

Impact of DEM Processing on the Geotechnical Instability Analysis of Waste Heaps in Wallonia

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Abstract— This paper evaluates the effects of Digital Elevation Model (DEM) processing on the geotechnical instability analysis of four waste heaps located in Western Wallonia. For this purpose, an infinite slope stability equation has been computed on each cell of two DEMs (LiDAR and ERRUISSOL, available on the geoportal of Wallonia). By processing raw LiDAR data with various interpolation techniques and spatial resolutions, we tested their influence on the slope stability analysis. In order to better understand the real geotechnical stability, several datasets have been used in the analysis (field observation, historical aerial photography and ortho-photos). Our results show that interpolation techniques and spatial resolution affect the DEM quality in regard to slope stability analysis. In particular, by removing striped patterns resulting from data acquisition, the Triangulation technique facilitates stability assessment. According to our findings, 10 m resolution is sufficient and adequate for stability analysis while 1 m resolution overestimates the risk of slope failure.

Keywords: Digital Elevation Model, LiDAR, geotechnical risk, geospatial web services, terrain analysis

I. INTRODUCTION

A first inventory of Walloon facilities at risk submitted to European Union authorities identified geotechnical failure as being one of the major risks linked to coal mine waste heaps [1]. The inventory responded to the obligation imposed on Member States by Directive 2006/21/EC to identify the risks related to waste facilities.

Light Detection and Ranging (LiDAR) Digital Elevation Model (DEM) was used by [2] for the investigation of landslides risks. However, these authors identified some interpretation issues in the stability results derived from the LiDAR DEM provided by the regional authorities on their web geoportal [3]. Their study has quantified the risk of geotechnical failure by using a geotechnical factor of safety computed on a cell basis using the topography of the facility. The topography was extracted either from a regional-scale DEM with a spatial resolution of 10 m (ERRUISSOL model; [4]) or a new DEM dataset using LiDAR scanner which has been acquired by the Walloon Region. This dataset with 1 m resolution has been averaged to 10 m for direct comparison with the ERRUISSOL DEM. As the ERRUISSOL DEM leads to underestimation of

geotechnical instabilities, it is possible through the LiDAR DEM to identify new waste heaps at risk.

LiDAR is a powerful system for producing a DEM on account of its ability to collect three-dimensional information very effectively over large areas [5]. However, there are many ways of processing a DEM that use different interpolation techniques and spatial resolution. Several authors [6]-[10] have shown that some interpolation methods are more appropriate than others in certain circumstances, the method chosen thus having the potential of affecting the quality of the DEMs produced [11]. For example, according to [14] Triangulated Irregular Networks (TINs) is the best interpolation algorithm for fluvial environment topics and [5] consider that the DEM generated by Binning is efficient for analysing the terrain features (communication, energy, agriculture, etc.).

This paper studies technical choices in terms of resolution and interpolation methods by processing raw LiDAR data rather than provided DEM and analysing their potential for the specific topic of landslide risks. Comparing processing methods with detailed field knowledge increases the applicability of these data in the Walloon decision making process.

The paper is structured as follows. Section II presents the studied area and the context of the study. Section III describes the different datasets. Section IV explains the methodology used. Finally, Section V presents our conclusions.

II. CASE STUDY

The present study evaluates the slope stability of four waste heaps located in western Wallonia (Heribus, 14-17 et Siege Social, Crachet 7-12 and Saint-Placide). The study area is located in the Borinage Region (Figure 1). In the past century, the economy of the Region was based on coal exploitation. However, this activity has been closed for a long time (the last operating coal mine in Wallonia closed in 1984). Nowadays, waste heaps and abandoned buildings are the only surviving traces of this period.

According to Directive 2006/21/EC, Member States have to establish an inventory of closed mining waste facilities potentially posing a serious threat to human health or environment. In Wallonia, two main risks associated with mining waste deposits have been identified: the risk of geotechnical failure and the risk of spontaneous combustion [1].

