

Terrestrial mobile LiDAR survey to manage rockfall risk along a motorway

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ABSTRACT: This work presents the validation of a terrestrial mobile LiDAR survey from a vehicle to provide the A22 motorway operator with a tool for rockfall risk management. The paper focuses on the A22 section between Bolzano Nord and Chiusa (South Tyrol, Italy), where the Isarco River valley morphology features steep rock slopes, and the motorway runs at their toe, primarily on cut-and-fill roads and viaducts. A qualitative rockfall risk assessment has highlighted a significant level of risk affecting a 13 km section of the A22 motorway. As a consequence, the motorway operator is required to develop a management strategy and implement tools—such as periodic LiDAR surveys—to support ongoing validation and updating of the risk assessment over time. Due to the morphology of the site and the characteristics of the infrastructure that locally does not have an emergency lane, managing the rockfall risk and detecting detachment zones through traditional static LiDAR surveys would require traffic closure to ensure safety conditions. In this area, the motorway mostly consists of superficial structures, so a terrestrial mobile LiDAR survey from a vehicle was assumed to be a convenient, innovative methodology. A survey was carried out in April 2023 to test its effectiveness and efficiency in detecting potential detachment zones in wide areas. The effectiveness of the mobile LiDAR survey is evaluated in terms of point density and percentage of detected areas of each potential detachment zone. The efficiency is proved in terms of time since the survey required only half a day and in terms of the safety of the workers without closing the traffic lane. The capabilities and limitations of the mobile LiDAR survey from a vehicle are also addressed in detail for some potential detachment zones of interest.

KEYWORDS: Transport infrastructure, rockfall risk management, mobile LiDAR, survey, detachment zones.

1 INTRODUCTION

Managing rockfall risk along transportation corridors crossing mountain belts is of increasing importance since road and railway traffic are growing due to a higher mobility of people and goods (Macciotta et al., 2015; Ferlisi et al., 2021). The current study focuses on the rockfall risk affecting the Italian side of the European Route E45, i.e. A22 motorway.

Rockfall risk management along the A22 motorway is challenging due to the complex morphology of the Isarco River Valley, where the infrastructure runs. In fact, steep slopes and cliffs are quite diffuse and they are sources of rockfalls whose trajectories can reach the motorway. A qualitative rockfall risk assessment has identified that rockfalls pose a significant risk for a section of 13km of the A22 motorway (Lelli et al., submitted). The motorway operator is then asked to define a strategy to manage this risk and adopt a tool, such as periodical LiDAR surveys, for continuously validating the assessment.

This work describes the testing of a Terrestrial Mobile LiDAR (TML) survey from a vehicle, in order to assess its suitability in detecting most of the slopes, performing the rock mass characterization, and identifying rock volumes that need more detailed on-site investigations.

It is worth noting that this study presents the preliminary results about the suitability of TML running on a highway for long-term monitoring rockfall risk along infrastructures, since further investigations and analyses are currently underway.

2 DESCRIPTION OF THE STUDY AREA

2.1 Geographical and geological settings

The studied A22 motorway section is located in the Autonomous Province of Bolzano (South Tyrol, Northern Italy) and it runs for 13 km in the Isarco River Valley. In this area, the lithology is mainly characterized by ignimbrites, tuffs, conglomeratic tuffs and lavas pertaining to the “Riodacitic Group” and the “Latitic-Andesitic and Dacitic Group” (Baccelle Scudeler et al., 1969). Along the Isarco River Valley, the A22 motorway runs parallel to the Isarco River, surrounded by sub-vertical rock slopes often reaching several hundred meters of height. The slopes surrounding the A22 motorway are predominantly covered by broadleaf vegetation, often masking rock walls even in sub-vertical cliffs.

