USE OF A LIDAR HIGH RESOLUTION DIGITAL ELEVATION MODEL FOR RISK STABILITY ANALYSIS

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ABSTRACT

Remote sensing data offer an accurate source of information to the administration. Walloon administration develops its capacities in using Earth Observation data to respond to the EU request of characterizing the risks related to closed and/or abandoned mining sites. This paper compares two Digital Elevation Models (DEM) derived either from aerial photos or from a LiDAR (Light Detection And Ranging) scanner in their capabilities of characterizing unstable land cover and risks of landslides for Walloon coal waste heaps.

A first inventory of Walloon facilities at risk provided to EU authorities identified geotechnical failure as being one of the major risks linked to coal mine waste heaps. The risk of geotechnical failure was quantified using a geotechnical factor of safety computed on a pixel basis using the topography of the facility. The topography was extracted from a regional-scale DEM with a spatial resolution of 10 m (ERRUISSOL model, information on http://geoportail.wallonie.be). Since the first inventory, a new DEM dataset using LiDAR scanner has been acquired by the Walloon Region. This paper compares both datasets in their ability to quantify the risk of slope instability on five specific heaps.

The DEM from LiDAR data offers a resolution of 1 m. It leads to significant differences in the spatial and statistical distributions of slopes, as compared to the regional 10 m-resolution DEM. To test this spatial effect, the resolution of the LiDAR DEM has been averaged by pixel aggregation to 2/4/8 and 10 m- resolution for direct comparison with the ERRUISSOL DEM. In all cases, the application of the geotechnical factor of safety criterion based on the high-resolution LiDAR DEM leads to larger portions of heap surfaces at risk of geotechnical failure. In the next months, this method will be proposed to the Walloon administration for application to all facilities considered at risk by the first inventory to improve the characterization of the risk of geotechnical failure, and confirm or not the risk.

INTRODUCTION

EU Directive 2006/21/EC requires Member States to identify closed mining waste facilities potentially posing a serious threat to human health or environment. A general pre-selection protocol was proposed by an Ad-hoc Group of the Technical Adaptation Committee (TAC) of the directive (1). The protocol is based on recommendations by the Health and Safety Executive of United Kingdom (2). It considers several criteria, including the presence of pollutants, the stability of the source, four types of pathways and four receptor components. Institut Scientifique de Service Public (ISSeP) modified the protocol in order to better account for specific regional conditions. A first inventory of Walloon facilities at risk was provided to EU authorities, based on a specific workflow between source/pathway and targets for each type of risk, taking into account the local conditions (3). According to this specific methodology, the risk of geotechnical failure was found to be the main discriminating factor when screening Walloon coal mine waste facilities.

Geotechnical failure can take the form of a landslide, either remaining confined within the waste heap or extending into heap foundations. In certain cases, depending on the type and level of alteration of the bedrock, heaps can slide as a whole on their foundation ground. The risk of land-

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slide failure was quantified with a criterion based on a geotechnical factor of safety computed for each pixel of a digital elevation model (DEM). While the inventory used a 10 m DEM derived from interpretation of aerial photos (4), a more precise dataset is currently acquired by the Walloon Region using the LiDAR technology. Jaboyedoff et al. (5) demonstrated that LiDAR-derived DEM can be used to investigate any type of landslides. According to these authors, these DEM are not yet common in operational application, but this technique opens new domains that still have to be investigated. The interest of using this new dataset for a better discrimination of geotechnical failure is assessed in this paper. The Walloon Region wants to integrate this technology in their production and decision support workflows.

PREVIOUS INVENTORY, DEM DATA AND TEST CASES

Coal exploitation started in Belgium as early as in the Middle Ages thanks to coal outcrops in the region of Liège and in the Borinage (from Charleroi to La Louviere). In 1830, Belgium was the second largest coal producer in the world after England, with 307 coal mines. In 1900, the national coal production reached 23.5 million tons, as compared to 18 million tons in 1880. At that time, total production started to decline. The total extracted coal in the Walloon region is estimated at more than 2 billion tons.

The main type of waste from coal extraction consists of lumps or stones ranging in size from 2 mm to 20 cm. These materials are generally stacked to form heaps. In its Decree of March 16, 1995, the Walloon Government lists about three hundred coal waste tips, representing a total weight in the order of 700 million tons. These coal waste tips are mainly located along the valleys of the Sambre and Meuse rivers, over a territory that covers no more than 1,000 km^2. Existing heaps have an average surface area of 70,000 m^2 and an average height of 20 m. The maximum surface area is about 800,000 m^2 and the maximum elevation does not exceed 80 m. The Walloon database of heaps is publicly accessible through the internet (geologie.wallonie.be) and lists 591 coal waste heaps classified in five categories. Category 1 corresponds to existing and delineated heaps and identifies 277 sites.

