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Dynamics, mobility-controlling factors and transport mechanisms of rapid long-runout rock avalanches in China

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ABSTRACT

The dynamics and occurrence conditions of 43 rapid and long run-out rock avalanches in China were summarized. Their dynamics were classified into 5 types. The standard dynamic type was designated to be "fail, squirt and flow", where part of the landslide path always has a parabolic airborne course because the slide body has an initial speed and the toe of the surface of rupture projects the landslide into the air. The occurrence conditions of rock avalanches of the standard dynamic type are huge kinetic energy, elevated toe to the surface of rupture and enough transport space to run out into. The occurrence conditions of the other four types were then compared with the standard dynamic type. Statistical analysis showed that volume, topography, huge kinetic energy and an elevated toe to the surface of rupture were the principal factors controlling mobility in the rock avalanches. Four of the rapid long run-out rock avalanches, each in a different geological setting, were then examined in more detail to reveal the transport mechanisms leading to their high speed and long runout. The results suggested that besides their huge kinetic energy, high pore water pressure produced by undrained shear and elastic energy released by grain fragmentation were the main transport mechanisms contributing to the long travel distances and high speeds of rock avalanches. Field investigation indicated that air was involved during the transport, but whether it influenced the transport or how much the influence was is still much disputed.

1. Introduction

Rapid and long run-out rock avalanches occur frequently in China, especially in southwest China, on the eastern edge of the Tibetan Plateau, where uplift and river downcutting for millions of years have formed an alpine-gorge landscape that is favorable for their occurrence. In recent years, extreme weather (intense rainfall, snow storms and floods) and earthquakes have increased the occurrence of rapid and long runout rock avalanches. The 1.7×10^6 m^3 Guanling rock avalanche in Guanling County, Guizhou Province, occurred due to heavy rainfall in 2010 and traveled 1.5 km, killing 99 persons and destroying two villages (Liu, 2010a; Yin et al., 2010). The 5.0×10^6 m^3 Jiweishan rock avalanche in Wulong County, Chongqing Municipality, occurred as a result of mining activity and heavy rainfall in 2009; it traveled 1.5 km, killing 74 people and burying an iron smelting plant (Xu et al., 2009a; Liu, 2010b). The 2008 Wenchuan earthquake in Sichuan Province triggered hundreds of rapid and long run-out rock avalanches, which killed more than 20,000 people (Yin et al., 2009).

The transport mechanisms and mobility of rapid and long run-out rock avalanches have been a hotly debated research problem since Buss and Heim's work on the Elm rock avalanche in 1881 (Buss and Heim, 1881). Many hypotheses have been proposed to explain the mechanisms leading to their extraordinarily high speed and long run-out, such as the fluidized-bed hypothesis (Kent, 1966), the air-layer lubrication (actually air-cushion) hypothesis (Shreve, 1966), grain-flow hypothesis (Hsu, 1975), molten rock layer hypothesis (Erismann, 1979), mechanical fluidization hypothesis (Davies, 1982), momentum transfer model (Eisbacher, 1979; Davies et al., 1999; Yoichi et al., 2000), and various hypotheses considering the effect of pore water (e.g. Sassa, 1988; Evans et al., 2001; Iverson and Denlinger, 2001; Hungr and Evans, 2004; Pitman and Le, 2005; Pudasaini et al., 2005a; Crosta et al., 2007, 2009; Deline, 2009; Pudasaini, 2012; Pudasaini and Miller, 2012). Meanwhile, many statistical relationships have been found between travel distance (or equivalent coefficient of friction, excessive travel distance) and influencing factors (mainly the volume) of the rock avalanche (e.g. Hsu, 1975; Nicoletti and Sorriso-Valvo, 1991; Dade and Huppert, 1998; Yoichi et al., 2000). Recently, Pudasaini and Miller (2013) analytically derived a mass-dependent hypermobility model as a function of the mechanical, volumetric and topographical parameters of the flow. This model was used to show that the wide scatter observed for very large mass wasting events in all environments (extraterrestrial events, and terrestrial non-volcanic, volcanic, and submarine events) collapses to a single relationship between event volume or inundation area and mobility. They also demonstrated that the effective Coulomb friction rheology and the hypermobility function are applicable to

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avalanche events of any size. Their results show that the dominant term is associated with the degree of fluidization (e.g., pore fluid pressure, or the internal pressure) involved in the flow.

However, the true dynamics and transport mechanism of rapid and long run-out rock avalanche are still debated today. The various hypotheses mentioned above cannot be proven or refuted completely because nobody has actually measured the transporting dynamic parameters of rock avalanches, and few have even filmed their transport course.

In this paper, 43 rapid and long run-out rock avalanches in China were selected. First, the dynamics and conditions of occurrence of the rapid and long runout rock avalanche were summarized. Then, through statistical relationships between the equivalent coefficient of friction and the possible factors influencing mobility, the factors controlling mobility were disclosed. Finally, four typical rapid and long runout rock avalanches were selected to study the transport mechanisms leading to the high speed and long runout.

The conclusions in this paper have implications for hazard assessment of the numerous potential rock avalanches in China and the other countries with similar geological settings, and also have some value for research on the transport mechanism of rock avalanches.

