3D Geometric Characterization of Moved Masses in Sea Cliffs Using Point Clouds

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Abstract

Sea cliff monitoring studies aim to classify cliff sections according to their susceptibility to rock fall so that risk prevention measures can be taken. The classification relies on inventories of well-characterized, past mass movements. Since the surface of a cliff is almost vertical and very irregular in all three space directions, a simple difference between two Digital Terrain Models does not yield the required volumes. A new approach to automatically estimate the volumes of lost masses in 3D point clouds is presented. Using Terrestrial Laser Scanning and Close Range Photogrammetry, very dense 3D point clouds can be obtained to describe the geometry of a sea cliff face. When generated periodically, these can be used to detect changes on the cliff due to erosion. Some of the variables needed to assess cliff susceptibility are location, the affected area and the volume of lost masses. The evaluation of the algorithm yielded a theoretical value for accuracy of ±10% for the volume calculated, which was confirmed by a test using a known volume. This accuracy satisfies the usual requirements of the inventories for cliff evolution studies, and the algorithm represents a significant advance in the geometric characterization of moved masses in 3D for extensive cliff faces.

Keywords:

volumes, 3D point clouds, 3D a-shape, cliff erosion

1   Introduction

Knowledge on the erosive phenomena of coastlines is of high importance due to the intensive use of these areas and their economic importance. Erosion of coastal cliff zones causes their retreat mainly through mass movements, which are responsible for substantial damage and losses of property and human life, since they tend to occur suddenly (Marques et al., 2013). Monitoring sea cliff faces for mass movements is a way to gather data for an inventory of events that help to classify the susceptibility of cliff sections to rock fall (Guzzetti, 2005). In this context, the algorithm VOLTERRE, developed by the authors for the automatic 3D geometric characterization of moved masses in cliffs, is presented. It is based partly on the approach of Stumpf et al. (2014), but with a new way of calculating the

volume, which is described in the following sections. An evaluation of the algorithm's accuracy is also presented.

2   Detection of change on cliff walls

The morphology of a cliff wall is normally surveyed either photogrammetrically or by using Terrestrial Laser Scanner (TLS) from the beach (Lague et al., 2013). These techniques produce dense 3D point clouds that adequately describe the cliff wall surface. By repeating the survey periodically at the same site, other georeferenced point clouds are obtained. A set of ground control points are determined at the time of the first survey, serving as a common spatial reference for all later surveys. The differences between two point clouds can reveal changes on the cliff wall which have occurred during the time that has elapsed. These changes are due in part to vegetation growth or decrease, especially near the top, but mostly to moved masses on the face, which have been either lost or accumulated (Figure 1).
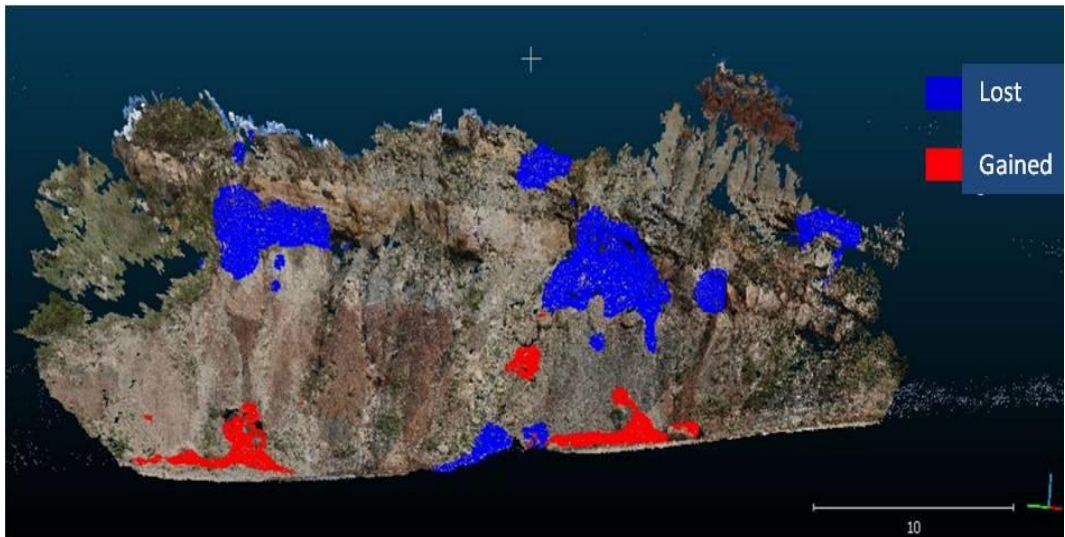

