4D GEOMATICS MONITORING OF A QUARRY FOR THE CALCULATION OF EXTRACTED VOLUMES BY TIN AND GRID MODEL: CONTRIBUTE OF UAV PHOTOGRAMMETRY

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ABSTRACT:
The purpose of this manuscript is to identify an appropriate survey technique and numerical method for the calculation of volumes extracted in a quarry. The impact of the TIN (Triangulated Irregular Network) and GRID method was evaluated firstly on a hypothetical stepped ground and one with a constant slope and, later, on a specific case study of a quarry of an important dimensions. In this case study, the survey at time t_0 was performed by ALS (Airborne Laser Scanning) and at time t_1 by the use of UAV (Unmanned Aerial Vehicle) photogrammetry. In the latter survey, the ease and speed in performing the 3D model by UAV photogrammetry was shown in the manuscript. Concerning the calculation of the volume over time, it has been shown how the TIN allows a calculation which is closer and more faithful to the reality than to the GRID model, in case the quarry conformation is in steps and, consequently, with important nearly vertical surfaces.

Key-words: *UAV photogrammetry, quarry, TIN, GRID, SfM.*

1. INTRODUCTION

The monitoring of the territory over time represents an important activity for the protection, management and preservation of the environment, especially in the case of consumption of non-renewable resources, such as quarries. Consequently, the choice of suitable geomatics survey techniques plays a very important role. In this context, UAV (Unmanned Aerial Vehicle) photogrammetry represents a valid tool to perform 4D monitoring of quarries. In fact, the possibility to acquire in a simple and fast way territorial information on particularly steep terrain, such as those that characterize the quarries, allows reconstructing the geometry of the study area in an accurate and detailed way. From a technological point of view, this represented a considerable step forward, since with aerial survey alone it is possible to obtain nadir and oblique images of the quarry. As a consequence of the technological progress of the aerial platform and of high performance cameras at low cost, a significant contribution to the diffusion and application of UAV photogrammetry is represented by the development of Structure from Motion (SfM) and Multi view Stereo (MVS) algorithms that have allowed to realize accurate 3D models in a simple and intuitive way (Snavely et al., 2007; Ahmadabadian et al., 2013; Furukawa and Ponce, 2010; Grünner and Dudáš, 2017; Masiero et al., 2019; Costantino et al., 2020). Given the ease of application of 3D reconstructions based on SfM/MVS, the automatism in UAV flight planning and image acquisition, UAV photogrammetry has been applied in an increasing number of fields, such as architecture, archaeology, geomorphology (Caroti et al., 2012; Gasperini et al., 2014; Baiocchi et al., 2018; Baiocchi et al., 2019; Pepe and Costantino, 2020). Over the last decade, UAV photogrammetry has become increasingly used as a method for the 3D construction of a quarry. González-Aguilera et al. 2012 describe a procedure to build a 3D modelling and accuracy assessment of granite quarry using UAV photogrammetry using

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VisualSfM software. Based on the results obtained from this case study, the authors claim that the UAV technology is an effective and economical method in comparison with other remote sensing techniques, such as classical surveying and laser scanning. Raeva et al., 2017 evaluate the accuracy of UAV data for volumetric measurements to the conventional GNSS (Global Navigation Satellite Systems) techniques and highlighting, through a case study, the high performance in terms of accuracy and speed of execution of the UAV survey. Therefore, the UAV survey represents one of the best methods of survey both from the point of view of efficiency (speed, economy, simplicity) and from the point of view of accuracy to evaluate the space-time evolution of a quarry, as shown in some recent papers (Rhodes, 2017; Nguyen et al., 2019; Török et al., 2020).

For this reason, in this paper, we use UAV photogrammetry to reconstruct the 3D model of the quarry over the years and calculate the volume eroded. In particular, the aspects that we intend to investigate in this research are: i) evaluating the difference between the choice of a TIN or GRID (raster) model; ii) the influence of the cell size in raster model; iii) the impact of the point cloud density in the volume calculation.

2. CALCULATION OF THE VOLUME AND ITS UNCERTAINTY

The difference in excavation volumes measured ΔV in a quarry at two different times (t_0 and t_1) is equal to:

$$\Delta V = V_{t1} - V_{t0} \tag{1}$$

where V_{t1} is the volume of the quarry evaluated at the time t_1 while V_{t0}.

To calculate the volume changed over the years to works of anthropic actions inside the quarries, the point cloud generated by UAV photogrammetry method must be converted in Triangulated Irregular Network (TIN) or grid.

