Li et al. (2010) developed a "*VIS* model" to determine the physical vulnerability of structures and persons. During a landslide event, effective evacuation can significantly decrease the human vulnerability to the landslide.

As with the definitions for flood evacuation proposed by Frieser (2004), two types of human evacuation from a landslide can be distinguished as follows:

> *Evacuation*: The removal of people at risk to a safe place beyond the reach of the landslide, which is initiated by an evacuation warning disseminated by authorities and takes place in an organized manner.
> *Flight*: The removal of people after they realize an impending landslide, with the corresponding verb "flee." A flight could be impeded; for example, the debris of a landslide could block the fleeing people and hinder their flight, which may, in turn, increase the number of fatalities.

This study focuses on the flight process of people caught in a landslide. Several questions arise regarding the human flight from a landslide. How do human beings flee from a landslide? What are the flight success rates when the people are facing landslides with various intensities? What are the controlling factors that affect human flight? To answer these questions, a flight model is required which can be used to help understand the flight process and thus assess human vulnerability.

Studies on human evacuation have been underway for nearly 30 years for mitigating natural or human-induced hazards. One of the earliest papers was concerned with the modeling of emergency egress during fires (Stahl 1982). Gwynne et al. (1999) conducted a comprehensive review of 22 evacuation models. These evacuation models fall into two categories: those which only consider human movements and those which attempt to link human movements with human behavior. An appropriate criterion to classify these evacuation models was presented by Tavares (2009), who promoted discussions about evacuation models and their relations with evacuation processes. Kang et al. (2007) and Nilsson et al. (2009) conducted evacuation experiments on tunnel fires and provided insights regarding evacuees' response in terms of perception of technical installations, behavior, and emotional states. Table 1 summarizes several evacuation models for fires, floods, earthquakes, and hurricanes developed in the past several years (Barendregt et al. 2002; Lo et al. 2004; Peng and Zhang 2012a, b, 2013a, b).

Although quantifying and modeling human movement and behavior during the evacuation from various natural hazards (e.g., floods, earthquake, and hurricanes) were studied (Table 1), evacuation models specifically for simulating the human flight process from a landslide are still not available in

Table 1 Summary of existing evacuation models

Model	Type[a]	Hazard	Description	References
SGEM	Computer-based model	Fire	Evacuation from buildings	Lo et al. (2004)
FIRESCAP	Micro simulation model	Fire	Emphasis on behavioral characteristics of individual	Feinberg and Johnson (1997)
EXODUS	Computer-based model	Fire	Evacuation from mass transport vehicles	Galea and Galparsoro (1994)
DYDEM	Manual capacity model	Flood	Dynamic decision making for dam-break emergency management	Peng and Zhang (2012a, b, 2013a, b)
Traffic Module	Manual capacity model	Flood	Emphasis on analysis of evacuation time	Barendregt et al. (2002)
Han and Sell (1974)	Dissipation rate model	Flood	Model based on analysis of flood data	Bellamy (1986)
Choice model	Logistic regression model	Earthquake	Model based on the investigation of residence preference with respect to earthquake shelter	Tai et al. (2011)
EMBLEM	Manual capacity model	Hurricanes	Supply–demand model	CF 04 (2003)

[a] The type of evacuation model is defined based on Frieser (2004)

the literature. A model that considers the interactions between a landslide and human behavior in response to the landslide is particularly lacking. Based on the models of human evacuation developed for other natural hazards, the present study aims: (1) to propose a model for simulating human flight from landslides, (2) to quantify the flight success rates, and (3) to identify crucial variables that affect the flight efficiency. To obtain human behavioral data, a questionnaire survey was undertaken along a highway in China to reveal the respondents' awareness of landslides and their flight behavior. A flight model is ultimately proposed to simulate the movements of people randomly located along a road threatened by a landslide. Based on this model, probability analysis is conducted to estimate the flight success rate. The key variables are identified through a sensitivity analysis. Finally, the flight model is compared with two existing methods.

Process of human flight from a landslide

The process of human flight needs to be clearly described to better understand and hopefully reduce the human losses associated with landslides. Figure 1 illustrates a simplified process of people fleeing from a potential landslide, which is simulated using Pathfinder 2012 (Consultants TE 2012). Initially, the people are distributed randomly in an affected area (Fig. 1a). They make a decision on a variable flight exit route and begin to flee after becoming aware of the danger (Fig. 1b). Some of them change their fleeing route due to congestion in the original flight path (Fig. 1c). One adult with prior experience of flight from landslides may flee faster than one elderly without prior experience (Fig. 1d).

The flight process includes two stages, i.e., the pre-movement stage and the movement stage. Pre-movement begins at an alarm and ends when the travel to an exit begins. When there is a lack of effective early warning of a landslide, those evacuees who have previous experiences can judge the occurrence of a landslide according to signs such as remobilized stones or fallen trees. They may communicate with their neighbors to confirm the danger at the very beginning. After they confirm the potential threat, they will take actions and may flee immediately. In this process, the evacuees may take family members or valuable belongings. The movement process begins when the travel to the exit starts and ends when the evacuees reach a safe place. It is necessary to consider the coping capacity of each evacuee. People with effective coping capacity and good mobility can save themselves by choosing an effective shelter or taking the right flight path. Others may lose their lives during the landslide disaster.

Field survey of human responses to landslides

Questionnaire survey

A strong earthquake of magnitude 8 on the Richter scale occurred in Sichuan Province, China on 12 May 2008 and triggered numerous landslides (Chang et al. 2011; Zhang et al. 2012). Approximately 20,000 fatalities were directly caused by these earthquake-induced landslides (Yin et al. 2009). The Wangjiayan landslide (Fig. 2a) and the New Beichuan Middle School landslide (Fig. 2b), located at Beichuan County, caused 1,700 and 700 deaths, respectively. After the earthquake, additional loss of lives occurred again in the earthquake area due to rainfall-induced landslides or debris flows. On 13 August 2010, a storm swept through Yingxiu and its vicinity, triggering a catastrophic debris flow with a volume of 1.17 million m^3 in the Xiaojiagou Ravine (Fig. 2c) on Province Road 303 (PR303; Fig. 3). This debris flow killed approximately 50 people. As shown in Fig. 2d, repeated slides occurred at milestone K34 of PR303 in the past few years, causing two fatalities and at least three serious injuries (Zhang et al. 2013).

In order to investigate how human beings respond and behave when exposed to a landslide, a questionnaire survey