The inventory is based on a general methodology proposed by the TAC (1) to identify abandoned and/or closed waste facilities posing a risk to human health or safety, and/or to the environment and the ecosystems. The 18 general questions address different key aspects of risk assessment, from the existing situation and current known impacts, to source of hazard, pathways, and targets. Stephenne et al. (6) described the input data used in the GIS built to represent the risk assessment based on this general methodology. A new methodology was developed by Frippiat et al. (3) in order to better take into account the specific conditions encountered in the exploitation of mineral resources in the Walloon region. Risks are no longer evaluated within a single workflow, but rather individually. This second methodology leads to the screening out of 247 heaps, leading to the need to further examine only 30 sites. This shows that, when data is available, a closer characterization of the physical mechanisms influencing the level of risk allows a more accurate assessment.

The high density point clouds of LiDAR data can provide a 3D view of the topographic features of a coal waste heap. An aerial light detection and ranging (LiDAR) dataset using a Riegl LMSQ680 scanner with an average point density of less than 1 point/m^2 is acquired by the Walloon Region. The LiDAR returns were classified as “ground”, “vegetation”, “building”, “water” or “unclassified” by the data provider. At the time of this paper, the DEM extracted from LiDAR data was only provided on the western part of the region. The ERRUISOL DEM has been produced in 2003 for a regional research project addressing risk of landslides and runoff at the level of the Walloon Region (4). Several datasets have been integrated in the processing chain of this DEM with this level of preference : (i) elevation points derived from the orthophoto interpretation of the PICC (Projet Informatique de Cartographie Continue) at a scale of 1/1,000 with a distance of 50 m between points, (ii) points from the DTM based on aerial photos as well and produced by IGN (Institut Géographique National) at a scale of 1/10,000 with a distance of 20 m between points, and (iii) DTM from the LiDAR flight on the watershed with 1 point/m^2 in 2000.

As LiDAR data only covers a limited area in the western part of Wallonia, the test calculations conducted in this paper only cover five particular heaps: Heribus, Saint-Placide, Frederic, 14-17 Siege Social and Crachet 7/12. Although there is a long history of landslides on the Heribus site, the calculation of the geotechnical failure criterion based on the 10 m-resolution DEM did not lead to list this heap as being at risk. However, the administration selected this facility in the inventory based on their knowledge. This case was then chosen as the first example to test the impact of the resolution of the DEM on the geotechnical risk assessment. Saint-Placide and 14-17 Siege Social were identified as being at risk of landslide in the first inventory, while Frederic and Crachet 7/12 were identified at risk of foundation failure in the first inventory.

METHODS FOR LANDSLIDE RISK ASSESSMENT

A factor of safety is generally defined as the ratio of a maximum admissible load and the load value actually applied on the slope (i.e. corresponding to heap weight and external loads). If the internal grain cohesion of the waste material is neglected, it can be shown that the factor of safety of an infinite dry slope can be computed based on (7):

$$F = \frac{\tan\phi'}{\tan\beta} \tag{1}$$

where: ϕ' : internal friction angle of the waste material, and β : slope angle.

Hence, intrinsic slope stability (i.e. $F \geq 1$) is ensured as long as the slope angle is smaller than the internal friction angle of the waste material. A criterion linked to slope angle is physically-based and will provide an improved characterization of the risk of slope failure, as compared to a criterion based on heap height.

To measure this criterion, we compute a factor of safety for each pixel of the DEM based on Eq. (1). Coal waste materials are generally shale rock debris of relatively coarse granulometry (from 2 mm to 20 cm) that could be characterised by friction angle values larger than 35°. A limit value of 35° is adopted here. It was considered in the first inventory by Frippiat et al. (3) that the risk of geotechnical failure existed as soon as one pixel was characterised by $F < 1$. This criterion considers that landslides of an area smaller than 100 m^2 (i.e. one pixel of 10 × 10 m^2) have a negligible impact. This criterion is also used in this study in order to determine whether the waste heaps will potentially undergo geotechnical failure or not.

While the application of the criterion to a coarse 10 m-scale grid is direct, a downscaling methodology is needed in order to apply it to a 1 m-scale fine grid. In this study, pixels are aggregated by mean values over 2 × 2, 4 × 4, 8 × 8 and 10 × 10 pixels and used to compute average slopes over 2 × 2 m^2, 4 × 4 m^2, 8 × 8 m^2 and 10 × 10 m^2 zones, respectively. Geotechnical factors of safety are then computed for the downscaled 10 × 10 m^2 pixel-size slope distributions, as they can be directly compared to factor of safety values computed from the large-scale 10 m-resolution ERRUISSOL DEM.

