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Terrestrial laser scanner and geomechanical surveys for the rapid evaluation of rock fall susceptibility scenarios

Abstract The primary objective of this paper is to present a semiautomatic procedure that, integrated with traditional methods, can be useful for a rapid definition of rock fall susceptibility scenarios with the purpose of civil protection. Due to its morphology (steep slopes and narrow valleys), regional seismicity, and rock mass characteristics, the Nera Valley (Valnerina, Umbria Region, Italy) is characterized by high rock fall risk. With the aim of covering a wide range of features and investigating the main advantages and drawbacks of the proposed approach, data collection (terrestrial laser scanning (TLS) and geomechanical surveys) was carried out at three different slopes. Detailed three-dimensional (3D) models were created to reconstruct the shape and volume of the most unstable blocks, to define the position of the main rock fall source areas, and to precisely distinguish the outcropping materials and the position of the elements at risk for reliable runout analyses. The proposed approach can be useful in supporting proper maintenance and land management programs both in ordinary and in emergency circumstances.

Keywords Rock mass · Landslide · Kinematic analysis · DiAna · Valnerina

Introduction

Rock fall is a common and widespread phenomenon that can affect long stretches of communication routes, entire villages, isolated dwellings, and other anthropic goods, where these elements at risk are located on or near the base of steep rock slopes. Due to their unpredictability and high velocities, these events can cause casualties, even if the mobilized mass is very small (less than 1 m^3) (Hungr et al. 1999).

Rock fall risk is usually analyzed through performing two-dimensional (2D) (Azzoni et al. 1995; Pfeiffer and Bowen 1989; Pfeiffer et al. 1991; Piteau and Clayton 1976; Rocscience 2005) or three-dimensional (3D) (Agliardi and Crosta 2003; Crosta and Agliardi 2004; Descouedres and Zimmermann 1987; Dorren and Seijmonsbergen 2003; Guzzetti et al. 2002; Lan et al. 2007; Scioldo 1991) simulations, with the aim of evaluating runout distances, velocities (and associated kinetic energy), and bounce heights of falling blocks.

Rock fall trajectory is controlled by local topography, the location of the source area, the mechanical properties of the outcropping materials (Ritchie 1963), and falling rocks and by their shape and mass (Giani 1992). However, these parameters are often difficult to evaluate and the most common approach is based on probabilistic analyses by statistically varying the input parameters that are characterized by the highest uncertainties (Azzoni et al. 1995; Giani et al. 2004; Hoek 2000).

The proposed methodology aims at objectively, rapidly, and accurately defining the detailed topography of the slopes, the exact 3D position of the objects of interest (such as element at risk, possible existing protective measures, etc.), block shape and dimension, and the main rock fall source areas (through a 3D kinematic analysis). A number of researchers have already dealt with some of these topics either from photogrammetric or LIDAR data (Abellan et al. 2006, 2010; Armesto et al. 2009; Bauer et al. 2006; Ferrero and Umili 2011; Ferrero et al. 2009, 2011; Lato and Vöge 2012; Mikos et al. 2005; Rosser et al. 2005; Strouth and Eberhardt 2005; Wickens and Barton 1971); however, in the authors' knowledge, this paper represents the first attempt to obtain all the necessary rock fall geometric input parameters through high-resolution laser scanning data processing, as explained in the flow chart of Fig. 1.

The approach is composed of two main steps: in situ data collection and data processing (scenario definition). During the first phase, a terrestrial laser scanning (TLS) campaign and a traditional geomechanical survey were performed.

All the acquired data are subsequently processed with the aim of creating high resolution 3D models, integrating traditional geomechanical surveys with TLS data, calculating the volume and shape of blocks involved in rock falls, performing kinematic analyses of the main mechanisms of instability affecting the rock walls, and reconstructing the trajectories followed by the blocks and their associated energy. The proposed procedure has been applied on three different test sites in order to be representative of the entire area under investigation. These are located in the central sector of Valnerina (Umbria Region, Italy) close to the Triponzo village (Fig. 2), where the Calcare Massiccio (massive limestone) and the Maiolica (micritic limestone) Formations outcrop.

Investigated area

Valnerina is a narrow and winding valley formed by the deepening of the Nera River. This valley is characterized by high rock fall risk because of its rough morphology, local seismic activity, and heterogeneous rock mass fracturing. Rock falls abound near the Triponzo village; in September and October 1997, a seismic sequence affected the investigated area (Amato et al. 1998; Carro et al. 2003; Marzorati et al. 2002) and many rock fall events seriously damaged the main roads (S.R. 209, S.R. 320) and the village itself (Guzzetti et al. 2004, 2009). All these features make the Valnerina a suitable place where the proposed procedure for the quick and complete definition of susceptibility scenarios associated with rock mass instability can be tested.

Three different rock slopes with heights ranging from 150 to 350 m were analyzed (Fig. 2): the Calcare Massiccio outcrops located at Ponte di Nortosce (Fig. 3a) and Bagni di Triponzo (Fig. 3b) and the Maiolica subvertical rock wall close to the Triponzo village (Fig. 3c). The whole area is surrounded by rugged mountains which peaks reach an elevation of 1,300 m. Almost everywhere, the rock outcrops are characterized by steep slopes, vertical walls, and ledges.

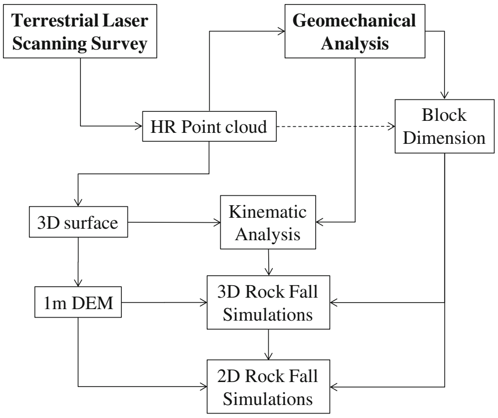


Fig. 1 Logic scheme of the proposed procedure: the geometric input parameters are all obtained through TLS data processing

In this area, the structures of deformation are related to the two tertiary tectonic phases of the Umbria-Marche Apennines. The overall stratigraphy is typical of the Umbria-Marche region: the lower part (lower Lias) consists of massive limestones of the carbonate platform (Calcare Massiccio) and the upper part is composed of stratified or thinly laminated formations, mainly marly and cherty limestones, deposited in a pelagic environment from the middle Lias to the Oligocene (Barchi et al. 1993). The latter can be characterized by pelagic carbonate sequences (Corniola, Calcari Diasprini, Maiolica, and Scaglia Bianca), pelagic marly-calcareous sequences (Rosso Ammonitico, Marne a Fucoidi, Scaglia Rossa, and Scaglia Cinerea), or marly-arenaceous turbiditic sequences (Bisciaro and Marnoso-Arenacea).

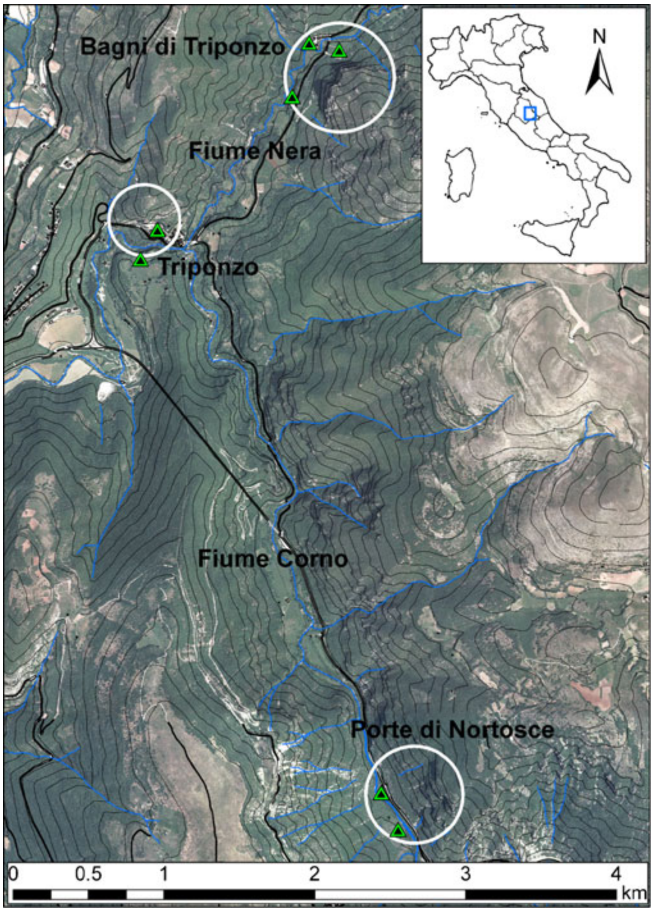


Fig. 2 Location map of the investigated sites (*white circles*). *Triangles* indicate TLS observation points