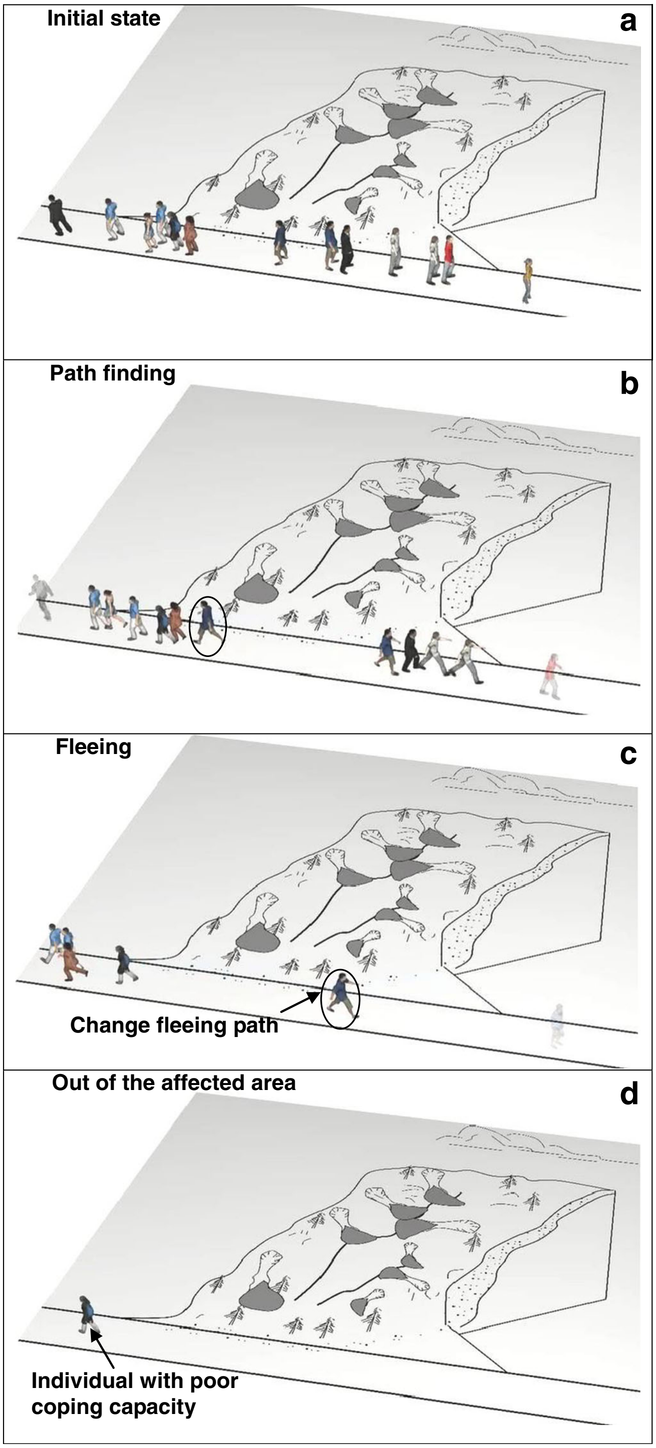

Fig. 1 Flight from a landslide: **a** initial state, **b** deciding the flight path, **c** fleeing, and **d** out of the affected area

was undertaken along PR303 (Figs. 3 and 4) from 20 December 2012 to 28 December 2012. The 45 km reach of PR303 is the only path from Yingxiu to the Research and Conservation Centre for Giant Pandas at Wolong (Fig. 3). People traveling along this road are vulnerable to landslides (Fig. 4). It is vital to flee from risky areas prior to or during the occurrence of a landslide.

The survey participants were mainly individuals who survived the Wenchuan earthquake and had personal experience in earthquake-induced landslides. The method used to analyze the human behavior included in-depth interviews (number= 61) and analysis of survey records. The survey attempted to cover key factors including population distribution, social characteristics of the interviewees, awareness of landslides, dissemination of warning signals, behavioral responses, etc.

Social characteristics of the interviewees

The social–economic characteristics of the interviewees are shown in Table 2. A total of 67 % of the respondents were locally employed and would stay in the investigated area at least in the following 5 years; 13 % of the respondents were local residents. In general, most of the respondents were educated and could identify landslide warning information.

In addition, a statistical analysis of the temporal distribution of road users along PR303 was conducted. The cumulative number of people who passed by PR303 was 1,586 during the day between 08:00 and 19:00 h. During the rush hours from 14:00 to 15:00 h, a total of 215 persons were recorded. The mean traffic flow during the daytime was 132 persons/h.

Human behavior analysis

Table 3 shows the primary results concerning the human flight behavior facing landslides. Of the respondents, 33 % passed along PR303 many times during a limited period, and 89 % of them were aware of landslides. Furthermore, the respondents had more fears about debris flows than slides and rock falls. If warning instructions were released, 69 % of the people stated that they would follow the instructions, and 26 % of them might make their own decisions depending on specific situations. Of all the respondents, 33 % had experienced some kind of landslide disasters, whereas 62 % had never previously experienced such disasters. When asked the question "What kinds of actions will you take before you decide to flee," 39 % replied "notifying people nearby," and the rest replied "taking care of family members" or "no delayed action."

The relationship between age and flight experience was also statistically examined. It was found that only 29 % of the people aged 20–39 had flight experience, compared with 46 % of the people aged 40 or older. Most of the participants aged between 20 and 39 answered "no delayed action," whereas 81 % of the people over the age of 40 chose to "notify people nearby" or to "take care of family members," rather than leave them behind.

Modeling human flight from landslides

Factors involved in human flight

The influencing factors involved in the human flight process from a landslide are classified into factors related to the evacuees, the landslide intensity, and the flight paths. The factors related to the evacuees include personal attributes of the evacuees, flight behavior, and exit choice decisions. Personal attributes account for differences in actions and reactions among the different types of evacuees, i.e., age, gender, disability, running speed, response, prior experience with

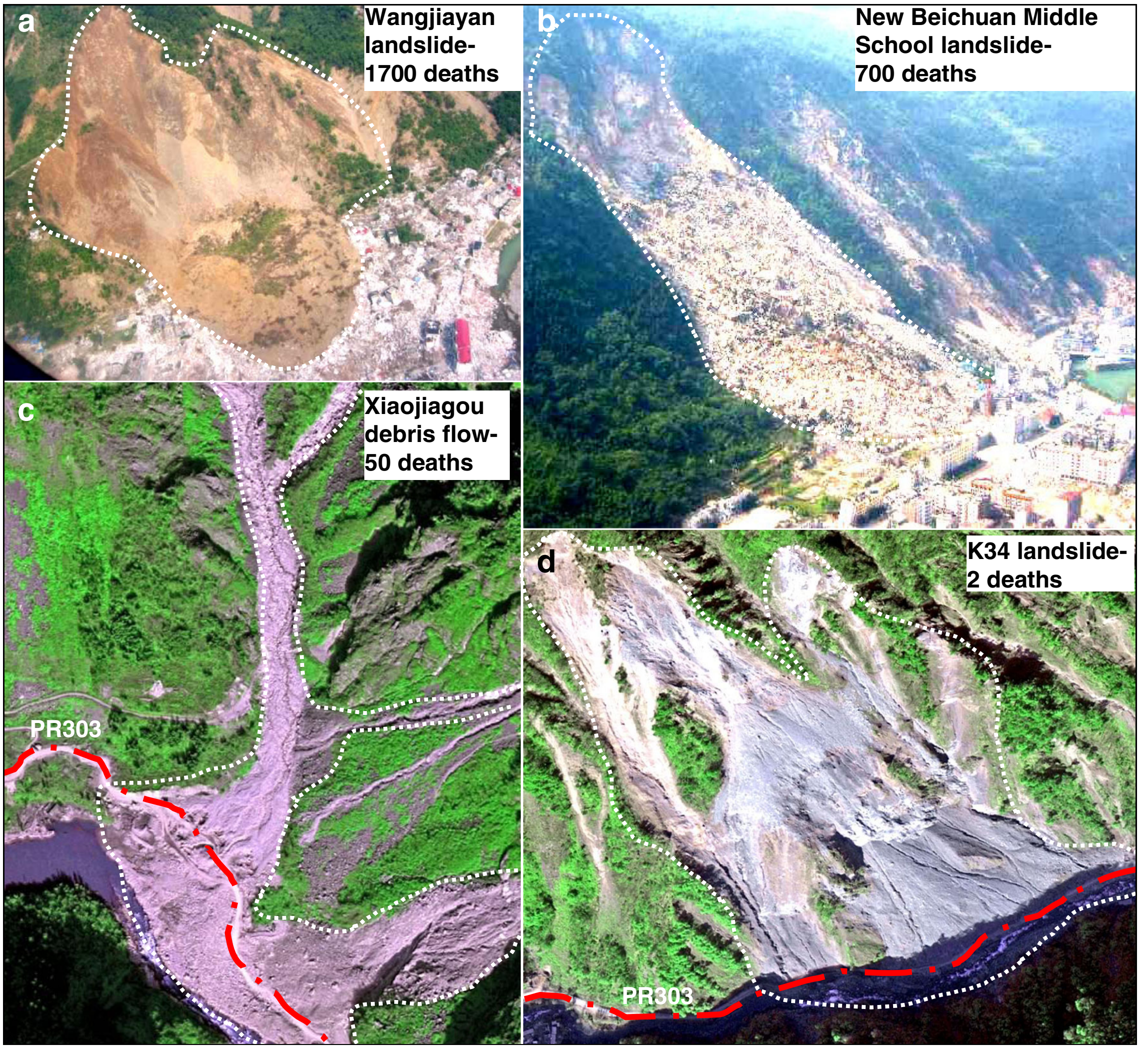

Fig. 2 Typical fatal landslides: **a** the Wangjiayan landslide, **b** the New Beichuan Middle School landslide, **c** the Xiaojiagou debris flow, and **d** the K34 landslide

