LiDAR derived high resolution topography: the next challenge for the analysis of terraces stability and vineyard soil erosion

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Abstract

The soil erosion in the vineyards is a critical issue that could affect their productivity, but also, when the cultivation is organized in terraces, increase the risk due to derived slope failure processes. If terraces are not correctly designed or maintained, a progressively increasing of gully erosion affects the structure of the walls. The results of this process is the increasing of connectivity and runoff. In order to overcome such issues it is really important to recognize in detail all the surface drainage paths, thus providing a basis upon which develop a suitable drainage system or provide structural measures for the soil erosion risk mitigation. In the last few years, the airborne LiDAR technology led to a dramatic increase in terrain information. Airborne LiDAR and Terrestrial Laser Scanner derived high-resolution Digital Terrain Models (DTMs) have opened avenues for hydrologic and geomorphologic studies (Tarolli *et al.*, 2009). In general, all the main surface process signatures are correctly recognized using a DTM with cell sizes of 1 m. However sub-meter grid sizes may be more suitable in those situations where the analysis of micro topography related to micro changes is critical for slope failures risk assessment or for the design of detailed drainage flow paths. The Terrestrial Laser Scanner (TLS) has been proven to be an useful tool for such detailed field survey. In this work, we test the effectiveness of high resolution topography derived by airborne LiDAR and TLS for the recognition of areas subject to soil erosion risk in a typical terraced vineyard landscape of "Chianti Classico" (Tuscany, Italy). The algorithm proposed by Tarolli *et al.* (2013), for the automatic recognition of anthropic feature induced flow direction changes, has been tested. The results underline the effectiveness of LiDAR and TLS data in the analysis of soil erosion signatures in vineyards, and indicate the high resolution topography as a useful tool to improve the land use management of such areas. The stability conditions have been analyzed under the influence of the measured geometry alterations of the wall structure.

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Introduction

Extended terraced slopes are a distinctive characteristic of landscapes all over the Italian peninsula. The terraces, in fact, allow the farming of many precious products, such as wine, also on very steep slopes. In this terraced landscape, the human interference on the natural morphology is evident, but terraces represent also a typical case of the ancient blending of anthropic communities and lands. Terraced vineyards, as much as olivegrove, are probably the most typical landscape in Tuscany, and the Chianti wine is one of the most prestigious wine produced in Tuscany, exported and appreciated all over the word. Neverthless, these terraced rural areas have gone through a series of social and economical changes that caused, since the Sixties, a gradual abandonement of the traditional agricultural practices and of the maintenance of the rural landscape. A serious consequence following the lack of maintenance of terraced slopes is the increasing erosion due to the loss of efficiency of drainage systems (Crosta *et al.*, 2003). Uncontrolled erosion in agricultural lands causes not negligible soil and nutrient losses (Poesen and Hooke, 1997; Douglas *et al.*, 1998; Corell *et al.*, 1999; Steegen *et al.*, 2001; Verstraeten and Poesen, 2002; Ng Kee *et al.*, 2002; Ramos and Martìnez-Casanovas, 2004) and the long-term productivity loss of degraded soil and plot level (Roose, 1996; Woodward, 1999), with a severe economic impact on farms (Martìnez-Casanovas *et al.*, 2005). The consequences of a strong soil erosion in terraced areas are serious, with possible negative effects over people's safety. In terraced slopes, in fact, concentrated flow incises rills and gullies that can damage retaining walls (Figure 1) and trigger small slides and slumps (Crosta *et al.*, 2003).

Due to the flow concentration during high-intensity or moderate-intensity but prolonged rainstorms, or after snow melting, small slides can evolve in shallow landslides (Moser and Hohensinn, 1983; Crosta, 1998; Crosta e Frattini, 2002) such as soil slips and debris flow that can travel distances up to several hundred meters (Crosta *et al.*, 2003).