TIN model, introduced in the early 1970s (Peucker et al., 1978) represents a three-dimensional vector where the points known in the three coordinates, however distributed in space, are joined by lines in order to form flat and adjacent triangles that allow to continuously represent the surface of the territory. To establish the triangles of the points that make up the individual triangles, i.e. to organize the reference meshes, algorithms based on geometric properties are used. Starting from Dirichlet's intuition for the decomposition of a domain into several adjacent (and not overlapping) convex polygons, the Delaunay method allows defining triangles of points such that the circle circumscribing each triangle does not contain other elements of the starting series. The nodes are the same sample points and constitute the vertices of the triangles; each node has a value of altitude h. The edges are the lines representing the sides of the triangles. Triangles express the approximation of the real surface with a mathematical model where each plane (triangular) describes the course of a portion of the surface of the TIN. From the spatial coordinates of the three vertices, it is possible to obtain information such as the slope, exposure, area and perimeter of the relative surface. Finally, the topological relationships define the set of links between nodes, edges and triangles through which the data structure of the TIN is stored. In TIN environment, the relation that connecting the different elements is:

$$T = 2n - t - 2 \tag{2}$$

where:
T   number of triangles;
t   number of boundary vertices
n   number of vertexes

A raster consists of a matrix of cells organized into rows and columns (or a grid) where each cell contains a value representing information, such as elevation. Indeed, with the gridding process, the trend of a given variable (such as the altitude) is reconstructed according to a regular grid of nodes, equally spaced, starting from a series of discrete values irregularly distributed in space. There are

many interpolation methods. Some methods, implemented in the most common GIS (Geographic Information Systems) software are Inverse Distance Weighting (IDW), Kriging, Natural Neighbour and Spline (Abidine et al., 2018). In the case of dense point cloud, the grid interval is typically larger than the point spacing, and a simple average of all coordinate z-values within each raster cell is sufficient (Hartzell et al., 2015):

$$h_p = \frac{1}{m} \sum_{i=i}^{m} h_i \qquad (3)$$

where:

h_i is the value of the height;

h_p mean height value evaluated on m points that is associated at each pixel.

In the representation of the quarry through the use of the raster, the volume is calculated as the product of the area of each single cell (pixel size) for the value of the pixel, naturally extended to the whole space of interest, that is:

$$V_{raster} = \sum_{p=1}^{r \cdot c} A_{cell} \cdot h_p \qquad (4a)$$

where:

V total volume evaluated on a raster by a number of rows r for a number of columns c;

A_{cell} area of the single cell (or pixel).

Of course, operability is feasible if the two grids have exactly the same pitch and origin. A representation of this volume in GRID environment is shown below (**Fig.1**).
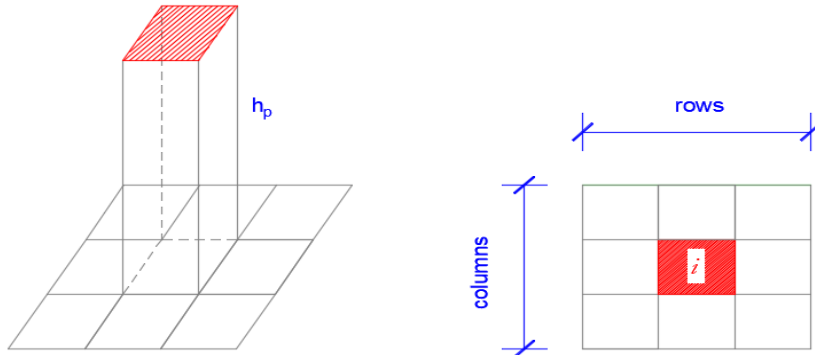

Fig. 1. Representation of the volume according to the GRID model.

Therefore, taking into account two temporal instants (time t_0 and time t_1) on which to perform the variation of volumes, it is possible to write:

$$V_{raster_{t_0}} = \sum_{p=1}^{r \cdot c} \left(A_{cell} \cdot h_p \right)_{t_0} \qquad (4b)$$

$$V_{raster_{t_1}} = \sum_{p=1}^{r \cdot c} \left(A_{cell} \cdot h_p \right)_{t_1} \qquad (4c)$$

If we adopt a TIN model and taking into account the volume of each prism model evaluated on u-th triangle, the total volume, i.e. extended to the whole space consisting of a number v of triangles, is:
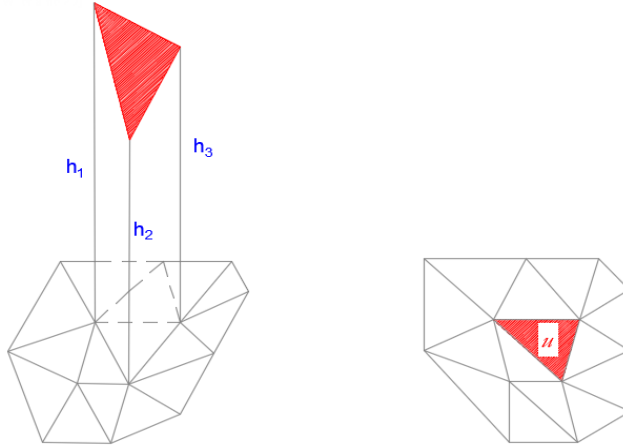
$$V_{TIN} = \sum_{u=1}^{v} \frac{1}{3} \cdot A_u \cdot (h_1 + h_2 + h_3)_u \tag{5}$$

where:

h_1, h_2, h_3 heights of the prism measured starting from the u-th triangle;

A_u area of the prism triangular base of the u-th triangle.