The local landforms are closely related to the nature of the rock types and to the structural setting (Guzzetti et al. 2004). In areas where limestones are characterized by high mechanical strength outcrop (e.g., Maiolica and Calcare Massiccio), the soil thickness is poor or absent, the slopes are very steep (ranging from 40° to 90°), and the most common instability mechanism is rock fall. Most of the landslide slip surfaces are located in areas dominated by calcareous-marly lithology, where the slopes are less steep even though the gradients are high (25°–40°). Here, the clayey elements constitute impermeable barriers for the groundwater flow, so that the mechanical weakness, in conjunction with the permeability limits at structurally oriented surfaces, is a key factor in influencing the location and the type of landslides (Barchi et al. 1993).

Data collection

Thanks to its high accuracy, resolution, and quick data collection, the TLS technique is becoming more and more used in rock fall studies (Abellan et al. 2006; Fanti et al. 2012; Gigli et al. 2012; Jaboyedoff et al. 2012; Lan et al. 2010; Lato et al. 2009, 2012; Lombardi et al. 2006; Rabatel et al. 2008; Tapete et al. 2012). The selected case study is an excellent application for exploiting the advantages of TLS, since it was impossible to directly reach the rock outcrops of interest, with the exception of the lowest limit of the rock face close to the Triponzo village. In this site, the main rock mass geomechanical properties were also collected using traditional survey methods in order to validate the results derived from the TLS elaborations.

Laser scanning survey

The laser scanning investigation was performed by means of a long range 3D Terrestrial Laser Imaging Sensor (RIEGL LMS-Z420i device), with an accuracy of 0.01 m (one σ at 50-m range under RIEGL test conditions). The laser scanning output is an array of points, called a point cloud, which is a set of vertices defined in a 3D coordinate system (x, y, z), able to reconstruct a highly detailed 3D environment.

With the aim of experimenting a rapid application of the proposed approach, TLS surveys were carried out from easily reachable points that, in Valnerina, are located along the main roads only (Figs. 2 and 3). The objective of the TLS campaign was to build 3D surface models of the whole slopes to be investigated (for the kinematic analyses and rock fall simulations) and to reconstruct the geomechanical features of the rock masses (for the identification of the main rock fall source areas and the evaluation of the shape and volume of falling blocks). To accomplish this dual objective, either raw point clouds or derived surfaces have been employed. For this reason, the angular resolution for each scan position (Table 1) has been selected by choosing the best arrangement between the number of points (to avoid large and too heavy datasets) and the distance between contiguous points on the rock slopes, which must be related to the minimum dimension of the features to be extracted (i.e., discontinuity surfaces, anthropic structures, and Digital Elevation Model (DEM) resolution).

Due to the roughness of the slopes and to the scan position constraints, with the aim of limiting the shadow areas as much as

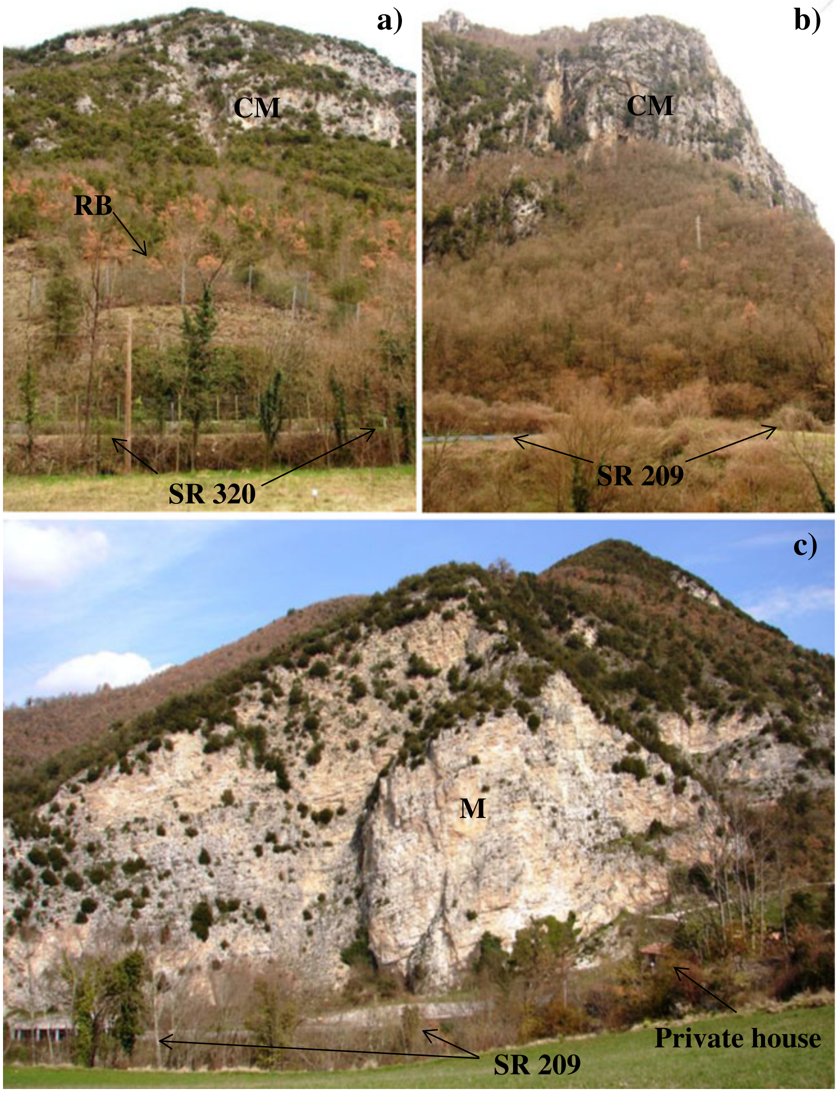


Fig. 3 View of the investigated rock outcrops: **a** Ponte di Nortosce, **b** Bagni di Triponzo, and **c** Triponzo. The main elements at risk, the location of rock fall barriers (*RB*), and the *symbols* of the outcropping geological formations are also reported. *CM* Calcare Massiccio, *M* Maiolica

possible, each slope has been investigated from different observation points. A total of seven scan positions have been performed to cover all the investigated sites, and more than 70 million points were collected. The angular resolution, the mean rock face distance, the mean point–point distance, and the number of acquired points for each scan position are also reported in Table 1.

The resulting point clouds were subsequently aligned by using a geodetic Global Positioning System (GPS) receiver to determine the position of a number of tie points physically represented by cylindrical reflectors (Morelli et al. 2012). This operation is always needed for correctly georeferencing the point cloud on a chosen reference system and to merge two or more scans of the same object realized from different points of view; the standard deviation of the corresponding tie points is reported in Table 1. Finally, all the point clouds were given their true colors acquired by a high resolution digital camera installed over the instrument (Fig. 4).

Traditional geomechanical survey

The traditional quantitative description of discontinuities was executed by using methods proposed by the International Society for Rock Mechanics (1978), which include a methodological analysis based on a scanline survey. This survey was carried out for validation purposes on the sole easily accessible rock mass exposure, located close to the Triponzo village (Fig. 3c).

Discontinuity orientation data were represented in stereographic projection (lower hemisphere) for the recognition of the main sets (Fig. 5a). The resulting modal plane orientation and standard deviation of each set are reported in Table 2.

TLS data processing

Within the framework of a rapid procedure, quick and reliable data processing methods have to be chosen. Notwithstanding this, the application to the presented case studies highlighted some problems, which slowed down the rock fall scenario definition, as described and commented in the following sections.

