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Unsteady sediment discharge in earth flows: A case study from the Mount Pizzuto earth flow, southern Italy

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ABSTRACT

Surface mapping, GPS surveys, T-Lidar surveys, boreholes, seismic profiles, and HVSR measurements were used to study the mechanisms of sediment transport along the Mount Pizzuto earth flow in southern Italy. The earth flow has several kinematic zones, with transitional areas marked by changing structural styles, from compressional structures (thrusts) upslope to extensional structures (normal faults) downslope. We relate sediment discharge at these transitional zones to internal strain. The results suggest that during surge events, flow acceleration starts within the head and propagates downslope inducing a cascade effect between kinematic zones. During surge events, the average sediment discharge is nearly constant, and a change from sliding to flowing allows propagation of movement towards the toe. During slow movement, kinematic zones are independent and sediment discharge varies along the flow. In general, the velocity profile and the structural style are controlled by the basal slip surface. The implications are: i) sediment discharge is not constant but is a function of the earth flow activity, ii) during surge, earth flow material behaves similar to an incompressible fluid, and iii) the distribution of surface structures can provide information about the geometry of the slip surface and the velocity profile. Additionally, earth flows with a well-defined neck seem to be more likely to surge with respect to those without.

1. Introduction

Earth flows (sensu Varnes, 1978) occur in hilly and mountainous areas and are pervasive in many rapidly eroding landscapes (Mackey et al., 2009). Earth flow landscapes are characterized by crescent-shaped or basin-shaped scars, loaf-shaped bulging toes, and long narrow tongue- or teardrop-shaped transport zones (Keefer and Johnson, 1983; Bovis and Jones, 1992; Booth et al., 2013; Calista et al., 2016). Large earth flows often span from the channel to the ridge and can persist for hundreds of years (Mackey and Roering, 2011). The evolution of large earth flows is often characterized by an alternation of long periods of slow and/or localized movement, and "surging events" (e.g. Keefer and Johnson, 1983; Zhang et al., 1991; van Asch et al., 2006; van Asch and Malet, 2009; Giordan et al., 2013; Guerriero et al., 2013b, 2014, 2015a, 2016c). Slow movement is driven by hydrologic forcing, and seasonal acceleration is induced by pore-water pressure variations (e.g. Iverson and Major, 1987; Iverson, 2005; Handwerger et al., 2013; Grelle et al., 2014). Pore pressure increase and landslide acceleration is caused by infiltration of rainfall and springs (Iverson and Major, 1987; Guerriero et al., 2015a). Pore pressure decrease and landslide deceleration is a consequence of drainage and possibly shear zone dilation (e.g. Krzeminska et al., 2012; Schulz et al., 2009; Iverson, 2005).

Surging events are characterized by velocities approaching several meters per day and in some cases several meters per hour. A surge can occur when prolonged rainfalls are associated with loss of drainage pathways, and new sediments in the source area are available through retrogression of the upper boundary (Guerriero et al., 2014; Pinto et al., 2016). Under these conditions, acceleration occurs when the source area becomes unstable. As material in this area accelerates, it overrides and compresses the soil downslope, locally generating structures similar to thrusts (e.g. van Asch et al., 2006; Guerriero et al., 2016a), and increasing pore pressure through undrained loading (e.g. Bertolini and Pizziolo, 2008; van Asch and Malet, 2009). In this way, a kinematic wave propagates through the soil and new material is transferred downslope until the toe advances (e.g. Hungr et al., 2014). The term

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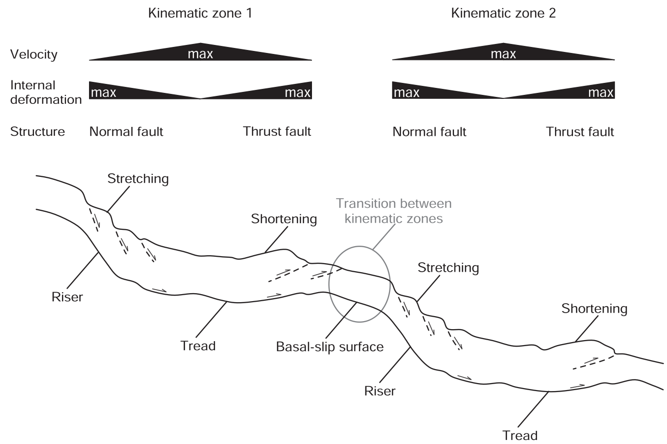

Fig. 1. Longitudinal profile of a sequence of kinematic zones along an earth flow. The upper part of the figure is modified from Guerriero et al. (2014).

Fig. 2. The Mount Pizzuto earth flow. The flow is about 1 km long. The photo is taken from the opposite side of the Ginestra torrent valley looking southwest.