A representation of the volume according the TIN model is show below (**Fig. 2**).

Fig. 2. Representation of the volume according to the TIN model

The calculation of the area of the u-th triangle can be performed with different methods. In GIS, the formula for calculating the area is that of Gauss, that is:

$$A_u = \frac{1}{2}[x_1(y_2 - y_3) + x_2(y_3 - y_2) + x_3(y_1 - y_2)]_u \tag{6}$$

where x and y of the three vertexes are the spatial coordinates of u-th triangle.

The above equation can also be written as:

$$V_{TIN} = \sum_{u=1}^{v} \frac{1}{3} \cdot A_u \cdot h_{1_u} + \frac{1}{3} \cdot A_u \cdot h_{2_u} + \frac{1}{3} \cdot A_u \cdot h_{3_u} \tag{7}$$

3. METHOD AND EXPERIMENTAL SETUP

The geomatics surveys allow producing accurate point clouds. Indeed, it is possible to obtain a raster o TIN model from the point cloud. In this way, by comparing raster or TIN obtained in two different epochs, it is possible to perform the calculation of the volumes.

To obtain a raster format, an interpolation of point cloud is required. Considering the high density of the points, the natural neighbour technique can be used. Natural neighbour interpolation is a method of spatial interpolation, developed by Robin Sibson and is based on Voronoi tessellation of a discrete set of spatial points (Sibson, 1981). In this way, it is possible to build a raster with a specific cell size. In order to identify the volume differences that may occur in choosing a GRID or TIN model, we will first analyse a theoretical case and then a real one. Indeed, after discussing the results obtained on hypothetical grounds (theoretical cases), a real case is taken into consideration. In addition, to evaluate the impact of geometric resolution in the calculation of volumes, three GSD (Ground Sample

Distance) values were taken into account: 0.25m, 0.5m and 1m. Once built the raster in two different epochs, it is possible to calculate the volume changed by the use of the equation (1). This task can be performed by raster calculator or by specific tool developed in GIS software. For example, in ArcMap software, which is a component of ArcGIS's suite of geospatial package developed and distributed by Esri Company, is available a tool called "Cut/Fill". This tool enables to create a map based on two input surfaces (before and after) displaying the areas and volumes of surface materials that have been modified by the removal or addition of surface material. Indeed, when the Cut/Fill operation is performed, by default a specialized renderer is applied to the layer that highlights the locations of cut and of fill. The determinant is in the attribute table of the output raster, which considers positive volume to be where material was cut (removed), and negative volume where material was filled (added) (Esri, 2020).