According to Crosta *et al.* (2003), terraces produce great changes in slopes hydrologic setting enhancing flow concentration and infiltration at specific sites. This explains the important role of morphology-derived hydrologic factors as triggering process of landslides. It is also clear the importance of having effective instruments to assess in a detailed way the morphology, to recognize those areas subject to potential erosion and slides. In the last year, many works have demonstrated the effectiveness of high resolution topography derived by Laser Scanner (LiDAR) to generate accurate Digital Terrain Models (DTM) to be considered in many different areas of research. Nowadays, common meter resolution DTMs are useful to recognize all the main surface processes signatures (Tarolli and Dalla Fontana, 2009; Passalacqua *et al.* 2010; Sofia *et al.* 2011; Tarolli *et al* 2012; Sofia *et al.* 2013a,b). In some specific situation, however, where the surveyed processes are related to micro morphologies, as in the case of terraced vineyard, a sub-meter DTM might be more suitable (Tarolli *et al.*, 2012; Lin *et al.*, 2013). Centimetric resolution DTMs are derivable from spatial data acquired through Terrestrial Laser Scanner (TLS), a LiDAR instrument that has been proven to be a useful tool for such detailed field survey at a hillslope scale. In this context, the aim of this paper is to present the TLS survey and the consecutive spatial data processing of a terraced vineyard subject to soil erosion risk in the typical landscape of "Chianti Classico" wine at Lamole (Tuscany, Italy). High-resolution results are compared with traditional resolution digital topography derived by airborne LiDAR.

Materials and methods

TLS survey and derived DTMs

The TLS survey was performed in March 2013. A "time-of-fly" Terrestrial Laser Scanner System Riegl® LMS-Z620 was used. This laser scanner operates in the wavelength of the near infrared and provides a maximum measurement range of 2 km, with an accuracy of 10 mm and a speed of acquisition up to 11000 pts/s. For each measured point, the system records the range, horizontal and vertical alignment angles, and the backscattered signal amplitude. The laser scanner was integrated with a Nikon® D90 digital camera (12.9 Mpixel of resolution) equipped with a 20 mm lens, that provided an RGB value to the acquired point cloud (Figure 2).

The TLS survey at Lamole was carried out from six scan positions, in order to capture precisely the complex morphology of the terraced slopes: one position was used for a panoramic high resolution scan of the main terraced slope, and five were considered to model, with a very high resolution, the recently restored wall, displaying signs of failures (see Figure 8 Chapt 3, and Figure 2). From the "panoramic" scan position 5,352,080 elevation points were collected with a resolution of 0.1 m at 200 m from the scanner. From the other scan positions 1,452,944 points were measured on the retaining wall and on its close proximity with a resolution of 0.02 m at 10 m from the scanner; other 1,737,818 points with a resolution of 0.05 m at 20 m from the scanner plus 2,254,414 points with various resolutions were acquired on the surrounding area (Figure 3).In order to georeference the survey in a global coordinate system, a GNSS network was set up. A couple of Topcon HiPer Pro® dual-frequency and dual-constellation receivers were employed. These differential GPS+GLONASS receivers guarantee a horizontal precision of 3 mm + 0.5ppm (per baseline length) and a vertical precision of 5mm + 0.5ppm (per baseline length) if used in static or rapid static mode.

The raw spatial data (X, Y, Z measurements) acquired were processed in two steps: first to georeferece them and filter all non-ground points, and then to create the DTMs.

The whole processing procedures have been carried out using the Riegl proprietary software RiscanPro®. In particular, with RiscanPro a semi-automatic iterative surface based approach is available to detect non-ground points within a defined range from the real ground surface.

Figure 1. Terraced walls with an implemented drainage system (A), and effects of a failed maintenance (B).

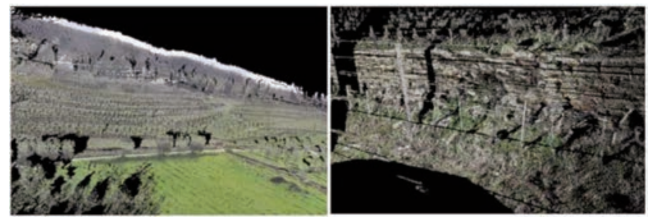

Figure 2. Point cloud derived with TLS with RGB color overlapped to each point.