Figure 1: Cliff wall point cloud with superimposed points of lost and gained mass. Scale in metres

In the present approach, a difference point cloud is calculated for each pair of point clouds using the open software CloudCompare v.2.6.2 (Girardeau-Montaut et al., 2005), which includes Multiscale Model to Model Cloud Comparison (M3C2), an algorithm that allows a reliable comparison between two point clouds, yielding indicators about the degree of confidence of the results (Lague et al., 2013). In addition, the algorithm indicates positive and negative differences according to the cloud chosen as reference.

The output of M3C2 consists of a text file with X,Y,Z coordinates for each point of the reference cloud and the associated 3D distance to the compared cloud, as well as an indication of the roughness of both clouds (standard deviation) around the point, the

distance uncertainty, the significance level of the calculated distance, and the three components of the normal vector to the surface in the neighbourhood of the point. All coordinates are global since the point cloud is georeferenced.

The algorithm VOLTERRE, developed in MatlabTM (MathWorks, 2017), is then applied to the output of CloudCompare.

Preprocessing

First, following the approach of Stumpf et al. (2015), the process is carried out separately for positive and negative significant differences, and a spatial clustering of the points with the same sign (positive or negative) is performed (Figure 2). At this juncture, the preprocessing of the clusters diverges from that proposed by Stumpf et al. Since the intention is to retrieve clusters that represent lost or gained masses, and these have the particularity of being very dense, as opposed to the clusters of differences due to vegetation growth that tend to be dispersed, the yielded clusters are filtered according, first, to the number of points they include, and then to the density of the points in each one. Density is calculated by applying a 3D α-shape (Edelsbrunner et al., 1983; Edelsbrunner & Mücke, 1994) to each cluster, calculating the shape's volume and dividing the number of points in it by its volume. The median of all densities is determined, and all clusters with a density lower than the median are ignored in the subsequent steps. The output of the preprocessing step is a matrix with all points of each remaining cluster, one line per point, and five columns containing their original coordinates X,Y,Z, the corresponding M3C2 distance (the distance between both clouds at the point in question), and the identification of the cluster to which the point belongs.