The TIN model, instead, is constructed by triangulating a set of vertices (point cloud). There are different methods of interpolation to form these triangles, such as Delaunay triangulation or distance ordering. ArcMap software allows building a TIN using Delaunay triangulation. The calculation of the volume changed using the TIN models (produced in the two reference periods) can be obtained from the difference of the two volumes compared to a plan. In ArcMap is implemented a tool called "Polygon Volume" which calculates the volume and surface area between a polygon and terrain or TIN surface. The output text file will store the full path to the surface, the parameters used to generate results, and the calculated area and volume measurements. Finally, calculations were performed to estimate the extracted volumes using both TIN and GRID models.
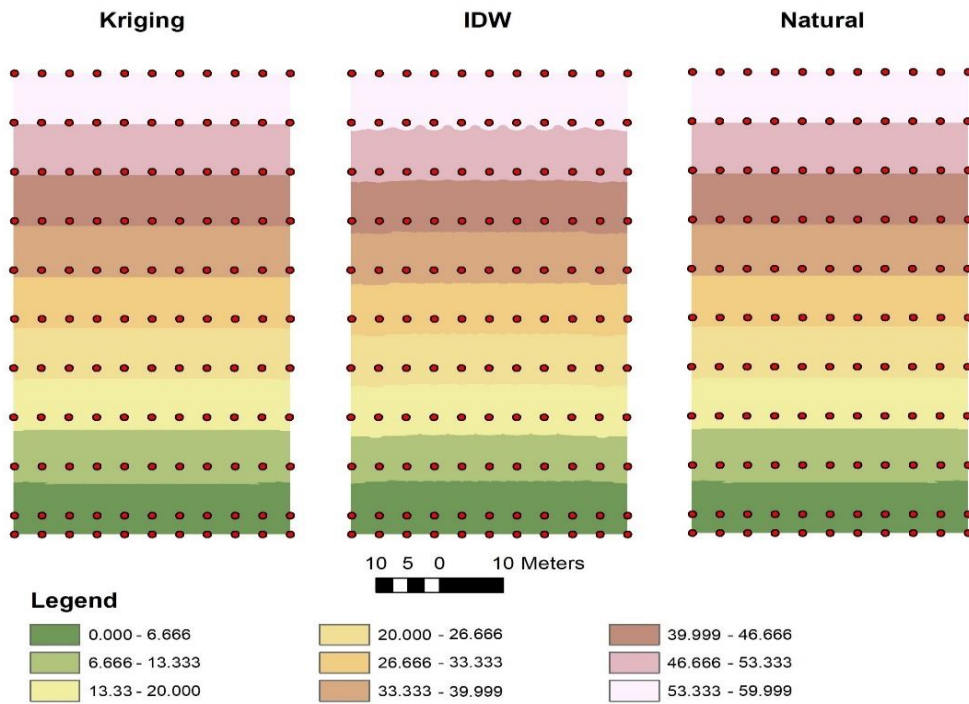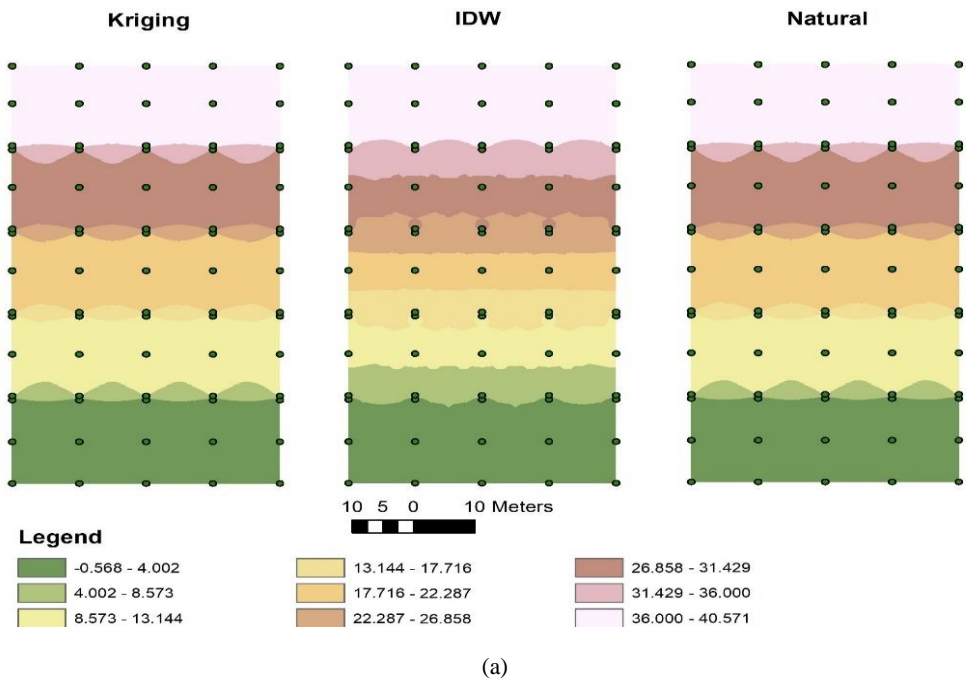
4. CALCULATION OF THE VOLUME ON HYPOTHETIC TERRAIN

To evaluate the impact of interpolation models depending on the type of terrain morphology, two terrain models have been taken into account, one with steps and another with a linear slope, as shown below (**Fig. 3b** and **3c**). The dimensions of the area of investigation are 100 m x 50 m (see **Fig. 3a**).

(a)

b)   (c)
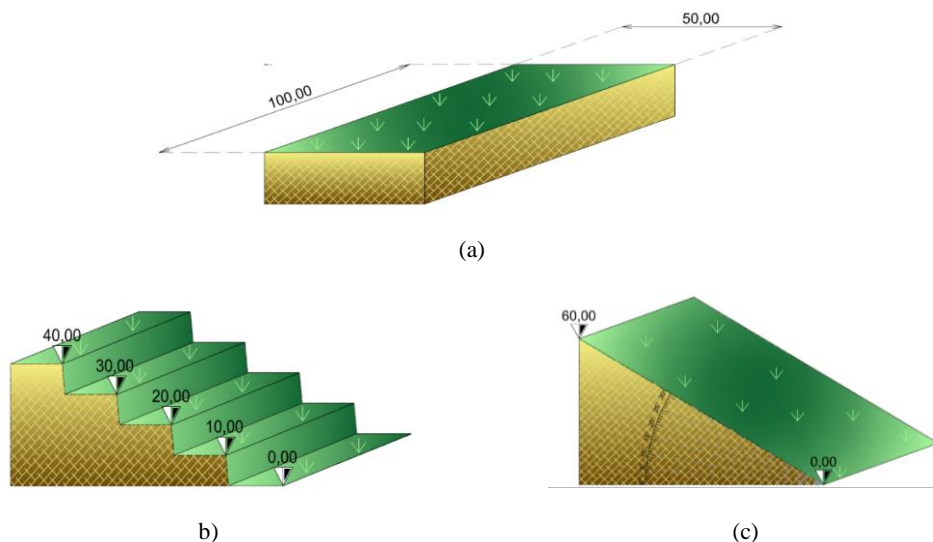
Fig. 3. Theoretical terrain models: dimension of the study area (a); stepped terrain (b) and terrain with linear slope (c)

