Drone-based 3D slope stability analysis of the Hitura mine serpentinite waste rock pile

Analyse 3D de stabilité de pente de déchets rocheux de serpentinite de la mine d'Hitura par drones

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ABSTRACT: Using a drone-based DEM and available geotechnical data on a waste rock pile from the Hitura mine (Finland), we assessed the use of open-source 3D modelling software (Scoops3D) for stability analysis. Drone-based remote sensing was used to generate a digital elevation model of a Hitura mine serpentinite waste rock pile to research the possibility of using the generated data for 3D slope stability analysis. A few digital elevation models with different resolutions were generated and post-processed to find the most suitable outcomes for the analysis. The open-source program Scoops3D was used to perform the 3D slope stability analysis for the modelled waste rock pile, and the results were compared to 2D analysis performed with GeoCalc 4.0. The comparison indicated that the 3D analysis offered a more comprehensive but less detailed view of the overall stability of the targeted area. Therefore, the most useful application for drone-based 3D slope stability analysis was found to be the mapping of the most critical areas for more precise further analysis with, for example, 2D modelling.

RÉSUMÉ : En utilisant un modèle numérique de terrain (MTN) provenant de drones et des données géotechniques disponibles d'une pile de déchets provenant de la mine d'Hitura (Finlande), nous évaluons l'utilisation d'un logiciel libre de modélisation 3D (Scoops3D) pour l'analyse de stabilité. La télédétection pas drone a été utilisée pour générer un modèle numérique de terrain d'une pile de déchets de minéraux de serpentinite provenant de la mine d'Hitura pour chercher les possibilités d'utiliser les données générées pour une analyse 3D de stabilité de pentes. Quelques modèles numériques de terrain avec des résolutions diverses ont été générés et post-traités pour trouver les meilleures données de sortie pour l'analyse. Un logiciel libre, Scoops3D, a été utilisé pour l'analyse 3D de stabilité de pente pour la pile de déchet rocheux modélisée et les résultats ont été comparés à une analyse en 2D réalisée avec GeoCalc 4.0. La comparaison indique que l'analyse 3D offre une vue plus compréhensive mais moins détaillée de la stabilité globale de la zone ciblée. Par conséquent, l'application la plus utile pour l'analyse 3D de pente par drone a été trouvé être la cartographie des zones critiques pour une analyse supplémentaire plus précise avec e.g. un modèle 2D.

KEYWORDS: 3D slope stability, open-source modelling, waste rock piles, scoops3D, remote sensing

1 INTRODUCTION

Huge amounts of waste rock are produced during mining. After the active phase of mining, safe closure procedures for waste areas need to be executed. A typical waste rock pile consists of loosely disposed crushed rock, which may cause stability risks and negative environmental consequences (e.g., Rassam & Williams 1999, Madejôn et al. 2021). To ensure the long-term stability of a waste rock pile, rehabilitation works are needed. Normally, waste rock piles are covered, and the steep slope angles are reduced. It would be beneficial to find a new, more efficient navigation method for the mapping of the weakest stability slopes of a large facility area.

One key element of slope stability analysis is accurate surface elevation data. Slope stability analysis is commonly performed using available field investigations and measurements or laser scanning data (Oguchi et al. 2011). The problem with using laser scanning data is one of relevance; data can be several years old, and the disposal of waste rock could have changed the elevation of the piles significantly and rapidly. In other words, the data used in stability analysis cannot be out of date.

A common way to generate data is via remote sensing, which has been performed for decades using satellites and aerial vehicles (Milas et al. 2018). An increase in the usage of drones has produced third-generation remote sensing techniques, making them more available and affordable for common use. Drones make it possible to acquire up-to-date data from a precise location in a rather short time without requiring large amounts of preparations. According to Rauhala et al. (2017), drone-based monitoring may yield sufficient accuracy for topographical models in this kind of use.

Research related to 3D slope stability analysis using drone-based photogrammetry data is increasing, but there are only a few studies that have used an open-source program like Scoops3D. Most research has focused on the post-analysis of landslides in mountain areas, and there has been little to no research related to the mining environment (Tran et al. 2017, Rashid et al. 2020).