Volume calculation

The following step is carried out for each cluster individually (Figure 2). It consists in determining the best-fit plane of the cluster and projecting each point of the cluster on to this plane. A new coordinate system X'Y'Z' is defined for the best-fit plane, so that X' and Y' lie on the plane, and Z' is normal to it. All projected points are transformed to this new coordinate system and all have Z' equal to zero. A 2D α-shape is now applied to the projected points on the plane and its area is retrieved. This is adopted as the cliff wall area affected by the mass movement. Then, a second set of points is created, so that for each projected point on the plane there is a point in the new set with the same X' and Y', but Z' equals the corresponding M3C2 distance (the distance between both clouds at the point in question). Applying a 3D α-shape to all points (the projected points and those of the second set), a convex solid is built by tetrahedralization (Figure 3). Although the shape of this solid does not correspond to the real shape of the moved mass, their volumes are similar, so we get an estimate of the volume of the moved mass (lost or gained).
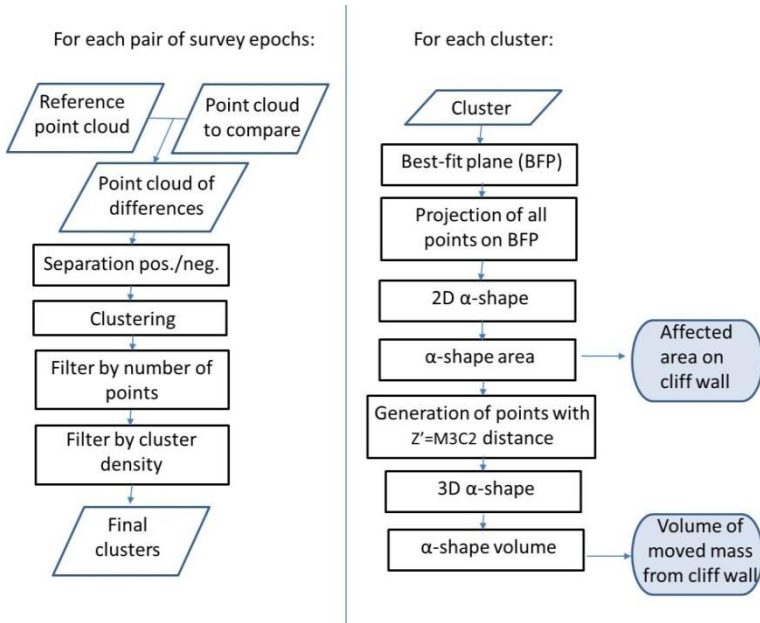
Figure 2: VOLTERRE methodology for determining volumes of moved masses.
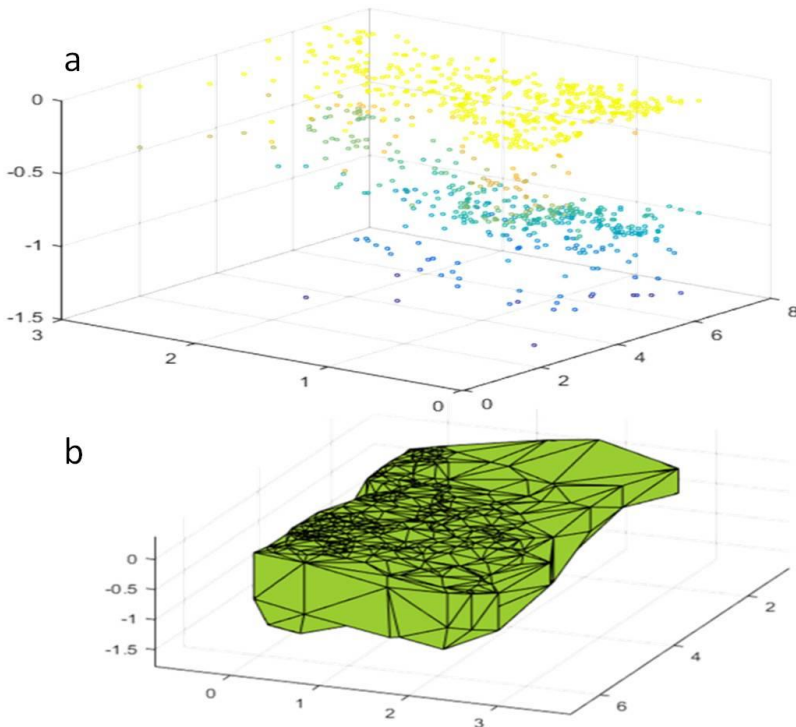

Figure 3: Volume of lost mass: (a) Projected points in the best-fit plane in yellow, generated points in shades of blue; vertical axis denotes M3C2 distance. (b) 3D a-shape applied to the points of both sets.

3   Evaluation of the algorithm

In order to estimate the precision of the volume calculated by the algorithm, two approaches were followed:

1. error propagation analysis of the tetrahedralization used by VOLTERRE to calculate the volume;
2. comparison of the 3D α-shape volume with the volume of a known solid described as a 3D point cloud.

The direct comparison of the volume of the difference point cloud at the scar with that of the fallen block was not feasible, since blocks tend to break during the fall and it is not easy to assign a fallen block to a cliff scar.