The volume obtained by TIN model in ArcMap environment was 101,000 m^3 in the case of stepped terrain and 150,215 m^3 in terrain with linear slope. As is well known, the grid format can be obtained with several interpolating functions. In particular, the functions applied on the two case studies are: *IDW*; *Kriging* and *Natural neighbour.*

In this way, it is possible to build several GRID models, as shown below (**Fig. 4**).

Kriging **IDW** **Natural**

10 5 0 10 Meters

Legend

-0.568 - 4.002	13.144 - 17.716	26.858 - 31.429
4.002 - 8.573	17.716 - 22.287	31.429 - 36.000
8.573 - 13.144	22.287 - 26.858	36.000 - 40.571

(a)

Kriging **IDW** **Natural**

10 5 0 10 Meters

Legend

0.000 - 6.666	20.000 - 26.666	39.999 - 46.666
6.666 - 13.333	26.666 - 33.333	46.666 - 53.333
13.33 - 20.000	33.333 - 39.999	53.333 - 59.999

(b)

Fig. 4. GRID models (elevation in meters) obtained using stepped terrain (a) and on terrain with linear slope (b).

From the analysis of **Fig. 4**, it is easy to see that in the case of terrain with a constant slope the interpolating functions assume more or less the same value. In the case of terrain with steps, however, depending on the function used, different values were obtained. Consequently, the volumes obtained on this terrain are different, as shown in **Table 1**.

<div align="right">

Table 1.
</div>

Volume calculation using GRID models.

Type of terrain	Volume (m³)			
	IDW	**Kriging**	**Natural**	**TIN**
Terrain with linear slope	149,893	150,331	150,221	150,215
Stepped terrain	99,085	99,557	99,386	101,000

The difference of the volumes between TIN models and grid model are of the order of about 2% in the case of terrain with steps (delta$_{max}$=1915 m³) while less than 1% in the case of terrain with constant slope (delta$_{max}$=322 m³).

5. CASE STUDY

5.1 Study area and geomatics surveys

Over the centuries, the exploitation of mineral resources has experienced alternating phases of more or less intense expansion that have led the Italian mining industry to a leading position at European level and recession, if not even a deterrent to mining activity. In any case, these vicissitudes have left and continue to leave their traces on our territory, as the extraction and exploitation of mineral raw materials always involves essential interactions with the natural environment, the territory, the socio-economic context. Of consequence, the monitoring of mining activities requires appropriate technological tools capable of detecting and calculating the volumes extracted from a quarry.

The quarry under investigation is located in a small town in southern Italy, located in the north-east of the city of Naples (Lat: 40°58'53.55 "N Long: 14°30'24.84 "E, RDN2008 - EPSG6706) and for its morphological conformation has a difference in height of about 180m. The geomatics surveys adopted are the ALS (Airborne Laser Scanner) sensor (at time t_0) and UAV photogrammetry (at time t_1).

5.2 Survey at time t0 by the use of ALS sensor

The survey of the investigated area was carried out using ALS sensor (Pepe et al., 2019; Zlinszky et al., 2011). The flight planning was designed in order to obtain a point density on the terrain of 10 pt/m².

To preserve the designed point density, during the flight, it has been paid much attention to respect the velocity of the project and the constant acquisition of the GPS (Global Positioning System) signal.

Once completed the flight planning, to obtain the point clouds in a specific mapping frame, it is necessary assembly the three datasets: calibration data and mounting parameters, laser distance measurements with their respective scanning angles and Position and Orientation System (POS) data. The post-processing of the ALS data was obtained using several software: Waypoint GrafNav for Differential Global Positioning System (DGPS) processing and Leica Geosystems IPAS Pro in order to manage the combination of GNSS and Inertial measurement unit (IMU).

