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Airborne and ground-based data sources for characterizing the morpho-structure of a coastal landslide

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A B S T R A C T

Landslide analysis is increasingly based on the combination of multiple information sources at different spatial and temporal resolutions, spatial coverage, accuracy and acquired using various airborne and terrestrial platforms and geomorphological, geophysical, and geotechnical methods. Morphological mapping and morpho-structure characterization are preliminary steps to analyze the observed and future landslide distributions. The objective of this work is to propose a morpho-structural model of an active landslide complex on the Normandy coast (north-west France) by combining different data sources. The methodology associates field investigation with interpretation of high-resolution topographic and geophysical images. The proposed morpho-structural model highlights the division of the landslide into several morphological features. This division may explain the spatial variability and temporal variability of the slope dynamics.

1. Introduction

Assessment of landslide morpho-structures requires information on the morphology, geometry and internal structure of the stable and unstable slopes (Malet et al., 2002; Quantin et al., 2004; van Westen, 2004; Bonnard, 2006; Travelletti et al., 2009, 2013; Crozier, 2010; Travelletti and Malet, 2012). A morpho-structural model allows delineation of the spatial extent of a landslide and is key information used by local risk managers in France to prepare hazard maps (MATE/METL, 1999). Field surveys and analyses of very-high resolution digital elevation models (VHR DEMs; Jaboyedoff et al., 2010; Razak et al., 2011) can be combined with historical information on landslide displacement (e.g. results of benchmark surveys and aerial photographs interpretation; McKean and Roering, 2004; Glenn et al., 2006; van den Eeckhaut et al., 2007) and information on slope geometry and structure from geotechnical and geophysical investigations (Grandjean et al., 2006; Jongmans and Garambois, 2007). For landslides developed in soft clayish sediments, seismic and geoelectrical surveys have been widely used to image material layering and detect shear surfaces and structural heterogeneities (Bichler et al., 2004; Grandjean and Sage, 2004; Grandjean et al., 2006; Naudet et al., 2008; Travelletti and Malet, 2012), although it remains difficult to investigate a very large landslide (Chambers et al., 2011). Therefore, combining different data sources is useful for characterizing a large landslide complex (Travelletti and Malet, 2012).

The southern coast of England and the northern coast of France along the English Channel (North Sea) are prone to landslides with soft sedimentary rocks (Jurassic marls to Cretaceous chalks) and marine erosion at the foot of coastal cliffs (Hutchinson, 1991; Bromhead and Ibsen, 2004; Jenkins et al., 2011). In Normandy, along the Pays-d'Auge coast, the Cirque des Graves landslide has been reactivated in 1982. Previous studies have demonstrated the complex dynamics of this landslide, related to highly variable slope conditions and the presence of several chalk blocks and low resistance layers (Flageollet and Helluin, 1987; Maquaire, 1990). The landslide also presents a complex hummocky surface morphology with scarps and horst–graben structures.

The objective of this work is to integrate multi-source data to formulate a morpho-structural model of the Cirque des Graves