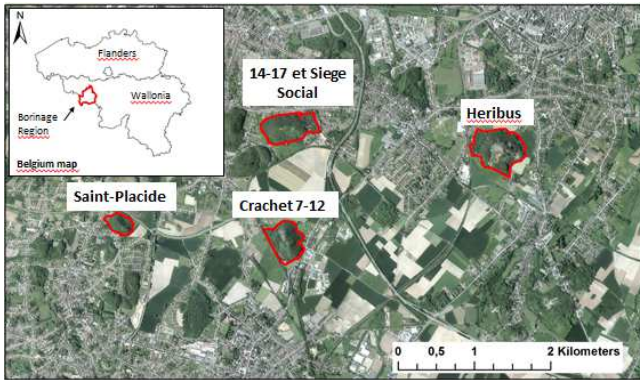


Figure 1. Location of the waste heaps

The inventory has been made in a Geographical Information System (GIS) using existing datasets provided either by European institutions (European Environmental Agency, EEA) or regional authorities (Service Public de Wallonie, SPW). GIS inputs include topographic data (location of settlements, surface waters, terrain, etc.), census figures, protected areas, land use/land cover surfaces, delineation of groundwater bodies (according to the Water Framework Directive), and site data that are specific to the waste facilities under consideration (location, contents, geometry, etc.). Table 1 illustrates some of the criteria used to define the level of risk for each Walloon coal tips. The four waste heaps object of this study were all classified in category 5, which means that they involve at least one specific risk and that there is at least one potential target located in the immediate vicinity of the closed waste facility referenced on the web site [12].

TABLE 1 CHARACTERISTICS OF THE FOUR WASTE HEAPS AND CLASSIFICATION

Risk Assessment criteria	Heribus	14-17 et Siege Social	Crachet 7-12	Saint-Placide
Height > 20 m	yes (75.2 m)	yes (78.3 m)	yes (60.2 m)	yes (35.1 m)
Slope > 1/12	no	no	no	no
Volume > 70,000 m ³	yes (5.2 10 ⁶ m ³)	yes (4.1 10 ⁶ m ³)	yes (3.4 10 ⁶ m ³)	yes (1.5 10 ⁶ m ³)
Main foundation slope > 33%	no	yes	yes	yes
Materials exposed to the wind	no	no	no	no
Waste facility uncovered	no	no	no	no
Target within 1 km	yes (watercourse and population)	yes (population)	yes (population)	yes (population)
Natura 2000 site within 1 km	yes	yes	yes	no
Risk classification	5	5	5	5

III. DATA

The quantitative inventory established to answer the Directive permits a pre-selection of the facilities that demand further risk analysis. The four heaps selected in this paper need this detailed analysis which refers to geotechnical modelling, field observations and visual interpretation of ancillary data such as ortho-photos and historical photos (table 2). These data support the understanding of the geotechnical risk but this paper has a specific technical focus on the comparison of both DEM data sources, LiDAR and ERRUISSOL.

A. Preliminary information

The preliminary knowledge about the waste heaps was gathered by analyzing ortho-photos and historical aerial photography. The ortho-photos are from different periods (2006-2007, 2009-2010, 2012-2013) and are available on the geoportal of the Walloon Region [13]. The historical aerial photographs are provided by the SPW on two dates: 1954 and 1969.

TABLE 2 PRELIMINARY AND FIELD INFORMATION OF THE FOUR WASTE HEAPS

	Aspects	Assessment
Preliminary information	Vegetation	Ortho-photos analysis (2006-2007, 2009-2010, 2012-2013) (http://geoportail.wallonie.be)
	Erosion	Ortho-photos analysis (2006-2007, 2009-2010, 2012-2013), DEM visualisation (http://geoportail.wallonie.be)
	Evidence of landslide	Aerial photography (1954, 1969)
	Evidence of spontaneous combustion	Literature
Field information	Vegetation	Presence of trees, grass
	Erosion	Presence of gully
	Evidence of landslide	Scarp, absence of vegetation, inclined vegetation
	Evidence of spontaneous combustion	Presence of burnt coal and fumaroles

B. Field observations

A field campaign was conducted on the four waste heaps to consider the following four aspects: (i) the presence of vegetation, (ii) the presence of gully erosion, (iii) traces of landslide and (iv) traces of spontaneous combustion. Vegetation cover is an important factor to consider when studying the susceptibility of slope failure because plant roots contribute to maintaining slope stability by increasing soil cohesion [15]. The second factor observed, gully erosion, is an erosional process whereby drainage lines are generated by ephemeral streams. This erosional landform may affect the soil stability by increasing the slope gradient [16]. The third factor examined, previous landslides, is significant because it indicates that the coal tip was not stable in the past. The absence of vegetation may indicate that a landslide has occurred. Finally, spontaneous combustion can lead to soil instability in two ways. Firstly,

it may induce the formation of cavities underneath the surface and be responsible for the apparition of a discontinuity plane between burning coal zones and unburnt coal zones that may lead to the occurrence of a landslide [17]. Secondly, the surface of a burning waste heap can reach a temperature superior to 100°C. These burning zones scatter the grass vegetation and prevent the growing of trees [18].