The CORS - Continuously Operating Reference Station) (Dardanelli et al., 2020) infrastructure present in the Campania region was used in order to obtain GNSS data consisting of carrier phase in support of three-dimensional positioning (Pepe, 2018). Since the elevation coordinates produced by direct georeferencing process take into consideration the ellipsoidal height, using a suitable tool developed in Matlab environment and Italgeo05 geoid (Barzaghi et al., 2005), it was possible to obtain the orthometric height. Finally, in ArcMap software, using *Kriging* method, it was possible to obtain a Digital Elevation Model (DEM) with a geometric resolution of 0.25m x 0.25m and a TIN model of the quarry.

An altimetry representation of the quarry (**Fig. 5a**) and a profile extracted from the DEM (**Fig. 5b**) are shown below.
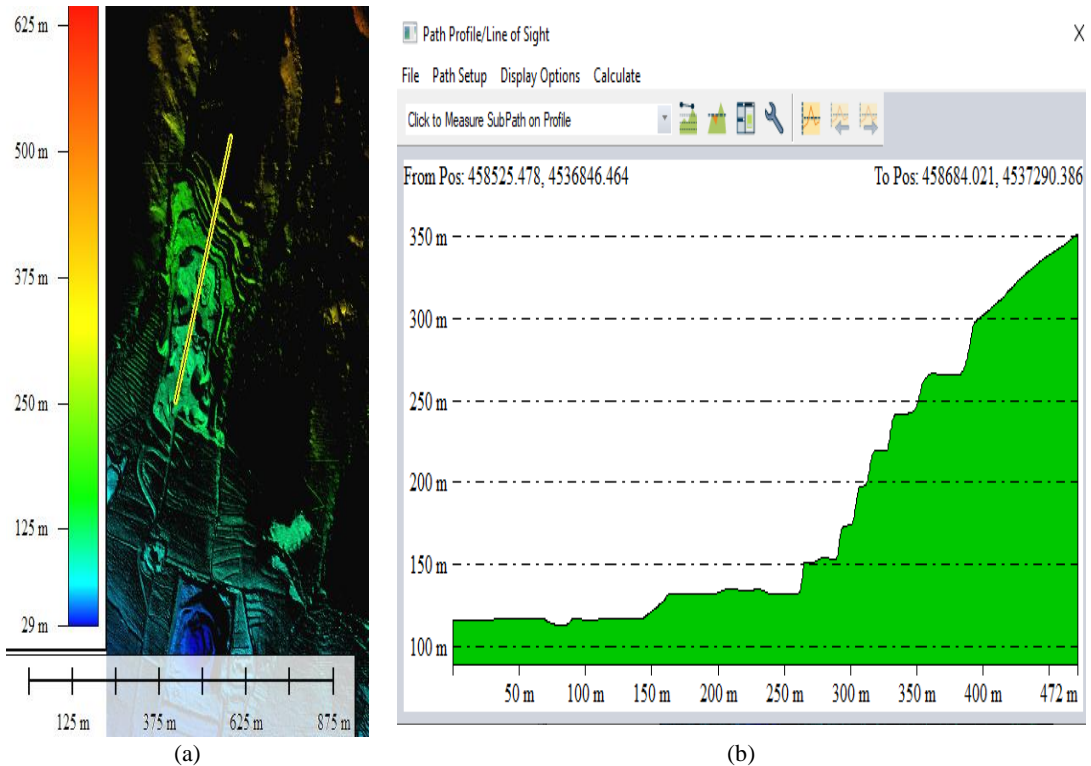
Fig. 5. Morphology of the quarry obtained by ALS survey at time t_0: DTM display in Global Mapper software (a); profile (b).

5.3. Survey at time t_1: UAV photogrammetry

5.3.1. Flight planning

The survey was performed using the Phantom 4 Pro quadcopter from the Chinese manufacturer DJI, which has a satellite assisted flight accuracy of 0.5 m vertically and 1.5 m horizontally. The UAV also has 5-way anti-collision sensors of optical and infrared type, which allow to avoid obstacles within a distance of 10 m and allow the drone to have a stable positioning even in cases where satellite coverage is not available. The main features of the UAS (Unmanned Aerial System) are reported in **Table 2**.

Technical characteristics of the UAS.

Features	Specifications
UAV Platform	
Max. take-off weight	1388 g
Maximum Speed	72 km/h / 6 m/s
Flight time	~30 min
Camera: DJI FC6310	
Sensor	Effective pixels: 20 million
Photo size	5472× 3648
Focal length	10.26 mm
Field of view	approx. 84°
Aperture	f/2.8-f/11
Shooting speed	Electronic shutter: 8–1/8000 s

In relation to the morphology of the terrain, two take-off/landing points have been identified for missions in order to guarantee the complete visibility of the UAV during the flight operations. The flight altitude adopted to acquire the images was of 30 m respect to the planned take-off/landing points.