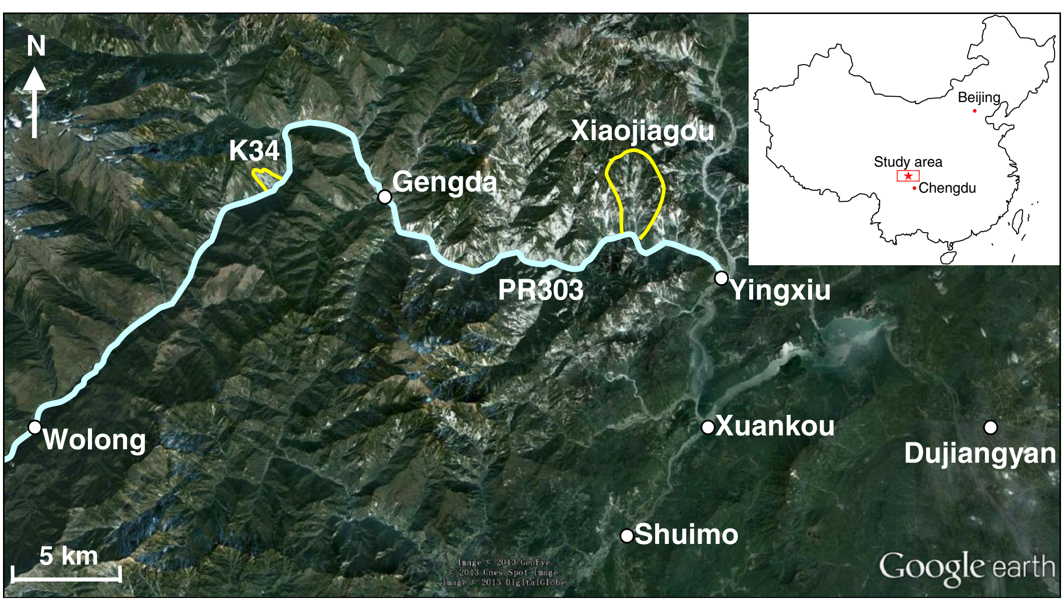

Fig. 3 Location of the survey area

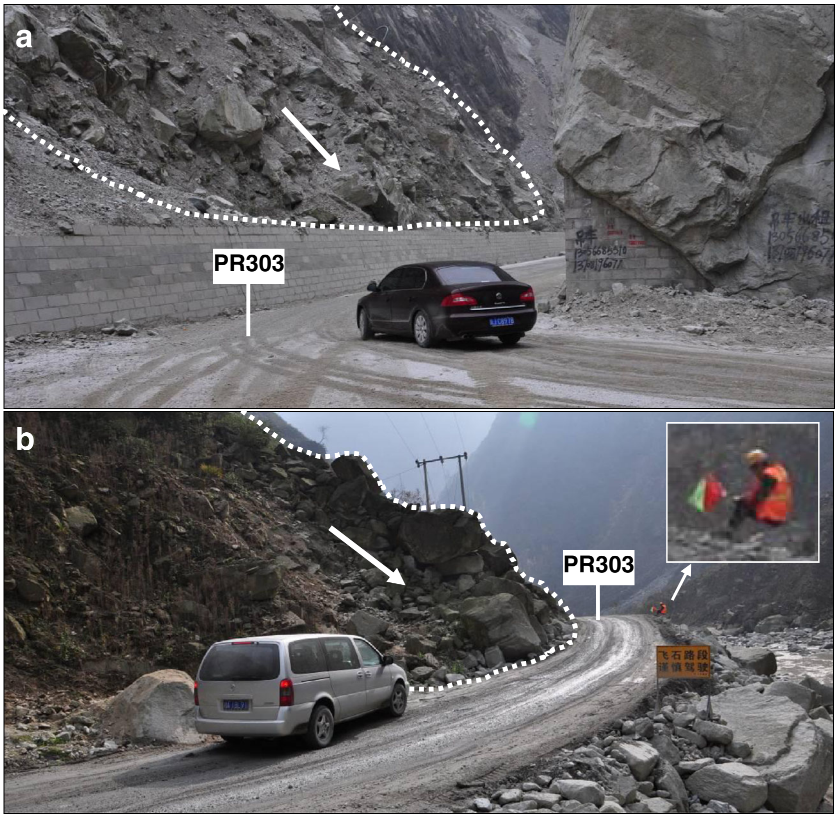

Fig. 4 Potential influence of landslide on road users along PR303: **a** potential threat posed by the landslides, and **b** notification of potential hazards by manual signaling

Table 2 Social description of evacuees in the field survey along PR303

Item	Variable	Number	Percentage (%)
Gender	Male	52	85
	Female	9	15
Age	<20	1	2
	20–29	21	34
	30–39	18	30
	40–49	17	28
	50–59	2	3
	>60	2	3
Education level	Elementary	3	5
	Junior high	15	25
	Senior high	7	11
	Undergraduate	33	54
	Graduate	3	5
Occupational category	Driver	6	10
	Construction worker	15	25
	Engineer	20	33
	Local resident	8	13
	Visitor	4	7
	Others	8	13

Table 3 Participants' view on response to landslides

Items	Distribution of participants' response				
Frequency of road use	Once per year 5 %	Once per month 13 %	Once per day 26 %	Several times per day 23 %	Many times during a limited period 33 %
Knowledge of landslides	Aware 89 %		Unaware 8 %		No idea 3 %
Fear of landslide effects	Slides 20 %	Rock falls 41 %	Debris flows 56 %		Others 3 %
Belief in early warning of landslides	Yes 69 %	No 2 %	Depends 26 %		Others 3 %
Clues of landslide for evacuation	Falling stones 44 %	Access restrictions 19 %	Notification from others 17 %	Traffic jams 13 %	Others 7 %
Reasons for delayed actions	Notifying people nearby 39 %	Collecting belongings 5 %	Taking care of family members 30 %	No delayed action28%	No idea 20 %
Previous experience of evacuation from a landslide	Experienced 33 %		Inexperienced 62 %		Others 5 %
Choice of shelter	Open space 64 %	Tunnel 15 %	Vehicle 0 %	Behind a big rock 15 %	No idea 10 %

Number of participants=61

landslides, and education. For instance, the mobility of people is found to be closely related to age. Ayis et al. (2006) selected 999 people over the age of 65 for a study of running speed. He found the aged usually had lower mobility and poor perceived health. Since people generally do not react instantaneously upon becoming aware of an emergency, a quick emergency response often depends on age. Flight behavior is considered since either communication with neighbors to confirm a situation or taking family members will affect the flight efficiency. Exit choice decisions determine the flight paths and will affect the flight efficiency as well. As illustrated in Fig. 1, all trapped people look for escape exits at both ends of the road. Once they make a decision, they will move toward that direction immediately (Fig. 1b and c).

The factors related to landslide intensities include the magnitude, sliding velocity, travel distance (quantified by reach angle, α), and affected area of the landslide (related to position angle, β). The reach angle is the angle of the line that joins the slope crest to the lowest point of the debris deposit (Fig. 5a). The position angle is the angle of the line that joins the slope crest to the feet of the person at risk (Fig. 5a).

The factors related to flight path include the locations of flight exits and the effective "road" width.

The nature of flight is complex owing to the inter-relationships among the evacuees, the flight path, and the landslide (Fig. 6). For example, the mobility of the evacuees is influenced by the degree of congestion along a flight path (i.e., crowd density). The reach angle of the landslide can be used to measure the extent of the flight path affected. The position angle defines the spatial location of the evacuees within the landslide affected area. These inter-relationships should always be considered in an evacuation analysis (Tavares 2009).