Analysis of rock mass discontinuities

An important limitation of traditional geomechanical surveys often consists in the difficulty (or impossibility) to reach the rock walls; another common problem, especially when dealing with active landslides or heavily fractured rock masses, is the intrinsic

Table 1 TLS technical data and geometric properties for each scan position

Scan position	Angular resolution (°)	Mean rock face distance (m)	Footprint at rock surface distance (cm)	Point–point distance (cm)	Number of points (×10^6)	Corresponding tie point standard deviation (m)
Ponte di Nortosce 01	0.02	350	8.6	12.2	10.2	0.020
Ponte di Nortosce 02	0.02	360	8.8	12.6	9.7	0.018
Bagni di Triponzo 01	0.02	390	9.5	13.6	12.1	0.018
Bagni di Triponzo 02	0.03	160	3.9	8.4	12.6	0.019
Bagni di Triponzo 03	0.015	320	7.8	8.4	11.6	0.012
Triponzo 01	0.018	280	6.8	8.8	9.4	0.012
Triponzo 02	0.01	90	2.2	1.6	16.2	0.017

danger of the site. The laser scanning technique, on the other hand, allows to remotely, quickly, and accurately measure all the main geometric characteristics of a rock mass.

To perform this task, the raw point clouds were employed (Fig. 1). This choice was supported by the need of keeping the maximum spatial resolution, so that even the smallest features could be detected. In this case, the presence of vegetation was not a problem. In fact, the TLS campaign was scheduled to be carried out during winter; moreover, the adopted methods described afterwards do not consider geometrically irregular portions of the point clouds, which are commonly associated to vegetation.

If the 3D model is correctly georeferenced, by estimating the best-fitting plane of a point cloud subset (associated to a discontinuity surface), it is possible to directly determine its dip and dip direction. This manual procedure was applied to the rock slopes where the Calcare Massiccio formation outcrops (Ponte di Nortosce, in Fig. 3a and Bagni di Triponzo in Fig. 3b) (Fig. 6a); here, the rock mass is characterized by very poor and irregular fracturing, and the point to point spacing is too high (due to the distance of up to 500 m from the scan positions) (Table 1) for the application of a semiautomatic procedure, as described afterwards. A semiautomatic extraction procedure was also tested on a portion of the point cloud representing the rock mass next to the Triponzo village.

Fig. 4 Point cloud of the rock face close to the Triponzo village true colored with high resolution optical images

Rock faces with rugged shape can be investigated by inspecting the discontinuity surfaces exposed on the slope. Such 3D approach requires the extraction from the point cloud of clusters of points belonging to the same discontinuity plane; subsequently, a spatial analysis for the quantitative description of discontinuities within the rock mass has to be performed.

The adopted approach consists of a MATLAB (Mathworks 2007) tool, which is described in detail in Gigli and Casagli (2011a). It is based on the definition of least-squares fitting planes on clusters of points extracted by moving a sampling cube on the point cloud; the cube size is based on TLS data resolution and on the dimension of the features to be investigated. If the associated standard deviation is below a defined threshold, the cluster is considered valid. By applying geometric criteria, it is possible to join all the clusters lying on the same surface; in this way, discontinuity planes can be reconstructed, and rock mass geometrical properties are calculated.

The advantage of using this procedure lies in its capability to investigate all the geomechanical parameters that do not require direct access to the rock mass. The output International Society for Rock Mechanics (1978) parameters are: orientation, number of sets, spacing/frequency (and derived RQD), persistence, block size, and scale-dependent roughness. The latter parameter can be measured if very high resolution data (i.e., centimetric point–point distance) are available on large discontinuity surfaces (Gigli and Casagli 2011b). Compared to the manual recognition of discontinuities, this methodology allows the identification of a larger number of surfaces, according to an objective choice criterion.

A total of 379 discontinuities were extracted from the investigated portion of the point cloud (Fig. 6b), and their dip and dip direction values were then represented in a stereographic projection (Fig. 5b). Again, three main discontinuity sets are evident, the modal orientations and standard deviation of which are reported in Table 2.

Estimation of block volumes

Block volume is one of the main input parameters for performing reliable rock fall simulations (Fig. 1), as it directly influences the kinetic energy expected along the trajectory. Moreover, block predisposition to move with a rolling behavior (and consequently, to reach higher runout distances) strongly depends on its shape and dimension (Evans and Hungr 1993; Giani et al. 2004). Within the proposed approach (Fig. 1), the information about the block volumes were acquired by analyzing TLS data and compared with field observations and bibliographic sources (Table 3).

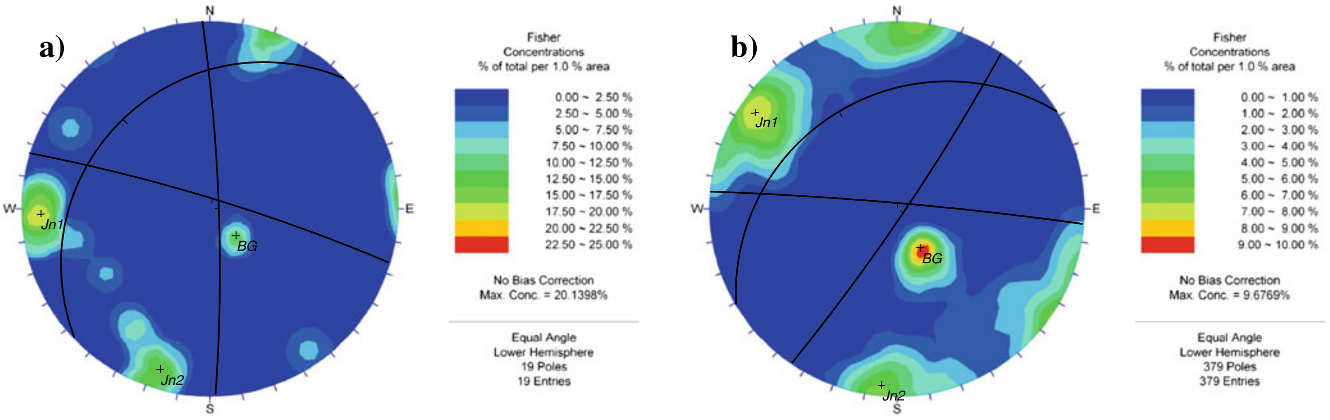


Fig. 5 Stereographic projection of concentration lines of discontinuity poles and modal planes of discontinuity sets: **a** from traditional geomechanical survey and **b** extracted from TLS data through the semiautomatic procedure

As regards the Triponzo site, where the Maiolica formation outcrops, complete geomechanical geometric data were extracted through the semiautomatic procedure described above and validated with field data. Thus, it has been possible to calculate mean and maximum block size based on the number of sets and their true spacing (Palmstrom 2005). The resulting mean size was 0.27 m^3, corresponding to a mass of approximately 750 kg; therefore, according also to field evidences, a precautionary mass of 1,000 kg was considered for the rock fall simulations at this site (Table 3).

By analyzing the high resolution point cloud, the volume of a large block about to topple was also reconstructed at Triponzo (Fig. 7b). Here, the rock mass is broken down into columnar elements because of the local discontinuity sets. Due to the block position and to the extreme verticality of the slope, direct surveys were not possible and consequently, accurate measurements were performed by means of the TLS data. The calculated volume was 136 m^3, with an estimated mass of about 379 t. The block is covered with rock fall protection wire net. However, such defensive system is designed just to keep boulders of limited size in adherence with the slope and will probably yield in case of column toppling.

A large unstable mass delimited by persistent discontinuities was identified from TLS data at Ponte di Nortosce (dashed line in Fig. 7a); within the same outcrop, a recent mass detachment was also present (continuous line in Fig. 7a). These blocks were virtually reconstructed and their calculated volumes were 1,024 m^3 and 15 m^3, respectively, representing masses of about 2,660 t and 39 t.