RESULTS AND DISCUSSION

Figure 1 illustrates the difference between slope distributions computed from the low-resolution ERRUISSOL DEM and from the high-resolution LiDAR-based DEM for the Heribus heap. The low-resolution dataset yields a relatively smooth spatial distribution of slopes (Figure 1a), with a single zone of higher slope values near the top of the heap, extending on its western and southern sides. On the contrary, the high-resolution dataset yields a much more scattered spatial distribution (Figure 1b). There are numerous small areas characterised by high slope values, distributed over the entire area of the heap. One can also distinguish a zone with a striped colour pattern, highlighting that the heap slope is not continuous in these areas, but could be a succession of high- and low-slopes areas. Such differences also appear in all four other test cases.

The corresponding statistical distributions for the Heribus heap are shown in Figure 2. While the distribution of slopes from the low-resolution ERRUISSOL DEM dataset is very symmetrical, with a clear peak (Figure 2a), the distribution of slope values from the high-resolution DEM has an almost uniform distribution between 0 and 20° without peak (Figure 2b). Similar differences can also be found for all other four cases. For some of them, the statistical distribution of slopes computed from the high-resolution DEM dataset even becomes clearly bimodal as a result of the striped pattern.

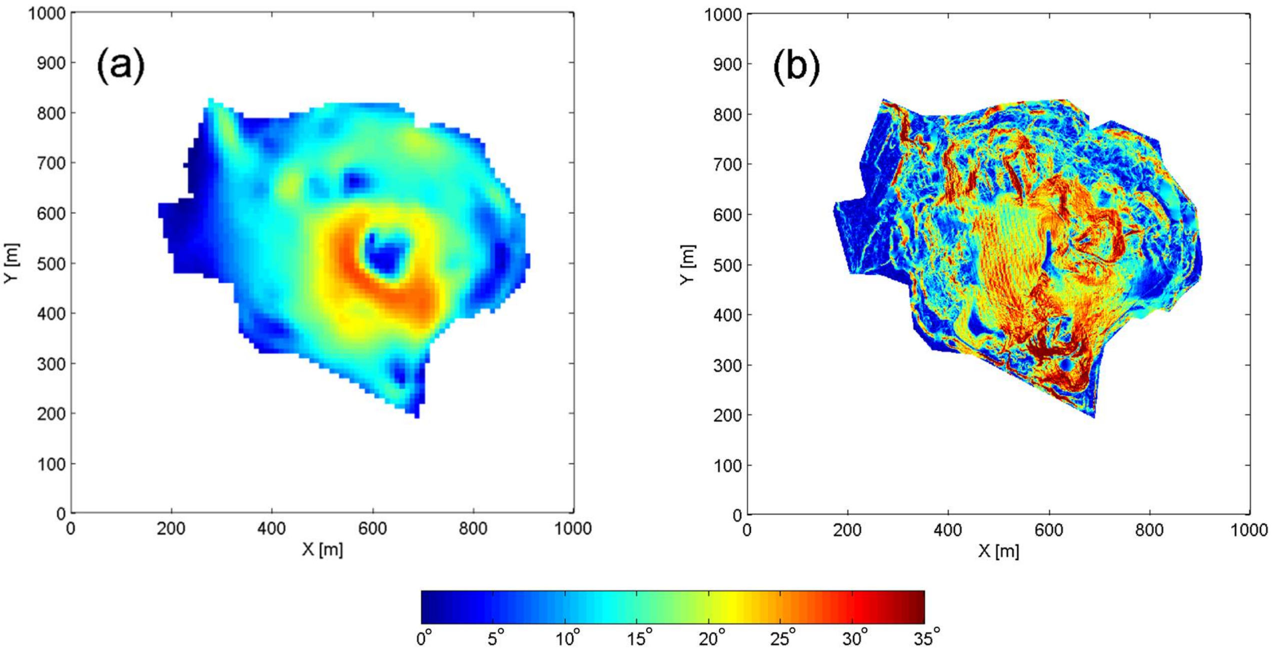

Figure 1: Slope of ground surface (in degrees) for the Heribus heap as computed based on (a) ERRUISSOL DEM data, and (b) LiDAR-based DEM data. Local spatial coordinate system aligned onto the Lambert 1972 Belgian national grid.