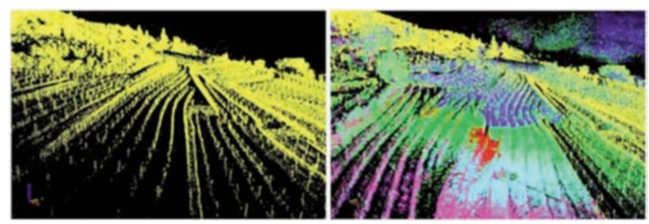

Figure 3. Example of point cloud taken from a single position (left), and overlapping of multiple scans (right).

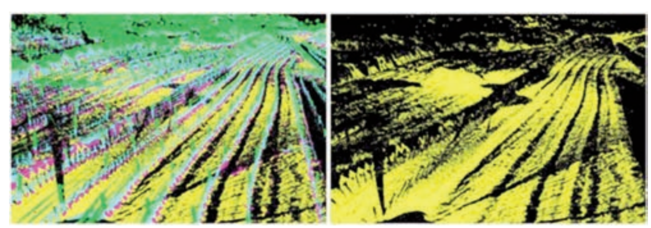

Figure 4. Detail of point cloud of Lamole study area in false colors: yellow points are the groundpoints; fuchsia points are points included from the ground and 50 cm height from the ground; blue points are points with a distance from the ground range from 50 cm to 1m; green points are points above 1m from the ground.

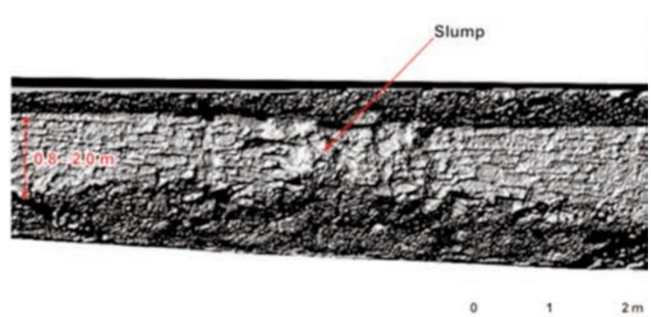

Figure 5. Surveyed retaining wall model hillshade at 0.01 m resolution.

Thanks to the algorithm, more and more fitting meshes are created applying a 2.5D raster filter – this filter generates a 2.5D raster point cloud of source data; in which that each raster cell will be represented by a single point. The points that lie over a threshold defined from the generated mash are eliminated. In the Lamole case, the minimum distance considered from the ground surface was been 0.2m. After this iterative process some corrections were necessary, because of the particular morphology, characterized regular big steps rich in vegetation, not easy to model by 2.5D filter. Figure 4 shows an example of the raw point data (A) and the ground point data (B) derived after the filtering procedure. Spatial coordinates of the remaining ground points were exported and elevation values were interpolated by the natural neighbors method (Sibson, 1981) to generate 0.2 and 0.5 m resolution DTMs of the terraced slope. The ground points density is really irregular on the study area, but at the center of the surveyed terraced slope average ground points density is more than 1000 pts/m^2. The absolute vertical accuracy, evaluated by a ground differential DGPS, was estimated to be less than 0.1 m.

Wall modeling

A centimetric survey of a 120 m long stretch of wall was carried out from four different scans positions. After a hand-made filtering of vegetation, the topographic information was exported flipping the order of x, y, z values: the coordinates of each point were exported as –y; z; x. Therefore, a front viewed 3D digital model of the retaining wall was generated interpolating x value by the natural neighbors method (Sibson, 1981). In the created wall model, with a resolution of 0.01 m, every single stone that compose the wall can be individuate (Figure 5). This level of precision allows to simulate the behavior of the wall in response to back load with a high detail and without many artifacts and much approximations.