2.2 Rockfall risk along the A22

The A22 motorway section of interest was built for 13% in tunnels, 55% in viaducts and 32% in cut and/or fill roads. As previously mentioned, the area is prone to rockfalls, which constitute potential hazards for the A22 motorway, as reported by the IFFI inventory (ISPRA, 2022). A total of 269 rockfalls have occurred in the study area and surrounding slopes between 1993 and 2020. Rockfall mitigation and protection structures (i.e. nets, barriers, embankments, walls, etc.) are widespread along the Isarco River Valley and their position and maintenance status can be found in the VISO inventory (Autonomous Province of Bolzano, 2022) or in the motorway operator databases.

3 ROCKFALL RISK MANAGEMENT

A qualitative rockfall risk assessment has been carried out for the studied motorway section and it has confirmed that rockfalls pose a significant risk (Lelli et al., submitted).

Risk was assessed based on the well-established framework combining Hazard, Exposure and Vulnerability (Figure 1). For the most susceptible rock slopes identified through bivariate statistical methods, (Chen et al., 2016; Valencia Ortiz et al., 2023), hazard has been estimated by combining rockfalls occurrences and rocks mass quality (i.e. GSI) data. Rockfall runout simulations have highlighted the elements of A22 motorway (tunnel portals, viaducts and cut-fill road sections) exposed at risk and provided the energy of the impacts. The latter have been used to discretized the vulnerability into the relative rating scales.

The qualitative rockfall risk assessment requires continuous validation and input updates. For this purpose, the use of TML surveys could update the hazard evaluation by detecting the occurrence of detachments and providing information for the rock mass characterization (Figure 1). Then, the suitability of the TML survey has been checked for a sample of 19 most critical slopes (i.e. most susceptible slopes which are likely to be sources of rockfalls impacting the motorway).

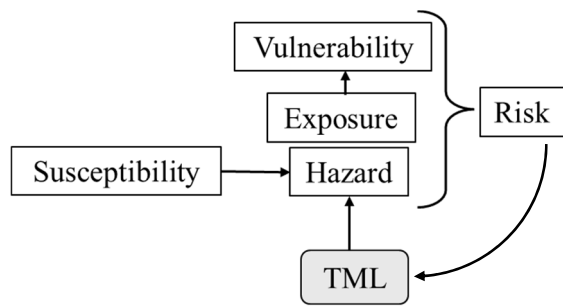


Figure 1. Risk assessment update through periodical TML surveys.

4 TERRESTRIAL MOBILE LIDAR SURVEY

In the present work, the TML survey system has been chosen as an alternative to the drone, since the latter is not allowed, due to the restrictions of the competent authorities. In addition, the presence of the motorway running at the toe of the steep rock slopes and the sporadic presence of the emergency lane along the A22 motorway easily suggested using the infrastructure as a “race track” for running a TML survey. Preliminary to the current study, the TML survey was simulated by means of a GIS analysis (Ferro et al., 2023) to verify its effectiveness and efficiency in detecting the most critical rock slopes with a suitable point density.

Thus, the TML survey set up was carefully designed to obtain a high resolution (i.e. point density) and high quality (i.e. standard deviation of the coordinates) of the survey points.

In April 2023, the Terrestrial Mobile LiDAR survey was carried out by using a TRIMBLE MX9 mobile mapping system mounted on a car. The technical specifications of this instrument are reported in Bianchi et al. (2025).

For the current survey, 63 Ground Control Points (GCPs) were positioned along the A22 motorway section of interest, thus allowing a precision of the 3D coordinates of about 2 cm in the horizontal component and about 3 cm in the vertical component. Four runs, two per direction, were carried out by using two different instrumentation settings in order to detect the largest number of points and to reach the maximum allowed distance. These repetitions ensured the high resolution and high quality of the survey. All four runs were carried out at about a constant velocity of 30-35 km/h. The TML survey was executed by two operators on a car, which was guarded by mobile work vehicles, thus ensuring the surveyors and motorway personnel’s safety. The materialization of the GCPs took one workday and the actual TML survey required only half a day. In the end, this procedure has been revealed safer and more convenient with respect to the “stop & go” procedure required by a classical Terrestrial Static LiDAR.

