Tectonophysics 605 (2013) 34–47

Contents lists available at ScienceDirect

Tectonophysics

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

Structurally-controlled instability, damage and slope failure in a porphyry rock mass

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ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form 14 May 2013
Accepted 23 May 2013
Available online 2 June 2013

Keywords:
Rock slope failure
Rock mass damage
GB-InSAR
Terrestrial Laser Scanning
Finite-Element modelling
Porphyry

ABSTRACT

Rock slopes fail through structurally-controlled mechanisms, global circular failures, or complex mechanisms depending on structural patterns and rock mass damage. Here, structural geology, rock mass characterisation, Terrestrial Laser Scanning (TLS), ground-based radar interferometry (GB-InSAR) and Finite Element modelling are integrated to explore relationships between structure, damage and global slope failure at Mt. Gorsa (Trentino, Italy). There a porphyry quarry has been excavated in complex, strongly anisotropic rhyolitic ignimbrite rock masses. The slope was affected by a major rockslide in 2003 and undergoes continuing instability. Site investigations and GB-InSAR monitoring revealed that the 2003 failure was a roto-translational rockslide involving about 400,000 m^3 of disrupted rock. Structural analysis of TLS and field data shows that the slope is affected by widespread structurally-controlled mechanisms (sliding, toppling, strain localization in kink bands). The non-obvious relationships between structurally-controlled and global roto-translational slope failure mechanisms are investigated by characterising rock mass damage in different slope sectors. A new approach to quantify rock mass damage by mapping the Geological Strength Index and interpreting its topographic signatures in TLS point clouds is presented. A persistent geological marker is systematically mapped in TLS point clouds, and correlations between attitude variability statistics and rock mass damage are established, providing an efficient assessment tool. Rock mass damage increases in kinematic domains affected by structurally-controlled instability (GSI = 35–40) and is maximum in areas of ongoing global instability (GSI = 15–20). The 2003 rockslide occurred inside a damaged rock mass zone with GSI < 35–40, also suggested to be a threshold condition for the onset of global slope displacements by GB-InSAR data. Finite-Element numerical modelling allows integrating available data and observations. It is suggested that rock mass damage induced by local, structurally-controlled slope instability provides the required conditions (loss of structural pattern, block size reduction, cohesion loss) for transition to equivalent continuum behaviour and global slope failure.

1. Introduction

Rock slopes are susceptible to deform and fail according to very different mechanisms, depending on combinations of slope size, discontinuity spacing and persistence, and the occurrence of slope-scale geological features (e.g. lithological changes) and structural patterns (Goodman and Kieffer, 2000). Local, structurally-controlled failure modes (e.g. planar, wedge, or toppling failures) are favoured at small scale and in rock masses with few sets of well-spaced discontinuities, whereas circular or composite global failure modes are expected at large-scale in rock masses characterised by several sets of closely spaced discontinuities, behaving as "equivalent continua" (Wyllie and Mah, 2004). Step-path failure modes represent a transitional situation and occur when brittle fracture through rock or rock masses between non-persistent discontinuities is important (Brideau et al., 2009; Eberhardt et al., 2004). Where slope-scale major structural features or anisotropic patterns occur, complex global failure modes are expected (Agliardi et al., 2012; Sjoberg, 1999), including: large-scale flexural or block toppling (Brideau and Stead, 2010; Nichol et al., 2002; Pritchard and Savigny, 1990), underdip toppling (Cruden and Hu, 1994), underdip slumping (block, flexural and kink band slumping; Kieffer, 1998), and buckling failures (Cruden and Hu, 1994). It has been emphasised that rock mass damage (i.e. degradation of mechanical properties due to fracturing related to different processes, such as: brittle and ductile deformation, creep, cyclic/thermal loadings, erosion, deglaciation, etc.) may promote or control large rock slope failures (Brideau et al., 2009; Stead et al., 2004). Such damage can be associated to inherited tectonic structures and related damage zones (Agliardi et al., 2009, 2013a; Brideau et al., 2009; Henderson et al., 2010), rock weathering (Martin et al., 2011) or progressive failure (Eberhardt et al., 2004; Martin and Chandler, 1994; Sjoberg, 1999; Terzaghi, 1962).

