Journal of Applied Geophysics 113 (2015) 103–113

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

Application of electrical resistivity imaging (ERI) to a tailings dam project for artisanal and small-scale gold mining in Zaruma-Portovelo, Ecuador

Mario Zarroca [a,*], Rogelio Linares [a], Patricio C. Velásquez-López [b], Carles Roqué [c], Roberto Rodríguez [d]

[a] Geology Department, Autonomous University of Barcelona, Bellaterra, Barcelona E-08193, Spain
[b] Instituto Nacional de Investigación Geológico Minero Metalúrgico, Las Malvas E15-142 y De Los Perales, Quito, Ecuador
[c] Àrea de Geodinàmica Externa i Geomorfologia, Universitat de Girona, Girona E-17071, Spain
[d] Instituto Geológico y Minero de España, Ríos Rosas, 23, Madrid E-28003, Spain

ARTICLE INFO

Article history:
Received 11 March 2014
Accepted 24 November 2014
Available online 5 December 2014

Keywords:
Electrical resistivity imaging (ERI)
Tailings dam
Artisanal gold mining
Weathered granitic massif
Zaruma-Portovelo Mining District

ABSTRACT

Thanks to advances in geoelectrical resistivity method over the past two decades, researchers can now gather massive geophysical data sets encompassing long distances and depths, at reasonable cost. The enhanced resolution and spatial coverage of these techniques make them, now, very attractive for use in geological engineering applications, an area for which they were previously charged to be unsuitable. The study shows the capability of electrical resistivity imaging (ERI) to identify key subsoil features that might affect a future tailings dam slated for construction at the Zaruma-Portovelo Mining District, Ecuador. The ERI profiles were gathered and processed with the aim of obtaining resistivity images of a sufficiently resolution for geotechnical use. A geophysical model was created based on these images. The resistivity images were calibrated according to geomorphological, hydrogeological and geotechnical data in order to translate geophysical information into rational geological information. The ERI results, supported by the geomorphological and geotechnical work, suggested that the rock massif is composed of weathering horizons of different rock qualities, slopes are affected by sliding surfaces and these features exert a control on the groundwater flow. These results indicated that the original site selected to construct the dam dike was susceptible to land sliding and an alternative construction site was suggested. Based on the same results, a geomorphological–hydrogeological conceptual model for layered weathered granitic massif in mountainous areas was also proposed.

1. Introduction

Socioeconomic progress in emerging countries such as Ecuador relies heavily on hydrocarbons and mining resources. This circumstance has created a pressing need for strategic infrastructure constructing, which is often a critical issue for their sustainable development. These major construction projects require, in turn, large tracts of territory to be rapidly explored to obtain rigorous geotechnical data. Mining industry is extremely sensitive to changes in financial markets and, for example, due to the recent surge in demand for metallic minerals, mining sites that were closed 50 years ago are now being reopened. This is the case of the Zaruma-Portovelo Mining District), in El Oro Province, Ecuador (ZPMD) (Fig. 1), where artisanal and small-scale gold mining has grown tremendously over the past decade (Adler-Miserendino et al., 2013). The production capacity of processing centers located along the Calera and Amarillo rivers has thus increased, and more than 90 processing centers now produce nearly 5,000 tons of tailings (Velásquez-López et al., 2011). The current scale of this artisanal mining industry, and the predictions for its future growth, caused that a tailings dam must be constructed in order to minimize the impact of mining waste on the Amarillo River waters to make the industry more sustainable (Fig. 1b) (Appleton et al., 2001; Tarras-Wahlberg, 2002; Tarras-Wahlberg et al., 2001; Veiga et al., 2014; Velásquez-López et al., 2010). Additionally, the volatility of the ore market advices that the dam must be commissioned quickly in order to ensure the repayment of its construction costs. These circumstances force the tailing dam to be projected and executed in a short term, which leaves little time for subsurface recognition of the site planned for its construction. Given the spatial scope that the planned dam will occupy and the antecedent of landslides in the area, the viability of the selected site must be assessed, requiring an extensive subsurface exploration campaign. The topographical roughness and the lack of suitable tracks to provide access for drilling rigs hindered drilling tasks. Despite these logistical constraints, high-quality data for geotechnical requests are essential for gauging a proper construction location, even more for a dam that retains mining passives whose malfunction might cause environmental severe impacts (Grangeia et al., 2011). Aside other geomechanical and dynamic–seismic considerations, the main geomorphological–hydrogeological aspects to be considered during the assessment of the viability of the site are as follows: (1) groundwater flow pattern,