Error propagation analysis

The 3D α-shape connects the points of a set through tetrahedralization – that is, a set of adjacent tetrahedra whose vertices are the points of the set is used to fill the space between the points. The shape volume is the sum of the volumes of all tetrahedra. The volume precision calculation of one representative tetrahedron expressed as a percentage of its volume provides an estimate of the precision of the whole 3D α-shape volume. A point cloud obtained by TLS was used, and after the application of VOLTERRE the generated 3D α-shapes were analysed for the dimensions of the tetrahedra. The largest one was selected and reproduced with similar dimensions and shape in a local coordinate system (Figure 4).
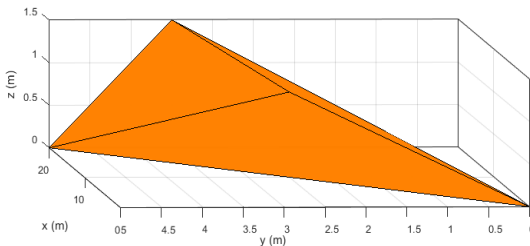

Figure 4: Representative tetrahedron

The vertices v1, v2, v3, v4 are at the positions indicated in (1) below in metres. By applying equation (2) below to determine the volume of a tetrahedron Vt, the representative tetrahedron presents a volume of 5m3.

$$x_{v1}, y_{v1}, z_{v1} = (0, 0, 0)$$

$$x_{v2}, y_{v2}, z_{v2} = (20, 5, 0)$$

$$x_{v3}, y_{v3}, z_{v3} = (20, 3.5, 1.5)$$

$$x_{v4}, y_{v4}, z_{v4} = (10, 2.5, 1) \qquad (1)$$

$$V_t = \frac{1}{3!} \begin{vmatrix} x_{v1} & y_{v1} & z_{v1} & 1 \\ x_{v2} & y_{v2} & z_{v2} & 1 \\ x_{v3} & y_{v3} & z_{v3} & 1 \\ x_{v4} & y_{v4} & z_{v4} & 1 \end{vmatrix} \qquad (2)$$

$$\sigma^2_{V_t} = \sum_{k=1}^{N} \left(\frac{\partial V_t}{\partial u_k}\right)^2 \sigma^2_k \qquad (3)$$

The volume accuracy σ_{V_t} comes from equation (3), where u_k represents the variables of the Vt expression, σk is the accuracy of each variable, and $\left(\frac{\partial V_t}{\partial u_k}\right)$ represents the partial derivative of Vt with respect to each of the variables: the coordinates of the vertices; the coordinates of two points P0 and P1 used for the projection of the cluster points in the best-fit plane; the variables r, el and az corresponding respectively to the range, elevation and azimuth of the laser ray from which each (x,y,z) is calculated.

From the equations that give the rectangular coordinates of a generic point from its polar coordinates (r, el, az), one obtains the expressions for the partial derivatives.

According to the specifications of the TLS Topcon GLS1500 used (at a distance of 150m, an accuracy of 0.004m for the range, and 6" for angle measurements), the accuracy of each variable, σk, was calculated. The worst case scenario was assumed: points with r = 150m, el1 = 60º and az = 160º, therefore σr = 0.004m, σel1= 0.000029088 rad, and a distance uncertainty of 0.1m. This value corresponds to the largest uncertainty associated with the point cloud differences considered for this simulation. Under these conditions, and given that only the vertices that are not on the best-fit plane are affected by the distance uncertainty, the values in (4) to (7) are obtained for the calculated derivatives of the coordinate functions in (3):

$$\sigma_{x_{v1}} = \sigma_{x_{v2}} = \sigma_{x_{v3}} = \sigma_{x_{v4}} = 0.0116 \text{ m} \qquad (4)$$

$$\sigma_{y_{v1}} = \sigma_{y_{v2}} = \sigma_{y_{v3}} = \sigma_{y_{v4}} = 0.0047 \text{ m} \qquad (5)$$

$$\sigma_{z_{v1}} = \sigma_{z_{v2}} = 0 \text{ m} \qquad (6)$$

$$\sigma_{z_{v3}} = \sigma_{z_{v4}} = 0.1000 \text{ m} \qquad (7)$$

As the total volume of the tetrahedron was 5m3 and the calculated uncertainty σVt = 0.5013 m³, an accuracy of ±10% can be estimated for the volume, not only for this tetrahedron but for the whole 3D α-shape.