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0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.05.033

When dealing with large natural slopes (local relief exceeding some hundreds of metres), understanding the spatial and temporal interplays among different local, structurally controlled and global, circular or composite failure modes is relevant both from a geomorphic point of view (e.g. to understand short-term and long-term hillslope evolution under changing conditions, and to quantify the volume and timing of sediment supply to river networks) and in a geohazard perspective (e.g. to select proper monitoring and analysis approaches to prevent slope failure). This is also a critical issue in temporary slopes as quarries and open-pit mines (Sjoberg, 1999; Wyllie and Mah, 2004) where: 1) slope excavation causes rock mass disturbance and daylighting of rock discontinuities and major geological features (e.g. master fractures, lithological boundaries); 2) different failure modes can involve individual benches, groups of benches (inter-ramp failure), or the entire slope (global failure); 3) slope topography rapidly changes in time.

In complex geological settings, the links between local structurally-controlled failure (individual block to "step-path" failure) and global, circular or composite failure mechanisms can be difficult to assess. In fact, the mode and timing of slope failures are frequently influenced by complex phenomena including creep, progressive failure and extensive internal rock mass disruption (Eberhardt et al., 2004; Goodman and Kieffer, 2000; Stead et al., 2006). Nevertheless, the control of rock mass damage on the transition between different failure mechanisms and scales has rarely been investigated in detail and should be the target of deep study. An interesting test site to do so is the Mt. Gorsa porphyry quarry district near Trento (Northern Italy), where rock masses made of very strong intact rock with complex, anisotropic structure are quarried. There we combine back-analysis of a past global failure event with a multi-approach analysis of high-resolution geomechanical data, Terrestrial Laser Scanning and GB-InSAR monitoring data collected at the quarry slope, in order to unravel the relationships between structurally controlled instability and large-scale, global failure mechanisms in porphyry rocks.

2. Rock slope instability at Mt. Gorsa

2.1. Geological setting

The Mt. Gorsa quarry district is located in the lower Cembra valley (Trentino, Northern Italy), few kilometres north-east of Trento (Fig 1a). The outcropping rocks belong to a huge volcano-sedimentary succession of the Southern Alps, i.e. the Athesian Volcanic Group (AG). The AG extends over >2000 km^2 in Trentino and South Tyrol, and is limited by the Valsugana Line to the S and the Periadriatic lineament to the N (Bargossi et al., 1998; Rottura et al., 1998). It consists of a suite of Permian calc-alkaline volcanic and subvolcanic rocks with interlayered discontinuous continental deposits, with maximum thickness locally exceeding 2000 m. The AG unconformably overlies pre-Permian metamorphics (Fig. 1b) and locally a clastic sedimentary cover. The AG filled Early Permian fault-bounded depressions, reflecting a post-Variscan transtensional setting. During Neogene, the stress regime changed to N–S compression, causing the complete tectonic inversion of inherited structures (Selli, 1998) as compressive structures (e.g. Valsugana, Calisio, Pinè, and Fersina lines; Fig. 1b) and the deformation of the AG sequences. These are cut by steep, NW-SE trending dextral strike slip faults and NE–SW trending oblique-slip inverse-sinistral faults (Avanzini et al., 2010; Bargossi et al., 1998).

Rocks cropping out at Mt. Gorsa are red to grey rhyolitic ignimbrites ("Upper Rhyolitic Ignimbrite" formation, Bargossi et al., 1998; "Ora Formation", Avanzini et al., 2010), up to 1000 m thick near Bolzano. Rock is characterised by an homogeneous porphyritic texture (with 35–40% of quartz, sanidine, plagioclase, biotite) and rare lithic fragments. Although intact rock is characterised by high strength (Unconfined Compressive Strength > 150 MPa) and durability, rock masses have a complex and strongly anisotropic structure, due to the occurrence of a typical pervasive jointing, characterised by cm- to dm-scale spacing and extremely high persistence (Figs. 1, 7 and 8).

