Tectonophysics 605 (2013) 13–33

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Invited Review

Deep seated gravitational slope deformations in the European Alps

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ARTICLE INFO

Article history:
Received 8 March 2013
Accepted 23 April 2013
Available online 10 May 2013

Keywords:
Deep seated gravitational slope deformation
European Alps
Review
Multivariate statistical analysis
Modelling
Inventory

ABSTRACT

Deep seated gravitational slope deformations (DSGSD) are widespread phenomena, recognized in different mountain ranges worldwide. The distribution of such phenomena at the scale of a mountain belt has rarely been systematically analysed in the past. Aim of the paper is to present and discuss an inventory map of DSGSD at the scale of the entire European Alps, in order to review existing knowledge and investigate general controls on these phenomena. The criteria adopted for their classification and distinction are presented. A total of 1033 DSGSDs, ranging in size between 0.03 and 108 km^2, have been mapped. The inventory has been validated against available local or regional landslide inventories at different scales and prepared by different authors using different approaches. The frequency–area relationship for the mapped features is presented. The spatial distribution of the mapped DSGSD has been quantified by discretizing the study area into regular square grids with different resolution, and analysed with respect to a variety of geological, geomorphological and morphometric variables, and of their clustering. Discriminant, principal component and cluster analyses have been performed to define the most important controlling and predisposing factors. Results suggest that the occurrence of foliated metamorphic rocks, LGM ice thickness, local relief (and related parameters), slope size, drainage density and river stream power are the local parameters most positively correlated to DSGSD occurrence. The impact of these phenomena on slope morphology, in terms of hypsometry and slope gradient adjustment is also discussed.

Contents

1. Introduction . . . 14
2. Deep-seated gravitational slope deformations . . . 14
3. Inventory of DSGSD in the European Alps . . . 16
    3.1. Methods . . . 16
    3.2. Results . . . 20
4. General controls of DSGSD: statistical analysis . . . 23
    4.1. Methods . . . 23
    4.2. Results . . . 25
        4.2.1. Principal Component Analysis . . . 25
        4.2.2. Discriminant analysis . . . 25
        4.2.3. Cluster analysis . . . 27
5. Discussion . . . 29
    5.1. DSGSD controlling factors . . . 29
    5.2. DSGSD activity . . . 30
    5.3. DSGSD control on slope gradient . . . 31
6. Conclusions . . . 31
Acknowledgments . . . 31
Appendix A. Supplementary data . . . 31
References . . . 31

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0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.04.028

1. Introduction

Mountain landscapes are influenced by a variety of slope instability processes acting at different scales. These processes can play a relevant role in the geomorphological evolution of the landscape by mobilizing different soil and rock mass volumes from different sectors of slopes, with different displacement rates and sensitivity to triggering factors. Large deep-seated, slow-moving landslides include a broad range of instability phenomena (e.g. rockslide, rock slump, lateral spread, rock mass creep and sackung) which in some cases can be found as combined or sequential processes, representing the progressive evolution of a complex slope instability. Deep seated gravitational slope deposits (DSGSD) are probably the most conspicuous and exceptional processes among the ones listed above. Because of their size, their evolution is controlled by the interaction of different factors and acting processes. At the same time, the typical long life of these phenomena implies them to have been subjected to controlling factors of completely different types, relevance, intensity and temporal recurrence (e.g. glaciation, deglaciation, slope steepening, post glacial induced earthquakes, seismic activity, long term climatic changes, exceptional rainfall events, valley infilling or incision, human activity). Furthermore, they survived or evolved together with major geomorphological changes (e.g. valley erosion and deepening, incision of the slope drainage network, secondary instabilities). For this reason, they have been often considered as extinct or fully stabilized palaeo-landslides.

The list of the most frequently quoted predisposing, controlling or causal factors for DSGSD includes: lithology and geologic structure (Agliardi et al., 2001; Ambrosi and Crosta, 2006; Zischinsky, 1966), long-term exhumation controls on topography (Agliardi et al., 2013), topographic relief and slope geometry (Ambrosi and Crosta, 2011), tectonic and topographic stresses and their concentration (Ambrosi and Crosta, 2006, 2011; Crosta, 1996; Martel, 2006; Miller and Dunne, 1996; Molnar, 2004; Savage et al., 1986), weather and climate (Agliardi et al., 2013; Ballantyne, 2002; Evans and Clague, 1994), glaciation and deglaciation (debuttressing, glacial rebound, changes in slope hydrology) (Augustinus, 1995; Ballantyne, 2002; Cossart et al., 2008; Crosta, 1996; Ustaszewski et al., 2008), seismicity (McCalpin, 1999; Moro et al., 2007; Radbruch-Hall, 1978; Solonenko, 1977), changes in groundwater regime (Crosta, 1996), rock dissolution, and human activity (e.g. artificial water reservoir, tunnel, water diversion tunnels) (Heim, 1932; Macfarlane, 2008; Zangerl et al., 2010). All these factors control the spatial and temporal evolution of these instabilities, their main morphologic evidences, as well as their influence on the landscape and its evolution. In particular, large slope deformations can control:

- geometry of very large sectors of valley flanks;
- evolution of drainage networks along the slopes;
- formation of knickpoints along the valley bottom;
- narrowing of valley cross-profiles, resulting in sediment capture and the development of flat alluvial plains upstream of the slope toe;
- erosion along major weakened structures or structural elements, which can be reactivated or exposed by large and deep displacements;
- occurrence of secondary fast moving instabilities (e.g. rock falls, rockslides, rock avalanches);
- groundwater flow at the scale of the valley flanks (e.g. increase in permeability, flow compartmentalization, development of perched groundwater tables);
- stability of man-made structures located within the slope (e.g. water diversion, railway or highway tunnels) or at its toe (e.g. dams, penstocks);
- formation of large debris cones and debris flow fans.

During the last decades a variety of data, models, and theories have been presented to explain the locations of large slope failures, their geometrical characteristics, time of occurrence, triggering mechanisms, rates and types of movement, and their consequences (Agliardi et al., 2012). Nevertheless, very little has been done to evaluate the actual impact of such phenomena at a regional scale and to connect field evidence and the various suggested models. In the literature only few DSGSD inventories have been presented, most limited to relatively small areas (a few thousand square kilometres) (Agliardi et al., 2009a; Braunstingl et al., 2005; Korup and Schlunegger, 2009) or of relatively low detail (e.g. points, low resolution) (Noverraz, 1990) with a limited number of mapped features (Mortara and Sorzana, 1987; Trigila et al., 2010). DSGSD mapping is based on the recognition of distinctive surface features, criteria specific to individual areas and the availability of adequate tools (e.g. aerial and satellite imagery, field surveys and local logistic). Therefore, these inventories have been completed using different criteria, definitions of phenomena, mapping methods, and topographic base maps. By the simple fact that they are limited in extent, or different surveyors mapped different subareas of limited extent, these inventories contain a limited number of DSGSD or some typologies peculiar of local geological characteristics (Trigila et al., 2013). Consequently, recognition and mapping for some inventories are considered unreliable for a comparison with the inventory presented in this work and covering the widest range of typology and controlling conditions.

Aim of this paper is to present an updated large-scale inventory of deep seated slope instabilities in the European Alps, and to discuss their distribution with respect to some of the most important geological and geomorphological features and variables. This will give the occasion to discuss the most important features associated with these phenomena and the criteria for their recognition, and to provide a broad, even if not complete, overview of the predisposing and controlling factors, as well the relationships with the main landscape topographic characteristics. In the following, we introduce the criteria adopted for the generation of a homogeneous and reliable inventory of these phenomena. Such criteria could be followed to replicate similar works in other contexts. Then results will be described and analysed in terms of spatial distribution, and with respect to the main geological and geomorphological variables. Controlling factors will also be analysed and ordered by relevance through discriminant and principal component analyses.

2. Deep-seated gravitational slope deformations

DSGSDs are large to extremely large mass movements generally affecting the entire length of high-relief valley flanks, extending up to 200–300 m in depth, which can frequently extend beyond the slope ridge. They have been recognized to affect different lithologies at many sites worldwide (Audemard et al., 2010; Bovis, 1990; Chigira, 1992; Cossart et al., 2008; Gutiérrez-Santolalla et al., 2005; Pánek et al., 2011; Savage and Varnes, 1987; Varnes et al., 1989; Zangerl et al., 2010), in active tectonic areas (Agliardi et al., 2009b; Ambrosi and Crosta, 2011; Crosta and Zanchi, 2000), and also on other planets (Mège and Bourgeois, 2011). These slope instabilities affecting large areas and volumes can be characterised by discontinuous or poorly defined boundaries, both laterally and at their lower ends. The main body can be dissected by prominent surface deformational features where low rates of movement over long periods have been measured (Agliardi et al., 2012; Ambrosi and Crosta, 2006; Bovis, 1990; Crosta et al., 2008a; Varnes et al., 1990). These features can be characterised by an extensional, shearing or mixed mode of deformation and can be found in different types of associations, strongly controlled by existing geological conditions. Frequently, this makes it difficult to assign a specific type of slope failure mechanism and to answer to the question concerning the continuity and full development of the failure surface.

Scarps, open or infilled trenches, downthrown blocks, ridge top depressions, graben, and double or multiple ridges (doppelgrat) suggest extensional or mixed deformation style along the upper slope sectors (Fig. 1A–K). Mountain splitting is also witnessed by the presence of rock glaciers without source areas (Fig. 1N, O). Counterscarps (also defined as uphill-facing scarps, antislope or obsequent scarps), parallel or oblique to the slope, are frequently observed in the upper