All the waste heaps examined exhibit evidences of past and/or current spontaneous combustion. Fumaroles have even been observed on 14-17 et Siege Social. The trace of a landslide has been observed in Heribus but was not noticed on the other coal tips. Heribus seems to be the most inclined to slope failures since it has already undergone two sliding events in the past (1992 and 1994) [17] and because of its land cover, burning zones and history. All waste heaps, except Saint-Placide, show traces of gully erosion. The vegetation cover was generally abundant except on the zones where spontaneous combustion has been observed and the zones on which landslides have occurred (Heribus).

C. LiDAR data

The data acquisition was performed between 2013 and 2014 over the Walloon Region with a Riegl Litemapper 6800i system. The LiDAR system operated a pulse repetition rate of 150 kHz. The flight altitude was between 1200 and 1500 meters and the point density was about 0.8 point/m². Point data is post-processed by analysing the laser time range, the laser scan angle (60°), the Global Positioning System (GPS) position and the Inertial Measurement Unit (IMU) [19]. LiDAR returns were classified as 'ground', 'vegetation', 'building', 'water' and 'unclassified' by the data provider [2]. The coordinate system used here was Belgian Lambert 72.

D. ERRUISSOL data

The ERRUISSOL data are the result of the integration of several datasets: (i) elevation points derived from ortho-photos interpretation of the Projet Informatique de Cartographie Continue (PICC) at a scale of 1/1,000 with a distance of 50 m between points, (ii) points from the Digital Terrain Model (DTM) based on aerial photos at a scale of 1/10,000 with a distance of 20 m between points and, (iii) Digital Terrain Model (DTM) from local LiDAR flights on the watershed with a resolution of 1 point/m². The ERRUISSOL DEM has been produced in 2003 [2][4].

VI. METHOD

This paper addresses technical questions raised by [2] in the processing of raw LiDAR data. These authors point out that the slope ground surface map of the LiDAR DEM present zones with striped patterns that do not appear in the ERRUISSOL model (Figure 2). Image 1 shows ERRUISSOL data (10 m) and image 2 LiDAR data (1 m). Striped patterns appear on the high resolution image. These striped patterns indicate a succession of high and low slope. Their signification has not been elucidated in previous study and deserves our attention. To evaluate the impact of this technical issue on geotechnical assessment, the infinite

slope stability model (section VI A) has been used on the basis of several DEM interpolation techniques (section VI B). The assessment of the susceptibility of slope failures is quantified by using a factor of safety that is computed on each pixel of a DEM with ArcGIS ©ESRI.

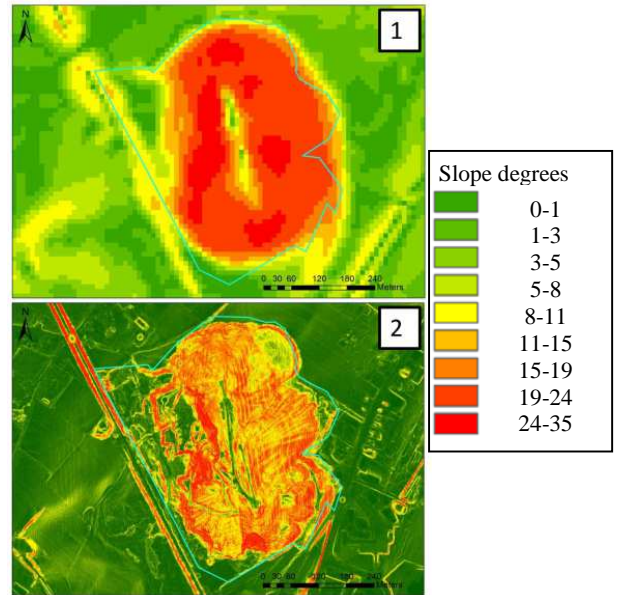


Figure 2 Slope ground surface (degrees) for crachet waste heap.

