International Journal of Applied Earth Observation and Geoinformation 42 (2015) 76–86

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

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

Open-pit mining geomorphic feature characterisation

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ARTICLE INFO

Article history:
Received 5 February 2015
Accepted 11 May 2015
Available online 24 June 2015

Keywords:
Open-pit mine
UAV
SfM
DSM
SLLAC

ABSTRACT

Among the anthropogenic topographic signatures on Earth, open-pit mines are of great importance. Mining is of interest to geomorphologists and environmental researchers because of its implication in geomorphic hazards and processes. In addition, open-pit mines and quarries are considered the most dangerous industrial sector, with injuries and accidents occurring in numerous countries. Their fast, accurate and low-cost investigation, therefore, represents a challenge for the Earth science community. The purpose of this work is to characterise the open-pit mining features using high-resolution topography and a recently published landscape metric, the Slope Local Length of Auto-Correlation (SLLAC) (Sofia et al., 2014). As novel steps, aside from the correlation length, the terrace's orientation is also calculated, and a simple empirical model to derive the percentage of artificial surfaces is tested. The research focuses on two main case studies of iron mines, both located in the Beijing district (P.R. China). The main topographic information (Digital Surface Models, DSMs) was derived using an Unmanned Aerial Vehicle (UAV) and the Structure from Motion (SfM) photogrammetric technique. The results underline the effectiveness of the adopted methodologies and survey techniques in the characterisation of the main mine's geomorphic features. Thanks to the SLLAC, the terraced area given by open-cast/open-pit mining for iron extraction is automatically depicted, thus, allowing researchers to quickly estimate the surface covered by the open-pit. This information could be used as a starting point for future research (i) given the availability of multi-temporal surveys to track the changes in the extent of the mine; (ii) to relate the extent of the mines to the amount of processes in the area (e.g. pollution, erosion, etc.), and to (iii) combine the two points, and analyse the effects of the change related to changes in erosion. The analysis of the correlation length orientation also allows researchers to identify the terrace's orientation and to understand the shape of the open-pit area. The tectonic environment and history, or inheritance, of a given slope can determine if and how it fails, and the orientation of the topographic surface or excavation face, with respect to geologic features, is of major significance. Therefore, the proposed approach can provide a basis for a large-scale and low-cost topographic survey for sustainable environmental planning and, for example, for the mitigation of environmental anthropogenic impacts due to mining.

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1. Introduction

Anthropogenic landscapes now cover a great deal of the Earth's surface (Ellis, 2004; Foley et al., 2005; Tarolli, 2014). In such landscapes, the direct anthropogenic disturbance of surface morphology and processes is significant (Ellis et al., 2006; Ellis, 2011; Vanacker et al., 2014). The progressive increase in intensive farming, industrialisation and urbanisation, aimed at servicing the needs of human populations, has transformed the natural landscapes by changing the topography, vegetation cover, physical and chemical properties of soil, and soil water balances (Tarolli et al., 2014). The analysis of human-landscape interactions in anthropogenic landscapes represents a challenge for better understanding the evolution of our present-day environment. This analysis can contribute to steering integrated environmental planning towards sustainable development, and can mitigate the consequences of anthropogenic alteration (Tarolli et al., 2015). Among the most evident landscape signatures of the human fingerprint (e.g. road networks and agricultural practices such as terracing), open-pit mines are of great importance. Mining is an activity integral to modern society that has a long history and occurs in a wide range of geomorphic settings. Mining activities can have a significant impact on the geomorphology and hydrology of catchments, both dur-

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http://dx.doi.org/10.1016/j.jag.2015.05.001
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Fig. 1. Daye iron mine, Hubei Province (P.R. China); one of the largest open-pit mines in Asia (Photo by Alex Chi – Panoramio®).

ing mining and for many years post-mining (Hancock et al., 2008; Herrera et al., 2010). According to Wilkinson (2005), humans move increasingly large amounts of rock and sediment during various construction activities, thus, becoming a geological agent. Mining has also become of interest to geomorphologists and environmental researchers because of its implications for geomorphic hazards and processes (Mossa and James, 2013). Open-pit mining imposes severe ecological effects on the land, with alterations that affect vegetation, soil, bedrock and landforms (Martín-Duque et al., 2010), which contribute to changes in surface hydrology, groundwater levels and flow paths (Osterkamp and Joseph, 2000; Nicolau and Asensio, 2000). In addition, open-pit mines and quarries are considered the most dangerous industrial sector, with injuries and accidents occurring in numerous countries such as the United Kingdom (e.g. Foster et al., 2008), South Africa (e.g. Hermanus, 2007), the USA (e.g. Esterhuizen and Gürtunca, 2006) and China (Zhangtao, 2010). A recent statistical study ranked Chinese coalmines among the top three sources of fatalities in the country (Zhangtao, 2010). Data for other developing countries are not available, but the media provides some indication of the current status of the global mining industry, painting a rather similar picture (Badri et al., 2011).