A quick in situ inventory of fallen blocks revealed a maximum block size of 3–4 m^3 (Table 3). This difference is mainly due to the breakage of the blocks along internal discontinuities whenever they impact on the ground during the movement on the slope. Two detached block volumes were also measured by analyzing TLS point clouds (Table 3). The block sizes found by the surveys agree with those sampled by Antonini et al. (2002) along an abandoned

Table 2 Discontinuity set orientation and standard deviation from field survey and TLS data processing at Triponzo site

	Field survey			Semiautomatic extraction		
	α (°)	β (°)	σ (°)	α (°)	β (°)	σ (°)
JN1	087	82	6.6	124	85	16.3
JN2	021	85	8.4	005	87	14.1
BG	318	23	11.0	329	28	12.9

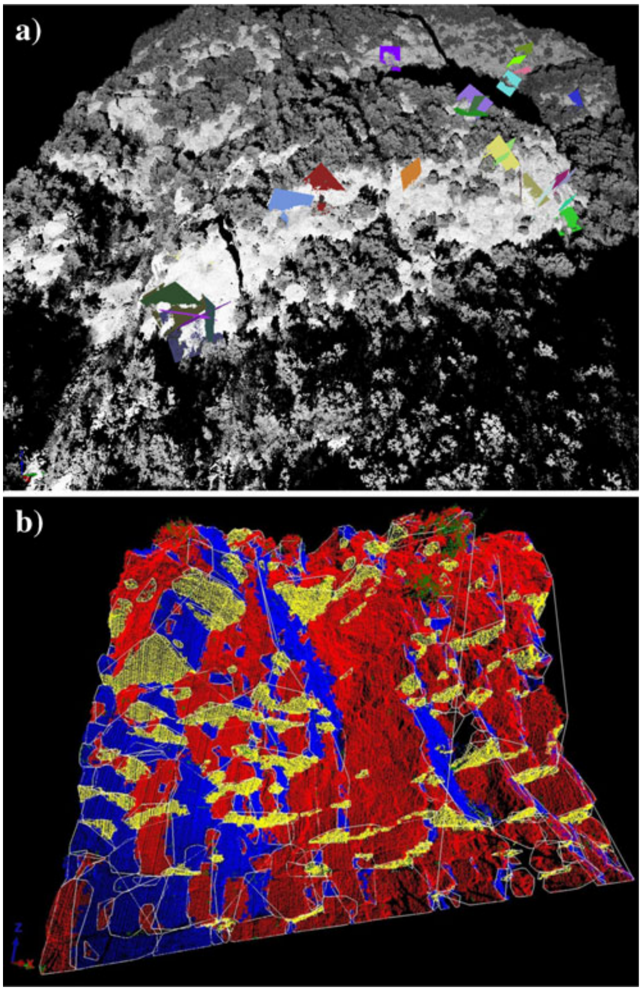


Fig. 6 Extraction of discontinuity orientation from TLS data: **a** manual selection and best-fitting plane calculation at Ponte di Nortosce and **b** semiautomatic extraction at Triponzo. *Red* discontinuity set Jn1, *blue* Jn2, *yellow* BG

Table 3 Comparison of block dimension (in m^3) for each investigated lithology, extracted from the field surveys, the literature, and TLS data processing, and the one employed in the rock fall simulations

	Field surveys				TLS		Employed in simulations
	From geomechanical data (Palmstrom 2005)	Inventory (max)	Inventory (mean)	Antonini et al. (2002)	From geomechanical data (Palmstrom 2005)	Measured mean[a]	
Calcare Massiccio	/	3.9	1.2	4.6	/	2.9	5
Maiolica	0.21	0.32	0.13	/	0.27	/	0.35

[a] Only two block volumes calculated from TLS data

stretch of the S.S. 320 road. In their study, the average size of the limestone blocks pertaining to the Calcare Massiccio Formation is 4.6 m^3. For these reasons, a volume of 5 m^3 was considered for the rock fall simulations both in Bagni di Triponzo and in Ponte di Nortosce (Table 3).

3D surface creation

The extraction of high-resolution surface models was necessary for performing the kinematic analyses and rock fall simulations (Fig. 1). To achieve this, first of all, it was necessary to filter the point clouds acquired with the TLS because of the strong presence of vegetation on the slopes (Fig. 3).

Currently, there are various methods to eliminate nonground points from a point cloud (Prokop and Panholzer 2009; Vosselman et al. 2004). Because of the shape of the slopes, and of the need to keep the procedure as rapid and objective as possible, a 2.5 D raster algorithm was chosen, and it was actually able to eliminate the vegetation and, at the same time, to maintain an accurate level of detail. The method involves the projection of the point cloud perpendicularly to a planar raster surface (1-m cell size) and the selection, for each cell, of the point nearest to the plane; identified points are then triangulated to generate a surface. For each scan position, the orientation of the best-fitting plane of the slope 3D model was considered as base reference, so as to keep overhanging sectors.

However, as regards the scans performed at Ponte di Nortosce (Fig. 3a) and at Bagni di Triponzo (Fig. 3b), data integration was necessary because of the presence of some shadow areas. For this reason, a second point cloud obtained from an existing 1:10,000 Regional Technical Map (CTR) created in the 80s was employed. The two point clouds were, thus, compared, and local high discrepancies were observed, which reached up to 25 m at the top of the steepest slopes. This difference is due to inaccuracies in the 10-m DEM, which is unable to correctly represent subvertical walls. It's evident that the source of the data heavily influences the accuracy of the DEM and, therefore, all the subsequent derived calculations.

On the other hand, the discrepancy between the two point clouds decreased to zero at the base of the slopes, where most of the holes were located. Thus, the point cloud resulting from the CTR map was exported to AutoCAD® and aligned, by rototranslation, to the one obtained with the TLS survey.

Once the point clouds were filtered and aligned, 3D slope surfaces were created through point triangulation. To remove possible spikes due to incomplete vegetation removal and to improve uniformity, a smoothing procedure was also applied. The three surfaces have the same resolution (1 m), and even the subvertical walls are properly and realistically reconstructed (Fig. 8), thus allowing performance of reliable kinematic analyses and rock fall simulations.

Finally, for 3D and 2D rock fall simulations, a DEM (1-m resolution) (Fig. 1) was created for each slope in a Geographical Information System (GIS) environment, and the position of roads, tunnels, and housing was extracted from the TLS products and overlapped to the terrain models.

Susceptibility scenarios

Kinematic analysis

For the definition of the main rock fall source areas, a spatial kinematic analysis was performed by using discontinuity orientation

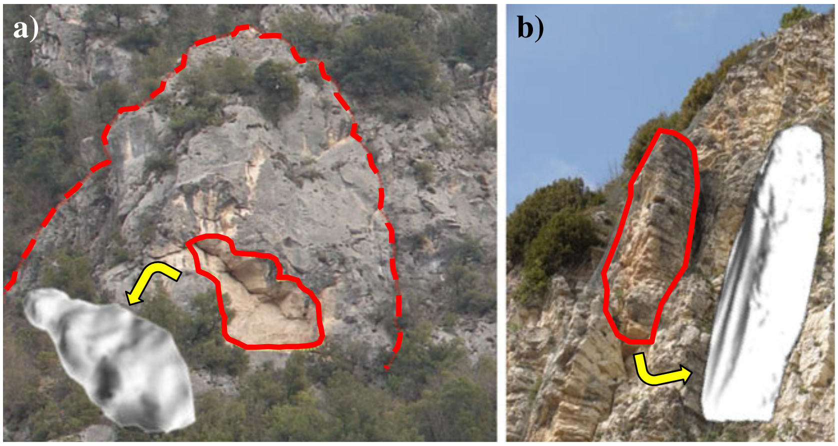
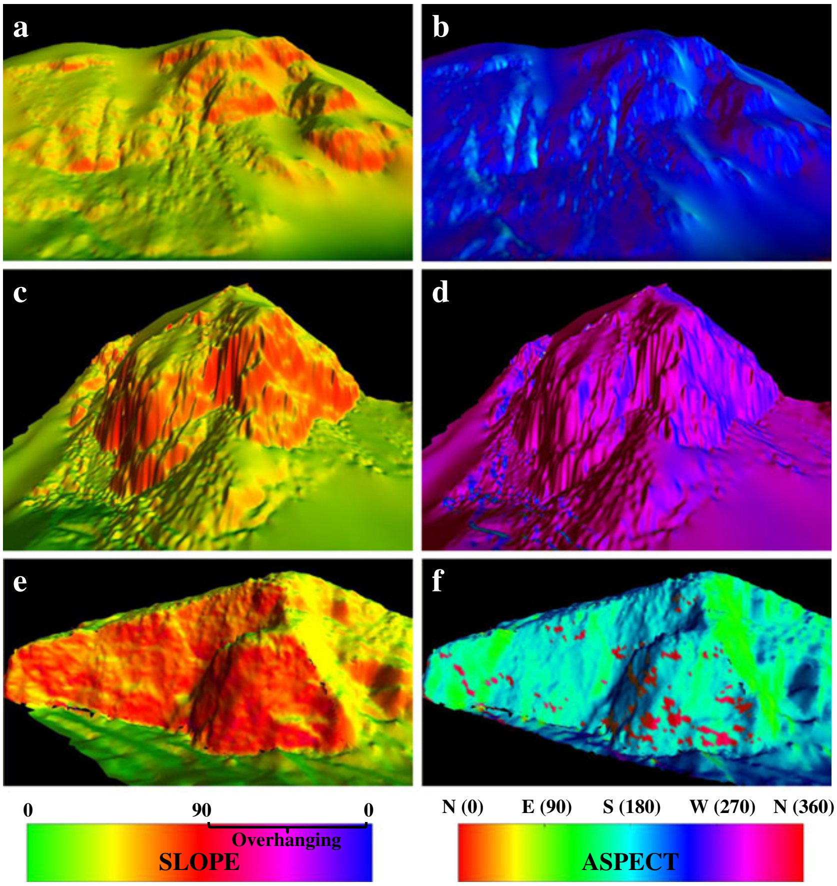