General framework

Assume that passengers are distributed randomly along a road threatened by a quick shallow landslide (Fig. 1). The evacuees run away from the landslide taking both ends of the road as the flight exits without considering possible shelters (e.g., cars, buildings, or a big stone). A general rule for judging flight success is as follows:

$$\text{Flight} = \begin{cases} \text{No response} & L < L_o \\ \text{Successful} & L > L_o,\ \ T_L \geq T_F \\ \text{Failed} & L > L_o,\ \ T_L < T_F \end{cases} \tag{1}$$

where L (m) is the travel distance of the landslide, which is defined as the horizontal distance from the topmost point of the head scarp to the farthest end of the landslide deposit (Corominas 1996; Fig. 5a); L_o (m) is the projected horizontal distance from the topmost point of the landslide to the inside edge of the road (Fig. 5a); T_L (s) is the available time, which is represented by the time for the debris to reach the elements at risk; and T_F (s) is the demand time, which is the total flight time needed. As shown in Fig. 5a, if $L<L_o$, the landslide debris does not reach the road and hence will not affect the individuals located on the road at the moment of the landslide; if $L>L_o$, the debris may bury the road and pose a threat.

In the general framework, the available time, T_L, and the demand time, T_F, are assumed to be two independent random variables, whose schematic probability distributions are illustrated in Fig. 7. The flight is considered as successful if the evacuees arrive at safe places before the landslide debris reaches them, i.e., $T_L \geq T_F$, and unsuccessful when $T_L < T_F$.

Figure 8 shows a flowchart for evaluating the human flight process from a landslide. If the landslide is initiated, whether the

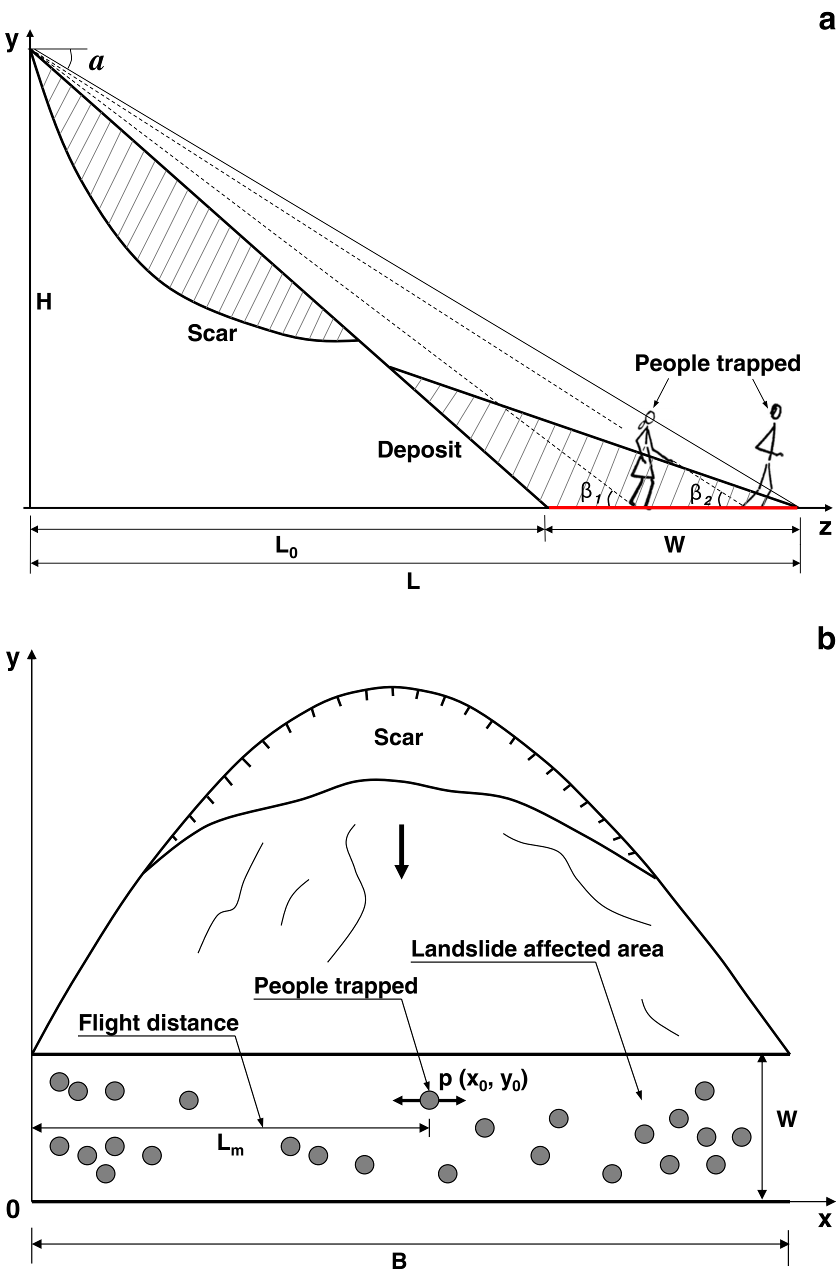

Fig. 5 Relationship between the landslide and the trapped people: **a** cross-sectional view showing the people on the road trapped by runout debris, **b** plan view showing locations of people trapped in the area affected by a landslide

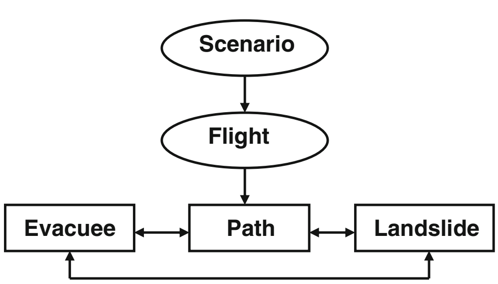

Fig. 6 Inter-relationship among the components involved in human flight from a landslide

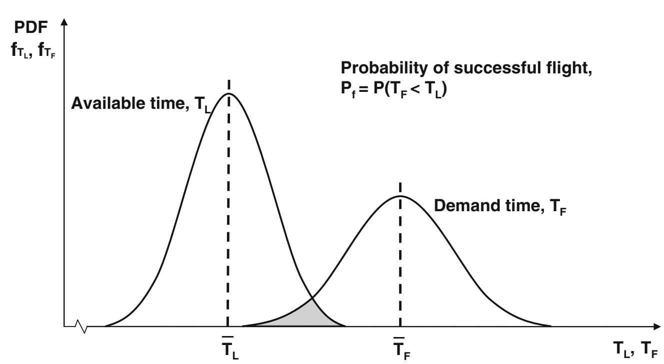

Fig. 7 Probability of successful flight from a landslide

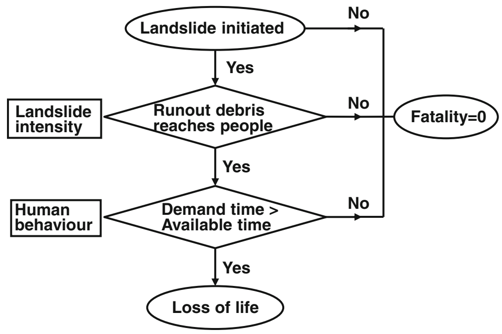

Fig. 8 Flow chart for evaluating human vulnerability to a landslide

landslide debris will reach the population at risk or not is evaluated first considering the intensity of the landslide. If the debris does reach the population at risk, then whether the population at risk has sufficient time to flee or not is evaluated considering the human behavior when facing the landslide. The flight success rate is the probability of $T_L > T_F$ (Eq. 1 and Fig. 7), which can be calculated through Monte Carlo simulation once the probability distributions of T_L and T_F are fully defined.

Available time, T_L

The available time, T_L, consists of pre-failure time and debris travel time:

$$T_L = T_{pt} + T_t \quad (2)$$

where T_{pt} (s) is the pre-failure time, which is the elapsed time from when precursors of landslide are identified to the time when the landslide initiates; T_t (s) is the time for the sliding materials to travel to the elements at risk and is directly related to the travel distance, L (m), and the horizontal component of the sliding velocity, v (m/s).