Comparison with test volume of regular shape

For this approach, a cuboid box (0.24m x 0.55m x 0.47m) was first measured (Figure 5) to calculate its volume, and then photogrammetrically covered to produce a point cloud whose volume was determined using the 3D α-shape volume.
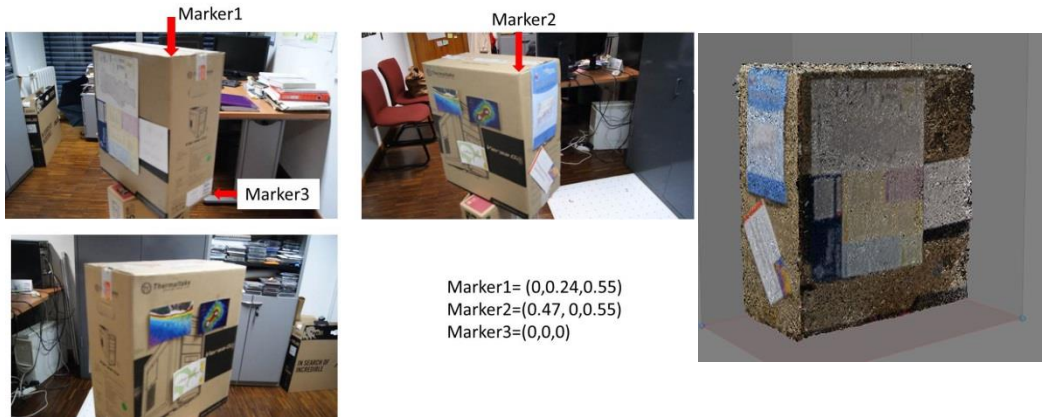
Figure 5: Test volume and coordinated markers (left); dense point cloud (right)

All sides of the box except the bottom were covered with photographs. Using the photogrammetric software Photoscan (Agisoft, 2017), a dense point cloud (Figure 5, right) was produced and scaled using three markers on the vertices. The dense point cloud was imported into MatlabTM (MathWorks, 2017) and a 3D α-shape was adjusted to the cloud. Since the α-radius determines the reconstruction quality of the shape, an α value was chosen so that the reconstructed form had as much detail as possible and presented no holes, guaranteeing that the yielded α-shape volume corresponded to the whole box. As seen in Figure 6 and Table 1, higher α values yield a generalization of the shape, overestimating its volume, while smaller values approximate the α-shape to the real box. Values that are too small create holes in the shape. An α-radius near 0.2 satisfies both conditions, approximating the real shape of the box and producing a closed hull. The volume $V1 = 0.0683m3$ was considered for comparison with the measured one, $V0 = 0.0620m3$, which corresponds to an accuracy of 0.1009, confirming the value of 10% for the volume accuracy of the algorithm.
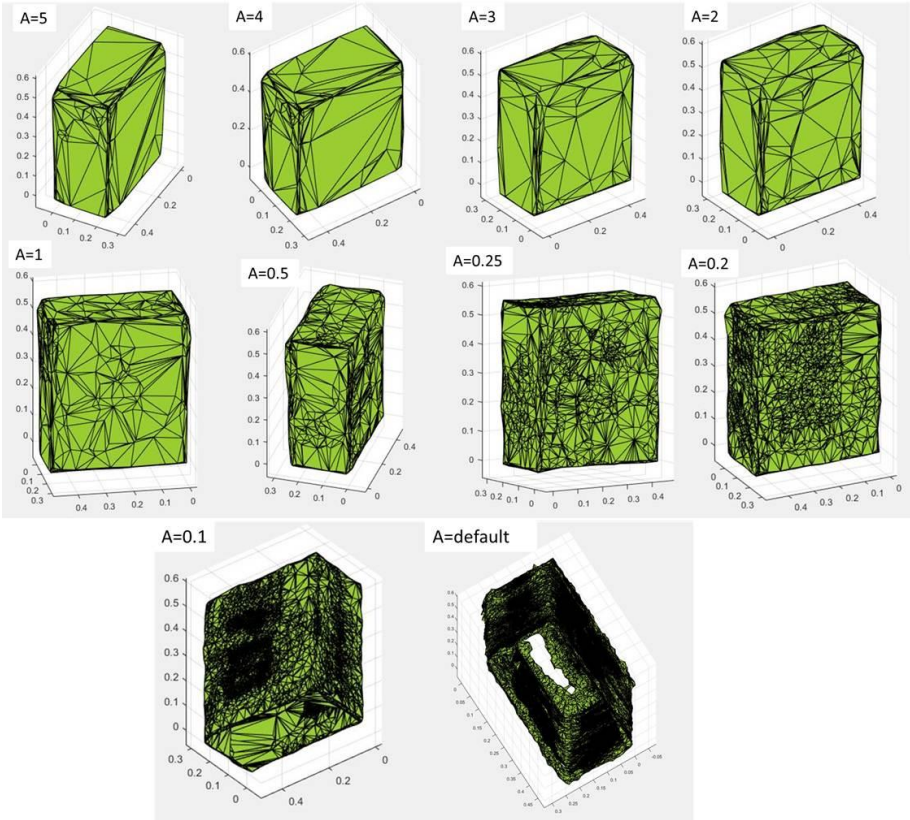
Figure 6: Form reconstruction using different a-radii (A)