* Corresponding author.
E-mail address: mario.zarroca.hernandez@uab.cat (M. Zarroca).

http://dx.doi.org/10.1016/j.jappgeo.2014.11.022
0926-9851/

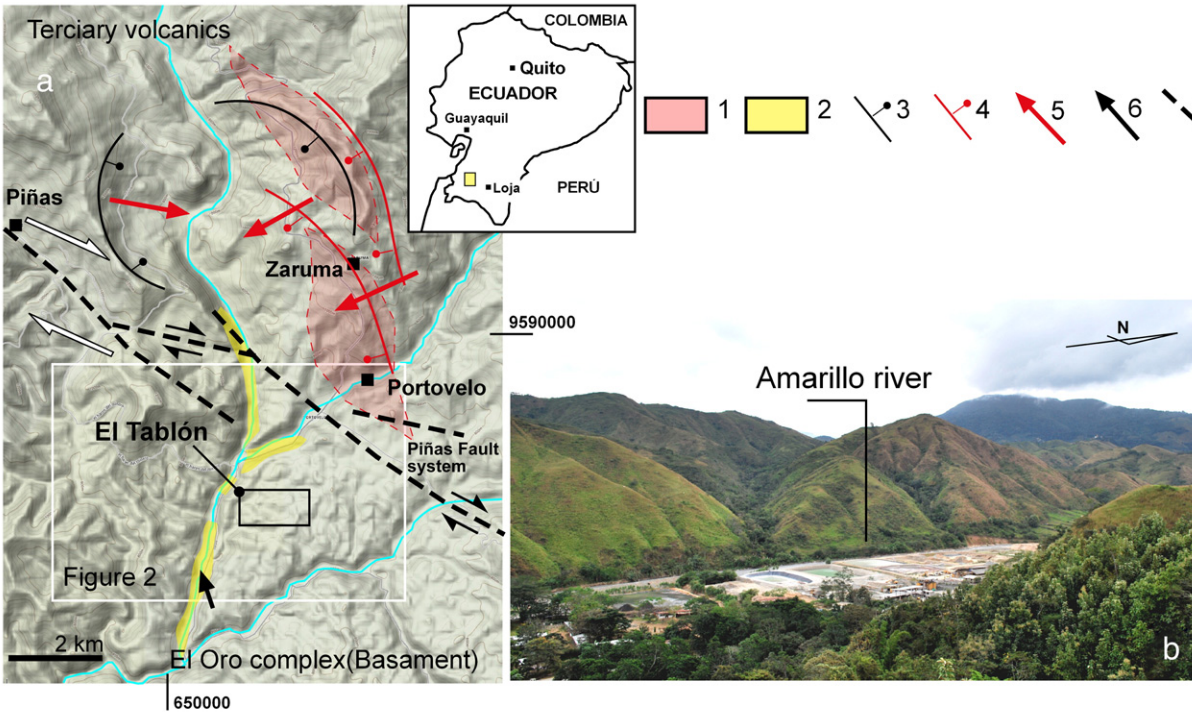

Fig. 1. Geo-environmental framework of the Zaruma-Portovelo Mining District, in El Oro province, Ecuador. (a) Simplified geostructural sketch and location of the main mining and mineral-processing activities. Northward of the Piñas fault (7) outcrops Tertiary volcanics, and southward outcrops the igneous-metamorphic Paleozoic basement of the El Oro metamorphic complex. The base map is a hill-shaded elevation model (Map data credits: ©2014 Google). (1) Major concentrations of gold veins (after Bain, 2006; Spencer et al., 2002; Van Thournout et al., 1996). (2) Location of the main mineral-processing plants along the Amarillo and Puyango rivers. (3) Normal faults with a ring-type structure related to a dacitic/rhyolitic volcanic intrusion; probable Caldera structure (according to Tunningley and Wilson, 2008). (4) Gravitational faults. (5) Current direction of displacement of the slopes, as large deep-seated landslides. (6) The observer location of the photograph is depicted in panel b. (7) Strike-slip Piñas faults. (b) Detail of the mineral-treatment plants and tailings ponds on the alluvial plain of the Yellow River. June-2012.

under natural conditions and when altered by the deposition of mining tails; and (2) susceptibility of the area to landslides.