The travel distance, L, can be estimated using an empirical relationship between landslide volume V and reach angle α (i.e., $\tan\alpha = H/L$; Hunter and Fell 2003):

$$\frac{H}{L} = AV^C \quad (3)$$

where H (m) is the elevation difference from the scarp to the farthest end of the landslide debris; V (m^3) is the landslide volume, which can be estimated by multiplying the covering area by the average thickness of the deposit; and A and C are two coefficients.

Methods for modeling the runout behavior of landslide debris are often used to determine the sliding velocity, v, of a landslide, which include fluid mechanics models and distinct element methods (Dai et al. 2002). According to Cruden and Varnes (1996), the sliding velocity can be classified into seven categories. Hungr (2005) studied various human responses when facing landslides of different velocities (Table 4). People at risk will flee when facing a landslide moving at a velocity larger than 0.05 m/s.

The pre-failure time, T_{pt}, may be affected by uncertainties in soil properties, topographic conditions, and triggering factors. In this study, T_{pt} is assumed as a uniform distribution, U(0,300), with a lower bound of a and an upper bound of b. The uniform distribution is a diffused distribution that is commonly used to describe a highly uncertain random variable. The boundaries of T_{pt} are determined based on information of four landslide videos and listed in Table 5. Due to the limited records on the pre-failure time, the boundaries could be affected by a tremendous uncertainty. In addition, coefficients A and C in Eq. 3 are also uncertain. Following Corominas (1996), A and C are assumed to follow a normal distribution with the mean values of 1.005 and -0.1056, respectively, and a common COV of 5 %. Finally, the available time, T_L, is given by:

$$T_L = T_{pt} + \frac{L}{v \cdot \cos a} = T_{pt} + \frac{H}{v \cdot \cos a \cdot AV^C} \quad (4)$$

Demand time, T_F

The demand time, T_F, can be quantified by studying the human behavior during the flight process, which requires data on the factors regarding the evacuees and the flight paths (refer to section 4.1). Figure 9 schematically shows the distribution of the demand time for fleeing from a landslide. Three flight phases are distinguished. The partial "failure" of each phase of flight has to be accounted for by including the failure of response (% non-compliance), namely the possibility that the population at risk does not take actions to escape (% giving up escape) and the possibility that the population at risk fails to leave the affected area (% flight failure). The partial "successful" phase describes the fraction of the popluation at risk that is able to leave the affected area before conditions become harmful.

Table 4 Sliding velocity scales and typical human responses (based on Cruden and Varnes 1996; Hungr 2005)

Velocity class	Description	Velocity (mm/s)	Typical velocity	Human response
7	Extremely rapid	$>5\times10^3$	>5 m/s	Flee from landslide
6	Very rapid	5×10^3–5×10^1	5 m/s–3 m/min	Flee from landslide
5	Rapid	5×10^1–5×10^{-1}	3 m/min–1.8 m/h	Evacuation
4	Moderate	5×10^{-1}–5×10^{-3}	1.8 m/h–13 m/month	Evacuation
3	Slow	5×10^{-3}–5×10^{-5}	13 m/month–1.6 m/year	Maintenance
2	Very slow	5×10^{-5}–5×10^{-7}	1.6 m/year–16 mm/year	Maintenance
1	Extremely slow	$<5\times10^{-7}$	<16 mm/year	No response

Table 5 Pre-failure times of landslides from video records

Variable	Landslide	Location	Duration	Reference
Pre-failure time, T_{pt}	Road 168	Japan	50 s	Faliextrchas (2006)
	Pangi Valley	India	60 s	Gulshan (2010)
	Caopo	China	50 s	Dempsey (2013)
	Moudixia	China	300 s	Xinhua News Agency (2010)

As shown in Fig. 9, the demand time consists of pre-movement time T_{pm} (s) and movement time T_m (s):

$$T_F = T_{pm} + T_m \tag{5}$$

The pre-movement time, T_{pm}, is defined as the elapsed time from when a person perceives that a landslide is occurring to the time this person attempts to flee from the affected area. It consists of response time, T_r (s), and delayed time, T_d (s) (Fig. 9). All the parameters involved in the determination of the pre-movement time are random variables and their distributions are listed in Tables 6 and 7.

The response time, T_r, refers to the time to interpret clues of an impending landslide as a cause for fleeing. Only one action is involved in this period, which is the decision on whether to respond to the landslide clues or not. The quantification of this period involves specifying a time for the interpretation and decision making (Vistnes et al. 2005). Due to the lack of experimental data, Lindell et al. (2002) assumed a Weibull distribution for the response time for a hurricane disaster. According to the questionnaire survey along PR303 as shown in Table 3, the response time depends on the age; adult with prior landslide flight experience need less response time than young people without any prior experience. The average response times of evacuees in different age ranges to landslides are listed in Table 6. The values in the table are obtained from experimental studies on fire evacuations reported by Zhang (2004).

The delayed time, T_d, is determined by the delayed actions in the period between deciding whether to respond to the landslide clues and beginning to flee. The most common delayed actions prior to fleeing from a landslide are summarized in Table 3. According to the survey on the behavior of the potential evacuees along PR303, most people aged below 40 will not take any delayed actions before fleeing from a landslide, while the people aged 40 or above tend to take delayed actions. The most common delayed actions during flight from a landslide are "notifying others" and "taking care of families" as shown in Table 7. The delayed time, T_d, fits a lognormal distribution according to the assumption made by Vistnes et al. (2005). The mean values of T_d for the actions of "notifying people nearby" and "taking care of family members" are 10 and 30 s, respectively, and their standard deviations are 3 and 9 s, respectively, following Vistnes et al. (2005). It should be noted that the analysis of delayed actions in this study is conducted based on the field surveys with a limited sample size, i.e., 61 participants.

The movement time, T_m, is defined as the elapsed time from when a person begins to flee to the time this person arrives at a safe place or leaves the landslide affected area. By referring to a real landslide flight case in Wenchuan, China (Dempsey 2013), it is considered that people at risk flee by running when they face an emergency event in an open space. Regression models exist for the estimation of movement time during a fire emergency (Pauls 1995; Proulx 2002). In this study, the movement time is related to flight distance L_m (m) and running speed v_m.

The flight distance, L_m, depends on the location of an individual within the landslide affected area (Fig. 5b), which is a function of the position [i.e., $p(x_o,y_o)$] of the evacuee upon realizing the impending landslide. It is assumed that the only way to flee is along the road. Thus, when the people flee toward the left, L_m is x_o; when the people flee toward the right, L_m is x-x_o. The people make a decision on a flight route either toward the left or the right (as shown in Fig. 1b). Hence, the maximum flight distance is the length affected by the landslide, B (m), as shown in Fig. 5b if no direction change is assumed. In this study, L_m is assumed as an

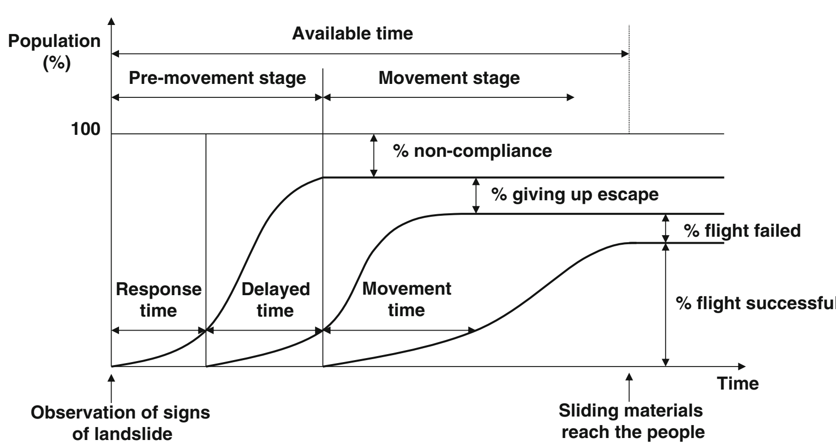

Fig. 9 Process of flight from a landslide in time scale (modified from Jonkman 2003)

Table 6 Response time depending on the age of the evacuee (modified from Zhang 2004)

Variable	Age	Distribution	Mean	COV
Response time, T_r	0–18	Weibull	210 s	35 %
	18–60	Weibull	150 s	25 %
	>60	Weibull	280 s	45 %

uniform distribution, $U(0,B)$, to consider the random distribution of the evacuees.