Fig. 7 Reconstruction of the shape and size of unstable blocks from the TLS data: **a** Ponte di Nortosce and **b** Triponzo

Fig. 8 3D surface orientation (slope and aspect) of the investigated slopes. Ponte di Nortosce (**a**, **b**), Bagni di Triponzo (**c**, **d**), Triponzo (**e**, **f**). Overhangs are visible in the aspect map of the latter site. Smooth sectors correspond to the *shadow areas*, filled by means of low resolution data



data semiautomatically and manually extracted from the point cloud and the 3D surface models obtained from the TLS data. This kind of analysis is able to establish if and where a particular instability mechanism is kinematically feasible, given the slope geometry and the discontinuity orientation (Goodman and Bray 1976; Hoek and Bray 1981; Hudson and Harrison 1997; Matheson 1989).

The main instability mechanisms investigated with this approach are: plane failure, wedge failure, block toppling, and flexural toppling. Casagli and Pini (1993) introduced a kinematic hazard index for each instability mechanism. These values are calculated by counting poles and discontinuities falling in critical areas of the stereographic projection.

A spatial kinematic analysis (Fig. 1) was performed on each unit triangle of the 3D surface models (Fig. 8) by employing a new Visual Basic software called Rock Slope Stability (RSS) proposed by Lombardi (2007) and developed specifically for true 3D kinematic analyses.

This tool overcomes many limitations of the traditional approaches, as it is possible to employ true 3D surfaces, and the kinematic conditions leading to the investigated instability mechanisms have been extended to overhanging slopes. This method fits the proposed procedure well, as its input data are the high-resolution 3D meshes obtained from TLS surveys and the discontinuities extracted with the manual and semiautomatic methods described above.

The kinematic analysis results are presented in Figs. 9, 10 and 11. All the investigated sites show quite high probability of occurrence of kinematic instability mechanisms (max kinematic index up to 20 %), mainly located in the steepest sectors of the slopes. The latter correspond to the main source areas, where blocks were seeded from in rock fall simulations. The prevailing instability mechanism is toppling, associated to planar failure (at Ponte di Nortosce and Triponzo) and wedge failure (at Bagni di Triponzo and Triponzo).

Rock fall simulations

2D and 3D rock fall simulations were performed (Fig. 1). 3D modeling was used in order to evaluate at large scale the influence of the slope morphology on the block trajectories, while 2D analyses allowed us to perform a larger number of simulations (statistically more significant) on the most critical profiles identified with the 3D approach. Both methods apply lumped mass logic: each single block is represented by a simple point with its mass concentrated at the center, and its trajectory is analyzed considering the physical laws governing the sequence of different types of motion (free fall, bouncing, rolling, and sliding) (Giani 1992). Thus, the block speed, kinetic energy, and bounce height can be calculated depending on the position on the slope or along the profiles.

Although the physical principles employed are quite simple, the uncertainty, variability, and sensitivity of the input parameters strongly influence the simulation results. As described above, the proposed procedure aims at quickly and objectively defining most of these parameters by analyzing high-resolution TLS point clouds.

Input data for rock fall simulations can be classified as geometric parameters (topography, identification of seed points, limits of outcropping materials, location of element at risk or points of interest, block shape, and volume) or mechanical parameters (normal and tangential coefficient of restitution and friction angle).

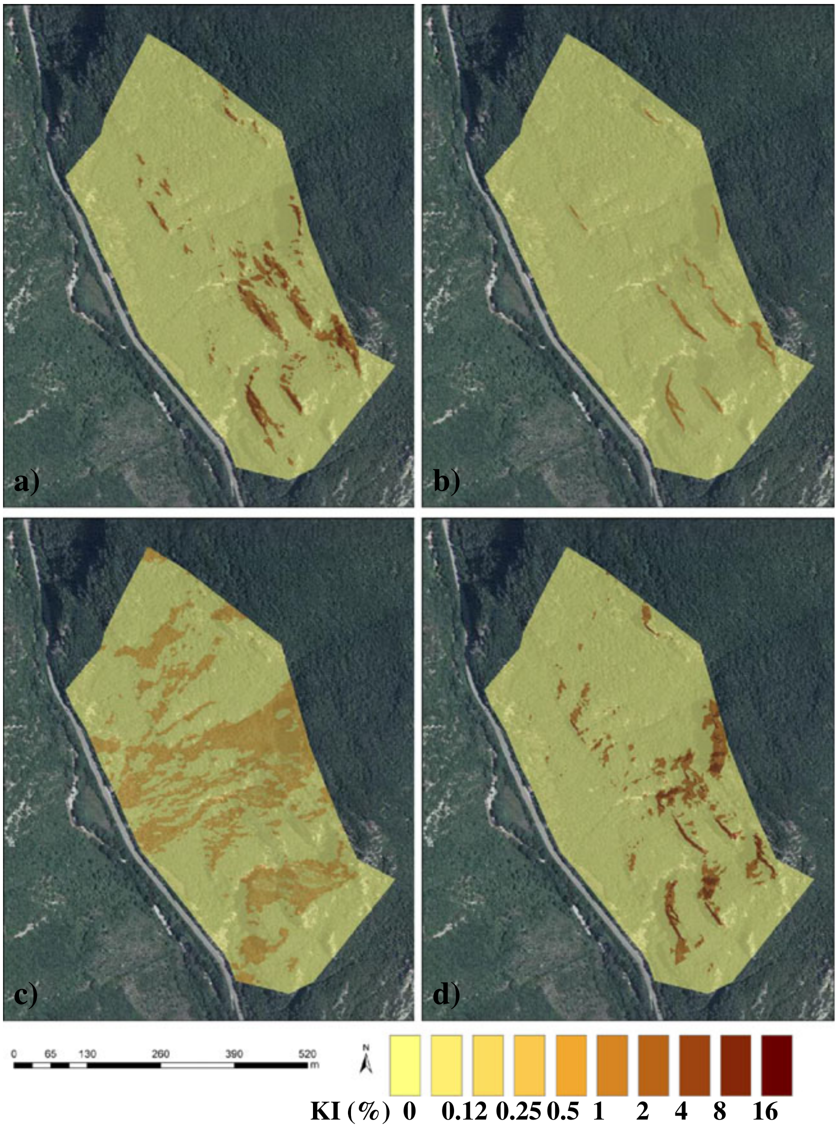


Fig. 9 Results from the kinematic analysis for the Ponte di Nortosce site. High kinematic indexes (*KI*) correspond to a higher probability that the investigated instability mechanism will take place: **a** planar failure, **b** wedge failure, **c** block toppling, and **d** flexural toppling

All geometric data can be retrieved through the analysis of TLS point clouds. The extraction of high resolution DEMs, block volumes, and rock fall source areas for the investigated cases have been described in "3D surface creation", "Estimation of block volumes", and "Kinematic analysis", respectively. In addition, an accurate location of the limits of the outcropping materials and the location of other elements of interest was possible thanks to the coupled observation of the point clouds and the oriented optical images acquired during the TLS survey.