More details about the mobile mapping survey can be found in Simeoni et al. (2024).

5 RESULTS

5.1 Detected areas and point density

To evaluate the effectiveness of the TML in surveying a wide area, the post-processing was aimed at assessing the point density and the percentage of area of the 19 most critical rock slopes that were effectively surveyed.

The output of the TML survey consists of georeferenced 3D coordinates of survey points covering almost all the slope areas previously evaluated as susceptible to potential rockfall detachments.

Figure 2 depicts three examples of detected critical rock slope areas: a) above an entrance of tunnels, b) along a portion of A22 running on a cut and/or fill road and c) along a viaduct.

Four out 19 susceptible rock slope zones were not detected at all, while 9 out 19 susceptible rock slope zones were detected with an extension wider than 80%. The four areas were not detected because of the presence of high sub-vertical rock slopes that completely hide their view from the highway. If neglecting the not detectable areas, on average, the TML survey was able to detect more than 70% of the interested areas, even if the presence of other small sub-vertical slopes beside the viaduct and broadleaf vegetation hides the areas of interest.

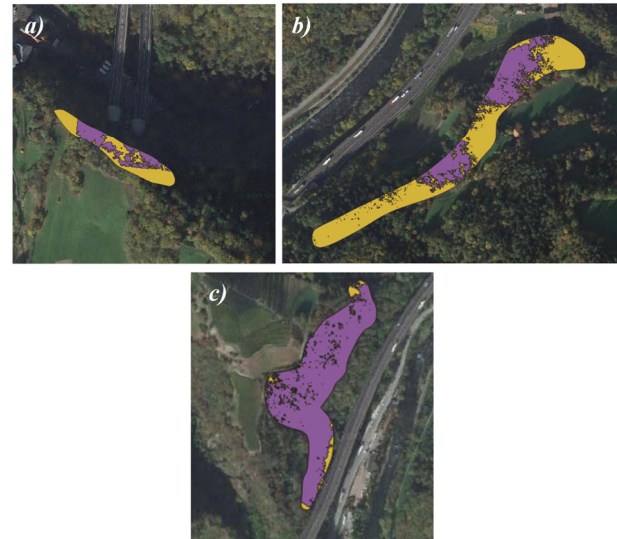


Figure 2. Examples of detected rock slope portions: a) on the entrance of a tunnel, b) along a cut and/or fill road and c) along a viaduct.

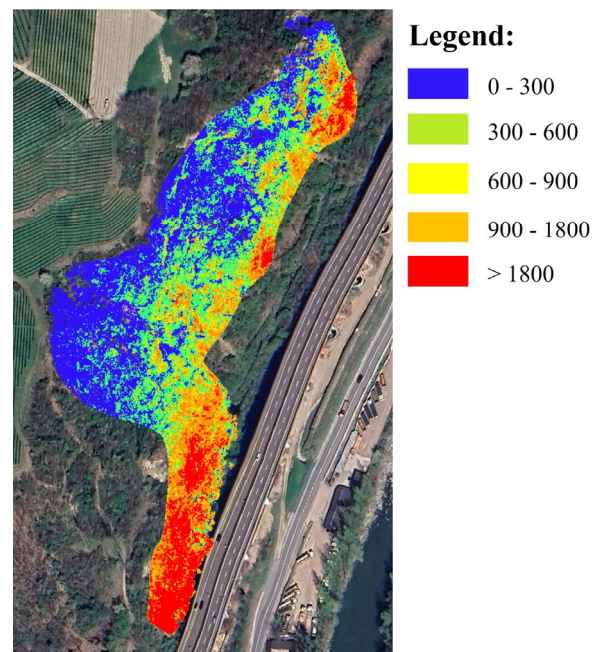


Figure 3. Example of point density achieved by the TML survey over the critical area of Figure 2c.