The running speed, v_m, of an individual evacuee depends primarily on the surrounding crowd density, D, and personal physical ability. Cavanagh and Kram (1989) measured average running speeds for normal people according to physical abilities, and the results are listed in Table 8. The running speed follows a Weibull distribution as confirmed by Rinne et al. (2010), who conducted an analysis based on the data collected from 18 fire evacuation cases. Running speeds of wheelchair users were also measured (Tsuchiya and Hasemi 2007). There was no gender difference for wheelchair users at a 5 % significance.

The evacuee crowd density, D (person/m^2), can be expressed as $N/(WB)$, where N is the number of people trapped within the landslide affected area and W (m) is the width of the landslide affected area (Fig. 5b). According to Melinek and Booth (1975), the crowd is free to flow and stable at densities lower than 1 person/m^2, which means that the evacuee density will affect the demand time only when $D>1$ person/m^2. Thus, a reference threshold, $D_r=1$ person/m^2, is set. The crowd density is considered in quantifying the demand time only when D is greater than D_r.

The demand time varies with an individual's physical ability when facing landslides, which is indicated by a physical ability factor, $\sum_{j=1}^{n} w_j a_{jk}$ in the range of 0–1, where w_j is the weight for basic element i (e.g., gender, age, disability, etc.), and a_{jk} is the ability factor for the basic element (e.g., male and female are the basic variables for gender). A basic element can be weighted using a SMCE method (multi-criteria evaluation) in a Geographic Information System (ILWIS-GIS; Pellicani et al. 2013). The theoretical background for the SMCE is an analytic hierarchy process developed by Saaty (2008). The values for the dimensionless physical ability factors are determined using the methods introduced by Pellicani et al. (2013) and shown in Table 9. For instance, for a healthy male with good experience at the age of 40, the weights for the four basic factors in Table 9 are 0.16, 0.31, 0.43, and 0.1, respectively, and the corresponding coping factors are 0.7, 0.7, 0.9, and 0.6, respectively. Thus, his physical ability factor is $0.16\times0.7+0.31\times0.7+0.43\times0.9+0.1\times0.6=0.776$.

Finally, the demand time, T_F, is given by the sum of the individual time components:

$$T_F = T_r + T_d + T_m \tag{6}$$

$$T_F = T_r + \sum_{i=1}^{n} T_{di} + \frac{L_m}{v_m \cdot \sum_{j=1}^{n} w_j a_{jk}} \cdot \frac{D}{D_r} \tag{7}$$

Analysis of flight success rate

When exposed to a specific landslide, the flight success rates for people in different age ranges can be determined according to Eqs. 1, 4, and 7.

The volumes and heights of rainfall-induced shallow failures vary significantly. To illustrate the proposed model, consider a rapid shallow landslide with a volume of 2,000 m^3, an elevation difference of 200 m, a slope width of 200 m, and an assumed reach angle of 25°, which occurs along a road (Fig. 10). The road width in the study area was measured as $W=8.5$ m. Three sliding velocities of 1, 5, and 10 m/s are considered separately. The population at risk is distributed randomly within the affected region with a crowd density smaller than the reference threshold, D_r, and an assumed position angle of 35°. The probability distributions of the available time and the demand time are listed in Tables 5–9.

A special analysis case in which all the factors take their mean values is presented here to illustrate the calculation process. The available time for a shallow landslide with a sliding velocity of 5 m/s to reach the road is:

$$T_L = T_{pt} + \frac{H}{v \cdot cos a A V^C} = 150 + \frac{200}{5cos25 \cdot 1.005 \cdot (2,000)^{-0.1056}} = 248s \tag{8}$$

and the demand time for a male at the age of 40 can be obtained as:

$$T_F = T_r + \sum_{i=1}^{n} T_{di} + \frac{L_m}{v_m \cdot \sum_{j=1}^{n} w_j a_{jk}} \cdot \frac{D}{D_r} = 150 + 10 + 30 + \frac{100}{4.12 \cdot 0.776} = 221s \tag{9}$$

Table 7 Possible delay action based on the field survey along PR303

Variable	Age years	Delay action	Distribution	Mean	SD	References
Delay time, T_d	<40	No delay action				
	>40	Notifying people nearby, T_{d1}	Lognormal	10 s	3 s	Vistnes et al. (2005)
		Taking care of family members, T_{d2}	Lognormal	30 s	9 s	Vistnes et al. (2005)

Table 8 Average running speeds related to different physical factors

Physical ability	Age	Occupant	Mean speed (m/s)	Dimension parameters*	References
Normal	0–18	Children	1.58	(1.65, 12.15)	Cavanagh and Kram (1989); Rinne et al. (2010)
	18–60	Adult	3.64	(3.62, 24.25)	
		Male	4.12	(4.21, 24.95)	
		Female	2.08	(2.14, 17.63)	
	>60	Elderly			
		Male	2.5	(2.57, 20.68)	
		Female	2.29	(2.33, 31.36)	
Wheelchair		Male	1.06	(1.08, 24.95)	Tsuchiya and Hasemi (2007)
		Female	1.06		

*Parameters for a Weibull distribution: (a, b), where a is the scale parameter and b is the shape parameter

According to the general rule for judging flight success as indicated in Eq. 1, the flight is considered successful since the available time is larger than the demand time.

To conduct Monte Carlo simulation in MATLAB, 100,000 pairs of samples of available time and demand time are generated. The flight success rates for male, female, and the disabled facing a landslide with a sliding velocity of 1 m/s are shown in Fig. 11a. The flight success rates are 0.87 and 0.79 for male and female adults at the age of 40, respectively. The flight success rate decreases to 0.59 for disabled people of the same age. For all the evacuees aged around 80, the flight success rates drop to 0.25 for males, 0.23 for females, and 0.12 for the disabled. This is because the response time for the elderly is assumed to be longer and their running speeds are lower. When facing a landslide with a sliding velocity of 5 m/s as shown in Fig. 11b, the flight success rates are 0.64 and 0.57 for male and female adults at the age of 40, respectively. The flight success rate decreases to 0.37 for the disabled people of the same age. When the sliding velocity increases to 10 m/s, the flight success rates are 0.22 and 0.16 for male and female adults at the age of 40, respectively. With the increase of sliding velocity, the available time is decreased. Comparing the values in Fig. 11a, b, and c, the flight success rate decreases with the sliding velocity.

Sensitivity analysis

Sensitivity analysis studies how the variation in the model output can be apportioned to different sources of variations, and how the given model depends upon the input information (Crosetto et al. 2000). It quantifies the importance of the input factors and can be used to rank the critical causes. In this study, sensitivity analysis is conducted by altering the value of a selected factor (SF) and checking the changes in the flight success rates through repeated Monte Carlo simulations. The importance of a selected factor, SF, is represented by an importance index, I:

$$I = \frac{\left|P(SF_1) - P(SF_2)\right|}{P(SF)} \tag{10}$$

where $P(SF)$ is the flight success rate for a person facing a landslide considering all the random variables expressing

Table 9 Weights determining the physical ability factors of evacuees

Basic element	Weight	Sub-element	Coping factor
Gender	0.16	Female	0.3
		Male	0.7
Age	0.31	0–18	0.2
		18–60	0.7
		>60	0.1
Disability	0.43	Yes	0.1
		No	0.9
Experience	0.10	Poor	0.1
		Medium	0.3
		Good	0.6

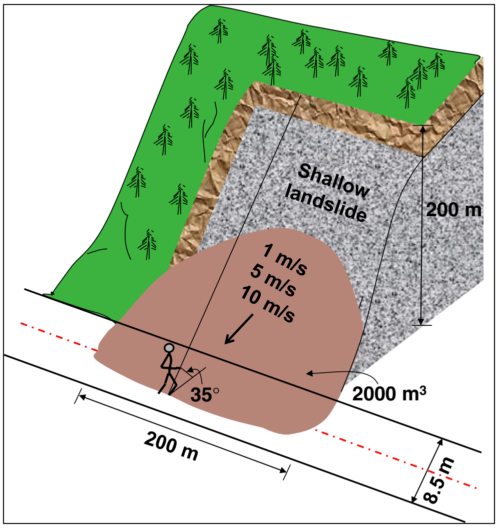

Fig. 10 Pre-determined conditions of a shallow landslide for the analysis of flight success rate

the "available time" and the "demand time"; $P(SF_1)$ and $P(SF_2)$ are the flight success rates at which the selected factor is equal to its mean value plus two standard deviations and its mean value minus two standard deviations, respectively, while the rest factors are taken as random variables. A higher *I* means a larger influence of the selected factor on the flight success rate. The sensitivities of pre-failure time, sliding velocity, landslide volume, response time, delayed time, flight distance, and running speed are investigated in the sensitivity analysis. Their standard deviations are listed in Tables 5–9.