The assessment of open-pit mines as case studies is important, considering that (1) mining significantly affects the Earth's surface and its related processes (e.g. erosion); (2) the increase in raw-material demand connected to an increase in the population (the global production of concrete, steel, aluminium, copper and glass will significantly increase by 2050 (Vidal et al., 2013); and (3) only a few analyses are available in the Earth Science community discussing and quantifying the role of open-pit mines as one of the major anthropogenic forcing (i.e. Osterkamp and Joseph, 2000; Nicolau and Asensio, 2000; Rigina, 2002; Martín-Duque et al., 2010). Fig. 1 shows an example of an iron open-pit mine in China, where the characteristic terraces that affect the landscape are clearly visible, creating a significant topographic signature.

Analysing open-pit mines through geomorphology, therefore, can provide a useful framework both for an understanding of their environmental effects, including changes in erosion-sedimentation processes and soil properties (Wilkinson and McElroy, 2007), and the design of the most appropriate strategies for reclamation (Toy and Hadley, 1987). In the last decade, a range of new remote-sensing techniques has led to a dramatic increase in terrain information, providing new opportunities for a better understanding of Earth surface processes based on geomorphic signatures (Tarolli, 2014). Light detection and ranging (LiDAR) technology (Slatton et al., 2007; Roering et al., 2013) and, more recently, Structure from Motion (SfM) photogrammetry (Westoby et al., 2012; Fonstad et al., 2013; Javernick et al., 2014; Micheletti et al., 2014; Prosdocimi et al., 2015) provide high resolution topographic data with notable advantages over traditional survey techniques. A valuable characteristic of these technologies is their capability to produce sub-meter resolution digital terrain models (DTMs), and high-quality land coverage information (digital surface models, DSMs) over large areas (Tarolli et al., 2009; Pirotti et al., 2012; Passalacqua et al., 2014). LiDAR high-resolution topographic surveying is traditionally associated with high capital and logistical costs, so that data acquisition is often passed on to specialist third party organisations (Westoby et al., 2012). UAVs (unmanned aerial vehicles) on the other hand, offer a remote sensing tool capable of acquiring high-resolution spatial data at an unprecedented spatial and temporal resolution at an affordable cost (Westoby et al., 2012). The scientific community is now providing a significantly increasing amount of analyses on the Earth's surface using UAVs in different environmental contexts (Jaakkola et al., 2010; Watts et al., 2012; Colomina and Molina, 2014; Hugenholtz et al., 2013; Woodget et al., 2015; d'Oleire-Oltmanns et al., 2012; Mancini et al., 2013; James and Robson, 2014; Lucieer et al., 2014; Mesas-Carrascosa, 2014).

Although high-resolution data and UAV technology have been increasingly used in the last few years, there are only a few published references related to their applicability in open-pit mining (e.g. Francioni et al., 2015). Currently, geologists and mining engineers use simplified representations of slope geometry to assess mineral resources, mining reserves, and final pit layouts (Grenon and Laflamme, 2011). At the same time, mining slope monitoring is generally done using radar, geodetic prisms, visual observations and other geotechnical instruments (Severin et al., 2014). Comparatively fewer studies have comprehensively examined the use of remote sensing to map surface mine extent, especially through time (e.g. Townsend et al., 2008). Therefore, the main goal of this paper is to establish (and test) a rapid, low-cost methodology to characterise the open-pit mining geomorphic features using UAVs and digital terrain analysis based on SfM elevation data. A local scale rapid geomorphologic characterisation of mines could be used to support sustainable environmental planning and mitigate the consequences of anthropogenic alterations due to mining.

2. Study area

The Miyun Iron Mine (Fig. 2a), located at Juge Town (117°1′54″E, 40°22′51″N) in the northeast suburb of Beijing and on the south end of the Miyun Reservoir, is one of the largest mines in Beijing. The mine covers an area of 17 km^2, making it one of the biggest state-owned enterprises in Beijing, reserving more than 140 million tonnes of iron ore. It was founded in 1959 and became operational in 1970. As of today, the main product of the company is iron powder. In its early stage of construction, the mine was designed as a multiple open-pit mine with potential for underground development as well. For more than 40 years, this mine hardly modified the morphology of the area; a hill with an altitude of 240 m was turned into a giant pit with a diameter of about 700 m and a bottom altitude of about −40 m. The field sites considered in this study consist of two opencast mines (mine I and mine II in Fig. 2b–c, respectively) as part of the large Miyun Iron Mine area. The mine areas include active extraction sites (about 1.6 km^2 in mine I and 1.5 km^2 in mine II), administrative areas and small villages.

2.1. UAV data specifications

A UAV survey was carried out during the summer of 2014. The aircraft used was a Skywalker X5 (Fig. 3). This is a small, fixed wing UAV, measuring 0.6 m in length, with a 1.2 m wing span. It weighs less than 2.5 kg and can fly for up to 40 min using four-

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