The superficial point density has been evaluated with Cloud Compare (Lague et al., 2013). The percentage of points with a density higher than 300 points/m² has been evaluated, since this value has been considered the threshold to detect the detachment of small blocks if surveys are carried out periodically. On average, 48% of the potential detachment zones were detected with a point density higher than the fixed threshold. Figure 3 represents an example of the distribution of the point density over a critical rock slope (i.e. the corresponding critical area is reported in Figure 2c). It is easy

to note that the portion of the rock slope closer to the viaduct has been detected with the highest value of point density, i.e. higher than 1000 pts/m². Then, the point density decreases as going further from the highway, reaching the lowest values (i.e. around 100 points/m²) at a distance of almost 150 m (i.e. the blue areas in Figure 3).

The current results underline the TML survey effectiveness in terms of both detected area and superficial point density.

5.2 Geomechanical characterization of the rock walls

Given the high precision of the point coordinates and the overall quality of the TML survey, an additional objective was to explore its potential for geomechanical characterization of the rock faces. This would allow the identification of potentially unstable rock volumes, which could then be targeted for site-specific investigations to assess their actual stability conditions.

A rocky jutting wedge at a distance of around 90 m from a viaduct and a height of around 130 m, located above the entrance of a tunnel, is hereinafter taken as an example.

This wall was chosen because on-site measurements are also available and, therefore, it is possible to compare the results obtained with the TML survey data with those obtained with an on-site survey. Moreover, for this critical rock wall, the TML survey was able to detect only 33% of its area due to the change in convexity of the rock cliff. However, on average, 79% of points of the rocky jutting wedge have been detected with a density ranging between 300 pts/m² and 600 pts/m² and, locally, it reaches values even higher than 900 pts/m² (Figure 4).

The site survey was carried out with the Terrestrial Static LiDAR, aerial photogrammetry and climbers who used the geological compass. The volume of the rocky wedge has been contoured by the planes reported in Table 1. Globally, the rocky jutting wedge is contoured by the sub horizontal plane (K6) and two parallel planes (K1 and K3) on the sides (Figure 5).

The recognition of discontinuities and planes is challenging because the point cloud of the wedge, acquired by the TML, is incomplete due to the combination of rock wall morphology and the LiDAR's line of sight (Ferrero et al., 2011). Figure 5 shows that, according to the planes listed in Table 1, the on-site survey was able to reconstruct the wedge point cloud (Figure 5a), while the TML survey did not detect one lateral side (in yellow in Figure 5b) and the upper plane, as it is shown in Figure 5b. The lateral side was not visible by the LiDAR, since it was hidden by the body of the rocky jutting wedge when it was in front of the car, and by the entrance structure of the tunnel when it was just passed by the running car.

Given the convexity of the shape of the point cloud, it was possible to use the MeshLab filter "Convex hull" to estimate the volume and the area of this element. The estimated volume is 690 m³, which is lower respect the estimated value of 915 m³ from the on-site survey. This mismatch is attributed to the difference between the two reconstructed meshes caused by the poor information of the faces of the rocky jutting wedge detected by the TML.

In addition, RANSAC method has been applied to the TML point cloud representing the rocky jutting wedge, in order to estimate the planes that form this element in terms of dip and dip direction. Those results have been reported in a stereogram (Figure 6).and compared with the measurements from the on-site survey (Table 1).

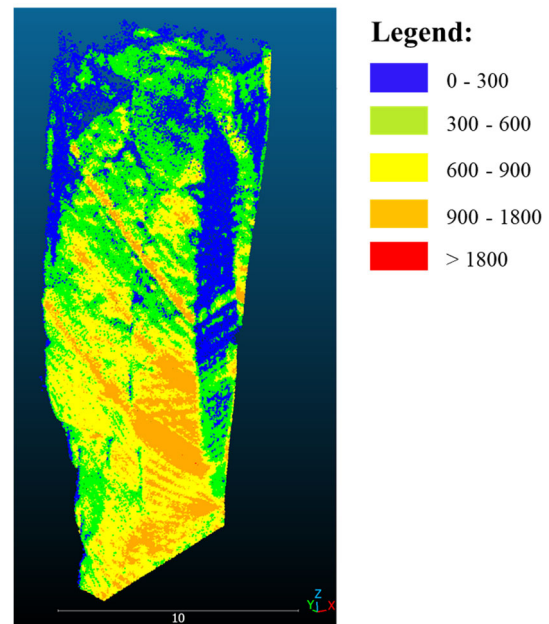


Figure 4. Superficial point density of the rocky jutting wedge.