In the sensitivity analysis, the landslide volume and sliding velocity are treated as two random variables to consider the influence of landslide intensity on the flight success rate. Both parameters are assumed to follow a lognormal distribution since they are non-negative variables. Their COVs are both assumed to be 5 %. For a male adult at the age of 40, the normalized results based on the sensitivity analysis using the present model are shown in Fig. 12. The pre-failure time (I=1.0 after normalization) is identified as the most sensitive parameter, followed by the response time (I=0.81). The running speed of evacuee (I=0.004) has the smallest value and only slightly influences the flight success rate. Since the pre-failure time cannot be controlled, the most effective ways to flee from a landslide are to reduce the response time, to decrease the delayed actions by the evacuees, and to find the shortest flight path to a safe place.

Comparisons with other models

Assuming that all the people trapped within the landslide affected area will be buried and die, the probability of unsuccessful flight from a landslide can be then taken as the vulnerability factor. Two judgemental methods for assessing the vulnerability factors are selected to compare with the proposed model.

Li et al. (2010), Lacasse and Nadim (2011), and Lacasse et al. (2012) proposed a *VIS* model, which can be expressed as:

$$V_V = I \cdot S \tag{11}$$

where V_v is the vulnerability factor; *I* is the landslide intensity; and *S* is the susceptibility of the vulnerable elements.

The intensity, *I*, expresses the potential damage caused by the landslide:

$$I = k_s \cdot [r_D \cdot I_D + r_G \cdot I_G] \tag{12}$$

where k_s is the spatial impact ratio in a range of [0,1], which expresses how much the category of the elements at risk is affected spatially by a landslide and can be

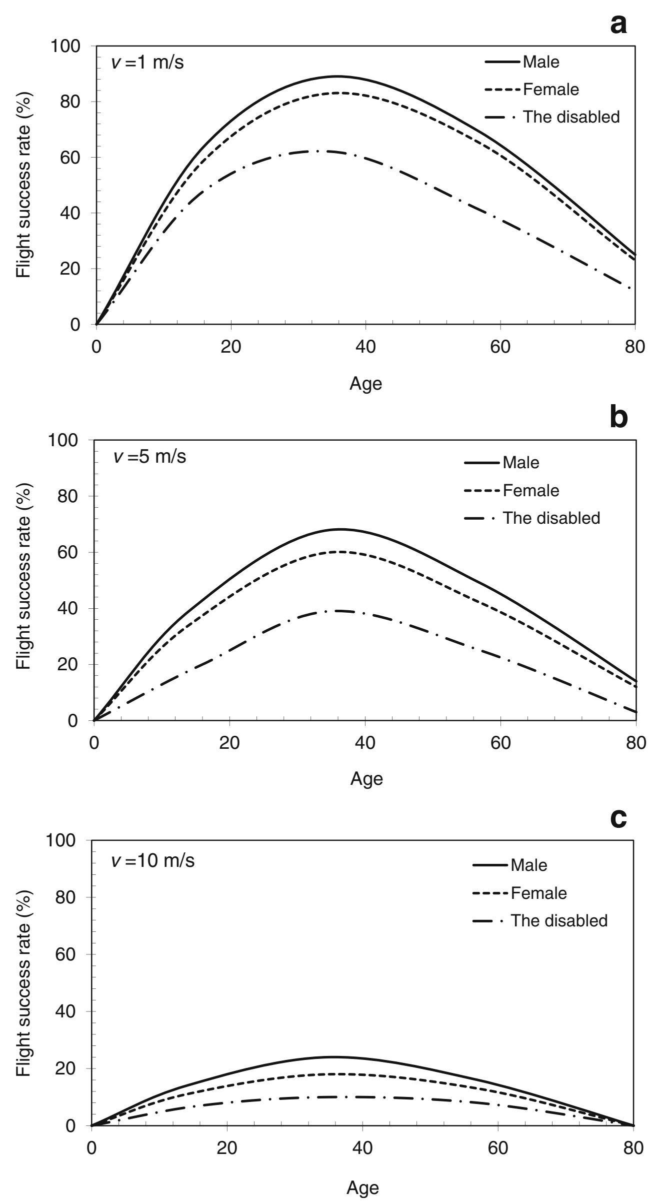

Fig. 11 Flight success rates for male, female and the disabled facing a landslide with a volume of 2,000 m^3, a travel distance of 100 m, a flight distance of 100 m, and a sliding velocity of **a** 1 m/s, **b** 5 m/s, and **c** 10 m/s

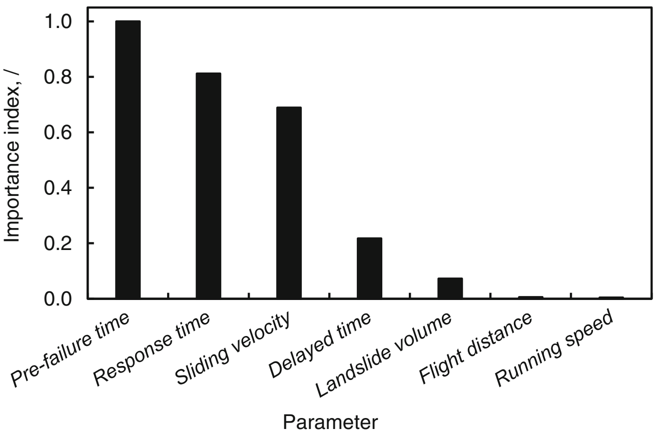

Fig. 12 Sensitivity analysis of human flight from a landslide

quantified by the area occupied by the elements at risk divided by the landslide covering area; r_D and r_G are the dynamic and geometric relevance factors, which are assigned by the user, specific to a landslide type and the vulnerable categories, and reflect the available knowledge (or belief) on the relevance of the dynamic and geometrical characteristics of the landslide in causing loss, r_D=0.75 and r_G=0.25 for persons exposed to a rapid landslide; and I_D and I_G are the dynamic and geometric intensity components, respectively. The dynamic intensity (I_D) expresses the destructive potential of a landslide's kinetic energy and momentum and is defined in the range of [0,1], the geometric intensity (I_G) accounts for the dimensional properties of the sliding masses (e.g., depth, volume, displacement, and area) and is defined in the range of [0,1]. For a landslide with the same intensity as introduced in Section 4.3, these parameters are presented in Table 10 based on Li et al. (2010) and Lacasse and Nadim (2011).

The susceptibility depends on the physical characteristics of the element, which is expressed as:

$$S = 1 - \prod_{i=1}^{n} (1-\xi_i) \tag{13}$$

where the susceptibility factor, ξ_i, reflects the user's belief or knowledge on the susceptibility. The factor ranges from 0 to 1. Table 11 lists the values of ξ for persons in different age ranges.

