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Numerical study on deep-seated gravitational slope deformation in a shale-dominated dip slope due to river incision

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ABSTRACT

Based on numerical simulation, this study investigates the triggering factors and evolution of deep-seated gravitational deformation in a dip-slope consisting of a shale-dominated sequence of sediments. Results from continuum-based (finite difference) numerical modeling demonstrate that long-term strength degradation of a rock mass is a prerequisite for the development of gravitational slope deformation, and that river incision, resulting in change of slope geometry and corresponding stress concentration and redistribution, is a major driving mechanism for the progressive evolution of deep-seated gravitational slope deformation (DSGSD). Numerical simulation considering the influence of weak planes indicates that the bedding planes control the strength of rock mass and form a structural constraint on the development of gravitational slope deformation. A satisfactory correlation between the distribution of numerically simulated plastic shear bands and weak zones in drill cores demonstrates that the weak zones within the slope are formed due to gravitational slope deformation. Furthermore, numerical simulation shows a link between geomorphological development and internal deformation of the slope, which aids in the understanding of relationships between interior deformation of the slope, the exterior geomorphology and related effect factors including river incision and strength degradation.

1. Introduction

Study and knowledge on DSGSD are very important for landside hazard assessment and mitigation, especially in mountainous regions where many catastrophic landslides often occur in DSGSD influenced areas (Agliardi et al., 2001; Apuani et al., 2007; Hradecky and Panek, 2008; Agliardi et al., 2009; Chigira, 2009; Chigira et al., 2013b). The most famous case is the 1963 Vajont landslide (Kilburn and Petley, 2003), which occurred in a dip slope. The long-term accumulated gravitational deformation resulted in brittle fracture of materials and devastating slope collapse. Based on different study methods and mechanical evolutionary mechanisms, DSGSD has been variously called sackung (sagging) (Zischinsky, 1966) or mass rock creep (Chigira, 1992). Essentially, it indicates large-scale continuously developed mass movements with relatively small displacements compared to the mass itself; while the absence of a well-defined shear sliding surface is not considered as an essential diagnostic feature of DSGSD (Dramis and Sorriso-Valvo, 1994; Agliardi et al., 2001).

Over the years, the studies on formation and development of DSGSD have been mainly performed based on the following approaches: 1) field geomorphological investigation, photo-interpretation and geophysical survey to perform morphological interpretation and structure identification (Chigira, 1992; Agliardi et al., 2001; Jomard et al., 2007; Agliardi et al., 2009); 2) physical modeling to relate internal deformation and morpho-structural features (Bachmann et al., 2006, 2009); and 3) numerical simulation to identify the mechanical triggering and evolution mechanisms of DSGSD or deep-seated landslides (Agliardi et al., 2001; Eberhardt et al., 2004; Apuani et al., 2007; Bachmann et al., 2009; Chemenda et al., 2009). Most studies on long-term gravity-driven deformation of slopes to date have focused on morphological, geological or macroscopic structural analyses. Only few studies have involved the internal structures formed during DSGSD. Based on the detailed observation of high-quality drill cores with 100% recovery, Chigira et al. (2013a) distinguished gravitational deformation structures and tectonic brittle structures, indicating that the disintegrated and pulverized zones within the slope may be related to river incision-induced stress redistribution.

The influencing factors and triggering mechanisms resulting in the initiation and development of DSGSD have been investigated by many researchers to explain gravitation-associated morpho-features such as scarps, trenches, double ridges, bulging, bulking and so on (Radbruch-Hall et al., 1976; Agliardi et al., 2001). As shown in Fig. 1, these factors can be grouped into two categories: 1) intrinsic factors including geological conditions and topographic conditions, which basically determine the gravitational slope deformation and cause the slope to be in an equilibrium state if the external loading is unchanged. These factors usually strongly control the rock mass mechanical properties, the drainage conditions and the height and gradient of the slope; 2) external factors

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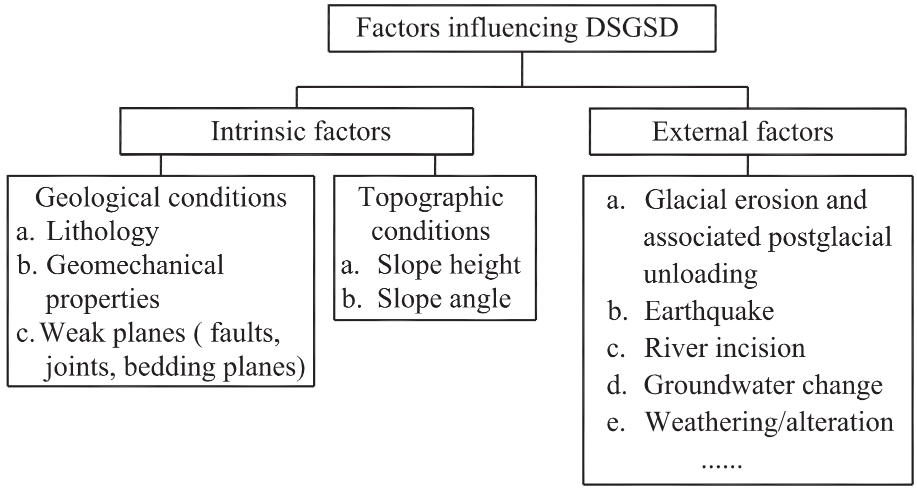