In 2D stability analysis, a number of sections are determined by evaluating the most interesting areas on the surface, while 3D analysis provides the possibility to examine the whole surface model and its slope stability with one calculation process (Reid et al. 2015). For example, this allows an overall determination of safety factors for existing landfill areas. In this paper, we studied the possibilities of utilising drone-based remote sensing data and 3D slope stability analysis as design tools by using a mine waste rock pile as the examined area and the open-source software Scoops3D for slope stability analysis.

2 MATERIALS AND METHODS

2.1 *Study area*

The study area is located at the Hitura nickel mine in the North Ostrobothnia region in Finland (Figure 1), which was experiencing ongoing closure at the time. Therefore, the site was optimal for the comparison of 3D stability calculations to traditional 2D analysis. Production at the mine started in 1970, and the mine's closure process began in 2017. Remote sensing was performed at a serpentinite waste rock pile near the open pit approximately 35 m in height with a base area of 13 ha and a volume of 2.2 Mm^3.

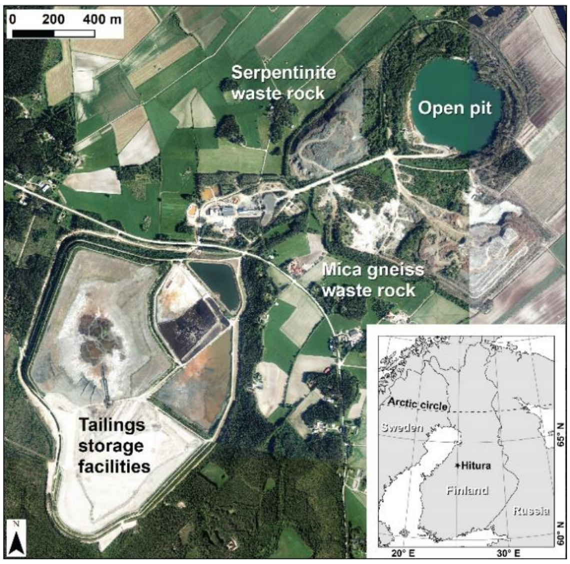

Figure 1. Overview and location of the Hitura mine and waste storage facilities; orthophoto courtesy of the National Land Survey of Finland.

2.2 *UAV and field measurements*

The measurements were done in June 2020 using a DJI Phantom 4 Advanced multicopter with a flight altitude of 110 m from the top of the pile using a photo coverage of 75% for parallel and sequential imaging (Figure 2). Georeferencing was done using 16 control points spread evenly around the waste rock pile, which is an optimal distribution, according to Martinez-Carricondo et al. (2018).

Figure 2. The flight plan used for the waste rock pile.

Properties of the soil layers and the serpentinite were determined earlier in 2018 with geotechnical investigations and laboratory tests. The unit weight and friction angle values from these investigations used for the slope stability analysis are presented in Table 1. Because the focus was on the slopes of the waste rock pile, the soil models were simplified.

Table 1. Soil layer properties.

Layer	Unit weight (kN/m³)	Saturated unit weight(kN/m³)	Cohesion(kPa)	Friction angle (º)
Serpentinite	21	21	0	36
Dry crust	16	16	0	30
Silt	17	17	0	31

2.3 *Data Processing*

2.3.1 *Point cloud generation*

Agisoft Metashape was used to generate a sparse point cloud of the modelled area with an algorithm that recognises collective characteristics from the images and corrects their positions. The model was georeferenced with the control points, and a dense point cloud was generated with ultra-high quality, allowing them to retain the original resolution of the images. The point density of the generated point cloud was 781 points/m². An orthomosaic map with a resolution of 3.58 cm/pixel was also generated for the visual representations of the stability analysis results (Figure 3).

Figure 3. Orthophotomosaic of the waste rock pile generated from drone-based data.

The point cloud was post-processed in CloudCompare by removing the vegetation from the top and vicinity of the waste rock pile using cloth simulation filtering (CSF; Figure 4.). The filtering technique consists of an algorithm that inverts the point cloud upside down and models a cloth over it. Using the given filtering settings, the algorithm sets the cloth surface as the new point cloud surface, filtering everything beneath it (Zhang et al. 2016).