Table 1: Volumes corresponding to the different a-radii

α-radius	5	4	3	2	1	0.5	0.25	0.2	0.1	default
V[m³]	0.0755	0.0750	0.0744	0.0731	0.0712	0.0699	0.0687	0.0683	Opens holes	Opens holes

4   Final considerations

To evaluate the algorithm used in VOLTERRE, two aspects were considered: the accuracy of the results, and fitness for the purpose.

The first aspect was discussed in sections 3.1 and 3.2 above. An accuracy of ±10% of the calculated volume is attainable with the algorithm. The second aspect requires more consideration. Metrics to characterize moved masses in 3D have to be defined differently than in 2D studies. While the affected area on a cliff top is normally measured over a 2D map of the changes and corresponds to the horizontal area (Young et al., 2011), the affected area on a cliff face, which presents arbitrary slope and aspect, is better defined on a plane

with similar local slope and aspect. The best-fit plane of each cluster calculated using all points defining the scar of the mass movement in 3D seems to be a reasonable reference choice.

This reference plane is used in VOLTERRE both for the definition of the affected area and for the reconstruction of the moved mass volume. Volume determination as normally done in GIS platforms only works for 2.5 D surfaces – that is, for surfaces where Z-values are a function of X and Y. It is not reasonable to determine volumes for the whole cliff in a similar manner, since the irregularity of the cliff surface occurs in all three spatial directions. Only a local approach seems appropriate. An occurrence (mass movement) is represented by a 3D point cluster in which significant positive or negative differences between point clouds of the same site generated at different times have occurred. The best-fit plane proposed by Stumpf et al. (2015) is a suitable choice for a reference plane. All points of the cluster are projected on to this plane for further processing. Instead of surface Z-differences, 3D distances between point clouds calculated by CloudCompare-M3C2 are used as proxy for the local depth of the moved mass at each point of the scar. The volume emerges from a 3D α-shape involving both the projected points on the plane and the generated set of points. Each of the latter set of points is an M3C2-distance from its corresponding point on the plane, in the direction of the plane normal. This approximates to an indirect reconstruction of a solid with equivalent volume but not with the same shape as the moved mass. Divergences from the real volume can appear due to the projection of the cluster points on the best-fit plane, divergence increasing with the irregularity of the cluster. Furthermore, the M3C2-distances between clouds are measured on local normals which are not necessarily parallel, a fact that the reconstruction assumes. These drawbacks are also present in the approach of Stumpf et al. (2015).

Nevertheless, VOLTERRE estimates the volume of moved masses by using only the distance information associated with the cluster points, without the need for interpolations. The solid created by the 3D α-shape should have the minimum α-radius required to enclose all cluster points as extremes of the shape without generalization and should not present holes. The way the point set is generated and its high density guarantee these conditions.

The algorithm presented yields a valid estimation of the affected area and of the volume of moved masses in sea cliff walls with an accuracy of ± 10% (for the volume) and is a therefore a relevant input for the inventory of mass movements needed in susceptibility studies of coastal zones.

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