Topographic analyses

To quantify the effect of retaining walls on contributing area distributions (and therefore, on flow paths) within catchments, we applied the Relative Path Impact Index (RPII) index proposed by Tarolli *et al.* (2013) to quantify the forest road effects on slope stability. This morphometric index is calculated as follows:

$$\mathbf{RPII} = \ln\left(-\frac{A_{sm}-A_r}{A_{sm}}\right) \quad (1)$$

where A_r is the contributing area (computed according to the D-Inf method proposed by Tarboton 1997) evaluated in the presence of any roads or paths on hillslopes, while A_{sm} is the contributing area without morphological alterations on hillslopes.

The negative sign and the logarithmic function is applied to emphasize and map only those areas where an increasing of drainage area is observed due to human induced alteration. The higher the RPII index, the stronger the alteration.

To simulate the absence of anthropogenic features (roads, paths, walls), a smoothed DTM is considered, based on an approximation of the original surface solved within a local moving window. To produce this smoothed surface, we decided to use the bivariate quadratic function introduced by Evans (1979), expressed as:

$$Z = ax^2 + by^2 + cxy + dx + ey + f \quad (2)$$

where x, y, and Z are local coordinates, and *a* to *f* are quadratic coefficients. This function was found to perform well in the presence of elevation errors (Albani *et al.* 2004; Florinsky 1998), and it has been successfully applied also in several other analysis on Earth surface morphology and feature extraction (Pirotti and Tarolli, 2010; Sofia *et al.*, 2011; Tarolli *et al.*, 2012, Sofia *et al.* 2013a,b).

Study area

The study area is in the "*Chianti Classico*" wine area, in the center of Tuscany, and it is located in the small village of Lamole (Figure 6) within the municipality of Greve in Chianti (province of Florence).

The study area is a typical hilly environment, along a slope facing North-North West, on soils that have been developed from sedimentary rocks such as sandstones and marls. Vineyards here are growth on terraces made only of dry-stones, that represent a typical landscape element of this region (Figure 7).

The terraces have been restored since 2003 in order to maintain their original role of soil erosion prevention, and to realize the production of a very fine wine. Few months after the restoration, one of the terraces displayed deformations and slumps (Figure 8). This particular wall was therefore considered as an interesting element for the analysis described in the following chapters.

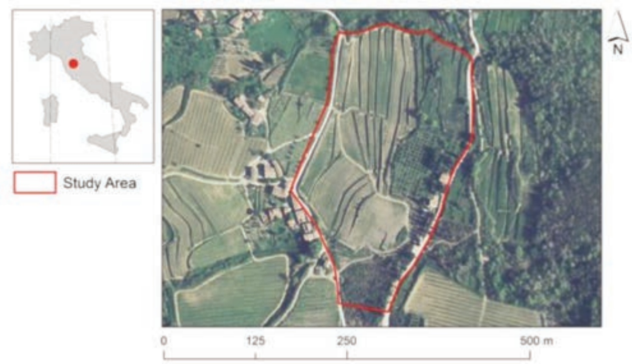

Figure 6. Geographical setting of study area of Lamole.

Figure 7. Panoramic picture of the Lamole area and its terraces.

Figure 8. Surveyed terraced walls with slumps and erosion

Available data

Airborne LiDAR elevation data

For the study area, a DTM with a 1 m resolution derived from Airborne LiDAR survey is available (Figure 9). This model is readily accessible to public authorities in Italy, and it is promoted by the Ministry for Environment, Land and Sea (*Ministero dell'Ambiente e della Tutela del Territorio e del Mare, MATTM*), the Department of Civil Protection and the Mininstry of Defense, in agreement with the regional governments. The DTM has a horizontal accuracy of about ±0.3 m and vertical accuracy of ±0.15 m (RMSE estimated using DGPS ground truth control points).

Results

The lamole study case highlights the effectiveness of TLS surveys for two different analysis at least. The first is that the super resolute and systematic short range scan of a retaining wall allows the generation of a centimetric resolution 3D digital model of the wall with a very high accuracy. A model with this high resolution could be used in strengths and stability simulations. With centimeter wall-model, the behavior under soil pressure of the most of the stones can be correctly simulated and therefore, the final results might be more realistic than the results achievable with a totally artefacted wall-model.

The second result is the RPII index calculation. Figure 10 shows the RPII index evaluated using the ALS-Derived DTM with 1 m resolution (A) and the TLS DTMs with 0.5 m (B) and 0.2 m (C) resolution.