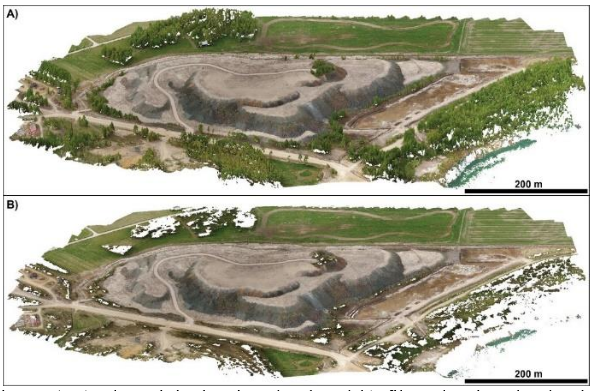

Figure 4. a) The original point cloud and b) filtered point cloud using cloth simulation filtering.

The filtered point cloud was brought to ArcGIS as an LAS file and converted into a raster image. Since the generated model included unnecessary ground surfaces around the waste rock pile, the raster image was cropped to represent the actual area relevant to the stability analysis. Additional rasters with constant elevations were created to represent the soil layers beneath the waste rock pile. The surface and soil layer rasters were converted into ASCII files for Scoops3D. A cross-section of the modelled layers is presented in Figure 5.

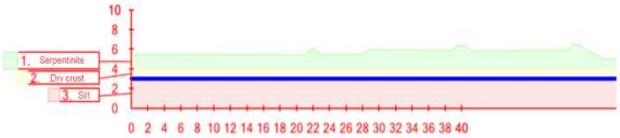

Figure 5. A cross-section of the modelled layers.

2.3.2 *Stability analysis*

Multiple 3D slope stability analyses were performed in Scoops3D using Bishop's simplified method. To examine the sensitivity of the calculation model, another surface model was created by decreasing the original resolution in half, and the two surface models were used with different kinds of calculation settings. The effects of a number of other settings were also examined to optimise the calculation precision and time. The soil parameters were also altered to test the sensitivity of the model (Reid et al. 2015).

For the minimum ranges of failure surfaces, the smallest was 200 m³, and the largest was 40 500 m³. Altogether, 18 different minimum volumes were used. For each calculation, Scoops3D created an ASCII file where each column received its factor of safety as z-values. The calculation result files were brought to ArcGIS and color mapped to represent factors of safety. The color map was made transparent over the generated orthomosaic map to visualise the calculation results.

For comparison, 2D slope stability analyses were also performed in GeoCalc 4.0 using Bishop's simplified method. Two sections were determined through the waste rock pile, and their most interesting slopes were marked for analysis. The failure surface size ranges were evaluated to represent the 3D slope stability analysis's minimum volume ranges as precisely as possible, even though the 3D and 2D failure surfaces were difficult to compare. According to Chaundhary et al. (2016), Fredlund et al. (2010) and Zheng et al. (2014), the difference between 2D and 3D values regarding factor of safety can vary between 4–40 % depending on the site geometry, soil type and level of groundwater. Soil parameters were also altered in the same manner as in the 3D analysis to acquire information about the differences between the 2D and 3D models' sensitivity.

3 RESULTS AND DISCUSSION

The most significant factors leading to notable changes in the results were the set size ranges of potential failure masses, and most notably, the minimum volume of the range. A TIN surface was generated from the point cloud, and the orthomosaic map was laid over it to make a visual representation of the 3D surface model. The transparent calculation result maps were also laid over the TIN surface for a more precise examination of the failure surfaces around the 2D analysis surfaces (Figure 6). The minimum failure surface volume controls the slip surface depth and therefore gives exaggerated FOS values for non-cohesive soils when a minimum volume that is relatively too small is used. The color maps presented in Figure 6 show that shallow failure surfaces with low factors of safety occur only with smaller failure surface volumes and disappear when the minimum volume is increased. Since cohesion was set to 0–1 kPa, the critical surfaces with smaller minimum failure masses were expected to be shallow (Reid et al. 2015), which explains the low factors of safety with relatively small user-defined lower size limits for potential failures.