A. Infinite slope stability model

Slope stability analysis is commonplace in soil mechanic, engineering geology and geomorphology. Usually, to express the stability of a slope, a safety factor, F, is used. This factor is defined as the ratio of a maximum admissible load and the load value actually applied on the slope [2]. In this study, we refer to the infinite slope stability equation from [20] for dry conditions in the soil, adapted by [15]:

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

Where ϕ' is the effective soil friction angle (degrees) and β is the slope angle (degrees). The infinite slope model relies on the assumptions that the failure plane is mainly planar and parallel to the topographic surface and that the cohesion of the materials can be neglected [21].

According to several authors [21] [22], there is no risk of slope failure as long as the effective soil friction angle is greater than the slope angle value ($F > 1$). When $F = 1$, this indicates a state of limit equilibrium and when $F < 1$, this indicates a slope failure. Waste heap materials are generally composed of shale rock debris from 2 mm to 20 cm. Thus, the effective soil friction angle adopted here, following the paper of [2], is 35°. The factor of safety has been calculated for each pixel of the different DEMs produced.

B. The interpolation techniques and spatial resolution

Several factors may affect the quality of a DEM. First, are the factors related to the data collection, which mostly depend on the technology used and may have an impact on

the DEM's quality. LiDAR data collection consists of several overlapping parallel strips acquired during flight plans. Most errors in LiDAR-derived DEM can be attributed to systematic and random errors by both laser scanner system and the GPS/IMU during data acquisition procedures [22]. These errors produce discrepancies in overlapping regions between neighboring strips [23]. The striped patterns observed on the waste heaps are thus probably related to an improper calibration of both systems [24]. Second, the density of points can be a source of errors. Indeed, a low-point density may result in an over-estimation of the height. Finally, the interpolation techniques used can influence the quality of a DEM [11].

In this study, we will not investigate collected data nor points of density because of missing information about data collection. Rather, we will concentrate on evaluating the performance of the two main techniques for generating DEMs with ArcGIS©ESRI: Binning and Triangulation.

- Binning technique

The principle of the Binning interpolation technique is to examine the elevation values that fall within a cell to determine the final value. In case of empty cells, natural neighbor works with Voronoi and Delaunay diagrams to find the closest point to input points and applies weights to them based on proportionate areas to interpolate a value [26]. With this technique, the interpolate elevations are guaranteed to be within the range of the sample used [27].

- Triangulation technique

The Triangulation interpolation method derives the cell value with a Triangulated Irregular Networks (TIN) based approach. TIN models and DEMs are two different ways of representing Earth surface in a digital data structure. Whereas DEMs rely on a regular grid surface representing the height of the terrain, TINs use irregular gridded models. A characteristic underlying the definition of the TIN is that it provides more points in rough irregular areas than in flat ones. The principle consists in connecting sampling points by lines to form triangles of irregular size and shape. The triangles are represented by planes, thereby permitting a more continuous representation of the terrain surface [28]. Moreover, TINs have shown their reliability for discontinuous shape (such as ridges) and breaks of slope [14], [29].

V. RESULTS

A. Integration of several data

Combination of field observations, ortho-photos, historical aerial photographs and DEMs support the assessment of the slope stability of the four coal tips with the example of Heribus (Figure 3).

The vertical cross-section analysis (G) calculated on the 1 m LiDAR data processed with Binning technique discloses a break of slope illustrated by an arrow. This zone is related to the slope failure zone in (D) and (E). This instability does not appear on the ERRUISSOL data with 10 m resolution (F). When looking at the most recent ortho-photo of 2012-2013 (C), this zone is hidden by vegetation

but a discontinuous topography can clearly be identified on the historical photography (B). The aerial photography from 1969 permits to discerns the ground heterogeneity, imperceptible nowadays due to the presence of dense vegetation.

B. The interpolation techniques and striped patterns

The factor of safety is calculated on the basis of different interpolation techniques and spatial resolutions as illustrated for the Saint-Placide waste heap (Figure 4). With a 1 m resolution DEM, the striped patterns are present on the Binning technique (C) but not on the Triangulation technique (B). This discrepancy is due to the fact that whereas the Binning techniques interpolates on regularly gridded surface, the Triangulation technique interpolates elevation values on triangular surfaces of different size. Thus, the height differences between the overlapping areas resulting from the acquisition of the data are erased by means of the elevation value recorded in those triangles. Consequently, the problematic height discrepancy may be suppressed through the means of elevation values executed on an irregular surface. However, both interpolation techniques converge when the spatial resolution is 10 m and there are no striped patterns (E and F). The factor of safety for the ERRUISSOL DEM differs on some spots (D) from the other DEMs or field observations. The localisation of the instability areas does not coincide spatially on the three figures D (ERRUISSOL) in comparison to E and F (LiDAR data aggregated to 10 m). The reasons for these disparities are linked to the integration of inputs with various resolution and precision. However, this dataset was the only available for the Walloon inventory [1].