A comparison is made between the flight success rates from the present model and the results estimated using the *VIS* model for males at different ages when facing a landslide with the same intensity as introduced before (Fig. 13). The flight success rates determined using the proposed model are slightly smaller than the values calculated using the *VIS* model since only the coping capacities of the evacuees, landslide velocity, and dimensions of the deposition area are considered in the *VIS* model. For example, when the sliding velocity is 1 m/s, the flight success rate for males aged 40 is 0.87 based on the present model, compared with 0.93 from the *VIS* model (Fig. 13a).

Based on expert judgment and available data of landslides with volumes ranging from 500 to 2000 m^3, Wong et al. (1997) proposed vulnerability factors for slope toe facilities accounting for reach angle, α, likely volume of failure, V, and position angle, β. The sliding velocity is not a variable in Wong et al. (1997). For example, in the case of an α of 25°, the estimated flight success rate for a road user located at a position angle between 25° and 30° is judged to be 0.85. In order to check the flight success rates for evacuees located in various position, a comparison of the calculated flight success rates with the suggested values by Wong et al. (1997) is plotted in Fig. 14. The position angle is altered, but the physical factors of evacuees are kept constant. As shown in Fig. 14, for a male adult at the age of 40 located on a road with a position angle of 35°, when facing a landslide with same characteristics as introduced before, the suggested flight success rate by Wong et al. (1997) is 0.52, and the predicted values using the present model are 0.85, 0.63, and 0.20 at sliding velocities of 1, 5, and 10 m/s, respectively. When the position angle increases to 60°, the suggested flight success rate by Wong et al. (1997) is 0.1, and the predicted values using the present model are 0.39, 0.19, and 0.09 at sliding velocities of 1, 5, and 10 m/s, respectively.

Summary and conclusions

Based on previous evacuation models for natural or human-induced hazards (i.e., earthquakes, floods, hurricanes, and fires), a mathematic model is proposed to simulate the human fleeing process from a quick shallow landslide and to quantify the flight success rate of people randomly located along a road threatened by a quick shallow landslide. Due to limited records concerning the human flight behavior in response to landslides, several assumptions on the input parameters are made. The evacuees run away from a quick shallow landslide taking both ends of the road as the flight exits without considering possible shelters (e.g., cars, buildings, or a big stone). The length of the affected area of landslide is assumed as the width of the slope. Besides, the human behavior during the flight from landslides is idealized and described using several random variables. The following conclusions can be drawn:

Table 10 Parameters for the estimation of vulnerability factors using the *VIS* model (modified from Li et al. 2010)

Sliding velocity, v (m/s)	k_s	r_D	r_G	I_D	I_G
1	0.5	0.75	0.25	0.8	1
5	0.5	0.75	0.25	0.9	1
10	0.5	0.75	0.25	1.0	1

Table 11 Susceptibility factors, ξ, for person in different age ranges (modified from Li et al. 2010)

Age (years)	ξ	Age (years)	ξ	Age (years)	ξ
0–4	0.33	30–34	0.92	60–64	0.7
4–9	0.57	35–39	0.91	65–69	0.63
10–14	0.9	40–44	0.90	70–74	0.57
15–19	0.92	45–49	0.87	75–79	0.47
20–24	0.94	50–54	0.83	80–84	0.36
25–29	0.95	55–59	0.78	85–	0.26

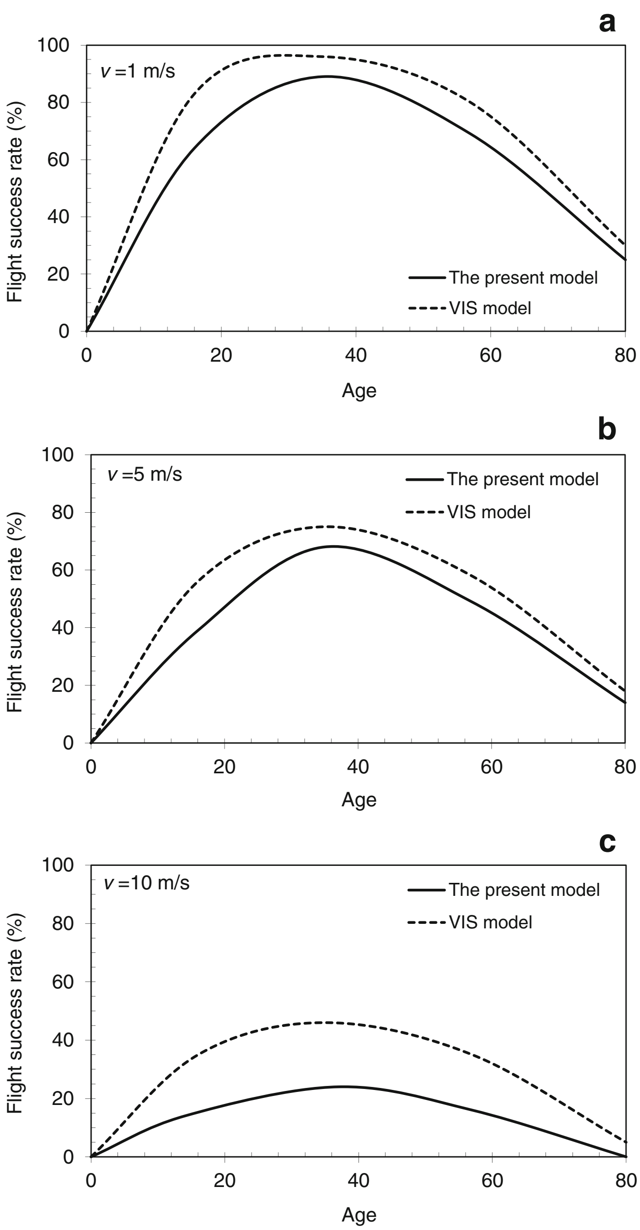

Fig. 13 Comparison of the proposed flight success rates with the *VIS* model for males in different age ranges when facing a landslide with a volume of 2,000 m^3 and a sliding velocity of **a** 1 m/s, **b** 5 m/s, and **c** 10 m/s

(1) The factors influencing human flight from landslides can be classified into factors related to the evacuees, the landslide intensity, and the flight paths. A questionnaire survey was conducted to provide information regarding human responses and behavior when threatened by landslides.

(2) The flight model is expressed in terms of the available time and demand time for escaping from a landslide. Both the available time and the demand time are random variables. The flight success rate for an individual when facing landslides with various intensities can be obtained through Monte Carlo simulation. For a rapid landslide with a volume of 2,000 m^3 occurring along a road and sliding at velocities of 1, 5, and 10 m/s, the flight success rates for a normal male at the age of 40 without consider the crowd density are 0.87, 0.64, and 0.22, respectively.

(3) Sensitivity analysis shows that the pre-failure time is the most important factor governing human flight success, followed by the response time of the evacuees. The most effective way to flee from a landslide is to reduce the response time and delays of the evacuees.

(4) The estimated flight success rates from the proposed model are comparable to the vulnerability factors proposed by Wong et al. (1997) and estimated by the *VIS* model. The present model provides a valuable reference as it considers multiple influence factors in a quantitative way.

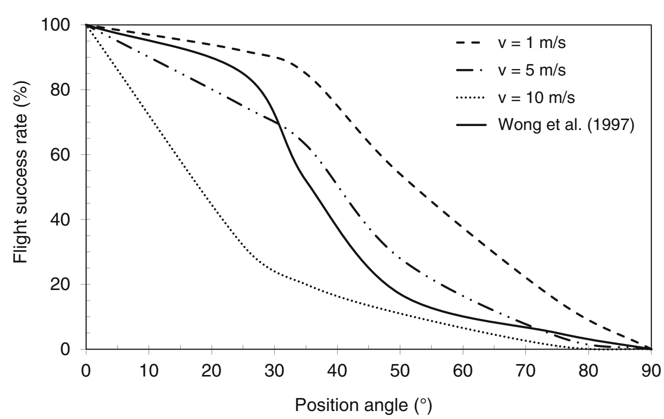

Fig. 14 Comparison between the calculated flight success rates using the proposed model and those suggested by Wong et al. (1997) for a male at various position angles when facing a landslide with a volume of 2,000 m^3 and sliding velocities of 1 m/s, 5 m/s, and 10 m/s

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