The survey was planned through the UGCS software. This software, developed by UgCS Company (Latvia), allows to plan and fly drone survey missions providing convenient tools for areal and linear surveys and enabling direct drone control. Indeed, the software supports a wide range of UAVs, including the vehicle used to carry out the survey and two distinct types of acquisition mode, one nadir direction and the other prospective.

For a better design of flight planning, the software's ability to import custom elevation models was exploited; therefore, a DTM based on ALS data was used.

Two flight plans were designed in order to obtain an average GSD of 2 cm, using the "*terrain following*" function that allows the UAV to have a constant distance to the ground.

5.3.2. Acquisition data

The flight planning for the nadir acquisition is composed by 8 Flight Lines (FLs). A total amount of 216 frames per 216 frames, with an average overlap of 80% and sidelap of 60% was designed (**Fig. 6a**). To cover the vertical part of the steps of the quarry, a specific flight planning was designed; the inclination of the camera was adjusted with an angle of 45°. Additional 10 FLs were planned for a total of 295 frames (**Fig. 6b**).

The waypoints were uploaded into the UAS via the dedicated application (**Fig. 6c**). The correct positioning was obtained thanks to the use of integrated GNSS (Global Navigation Satellite System) receiver.
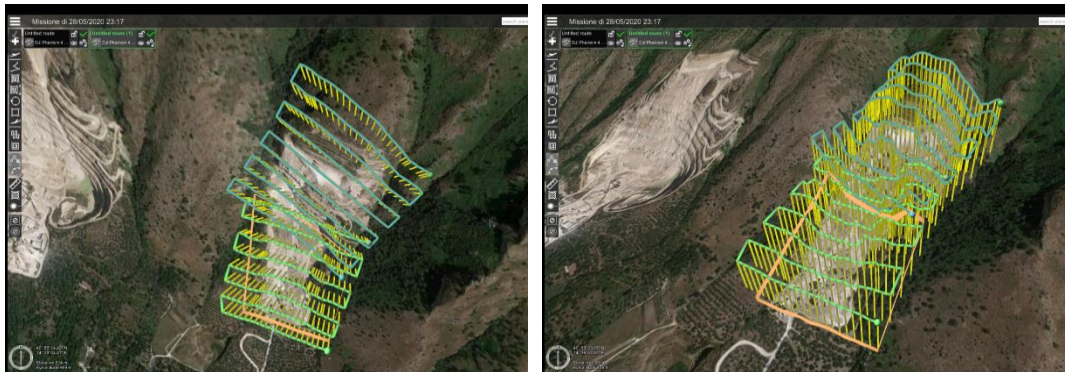
At the end of the acquisition step by UAV photogrammetry, a GNSS survey in RTK (Real Time Kinematic) with correction by CORS was carried out in order to determine the coordinates of the Ground Control Points (GCPs), which were distributed and materialized by means of high contrast markers within the area to be surveyed.

(a)

(b)

(c)

Fig. 6. Design of the flight plan on the study area: nadir acquisition (a), oblique acquisition (b) complete flight plan (c).

5.3.3. Data processing at time t1

For image processing of UAS dataset, Agisoft Metashape (2018) software was used. Recent studies on the impact of the image format in the SfM/MVS environment have shown the importance of using raw image both from the point of view of geometric accuracy and from the point of view of the quality of the dense point cloud (Alfio et al., 2020); consequently, the images were processed in the raw format.

The process of registration of image was obtained in "highest" quality setting: in this mode, the image is scaled by a factor of 4 (factor of 2 for each side) and allows for high precision in the localization of a point. A high-performance workstation was required to perform the image registration process, as the "highest" parameter requires high processing times.

Table 3 shows the error values obtained from the image recording process and the Total Error (root mean square error for East, North, and Altitude coordinates for all the cameras) on several GCPs easily recognized on images, as supplied by Agisoft Metashape software.

Table 3.

Evaluation of the accuracy on GCPs

GCP	East Error (m)	North Error (m)	Alt. Error (m)	Total Error (m)	Image Error (pix)
1001	0.010	-0.001	0.014	0.017	0.65
1002	0.001	0.021	-0.043	0.048	0.83
1003	0.029	-0.013	0,037	0.049	0.53
1005	-0.009	-0.003	-0.020	0.022	0.88
1006	-0.028	-0,012	0.004	0.031	0.60
1007	0.003	-0.003	-0.014	0.015	0.57
1008	0.002	0.004	0.004	0.007	0.52
1009	-0.009	0.007	0.016	0.020	0.49
TOTAL	*0.015*	*0.010*	*0.023*	*0.030*	*0.66*

Once the image alignment phase was finished, it was possible to process the dense cloud (see **Fig.7**) at three different quality levels, namely *Lowest, Low and Medium*. The setting Lowest mean that the images were downscaled to 6,75%, low mean downscaled to 12,5% and medium mean downscaled to 25%.