As regards the remaining parameters, an inventory of fallen blocks has been carried out at all the investigated sites by integrating field observation and TLS data (black points in Fig. 12); the mechanical properties were calibrated by performing a 3D back analysis to obtain the best agreement between the distribution of the blocks found in situ and the one derived from the simulations. The resulting values and associated standard deviation employed in the simulations are summarized in Table 4.

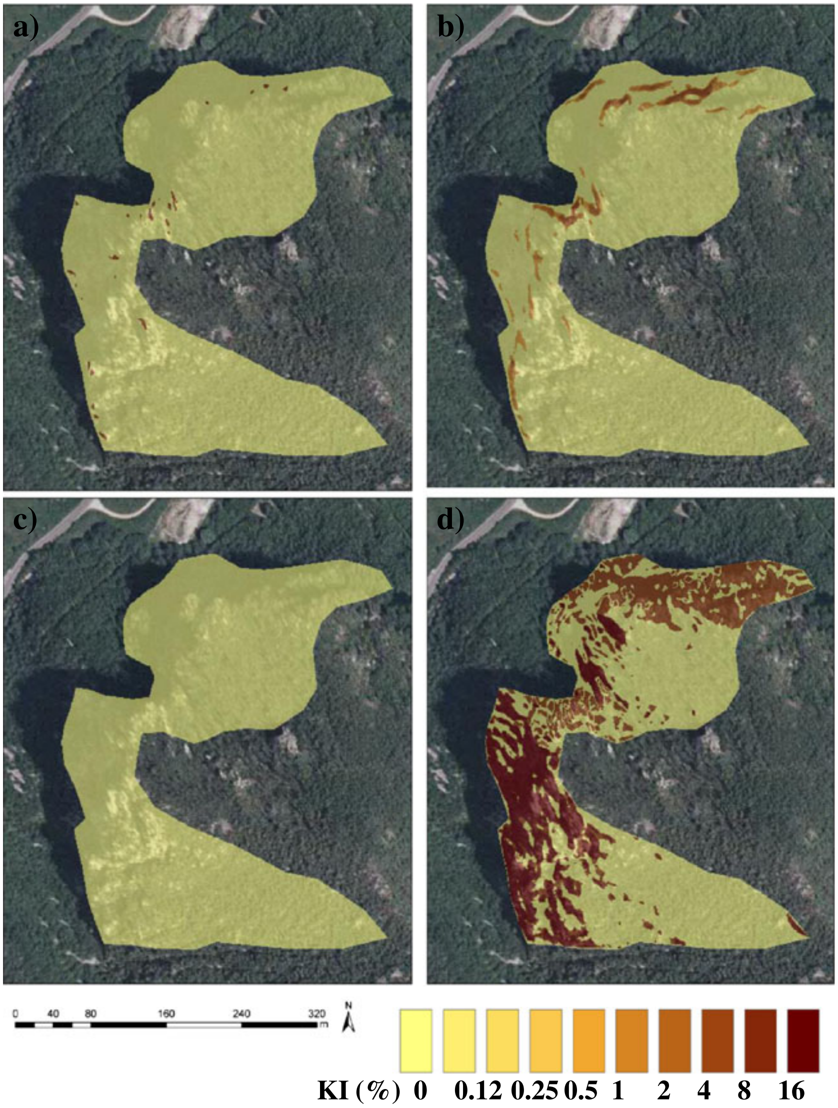
The initial block velocity was assigned a precautionary value of 1.5 m/s (both to the horizontal and vertical components). 3D simulations were performed by using the Rock fall Analyst software (Lan et al. 2007), which directly works in GIS environment. The employed reference surface was the 1-m DEM obtained from the TLS data, and blocks were seeded from the areas associated to kinematic indexes higher than 10. The resulting rock fall paths are presented in Fig. 12.

In order to obtain a more accurate assessment of susceptibility scenarios, 2D rock fall simulations were also performed by using the RocFall software (Rocscience 2005).

The analysis was carried out along three profiles for each rock slope analyzed, according to the criticalities from the 3D approach (Fig. 12), and the same input parameters of 3D simulations were employed. In particular, the trajectories associated to the highest runout distance for three different sectors of each area have been considered, and the corresponding topographic profiles have been extracted from the DEMs obtained from TLS data.

For each profile, 10,000 rock falls were simulated, since the larger the number of simulations, the more statistically significant the results will be (Fig. 13a, b, and c). Fundamental output

Fig. 10 Results from the kinematic analysis for the Bagni di Triponzo site. High kinematic indexes (*KI*) correspond to a higher probability that the investigated instability mechanism will take place: **a** planar failure, **b** wedge failure, **c** block toppling, and **d** flexural toppling



parameters (such as the horizontal location of rock end points, the kinetic energy, and the bounce height) were, thus, determined according to the progression along the profile or in correspondence of sensitive elements (rock fall barriers, roads, and buildings).

Results and discussion

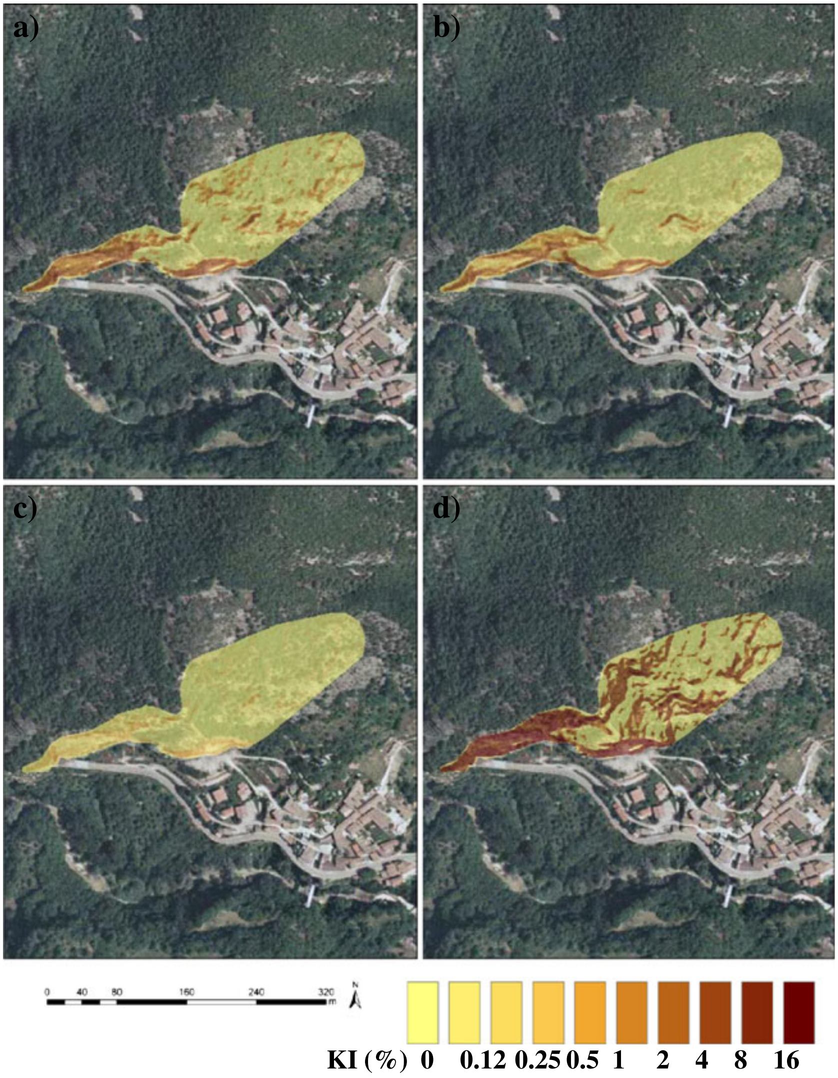
The application of the presented methodology to the Valnerina case study allowed us to reach important results, both in terms of the behavior of falling blocks in correspondence of the elements at risk and regarding the applicability of the methodology itself. The choice of the site was, in fact, based on the high frequency of rock fall phenomena (enhanced by the intense seismicity of the valley), on peculiar challenges related to the logistics (the area is poorly anthropized; therefore, most of the slopes are not reachable and need to be analyzed from remote observation points), and on the presence of anthropic structures limiting slope visibility (such as rock fall nets or barriers). The main advantages and drawbacks of the proposed approach are discussed here, keeping in mind its original purposes (rapidity, objectivity, high resolution, and reliability).