2. Rock avalanches studied

Forty-three rapid and long run-out rock avalanches in China were selected (Tables 1 and 2) for study. Eighteen rock avalanches (Table 1) were from published previous studies: the criteria for selection were that (1) the reference was the primary data source, and (2) it provided sufficient information, such as topography, volume, lithology, and especially a longitudinal section. The data were all collected by the authors themselves.

The other 25 rock avalanches (Table 2) were all triggered by the 2008 Wenchuan earthquake. The information in Table 2 was obtained through field investigation and interpretation of remote sensing images, undertaken as a part of the research project "General investigation of geohazards triggered by 2008 Wenchuan earthquake". The first author was the principal participant of the project and obtained first-hand original investigation data.

Two criteria were also used to select the 43 rock avalanches. First, its volume had to be equal to or larger than 1.0×10^6 m^3. Beyond this threshold, as the volume of rock avalanche increases, the equivalent coefficient of friction decreases; this has been called the "size effect" (for further discussion on this, see Pudasaini and Hutter, 2007; Pudasaini and Miller, 2013). The threshold volume differs in different studies (Hsu, 1975; Davies, 1982; Nicoletti and Sorriso-Valvo, 1991; Friedmann et al., 2006). Second, the equivalent coefficient of friction was smaller than 0.6, which is the threshold for whether the rock avalanches could be called "long run-out" (Hsu, 1975).

For the 18 rock avalanches from previous studies, Table 1 lists the name, date, site, volume, equivalent coefficient of friction, triggering factor, topography, deposit structure, lithology, dynamic type and reference citation.

In Table 2, the triggering factor is changed to "distance from the main seismic fault", in order to analyze for possible influence of the energy released by the earthquake on the mobility of rock avalanches. The main seismic fault here is the Main Longmenshan Fault in the 2008 Wenchuan earthquake, other faults in the area are not used in the analysis, although they may have had some impact on the rock

Table 1
Data of eighteen rapid long run-out rock avalanches from the literature.

Name	Date	Site	V (10^6 m^3)	H/L (equivalent coefficient of friction)	triggering factor	topography	Deposits structure	Lithology	Dynamic type	References
Yigong	2000	Bomi, Tibet	340	0.26	Freeze thawing	Valley	Debris	Granite, metamorphic rocks	(1)	Yin (2000) and Lv et al. (2003)
Touzhaigou	1991	Zhaotong, Yunnan	9	0.23	Rainfall	Valley	Debris	Basalt	(1)	Tang (1991) and Xu et al. (2007)
Jiweishan	2009	Wulong, Chongqing	5	0.30	Rainfall	Valley	Debris	Limestone	(1)	Xu et al. (2009a) and Liu (2010b)
Saleshan	1983	Dongxiang, Gansu	50	0.23	Rainfall, irrigation	Open	Debris	Mudstone, sandstone, loess	(1)	Wang et al. (1990) and Yu and Yang (1988)
Guanling	2010	Guanling, Guizhou	1.7	0.28	Rainfall	Valley	Debris	Siltstone	(4)	Liu (2010a) and Yin et al. (2010)
Shijiapo	1981	Ningqiang, Shanxi	1.0	0.17	Rainfall	Valley	Debris	Sandstone, schist	(4)	Hu et al. (1988)
Xikou	1989	Huayingshan, Sichuan	1.0	0.31	Rainfall	Valley	Debris	Limestone	(1)	Jiang and Yin (1992)
Yanchihe	1980	Yichang, Hubei	1.0	0.58	Mining	Blocked	Debris	Dolomite	(5)	Sun and Yao (1983)
Chana	1943	Dongxiang, Gansu	150	0.24	Earthquake	Open	Debris	Mudstone, sandstone, loess	(4)	Yan et al. (1998)
Cuihuashan	Ancient time	Xi'an, Shanxi	8	0.24	Earthquake	Valley	Debris	Granite	(4)	Nan and Cui (2000)
Xiaonanhai	1856	Qianjiang, Chongqing	60	0.40	Earthquake	Open	Debris	Mudstone, sandstone	(4)	Cui et al. (2009)
Qianjiangping	2003	Zigui, Hubei	24	0.26	Rainfall, reservoir water	Blocked	Deformed body	Sandstone, mudstone	(5)	Yin and Peng (2007)
Animaqingshan	2004	Maxin, Qinghai	24	0.30	Freeze thawing	Valley	Debris	Glacial till	(4)	Yin (2007)
Dabanqiao	Ancient time	Baoxin, Sichuan	15	0.53	Earthquake	Blocked	Debris	Sandstone	(2)	Chen and Hu (1999) and Fu et al. (1998)
Huihuichuan	1920	Xiji, Ningxia	7.7	0.14	Earthquake	Open	Debris	Loess	(1)	Wang and Zhang (1999)
Qilipu	1920	Jingning, Gansu	20	0.29	Earthquake	Valley	Debris	Mudstone	(4)	Zou and Shao (1996)
Sunjiagou	1920	Jingning, Gansu	20	0.15	Earthquake	Valley	Debris	Loess	(4)	Zou and Shao (1996)
Jipazi	1982	Yunyang, Sichuan	15	0.38	Rainfall	Open	Deformed body	sandstone	(3)	Xu et al. (1990)