The Mt. Gorsa quarry district includes two perpendicular quarry faces (Fig. 1c), providing a complete exposure of the geological structure. In particular, the 170 m high, NW trending eastern face (Fig. 1e) is characterised by subvertical benches up to 30 m high, parallel to the dip direction of the main rock anisotropy and structures, thus exposing a geological cross section of Mt. Gorsa. Conversely, the 250 m high, WSW trending northern face (Fig. 1f) has an average slope of about 37° and is characterised by benches up to 15–20 m high, quarried by either mechanical excavation or blasting depending on the highly variable conditions of exposed rock masses. The morphology of the northern slope has been significantly changing during the last ten years (Fig. 2).

2.2. The 2003 rockslide event

Since 14 September 2003, the entire northern quarry slope experienced large-scale instability (extent in Fig. 2a), from the bench at 638 m a.s.l. (toe) up to 870 m a.s.l. (crown), with the head of the displaced mass at about 855 m a.s.l. Slope bulking and rock mass disruption were detected between 800 and 870 m a.s.l. (SGA, 2004), with a crest down throw of about 7 m. At lower elevation, rock mass was essentially pushed outwards without collapsing, excepted for some debris reaching the quarry bottom at 615 m a.s.l. Evidence of ongoing slope displacement during September and October 2003 motivated a geotechnical site investigation, including borehole drilling and seismic tomography. Three 50 to 60 m deep boreholes (Fig. 3) were drilled and instrumented with inclinometer casings. Monitoring-while-drilling allowed identifying disrupted rock masses up to 30 m thick in the middle slope sector, overlying highly fractured rock masses passing at depth to crushed layers up to some metres thick. The latter may characterise a sliding surface at up to 50 m depth, based on the interpretation of inclinometer readings. Slope instability was thus classified as a roto-translational rockslide, involving about 400,000 m^3 of disrupted or highly disturbed rock mass (Fig. 3). Seismic refraction tomography was carried out along 14 bench-parallel survey lines (SGA, 2004) using 3 m geophone spacing arrays. Tomographic cross-sections (with the most representative portrayed in Fig. 3) outlined that severely disrupted rock masses, reaching up to 35 m in depth, occur in laterally discontinuous domains, reflecting a strongly inhomogeneous internal structure of the slope affected by the rockslide.

3. Patterns of global rock slope failure: GB-InSAR monitoring

In order to quantitatively constrain the patterns of rock slope instability for quarry rehabilitation and safety purposes, a pioneering 4-day "short-term monitoring" survey was carried out between 27 and 30 October 2003 using ground-based radar interferometry (GB-InSAR; Ellegi-LiSALab^{TM}). This technique (Luzi, 2010; Tarchi et al., 1997, 2003a) has been increasingly applied during the last decade to the monitoring of instabilities affecting both natural slopes (Antonello et al., 2004; Leva et al., 2003; Tarchi et al., 2003a, 2003b) and open-pit mines (Severin et al., 2011; Styles et al., 2011), and proved to be an efficient tool to support slope instability modelling and forecasting (Agliardi et al., 2013b; Casagli et al., 2010; Styles et al., 2011). In the 2003 survey, a LiSALab system (Ellegi-LiSALab^{TM}) was positioned on a fixed concrete base (Fig. 2a) located at a distance from the slope ranging between 125 m and 475 m in range. The system synthesised an aperture of 2.5 m, and acquired radar images with range resolution of 1 m and azimuthal resolution of 0.85 m (@240 m). Interferometric processing and subsequent phase unwrapping of acquired radar images resulted in 3D maps of the cumulative Line-Of-Sight (LOS) displacements affecting the quarry face in the 4-day monitoring period (Fig. 4a). These allowed capturing the movements of the entire quarry face in a spatially-distributed pattern, integrating