The remote sensing technique chosen for data collection is based on the TLS survey method, which allows us to quickly retrieve a dense point cloud of the rock walls, according to a regular scan pattern (objectivity). The main obstacle for the complete compliance of the quickness requirement was the occurrence, within TLS data, of shadow areas, which required a filling procedure in order to get complete spatial information. Moreover, even though these sectors were limited in number and extension, their filling caused a lack of accuracy and resolution homogeneity within the 3D surface models (Fig. 8); consequently, the results of kinematic and runout analyses in these areas should be considered with care.

With hindsight, in order to increase the reliability and objectivity of the 3D models, it could be better to retrieve more certain and objective data by spending time in performing raw data alignment in situ, with the aim of exactly identifying the shadow areas (which are usually small) and covering them with additional scans from new observation points.

For a complete and precise rock fall analysis, an accurate reconstruction of the main characteristics of the rock mass is required. In this work, three different approaches for geomechanical analyses were considered and compared: traditional in situ survey and manual and semiautomatic extraction of the most important geometric characteristics of the rock mass from the high resolution point clouds.

Fig. 11 Results from the kinematic analysis for the Triponzo site. High kinematic indexes (*KI*) correspond to a higher probability that the investigated instability mechanism will take place: **a** planar failure, **b** wedge failure, **c** block toppling, and **d** flexural toppling



First of all, it is important to remark that the field survey is the only method able to produce information about those parameters that require direct access to the rock face (such as aperture, seepage, wall strength, and filling). However, the latter are not relevant for rock fall simulations; for this reason, the in situ survey has been employed for data validation only.

On the other hand, the application of the semiautomatic procedure can give a contribution to improve the safety level (since it is not necessary to physically reach dangerous areas), the spatial resolution, the quickness, and the objectivity of the whole approach. In order to accurately locate the discontinuity sets of a rock mass, it is necessary to have the largest number of measures and a good sampling methodology. The semiautomatic procedure, through its analysis algorithm, allows acquisition of a huge amount of data with an objective criterion and investigation of major portions of the rock mass. By performing the discontinuity extraction from different rock mass portions, we are also able to evaluate possible spatial variations of discontinuity set orientation and other geometrical properties. The application of the presented semiautomatic approach, however, do not always provide satisfying results, such as in the case of rock masses characterized by prevailing discontinuity traces (Gigli and Casagli 2011a; Kemeny and Post 2003; Ferrero and Umili 2011) by very irregular (Lato et al. 2012) or poor fracturing, or if the spatial resolution of the point cloud is too low (usually due to the high distance of the object of interest from the scan position). Moreover, the TLS line of sight acquisition may result in wide shadow areas and significant bias if data are acquired from a single scan position (Lato et al. 2010). For these reasons, the Calcare Massiccio rock masses have been investigated by manually extracting discontinuity surfaces from the point cloud.

Thus, representative block dimensions can be semiautomatically calculated only if specific conditions take place (rock mass characterized by well-developed discontinuity surfaces and point cloud resolution high enough to appreciate geometric features); otherwise, additional integrative data processing is necessary. This is a very important point that should be kept in mind when exporting the procedure to other sites, since block size is a key parameter for the forecasting of the kinetic energy in correspondence of the elements at risk, and its quick and reliable definition is fundamental for correct rock fall analyses.

The kinematic analysis allowed quick and objective definition of the main rock fall source areas. These results were also confirmed by field observations that show evidences of occurrence of the predicted instability mechanisms (Fig. 7).

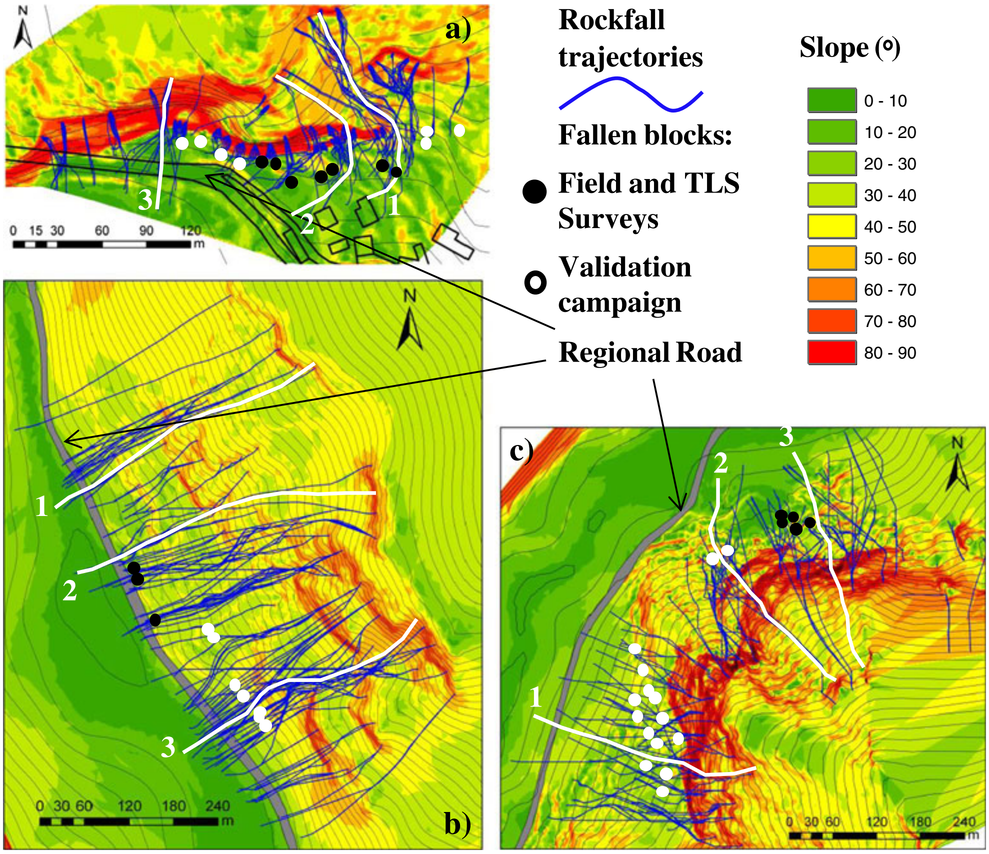


Fig. 12 3D rock fall simulation results: **a** Triponzo, **b** Ponte di Nortosce, and **c** Bagni di Triponzo. The position of fallen blocks extracted from TLS and field surveys (*black points*) and those found during the validation inventory (*white points*) are also reported. The *white lines* indicate the traces of the profiles employed in the 2D analyses

The geometric inputs of rock fall analyses are, therefore, completely defined; however, to improve simulation reliability, a back analysis for the calibration of the coefficients of restitution and friction angle of the outcropping materials is strongly suggested. This is usually done by performing an inventory of fallen block and carrying out a parametric analysis with the aim of obtaining the best agreement between the in situ block distribution and the simulated one. The high-resolution point clouds acquired by the TLS can be useful also for this purpose, allowing for accurate estimation of both the position and dimension of fallen blocks.

The results of rock fall analyses at Ponte di Nortosce show that the regional road appears to be heavily rock fall prone, since 88 % of simulations reach the roadway, stopping, in some cases, in the fields beyond it. The associated maximum bounce height and kinetic energy are about 1.5 m and 210 kJ, respectively.

At Bagni di Triponzo, the blocks reach the roadway only in exceptional cases (1 %). Almost all the simulations stop at the base of the rock slope, where the vegetation is denser.