VI. DISCUSSION AND CONCLUSION

This paper studies technical choices in terms of resolution and interpolation techniques when processing raw LiDAR data. Two interpolation techniques from ArcGIS©ESRI have been tested to analyze their potential for the topic of geotechnical instability analysis. This method has been applied to four waste heaps located in Western Wallonia but could also be applied to other study sites in Belgium (Liège, Charleroi and De Kempen coalfield) or even in the heavily mined Nord-Pas-de-Calais in France.

The different sources of data are interestingly combined in this paper for describing, understanding and quantifying the risk of geotechnical failure. Field observations did not lead to the conclusion that there is a great risk of landslide on the four waste heaps because of the presence of dense vegetation and the absence of sliding events in the past. However, the factor of safety for LiDAR DEM with 1 m resolution presented numerous zones indicating a slope failure. Yet, the integration of all data permits a moderation of these results. There is no risk to have a serious impact on environment and/or human health since all the coal tips are covered by vegetation, have remained stable for many years and are not located in a residential area. However, should the authorities plan to change the affectation of the heap, a new risk analysis would be necessary.

Computing a factor of safety based on an infinite slope stability model assuming a 1 m grid size yields inadequate results. The resolution of 1 m does not seem to be consistent with the model assumptions. First, it is difficult to consider a slope as infinite when a high resolution of 1 m is used. Second, neglecting the grain cohesion appears to be inappropriate when there is dense vegetation on the waste heaps.

The utilization of raw LiDAR data improves the understanding of the impact of processing on the safety factor. Indeed, figures 2 and 3 show that different processing steps can influence the factor of safety. The Triangulation technique has demonstrated its ability to remove the striped patterns by establishing triangles which average the value of several cells, by contrast with the Binning technique, which uses a regular grid to interpolate elevation values. Because it smooths the cell value, the Triangulation technique is more appropriate to assess the slope stability here, but it could be less so under different circumstances.

While both LiDAR and ERRUISSOL data have the resolution proposed by the Protocol of the Directive, LiDAR data improve the stability assessment by comparison with ERRUISSOL. Indeed, whereas the LiDAR data have revealed that Heribus presents a risk of slope failure, this had not been detected by the ERRUISSOL data. Conversely, the ERRUISSOL data have found a risk of geotechnical instability where the LiDAR data did not discover anything.

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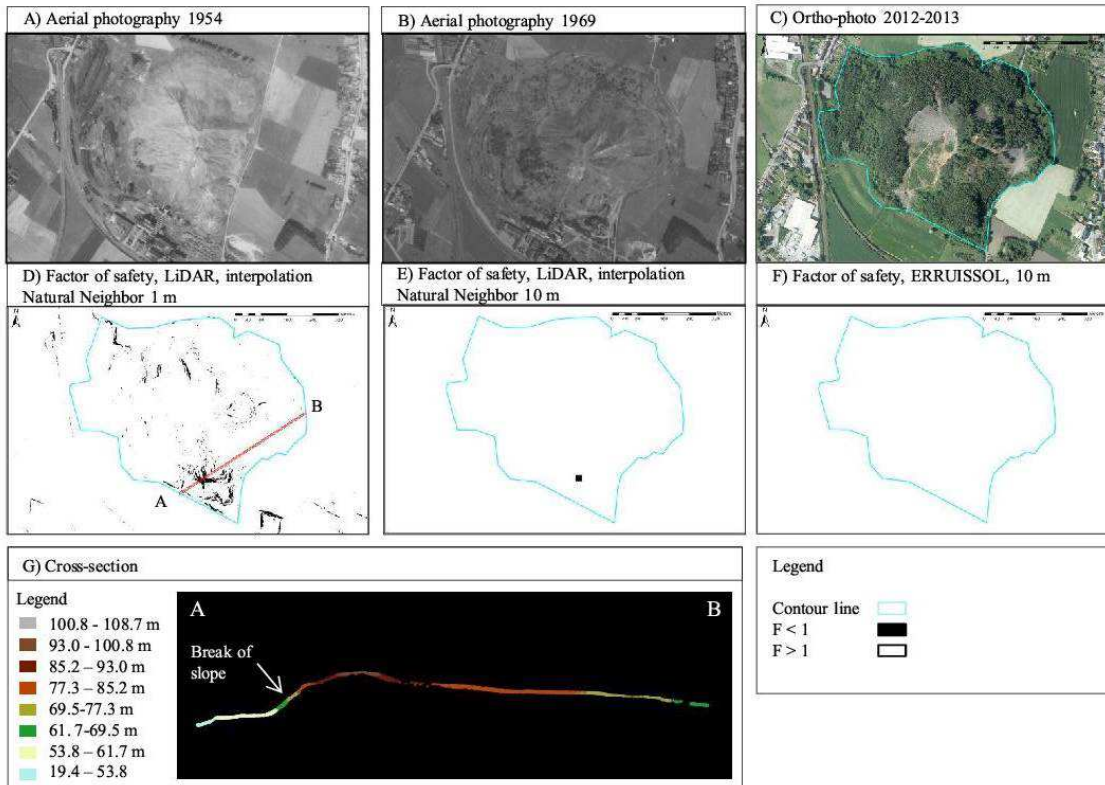


