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Identification of the gravitational boundary in weathered gneiss by geophysical survey: La Clapière landslide (France)

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Abstract

Geophysical surveys were conducted on the unstable upper part of the La Clapière landslide in the French Alps (Alpes Maritimes). Electrical resistivity and seismic measurements were carried out over a 2-year period to obtain, for the first time on this landslide, general information on the weathered zones, slipping surface and the network of water drainage. This geological information is derived from two different surveyed areas presented in this paper. For the characterisation and quantification of the weathering, the data showed a very good correlation between the electrical resistivity and the velocity of the direct waves which is dependant on the quality of the rock, and put into context by the survey of geological and structural outcrops. This comparison made it possible to differentiate the weathered zones from unweathered zones. The electrical resistivity profiles also allowed mapping of the weathering zones at depth, and provided information on channeling of the water within the slope and on the depth of the slip surface. Thus, the origin of the instability of the upper part of the La Clapière landslide seems to be strongly associated to the water circulation. The maximum depth of the slipping surface in the uppermost part of the landslide is around 30 m. Moreover, for the first time we have also identified from electrical resistivity tomography, (1) a boundary, at a depth of about 90 ± 10 m, which could be the depth of the slipping surface of the La Clapière landslide and (2) a possible perched aquifer.

Keywords: Geophysical investigation; Landslide; Resistivity imaging; Slipping surface; Weathered materials; Electrical tomography

1. Introduction

The understanding of rupture processes in deep seated landslides and hence the prediction of the evolution of such phenomena is difficult for two main reasons. The first one arises from the difficulty in estimating the mechanical behaviour of the affected rock mass which is very different from that of rock samples we can study in the laboratory. This is mainly true in the upper part of the slope subjected to weathering (Lebourg et al., 2003). The second reason is due to the necessity of taking into account the 3D geometry of the phenomenon, and particularly the geological discontinuities affecting the rock mass. The geometry and the structure can be obtained from geomorphological, geotechnical, geophysical, and mechanical data. In order to achieve this task, both direct and indirect investigations must be performed. The first approach is geomorphological, because it allows on the one hand to conceptualize a model of the studied site and, on the other hand to define a protocol of study of the site (Hutchinson, 1988; Chigira et al., 2003; D'amato Avanzi et al., 2004; Catani et al., 2005; Dymond et al., 2006; Komac, 2006). Concerning

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direct investigations, geotechnical methods may be used to obtain accurate data allowing slip surfaces to be located, but the high cost of such methods implies that they are not always suitable. Thus, an overall structural interpretation of the landslide is not easy and sometimes impossible. For this reason geophysical methods such as electrical resistivity tomography are employed (Mauritsch et al., 2000; Roth et al., 2002). Its main advantage is that it is possible to measure the ground response along continuous (or pseudo-continuous) profiles located on the ground surface in order to obtain 2D and 3D imagery of the structure with an identification of weathered zones that can be associated with lithologic, hydrologic and mechanical characteristics. Nevertheless, the technique requires calibration and validation and complementary information (geomorphologic, hydrogeologic, tectonic, etc.) or the application of other geophysical methods (seismic reflection and refraction, gravity) to validate the results obtained. Some recent works have shown that the application of resistivity methods can reveal very important details of the weathered zones, the hydrological system, and geological structure (Robain et al., 1996; Lebourg et al., 1999; Ritz et al., 1999; Jongmans et al., 2000; Sumanovac and Weisser, 2001; Lebourg and Frappa, 2001; Godio and Bottino, 2001; Wise et al., 2003; Perrone et al., 2004; Lebourg et al., 2005; Rey et al., 2006; Godio et al., 2006; Sumanovac, 2006). However, this method has been rarely used on deep seated landslides because of logistical difficulties with using resistivity equipment in steep and unstable terrain.

The purpose of this work was to investigate whether the electrical resistivity tomography could provide accurate information on the weathered zones, slipping surface, major discontinuities and the drainage network in the upper part of the La Clapière landslide (Alpes Maritimes, France). Although numerous studies have been carried out on this landslide (hydrological, geologic, tectonic, topographic) (Follacci, 1987; Ivaldi et al., 1991; Compagnon et al., 1997; Guglielmi et al., 2000; Cappa et al., 2004)), only one geophysical survey has been performed at the foot of this landslide (Lebourg et al., 2005). For this reason, we decided to undertake, for the first time, such a study by applying the geophysical approach to the La Clapière landslide and more precisely to the more unstable part located at the top.

2. Geographical, geomorphological, geological and hydrogeological setting

The La Clapière landslide is located in the French Southern Alps (Fig. 1), downstream from the village of Saint-Etienne-de-Tinée, at the edge of the Mercantour massif. This landslide affects an area around 100 ha between 1100 and 1800 m of elevation and mobilizes a volume of rock about of 60 million m^3. It is bordered on its northwestern side by the Tenibres river and to its southeastern side by the Rabuons river, flowing into the Tinée river. The three valleys define a N010°E trending prismatic geometry that allows a 3-dimensional view of the unstable area. The prism culminates at an elevation of 2200 m. Elevations of surrounding crests and peaks reach 3000 m.

The landslide currently overlaps the quaternary alluvial deposit of the Tinée River and affects the hercynian basement rocks composed mainly of migmatitic gneiss (Follacci, 1987, 1999). A subhorizontal bar of metadiorite, called the Iglière bar, crosses the landslide at an average elevation of 1350 m (Fig. 2). All geological units have a hercynian foliation with a near subhorizontal dip at the edges of the landslide and a 10° to 30° dip to the NE within the landslide (Follacci, 1987, 1999; Gunzburger and Laumonier, 2002; Delteil et al., 2003). The metamorphic foliation in the La Clapière zone appears undulated and microfolded. At the top of the slope, between elevations of 1700 and 2200 m, metamorphic rocks are weathered over a thickness ranging from 50 to 200 m. In the middle and at the foot of the slope, the gneisses are fractured. This landslide is largely fractured with three characteristic directions of faults (Guglielmi et al., 2000) which are N10–30°E, N90°E and N110–140°E with a dip angle close to 90°. A fault with a N20 direction divides the landslide into two parts.

The landslide is bounded at the top by a main scarp of 60–80 m height which forms two lobes, an upper NE lobe and an upper NW lobe (Follacci, 1987). Two secondary scarps have developed within the landslide. One of the scarps has a N120 direction and is located at an average elevation of 1500 m, the other scarp having developed since 1987 along a N90 fault just under the top NW lobe (Fig. 1).

In the upper NE lobe, a secondary landslide is superimposed on the major one. This area corresponds to a 5 million m^3 volume which has completely lost its cohesion and which behaves like a block landslide sliding along its own failure surface which is shallower than that of the main landslide. It overlaps the main landslide. The downward movement of this compartment ranges between 100 and 380 mm year^{-1}. This area is the site of the geophysical prospecting presented in this paper. The upper part of the landslide between the headscarp and the Iglière bar has a characteristic morphology in decametric steps (Follacci, 1987). This landslide has probably been active since the beginning of the 20th century. The first studies of the La Clapière landslide were carried out in 1977. Distance