Figure 13 shows the importance of employing a realistic topographic base for reliable rock fall analyses. A comparison between 2D simulations performed on profiles extracted from high-resolution TLS data (Fig. 13c) and from a regional technical map (scale 1:10,000) (Fig. 13d) is presented. Low-resolution topographic maps usually strongly underestimate slope steepness, especially in subvertical areas (thus, overestimating it at their base). Moreover, the profile line is constituted of a sequence of unrealistic steps, which can alter the true behavior of falling blocks.

Finally, at Triponzo, due to the high steepness of the slope, the horizontal component of block velocity is low, resulting in a higher energy dissipation and, consequently, in moderate runout distances. The road network and the buildings closest to the rock wall are, therefore, marginally affected by the rock falls, with the exception of the western portion of the regional road, where a rock fall gallery was built to reduce the risk.

Table 4 Mechanical parameters retrieved through back analysis, employed in the rock fall simulations

Material type	Rn		Rt		Friction	
	Mean	σ	Mean	σ	Mean	σ
Bare rock	0.6	0.05	0.8	0.05	30	2
Vegetated rock	0.5	0.05	0.6	0.05	30	4
Soil	0.3	0.05	0.5	0.05	30	2
Vegetated soil	0.3	0.05	0.4	0.05	30	4

Rn normal coefficient of restitution, *Rt* tangential coefficient of restitution, *Friction* fiction angle, σ standard deviation

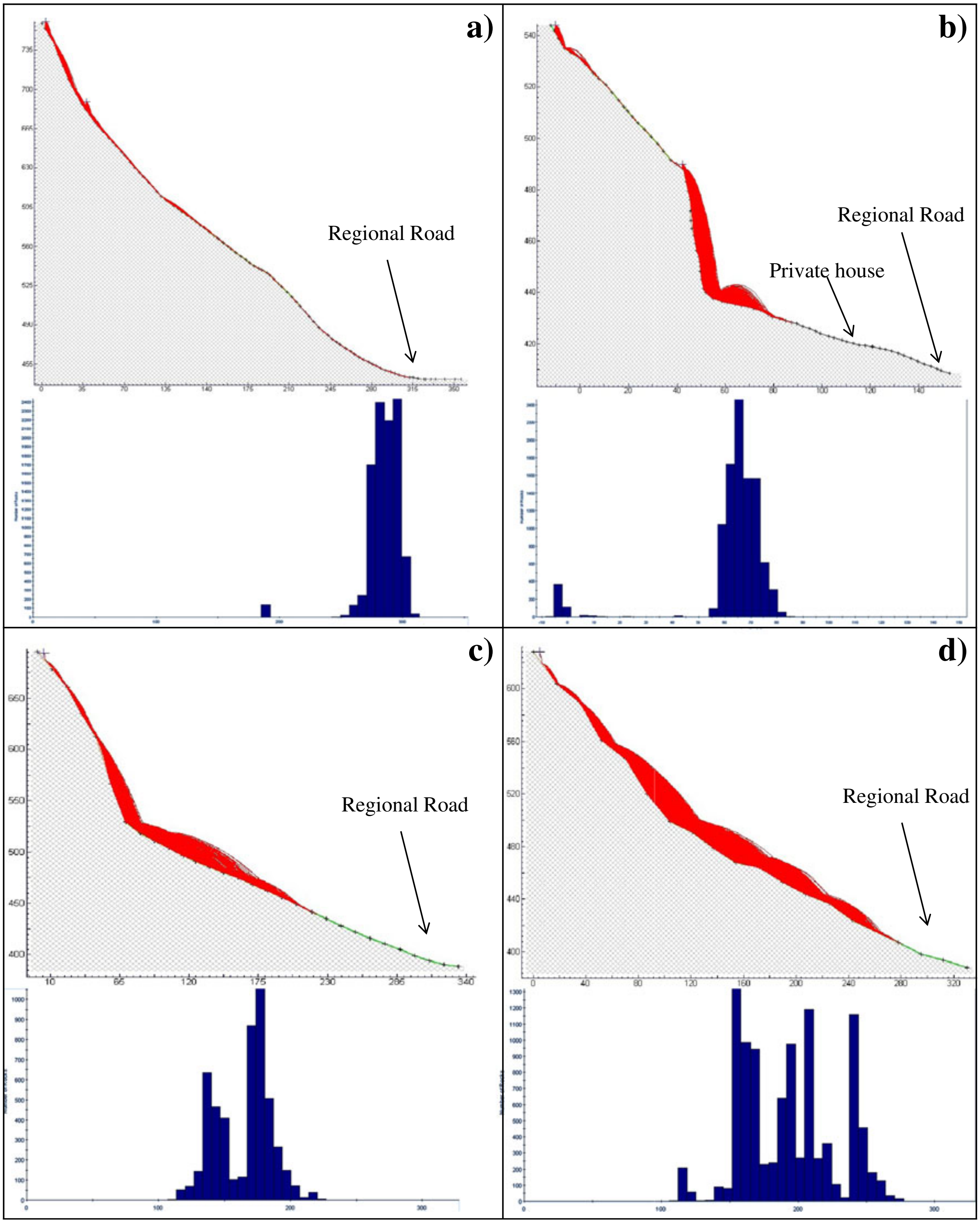


Fig. 13 2D rock fall trajectories and location of end points: **a** profile 3 (Fig. 12) at Ponte di Nortosce, **b** profile 2 (Fig. 12) at Triponzo, **c** profile 1 (Fig. 12) at Bagni di Triponzo, and **d** profile 1 at Bagni di Triponzo extracted from a topographic map 1:10,000

A validation inventory has been carried out after the application of the whole procedure (white points in Fig. 12). The results show a good agreement with 3D (Fig. 12) and 2D (Fig. 13) simulations as regards Ponte di Nortosce (where blocks are retained by a recent rock fall barrier) and Triponzo, while some discrepancies between true and simulated block distributions can be observed in the south-western of the Bagni di Triponzo site, where probably the restitution coefficient were overestimated due to the presence of thick vegetation (Fig. 3b).

Conclusions

The objective of this work was to experiment and evaluate the advantages and drawbacks of a procedure for the complete definition of susceptibility scenarios associated to rock falls using primarily the TLS technique. The methodology has been applied in three test sites located in Valnerina (Umbria Region, Italy). Due to its sharp morphology, the investigated area is characterized by steep slopes and deep valleys, and as a consequence, the risk of rock falls is particularly high, especially along the roads and in the villages next to the slopes. Furthermore, this predisposition is exacerbated by the intense seismic activity of the entire area.

The TLS technique turned out to be able to provide all the geometric parameters necessary for performing the rock fall simulations (high-resolution DEM, main source areas, block shape and size, and limits of the outcropping materials). The choice of the test site was also based on the need to try the limits of the procedure out. The morphology of the area, in fact, allowed performance of the scans only from limited and sometimes remote observation points. Therefore, the resulting point clouds were sometimes incomplete and, occasionally, had a too low resolution for performing automatic data processing. The overcoming of these problems (by integrating the point clouds with existing topographic data and carrying out manual data processing) required a delay of the whole procedure of about 100 %.

Even if the proposed approach has been conceived to employ primarily TLS data, it is important to remark that, in the authors' opinion, field check and in situ data collection are necessary, both to validate the results of the procedure and to calibrate the mechanical parameters of the outcropping materials for reliable simulations.

The application of the proposed methodology to the test site allowed identification of the main rock fall source areas and associated instability mechanisms, and the dwellings and transportation corridors stretches that are exposed to the highest risk. A validation inventory confirmed the reliability of the procedure. The presented approach proved to be objective, reliable, and exportable, even if, in particular conditions, integrative activities could be required, thus producing a delay, which, in emergency conditions, could be unacceptable.

Furthermore, the need to process high-resolution data allows analysis of only limited rock mass outcrops and the extension of the procedure to long stretches of roadside rock masses (which can be investigated through mobile devices) is, at the moment, unfeasible. The application of the procedure to a real case showed that an improvement in automation is also strongly needed (as regards, for example, the unstable mass detection and the link between the different steps), which will help to further strengthen objectivity and reduce processing time.

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