Figure 3. Integration of several datasets on the Heribus waste heap with two aerial photographs from 1954 (A) and 1969 (B), ortho-photo from 2012-2013 (C), a map showing the safety factor based on LiDAR data from natural neighbor Binning techniques with 1 m (D) and 10 m (E), a map displaying the safety factor based on ERRUISSOL data with 10 m (F) and a vertical cross-section (G) on a zone delimited on (D).

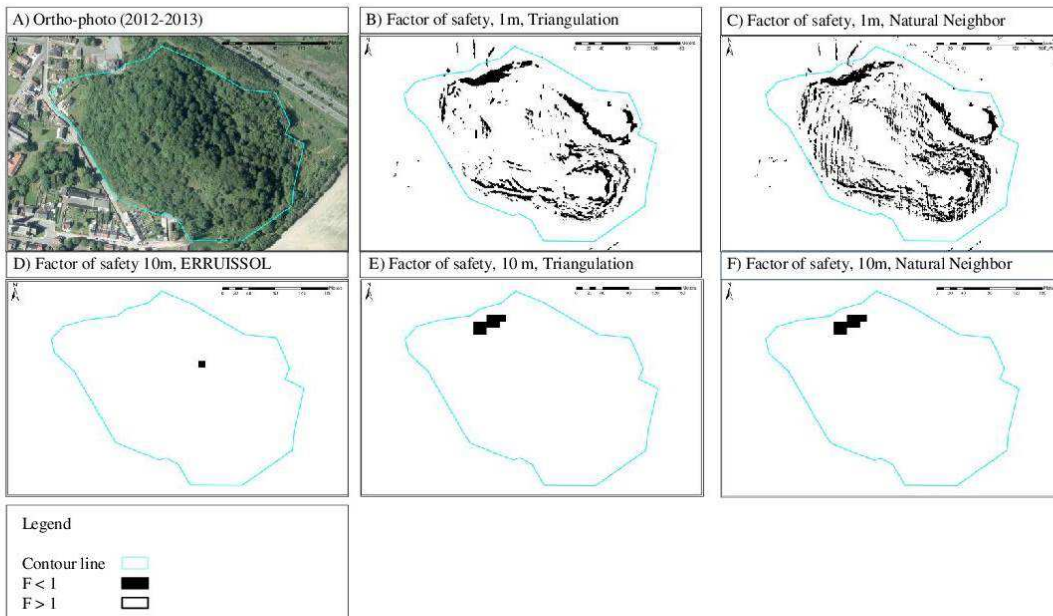


Figure 4. Factor of safety on the Saint-Placide waste heap seen on ortho-photo from 2012-2013 (A), calculated on 1m LiDAR data with the Triangulation technique (B) on 1m LiDAR data with natural neighbor Binning technique (C) on 10m on ERRUISSOL dataset (D), on 1m LiDAR data aggregated to 10m with the Triangulation technique (E) on 1m LiDAR data aggregated to 10m with the natural neighbor Binning technique (F).