"kinematic wave" is used here to describe the earth flow wave-like motion, without any consideration of forces. This process might be facilitated by a network of preferential flow pathways (i.e. extensional structures) that allow rapid infiltration of water within the earth flow (e.g. Krzeminska et al., 2012), and by fluidization of the moving mass (van Asch et al., 2006; van Asch and Malet, 2009). In general, fluidization occurs when increasing pore pressures lead to zero effective stress in the soil mass (frictional behavior; e.g., Wood, 1990; Darve et al., 2004; van Asch et al., 2006), or when the shear stress or strain rate approaches the critical state (non-frictional behavior; Coussot et al., 2002; Ancey, 2007). For a moving earth flow, van Asch et al. (2006) indicate that the fine-grained material can fluidize through compression of a sliding block.

Persistent-slow earth flow movement creates surface structures (i.e. faults and folds; Fleming et al., 1988; Fleming and Johnson, 1989; Parise, 2003; Manconi et al., 2014) that are similar to tectonic structures (i.e. normal, thrust and strike-slip faults; Gomberg et al., 1995; Savage and Wasowski, 2006; Guerriero et al., 2013a, 2014, 2015a, 2016a). Mesoscopic surface structures of earth flows in Utah, Colorado, and Italy (Baum and Fleming, 1991; Coe et al., 2009; Guerriero et al., 2014, 2015a) indicate that the material is subject to both longitudinal extension and shortening, and the structural style is controlled by the geometry of the basal slip surface (BSS; Guerriero et al., 2014). For structurally and lithologically controlled earth flows (e.g. Pinto et al., 2016), the BSS can be a series of steep surfaces (risers) and gentle surfaces (treads; e.g. Guerriero et al., 2014) along the earth flow profile (Fig. 1). Extension (normal faulting) occurs at risers and in the transition between treads and risers, while shortening (thrusting and back-tilting) occurs between risers and treads (Fig. 1). Guerriero et al. (2014) suggested that the geometry of the BSS might be unchanged during earth flow movement for periods of tens of years. Pinto et al. (2016) showed that it is directly controlled by the structural and stratigraphic setting of the region upslope from the neck, and roughly corresponds to the pre-earth flow topography (and drainage) downslope.

Recent research has revealed that large earth flows can be composed of several distinct kinematic zones (e.g. Guerriero et al., 2014, 2016a). A kinematic zone (Fig. 1) is formed by major paired driving and resisting elements (Baum and Fleming, 1991), and can be considered as a sector of the earth flow with a specific kinematic behavior (e.g. Guerriero et al., 2016d). Driving elements are comprised of an area of extension with normal faults at its head, and resisting elements are comprised of an area of shortening with back-tilted surfaces and/or thrusts at its toe. Under these conditions, a large earth flow can be considered as a chain of kinematic zones, and the transition between two kinematic zones is the area between the compressive structures of the upper kinematic zone and the extensional structures of the lower kinematic zone (Fig. 1).

While many studies have contributed to the understanding of earth flow kinematics and dynamics (e.g. Iverson and Major, 1987; Coe et al., 2003; Schulz et al., 2009; van Asch and Malet, 2009; Daehne and Corsini, 2013; Handwerger et al., 2013; Giordan et al., 2013; Prokešová et al., 2014; Handwerger et al., 2015), and sediment flux to the river network (e.g. Mackey et al., 2009; Mackey and Roering, 2011), no account exists about the mechanisms of sediment transport along an active, segmented earth flow, and the possible interaction between kinematic zones. In this paper, we use a combination of data from surface mapping, GPS surveys, T-Lidar surveys, boreholes, seismic profiles, and HVSR measurements, to characterize the short-term behavior of the Mount Pizzuto earth flow in the Apennine mountains of southern Italy (Figs. 2, 3).

We use velocity data from GPS surveys completed between April 2014 and March 2016, and the reconstructed 3D geometry of the earth flow to compute sediment discharge at the transition of kinematic zones. We relate sediment discharge entering a kinematic zone to internal strain (e.g. Baum et al., 1993), and use 2D mechanical modeling to link structures geometry to driving and resisting elements kinematics. To supplement our interpretation, we use Lidar data of the upper source area to understand sediment supply during slow movement, and compare rainfall data to earth flow movement to understand possible relationships with local climate. This allows us to better understand: i) flow movement and its relation with rainfall, ii) the control exerted by the geometry of the BSS on flow velocity, and iii) sediment transport along the flow during slow movement and surging events. It is important to note that the surface structures used in this paper are simplified from Guerriero et al. (2016a), and displacement data from two GPS surveys were already described by Guerriero et al. (2016b, 2016d).

2. The Mount Pizzuto earth flow

2.1. Earth flow description

The Mount Pizzuto earth flow (Fig. 2) affects the NE side of the Pizzuto Mount from about 500 to 720 m above sea level (masl), and involves ~300,000 m^3 of fine-grained flyschoid material (Fig. 3). The earth flow has a complex source area with two active branches, a well-defined neck, an inactive source zone downslope the neck, a 500 m long transport zone, and a fan-shaped bulging toe (Figs. 2, 3). The earth flow is located on the footwall of a E-vergent thrust between the Argille Varicolori Formation (Cretaceous–early Miocene; Pinto et al., 2016) on the hanging wall, and the flysch of the San Bartolomeo Formation (late