Using a common ALS-derived DTM, the RPII does not detect any flow alteration, and so any soil erosion, due to terraces and any possible damage to the retaining walls (Figure 10 A). With a TLS survey derived topographic base of 0.5 m resolution (Figure 10B) results are better but not yet completely satisfactory: just the most intense flow alterations are shown in the RPII map. In the RPII map of the terraced slope of Lamole a strong flow concentration is shown in corresponding of slump of the surveyed retaining wall. But the high values of the index are reported only below the collapsed stretch of the wall, and this could clearly appear as a not univocal result. In the 0.2 m resolution RPII map (Fig. 10C) there is no doubts that the flow deviation and concentration in corresponding of the slump are processes beginning above the slump, and they are due to the presence of the above terraces. In the 0.2 m resolution RPII map a considerable increase of contributing area due to terraced morphology is reported also in corresponding of a deformed segment of the surveyed retaining wall.

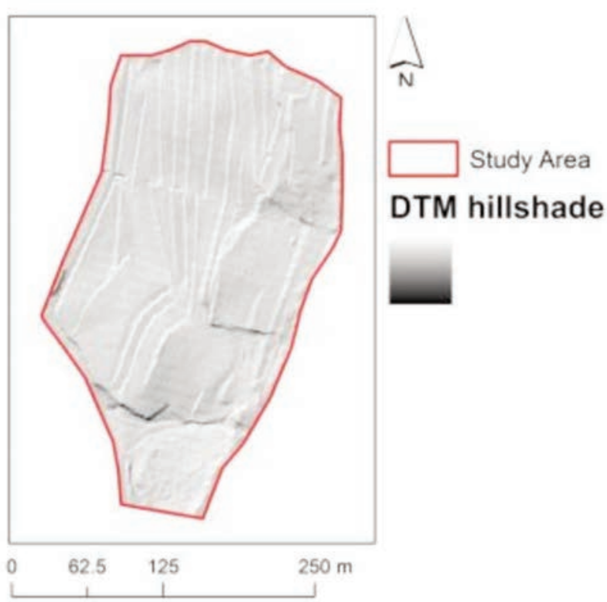

Figure 9. Airborne-LiDAR DTM (1m resolution) available for the study area.

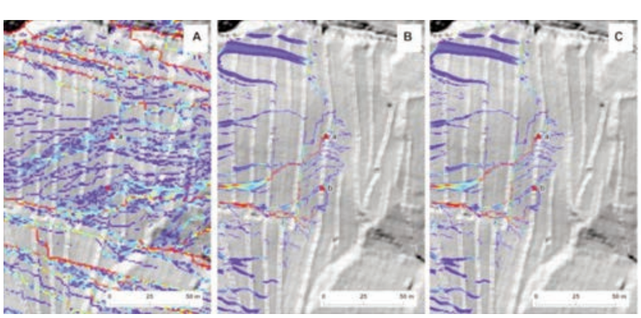

Figure 10. The RPII index evaluated using the ALS-Derived DTM with 1 m resolution (A) and the TLS DTMs with 0.5 m (B) and 0.2 m (C) resolution. a and b represent the wall deformation surveyed on the field.

Conclusions

This paper highlights the effectiveness of a centimetre resolution topography obtained from TLS survey in the analysis of terrace failure processes in vineyards. In the landscape of "*Chianti classico*" wine, the TLS has been proved to be a useful instrument to perform quickly high resolution and high accuracy topographic surveys. Interpolating the acquired points, two high resolution DTMs (0.5 m and 0.2 m resolution) have been obtained, and then a simple morphometric and hydrological analysis is performed. Using a 0.2 m resolution TLS derived DTM, overflow convergences are recognizable exactly where in the field erosion evidence were surveyed. This proves that TLS and the derived high resolution topography can be a useful tool to improve the land use management and planning for the maintenance of terraced areas. However, this method needs to be improved, to clean the alteration that might derive from complex terraced morphology by thick vegetation and DTM artefacts.

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