Fig. 1. The factors influencing deep-seated gravitational slope deformation.

which trigger the evolution of long-term gravitational deformation and move the slope from one equilibrium state to another equilibrium state or catastrophic landslide, such as glacial erosion and associated postglacial unloading (Agliardi et al., 2001; Agliardi et al., 2009; Leith et al., 2014a), earthquake (Moro et al., 2007), river incision (Azanon et al., 2005; Chigira, 2009; Tsou et al., 2011), and weathering/alteration (Chemenda et al., 2009). Hence, the evolution of DSGSD is dominated by either the change of external factors such as postglacial slope unloading, or the change of intrinsic factors induced by the external factors such as weathering-induced rock mass strength degradation. From a mechanical point of view, the evolution of gravitational slope deformation is a continuously developing dynamic equilibrium process between internal stresses and external loads at a large temporal and spatial-scale.

The development of numerical techniques provides significant opportunities for studying the driving mechanism and development process of DSGSD. The most widely used numerical methods for gravitational deformation study mainly include continuum-based finite element (Forlati et al., 2001; Bachmann et al., 2009) and finite difference methods (Agliardi et al., 2001; Apuani et al., 2007; Chemenda et al., 2009; Leith et al., 2014a,b). Other discontinuum-based discrete element and hybrid finite/discrete element methods (FDEM) have also been applied to analyze the deformation and progressive failure of natural rock slopes (Eberhardt et al., 2004; Stead et al., 2006). The hybrid FDEM uses the rotating crack model, which is based on fracture mechanics principles, to allow realistic modeling of progressive damage and fracture processes in intact rock (Owen et al., 2001; Klerck et al., 2004). Although the hybrid method maybe the optimal method to simulate the transition from a continuum to a discontinuum explicitly, it has not been widely used to date. Among the available numerical methods, the continuum finite difference method FLAC (Itasca, 2011) is commonly used in analyses of the deformation and stability of rock slopes, and of fracture propagation in near-surface bedrock (Leith et al., 2014a,b). These numerical simulations consider various factors that affect the rock slope mechanical response, including rock mass strength degradation due to weathering (Chemenda et al., 2009; Bouissou et al., 2012), high tectonic and bedrock exhumation-induced stress (Leith et al., 2014a), glacial erosion and river incision (Leith et al., 2014b). The constitutive models involved in these simulations include the Mohr–Coulomb failure criterion, Ubiquitous Joint model (Agliardi et al., 2009), creep rheological models (Apuani et al., 2007) and rock-damage related tri-linear failure criterion (Leith et al., 2014a,b).

The main aim of this study is to identify the triggering factors, the controlling conditions and evolutionary process of the gravitational deformation of a shale-dominated dip-slope through numerical simulation with FLAC, and to interpret the actual distribution of nontectonic shear zones observed from high-quality drill cores. Numerical study is performed to simulate the progressive propagation of plastic shear zones and the development of gravitational slope deformation accompanying staged river-bed incision. In the study, the long-term strength degradation of the rock mass and the effect of bedding planes on the gravitational deformation of a dip slope are modeled. A comparison between the shear bands modeled in numerical simulations and disintegrated zones observed from drill cores is then performed and used to interpret the formation of these weak zones within the slope. Finally, a comprehensive discussion of the relationships between evolution of internal gravitational slope deformation, geomorphologic processes and related driving mechanisms is provided.

2. Geomorphological and geological setting

The research site is in the north of the Kii Mountains, Nara Prefecture, west Japan, an area where uplifting and river incision predispose the mountain slopes to become gravitationally unstable (Hiraishi and Chigira, 2011). The study area is located on the left flank of the NW-flowing Yoshino River with an elevation ranging from 250 to 1200 m above sea level (Figure 2). A 1-m resolution Digital Elevation Model (DEM) based on LiDAR (Light Detection and Ranging) was obtained from the Ministry of Land, Infrastructure, Transportation, and Tourism. Several cross slope profiles along the Yoshino River, generated from the DEM show that one or two convex slope transitions, i.e. slope breaks, exist at a height of 100–200 m above the present river bed. Fig. 2 shows that the slopes are steeper at lower elevation compared with those in higher elevation. One cross slope profile within the study area has an average inclination of 22°, 30° and 40° in the upper section, the middle section and lower section respectively using the two slope breaks as reference points. This area has never been glaciated and the slope breaks are inferred to have been formed in geological time due to river incision. A shaded relief image covering the study slope (Figure 3) reveals that the slope is characterized by a rounded and undulating morphology. The topographic feature of the absence of macroscopically well-defined landslide scarps suggests that gravitationally deformed slope is not separated completely from its surroundings, and ongoing gravitational deformation and creep-type displacement occur in the study area.

With hybrid drilling techniques (Takeda et al., 2006), three boreholes (#1, #2, and #5 shown in Figure 3) were drilled up to maximum depth of 96 m (Chigira et al., 2013a). These techniques use air bubbles and surfactants with triple core tubes during drilling to ensure 100% recovery of undisturbed drill cores. High-quality drill cores with 100%