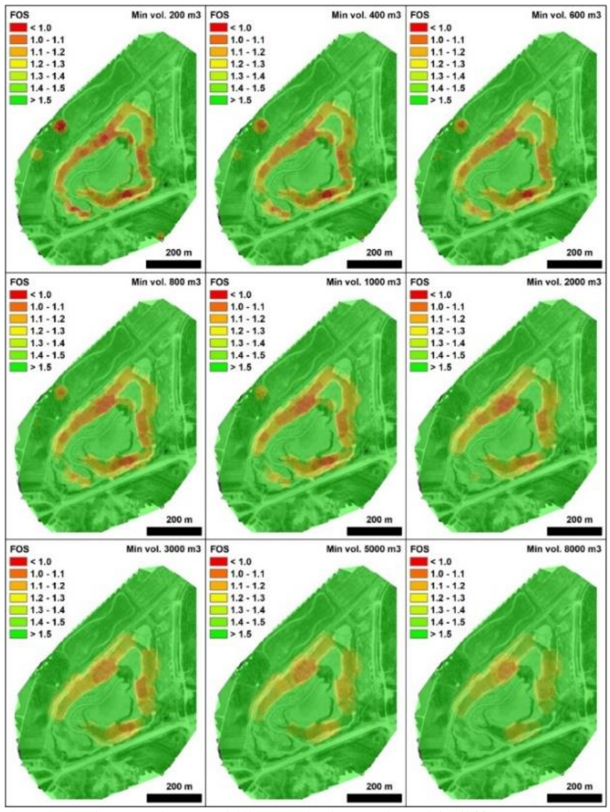

Figure 6. The 3D slope stability analysis results with different minimum failure surface volumes presented as color maps over the orthomosaic map.

The comparison of 3D and 2D analyses showed that the 3D analyses gave mostly smaller values for the factors of safety than the 2D analyses. The value of the minimum factor of safety increased steadily when the minimum failure surface volume was increased, but after surpassing certain minimum volumes, the factor of safety value became less logical, possibly due to the oversized failure surface volumes compared to the actual target slope. Altering the soil parameters of serpentinite to analyse sensitivity of the models affected the 3D and 2D analyses with the same magnitude. Results of the sensitivity analysis for the slope with the lowest factor of safety are presented in Table 2. Although the sensitivity analysis was performed for the strength parameters, the model itself was too homogeneous, which means the probable actual heterogeneity throughout the waste rock pile was not considered. Since Scoops3D calculates failure surfaces using either Bishop's simplified method or the Ordinary method, the more sophisticated methods were not available, and thus, Bishop's simplified method was used for the calculations.

The surface model resolution and calculation settings related to calculation precision affected the analysis time greatly. Using the original resolution and the densest failure surface grid, the calculation times were approximately 3 h. Using the surface model with a halved resolution and a coarser failure surface grid, the calculation times were approximately 6–15 min, and the results remained nearly the same.

Table 2. Results of the sensitivity analysis for the slope with the lowest factor of safety.

Unit weight (kN/m³)	Friction angle (º)	Cohesion (kPa)	Factor of safety 3D	Factor of safety 2D
21	35	0	1.00	1.05
21	34	0	0.97	1.01
21	33	0	0.93	0.97
20	36	1	1.10	1.16
19	36	1	1.10	1.15
18	36	1	1.10	1.16
20	35	1	1.06	1.11
19	34	1	1.03	1.07
18	33	1	0.99	1.04

4 CONCLUSION

Our study showed that 3D modelling using open-source software is an effective tool for quickly analysing the stability of mine waste rock piles in a comprehensive manner. Furthermore, comparing both 2D and 3D modelling results is difficult and should be analysed with care. The map visualising the factors of safety over the examined area gave a better understanding of the most critical areas of the site and made it possible to target the most suitable sections for a more precise 2D slope stability analysis. The goal was to test the usage of drone-based elevation models in 3D slope stability analysis with the open-source program Scoops3D. Further research should consider the use of other slope stability analysis programs with more advanced calculation methods and their comparison to Scoops3D.

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