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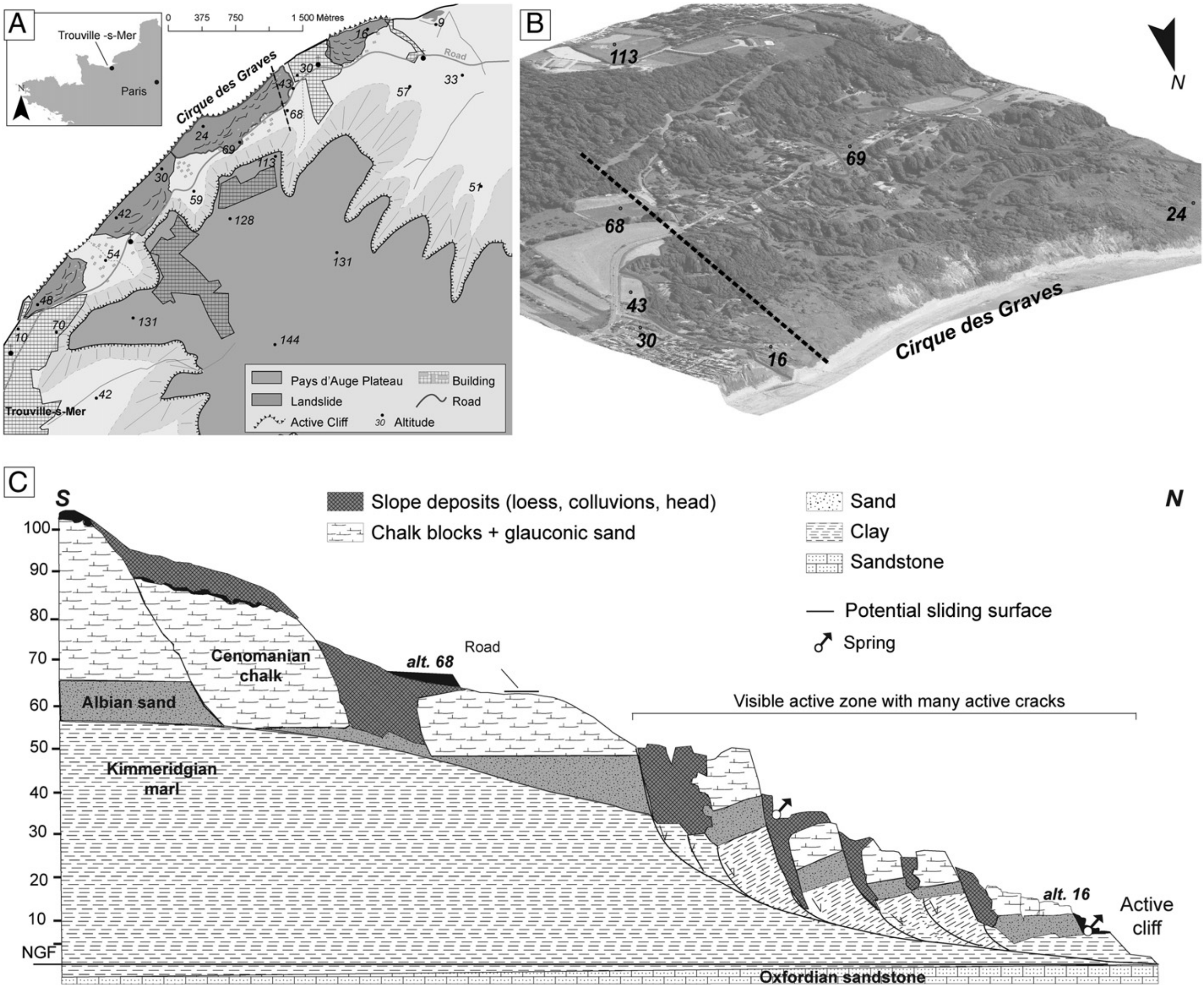

Fig. 1. Geomorphological setting of the Cirque des Graves landslide. (A) Topographic context with location of active landslides along the coast. (B) 3D view of the Cirque des Graves landslide in 2006. (C) Geological cross-section after Flageollet (1989).

landslide. The methodology, combining near-surface geophysical methods, geotechnical drilling and morphologic observations, provides information on: (1) the present state of activity; (2) the main petro-physical and geotechnical characteristics of the landslide material; (3) the volume and geometry of each compartment of the landslide.

2. Study area

Along the edge of the Pays d'Auge coast (north west of France; Fig. 1), several landslides occur below 140 m a.s.l. (Lissak et al., 2013a). These landslides are located on convex–concave slopes in highly-urbanized areas. This work focuses on the Cirque des Graves landslide (municipality of Villerville) which is the most active and largest landslide in this region (47 ha in 2012) and is characterized by the presence of composite rotational slides of >20 m thick (Maquaire, 1990). Four main failure events (Lissak et al., 2014) observed since 1982 have induced damages to buildings and traffic infrastructures (Fig. 2) and have affected the local economy (Lissak et al., 2013a).

The landslide occurs in Jurassic sedimentary rocks with a stratigraphic sequence, from the bottom to the top of: 10 m thick Oxfordian sandstone plunging gently to the south-east (10–20%); 25 m thick Kimmeridgian marl; 3 m thick Albian sand; and 50 m thick (at least) Cenomanian chalk (Maquaire, 1990). The slope surface is partly covered by weathered flint clay and periglacial slope deposits.

The slope was already unstable before the first recent major failure of January 1982 (Flageollet and Helluin, 1987; Lissak et al., 2013b) as indicated by the presence of high scarps (10–15 m high) (Fig. 2A). Three other significant failure events occurred in February 1988, March 1995 and March 2001 (Fig. 2B). In addition to these major failures, average surface displacement rates of 5–10 cm $year^{-1}$ are observed in the landslide accumulation zone (Lissak et al., 2013b, 2014). As a consequence, the resulting topography consists of multiple rotational slides with typical features such as open cracks, fresh scarps, small depressions, counter-slopes and lobes at the toe.

The landslide is monitored since 1985 (Lissak et al., 2010). Prior to this, field investigations focusing on the eastern part of the landslide (Flageollet and Helluin, 1987; Maquaire, 1990) highlighted the role of the displaced chalk blocks on landslide dynamics, and Maquaire