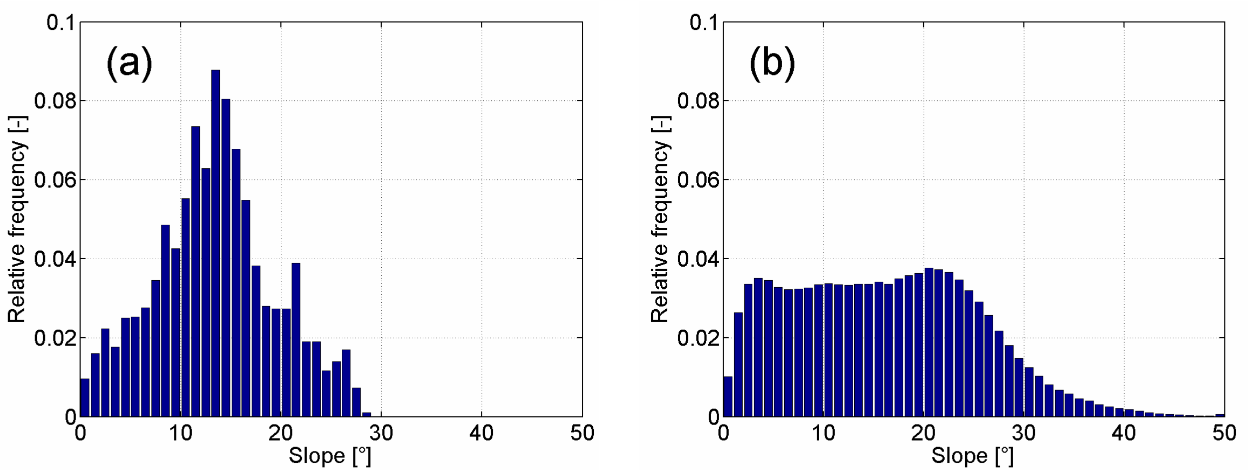

Figure 2: Statistical distribution of ground surface slopes for the Heribus heap as computed based on (a) ERRUISSOL DEM data, and (b) LiDAR-based DEM data.

To test the potential erroneous interpretation of the LiDAR signal when using it to compute DEM data, the statistical distributions of slopes for the 2 × 2, 4 × 4, 8 × 8 and 10 × 10 pixels aggregated DEM models are computed. While the striped pattern vanishes as elevation data are averaged over a larger number of pixels, the statistical distributions of slope values do not converge to that obtained from the low-resolution ERRUISSOL DEM. This behaviour is also systematically observed in all other test cases. This observation discards any bias in the interpretation of LiDAR data as being the cause of the discrepancy between both DEM datasets. However, this could be due to the interpolation method in DEM processing. At the time of this paper, we do not have enough information about the algorithm, but further analysis on the raw data will be carried out in the next months.

Finally, geotechnical factors of safety are computed based on Eq. (1) for the slope distribution based on the low-resolution ERRUISSOL dataset and for that based on the 10 × 10 pixels aggregated high-resolution LiDAR-based dataset. The geotechnical factors of safety are categorised into (i) values smaller than 1, (ii) values comprised between 1 and 1.2, and (iii) values larger than 1.2. While a value of 1 is theoretically considered to be the limit case for instability, the value of 1.2 is commonly accepted as a practical limit, accounting for uncertainties in the value of the friction angle or for model simplifications (i.e. no cohesion or dry material). Table 1 compares the values obtained for all five test cases. The use of the aggregated high-resolution LiDAR dataset systematically increases the number of pixels with a geotechnical factor of safety smaller than 1. Sites that were not identified as being at risk of landslide from the first inventory are now suspected of being prone to geotechnical instability.

Table 1. Number of 10 x 10 m^2-pixels with a geotechnical factor of safety indicating a risk of local landslide, in the low-resolution ERRUISSOL DEM and in the aggregated high-resolution LiDAR-based DEM.

		Heribus	14-17 Siege Social	Crachet 7/12	Frederic	Saint-Placide
FS<1	ERRUISSOL	0	1	0	0	3
	LiDAR 10x	3	56	72	30	23
1<FS<1.2	ERRUISSOL	0	94	0	0	23
	LiDAR 10x	33	478	20	185	228

CONCLUSIONS

In this study, it this shown that the use of a low-resolution highly smoothed dataset can lead to a drastic underestimation of the risks for the coal waste heaps tested. The ERRUISSOL DEM model is based on an interpolation of elevation points with a mean separation distance of about 50 m, which is found here to be insufficient for a proper characterisation of slopes over the surface areas tested here. The use of a high resolution DEM model, even if it is aggregated over much larger pixel sizes, can yield local slopes that are much larger than those computed from a smoothed model. This shows the need to update the inventory conducted by Frippiat at al. (3) using high-resolution DEM data, as such inventories are aimed at being used to design and plan actions for risk management. Additional reclamation works associated with re-naturalization, embankment strengthening and afforestation of coal heaps could be based on the improved stability analysis using LiDAR data.

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