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Unravelling the multiphase run-out conditions of a slide-flow mass movement

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ABSTRACT

In this paper an attempt is made to unravel the run-out characteristics of a mass movement in the Sichuan Province, SW China by means of 1D numerical modelling and calibration on the topography of run-out profiles. The Dagou mass movement started as a rockslide with an initial volume of 480,000 m^3, which transformed into a debris flow, increasing in volume due to entrainment of loose material in the upper part of the travelling track. The rapid mass movement had a run-out distance of 1380 m and a run-out time of about 50 s.

Numerical calculations were conducted with the depth average shallow water equation to explain the variation in thickness of the debris flow deposits along the run-out track. For the calibration of the first run-out phase, three rheological models were applied, namely the Bingham, Voellmy and Quadratic rheology. Calibration was done on 1) the run-out distance, 2) the run-out time and 3) the goodness of fit with the thickness of the deposits along the track. In addition the erosion constant in the entrainment equation was calibrated on the observed versus calculated run-out volumes. Sensitivity analyses of the resistance parameters for the different rheologies showed that the viscosity, the basal friction, the turbulence term and the resistance factor are the most sensitive ones. It appeared that the variation in thickness along the run-out track can be explained by entrainment of material in the upper part of the track and a change in parametric values during the run-out process. The three rheologies produced a reasonable fit with the observed geometry of the run-out profile, run-out time and run-out volume. It was argued that the Voellmy rheology seems to give the most appropriate explanation for the difference in resistance along the run-out path. The main problem in the simulation was to stop the debris flow on a slope with a gradient around 22°.

A reactivation of the mass movement by frictional sliding of the material half way the run-out track was simulated. It occurred 30 min after the first run-out phase due to an increase in pore pressure. The sliding material changed into a slow flowing mass that reached a newly built up area after about 1 h and moved into Wangong Town over a distance of 80 m.

1. Introduction

This paper tries to explain the development of the Dagou mass movement, China, which started as a rock slide and changed into a rapid debris flow. A reactivation took place shortly after the first run-out phase: A part of the mass started again as a translational debris slide, which transformed into a slow moving flow.

There are a number of important issues related to the run-out of rapid mass movements like the initiation mechanisms, type of rheology controlling run-out processes, various entrainment and stopping mechanisms, and threat of reactivation, which happened with the Dagou mass movement. However, it is extremely difficult to determine in the field or laboratory reliable rheological values for these rapid mass movements. Some researchers tried to reconstruct the rheology and run-out mechanisms of debris flows by analysing the sedimentological and morphological characteristics of the deposits (e.g., Kelin et al., 1992; Whipple and Dunne, 1992; Imran et al., 2001; Iverson and Valance, 2001; Remaître et al., 2005a; Staley et al., 2006). In many cases numerical models are used for back calculation of the rheological parameters (e.g., Ayotte and Hungr, 2000; Chen and Lee, 2003; Bertolo and Wieczorek, 2005; Naef et al., 2006; Rickenmann et al., 2006; Medina et al., 2008; Begueria et al., 2009). These back analyses of debris flows are based on simplifications that attempt to reproduce the general features. In most cases calibration is based on constant rheological properties, which is good practise for a general assessment of future hazard and risk estimations in a certain region or locality. Many results of these back calculations from all over the world can be found in Quan Luna (2013). However there are few examples in literature, which try to reconstruct in more detail the transient character of the rheology, additional processes and reactivation of debris flows. One has to realize that the movement of these debris flows is complex and influenced by different additional processes such as various erosion processes along the track controlling velocity and run-out distances (McDougall and Hungr,

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2005; Remaître et al., 2005b; Chen et al., 2006; Quan Luna et al., 2012; Xu et al., 2012). Van Asch et al. (2004) drew attention to the use of the run-out profile of debris flows as an indicator of these changing run-out conditions. It is the aim of this paper to find out whether the run-out geometry of the Dagou mass movement can be used to reconstruct the transient character of these processes like changes in rheology and resistance parameters, entrainment, deposition and stopping. This will be done by means of 1D-numerical modelling and curve fitting on the run-out topography. In addition we will use the changes in the topographic profile to analyse the conditions of a reactivation, which occurred in this mass movement and which destroyed a part of Wangong Town. The back ground information for this study was obtained from a morphological analysis of this mass movement based on field investigations, eyewitness accounts and aerial photo interpretation (Xu et al., 2010).

2. Short description of the Dagou mass movement

The location of the study area in the Sichuan province of China is given in Fig. 1. The evolution of the so-called Dagou mass movement is described here briefly. More details can be found in Xu et al. (2010). The upper part of the Dagou catchment consists of basalts of the Ermeishan group (Pe) and the lower part of limestones of the Liangshan–Yangxing group (Pl + y), a Permian system, with a monoclonal structure. The superficial strata are strongly weathered and almost degraded into blocks. The dissolution of limestone created an uneven rock surface with a lot of karren. Quaternary debris flow deposits (Q4sef) and colluviums (Q4c + dl) are found at the mouth of the Dagou valley consisting of boulders, gravels, and silty clays, according to the Unified classification System (USCS).