(a) (b) (c)
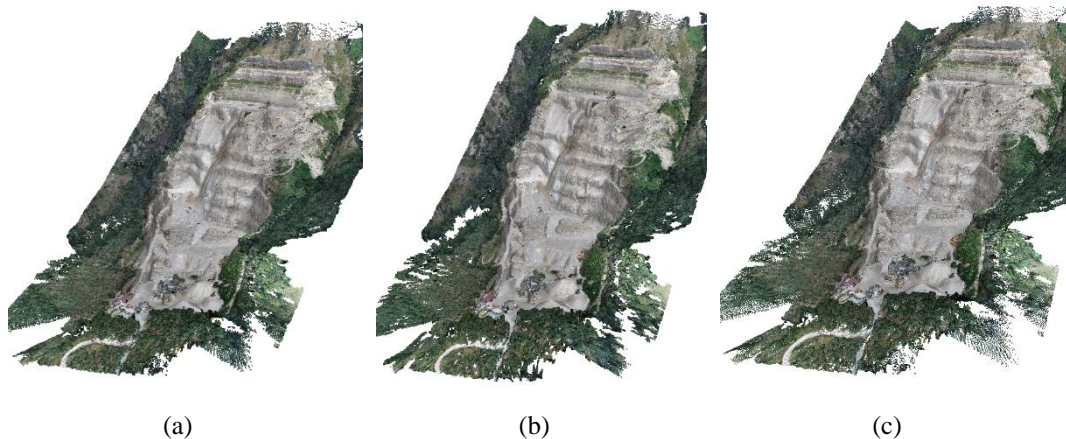
Fig. 7. Dense clouds obtained using different setting in SfM/MVS software: Lowest (a), Low (b) Medium (c).

The processing results, i.e. the number of the points generated in MVS process, using a different level of detail (lowest, low, medium) are summarized in the following **Table 4**.

Processing results using diverse settings

Quality	Tie Points	Dense Point Cloud
Lowest	930,889	3,262,349
Low	930,889	12,534,893
Medium	930,889	48,393,473

To evaluate the geometric difference between point clouds with different levels of point density, a comparison in Cloud Compare software was performed. The point cloud generated with medium setting was used as reference; the results of the comparison are shown in **Table 5**.

Point cloud comparison

Difference point cloud	Mean (m)	Standard Deviation (m)
Lowest- Medium	0.321	0.427
Low- Medium	0.104	0.201

The comparison between the point cloud processed with setting lowest and the one processed with medium shows an average difference value of 0.242m and a Standard Deviation (std) of 0.27m. The comparison between the point clouds processed in low and medium shows an average difference of 0.074m and a std of 0.116m.

6. RESULTS

As the geometrical resolution of the raster changed, it was possible to calculate the volumes in the time frame considered. The results obtained, varying the density of the point cloud, are shown in **Table 6**. In fact, the point cloud created with the setting medium required high computational performance. For this reason, it was not possible to create a TIN or GRID model with this setting.

Impact of the point cloud density and geometric resolution (GRID model) in volume calculation

Resolution (m)	Volume changes (m³)	
	Lowest	*Low*
1	493574	492838
0.5	490341	489935
0.25	485818	485174

Using the TIN as a reference surface, it is possible to obtain the volumes with respect to a reference plane, as shown in the table below (**Table 7**).

Impact of the point cloud density in volume calculations in TIN model

Volume at time to (m^3)	Volume at time t$_1$ (m^3)			Volume changes (m^3)	
	Lowest	*Low*	*Medium*	*Lowest*	*Low*
15576165	15124205	15116333	-	451960	459832

7. DISCUSSION AND CONCLUSIONS

UAV photogrammetry represents an easy, useful and accurate method to reconstruct the geometry of a quarry. Thanks to use of UAV platform, it is possible to collect a large amount of data that once analysed and processed allow to accurately representing the topographical and morphological aspects of the area under examination. The SfM/MVS algorithms allow producing very detailed point clouds of the area under investigation. The intuitive interface implemented in most commercial software based on these algorithms makes point cloud construction quick and easy.

The aim of this work was to evaluate, starting from the data obtained from the photogrammetric survey, how the decision to process a raster data or a TIN data influenced the final result; the choice between GRID and TIN model becomes important according to the morphology of the quarry.

If the quarry presents an almost regular gradient or with constant slope variations, both processing methods lead to an accurate result; on the contrary, if the quarry presents a stepped terrain or with sudden and important changes of slope, the grid model could lead to an incorrect estimation of volumes changes. Therefore, in these cases, it is preferable to adopt the TIN model to estimate volume changes. Finally, the implementation of specific tools in GIS software allows monitoring the quarries over time and, consequently, to estimate the volumes excavated in accurate and simple way.

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