The work reported here was aimed at demonstrating the utility of electrical resistivity imaging (ERI) in subsoil explorations supporting geo-engineering projects, such as the planned tailings dam slated for construction in the ZPMD. The main targets for the ERI surveying were identifying key geotechnical features encompassing: the thickness of the topsoil and surficial quaternary deposits, weathered and highly fractured horizons affecting the rock massif, fractures related to landslide scars, faults, high-permeability pathways for groundwater flow and the groundwater flow pattern. Resistivity DC methods had frequently been considered to offer poor resolution and to generate major uncertainties (Loke et al., 2013). Consequently, these methods were rarely used in geological engineering projects, which often require accurate quantitative models of the subsoil. However, fundamental advances in resistivity methods over the past two decades, fostered by the development of modern multichannel and multi-electrode surveying systems, and the advent of low-cost PCs and improvements in resistivity inversion routines, have led to a major increase in resolution. Large data sets encompassing thousands of apparent resistivity records, and covering distances of kilometers and depths of several hundred meters (e.g., Gélis et al., 2010; Le Roux et al., 2011), can now be collected within a few hours at reasonable cost. Regarding the purported uncertainties derived from use of ERI, these can be minimized or even eliminated by combining multiple surveying techniques and by calibrating geophysical data sets according to reliable geological information and borehole reports (e.g., Carbonel et al., 2013a, 2013b; Zarroca et al., 2014). These enhancements have prompted that actually multidimensional (2D, 3D and 4D) ERI surveys (Griffiths and Barker, 1993) are being used more widely in geotechnical, hydrological, environmental and mining applications (Loke et al., 2013). Despite its capabilities, ERI remains almost to a some extent restricted to specific geotechnical applications such as determining the depth to bedrock, exploration of buried cavities or assessment of karstic subsidence hazard (e.g., Carbonel et al., 2013a, 2014; Carrière et al., 2013; Zhu et al., 2011), landslide research (e.g., Jongmans et al., 2009; Zarroca et al., 2014) and identification and monitoring of pollution plumes (e.g., De Carlo et al., 2013; Grangeia et al., 2011). These applications involve very near-surface explorations and usually do not approach essential parts of geological engineering projects. Moreover, the utility of ERI for geo-engineering projects of singular interest has been scarcely covered in the literature (e.g., Bellmunt et al., 2012; Rucker et al., 2009, 2011). It should be noted that subsoil exploration is perhaps the task that consumes greater budget in the phase of design of large-scale infrastructures. Although the use of ERI does not obviate drilling of exploration boreholes, they do allow streamlining drilling programs, which aids to significant cost reductions. Accordingly, ERI was shown as an attractive exploration tool, as it may provide information of key subsoil features at a resolution suitable for many geo-engineering applications and capable to agreeing the logistical, schedule and economic constraints.

2. Geological and geomorphological context

ZPMD is located at the Cordillera Occidental, in the forearc of the Andean active margin in SW Ecuador. The main structural element in the area is the NW-trending Piñas regional fault (PF), which has been dated to the late Jurassic to early Cretaceos (Aspden et al., 1995; Litherland et al., 1994) (Figs.1a and 2). The PF cuts through the Tertiary volcanics northward and the Precambrian metamorphic-igneous basement southward (Fig. 1a). The Tertiary volcanic sequence unconformably overlies metamorphic rocks of continental origin (Dunkley and Gaibor, 1997; Spencer et al., 2002). N to S compression stress caused the hanging wall of the PF to bulge, forming the WNW–ESE trending Cangrejos Antiform (Coward, 2001). A splay system of NW-trending dextral-thrust *en echelon* faults occurred at the hinge of this antiform. Early Miocene magmatic pulses intruded into this stress field, yielding