Rainfall was the major triggering factor of the mass movement. From 23 to 25 July, two rainstorms hit the study area with a peak intensity of 6 and 50 mm h^{-1} respectively and a cumulative precipitation of 163 mm, which is 22% of the average yearly precipitation. In particular the rainfall on July 25 with an intensity of 50 mm h^{-1} and a return period of 50 years was fatal. The rainfall could penetrate into many vertical cracks in the source area and on 27 July, the mass movement started as a rock slide, which disintegrated quickly into debris.

Two consecutive run-out phases can be distinguished in the Dagou mass movement: a rapid rock slide/debris flow phase with a run-out distance of 1380 m and a run-out time of 50 s, and a reactivation phase characterised by a translational slide, which transformed into a slow moving flow. The whole secondary process lasted 4 h. Figs. 2 and 3 show the two phases in the run-out of the mass movement. The profiles of Fig. 3 were reconstructed in the field by means of topographical measurements and extrapolation of the original topography, measurements at the front of the mass movement, exposures due to excavation for rescue after the disaster, and exposures in the steep walls of the secondary gully, which developed in the second phase.

Xu et al. (2010) distinguished three zones in the first phase (Fig. 2): the source area (zone I), the transportation zone (zone II) and the deposition zone (zone III). Zone IV in Fig. 2 is the area, which was reactivated during the second run-out phase (see below). According to the local residents, a wide crack was generated on July 25 along the steep structural plane, before the occurrence of the mass movement on July 27. The crack finally formed the lateral boundary of the rockslide. At 4.40 AM on 27 July, several local residents heard a very loud sound combined with intensive ground shaking. The mass movement must have started as a rock slide and disintegrated into debris, moving down along the Dagou valley at a very high speed. The configuration and volume of the rock slide (480,000 m^3) could be determined in the field by two sets of joints forming respectively the head scarp and the sliding surface (Xu et al., 2010). The rock mass in the source area was densely jointed and strongly weathered and prone to degrade into a debris flow. The transportation zone II can be sub-divided into the main travelling channel (II-1) and the right and left bank entrainment zones (II-2 and II-3, respectively; Fig. 2). Here between 1500 and 1300 m asl., a significant amount of material was delivered to the flow from the plateau (zone II-2 (1)) and a valley side slope failure zone (zone II-2 (2)) of the left bank entrainment zone.

The grain size and weight of the sediments were measured in the field. A ruler was used to measure the grains with a size bigger than 100 mm, while the sieving method was adopted for the grains smaller than 100 mm.

Big boulders (USCS classification) were accumulated mainly in the upper part of the main travelling channel. The grain size of over 70% of the boulders is larger than 200 mm. Smaller grain sizes can be found in the lower part, which consisted of basalt fragments with soil. The grain size is evenly distributed over the different classes and 77% can be classified mainly as cobbles, and very coarse gravels (USCS classification) varying between 20 and 100 mm.

In the depositional zone III, the Dagou valley turns slightly to the right at about 1300 m asl., which led to a splitting of the debris into two branches (Fig. 2). Due to the inertial force, the left branch kept the original moving direction and climbed up to the left ridge. The right branch moved down along the Dagou valley concentrating most of the material into a channel with a width of around 50 m and a depth around 25 m. This channel ends at the exit of the valley and passes into the flat aforementioned Quaternary deposits. The thickness of the debris flow deposits increased from 5–10 m upstream to 15–25 m downstream. The grain size distribution of the right branch deposits shows that around 70% of the particles

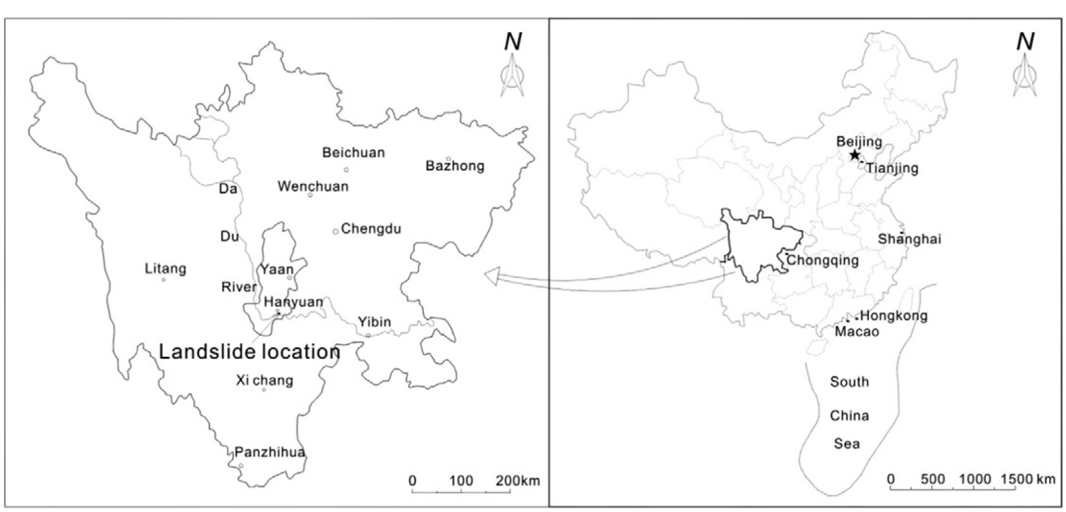

Fig. 1. Location of the study area in Sichuan province, China.