Table 1. Dip and dip direction angles of the planes forming the rocky wedge from geo-structural survey through Terrestrial Static LiDAR, aerial photogrammetry and geological compass.

Plane	Dip [°]	Dip Direction [°]
K1	65-90	300-325
K3	70-90; 65-90	50-85; 230-270
K6	15-45	200-260

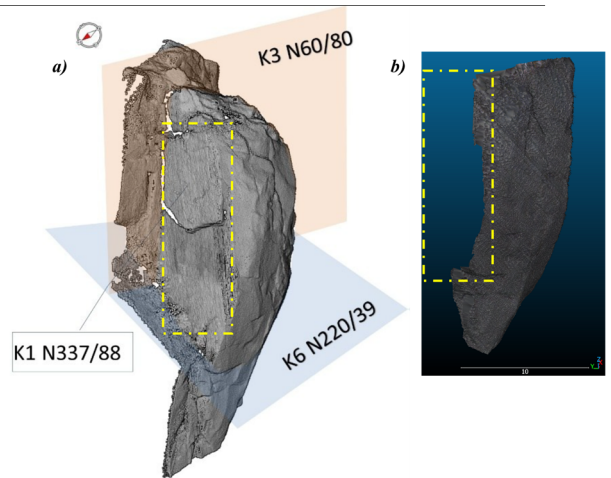


Figure 5. Rocky wedge point cloud reconstruction from a) an on-site survey and b) TML survey.

It is possible to note that the planes with a dip angle lower than 40° were not recognized (i.e. K6 plane of Table 1). This limitation is coherent if considering the relative position between TML and the detected object during all the runs of the vehicle. A tool that allows the recognition of sub-horizontal planes could be on-site measurements with compass-equipped technicians climbing the rock slope. Moreover, it is expected that also a classical terrestrial static LiDAR survey won't be able to detect the rocky wedge, while a drone survey could help in recognizing the sub-horizontal planes. However, this methodology will require additional time of work and the interruption of traffic.

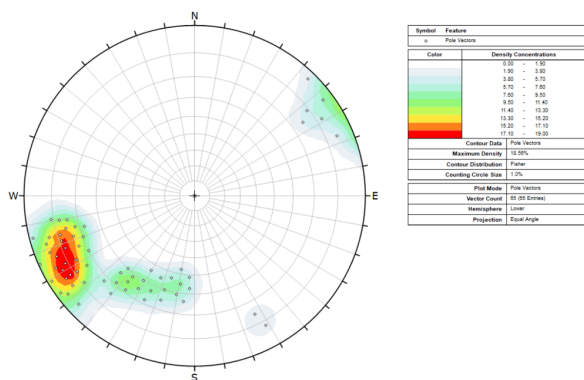


Figure 6. Stereogram of the recognized planes from RANSAC procedure applied on the TML point cloud.

6 CONCLUSION

The current work describes the validation of a terrestrial mobile LiDAR survey from a vehicle to be used by the A22 motorway operator as a tool for rockfall risk management.

In particular, the preliminary results of a Terrestrial Mobile LiDAR survey carried out on a 13 km of A22 highway are here shown. Along the considered portion of the motorway, the most critical rock slopes have been mapped with a preliminary rockfall risk study.

The TML survey effectiveness has been demonstrated by evaluating the percentage of detected area and the achieved point density on these critical rock slopes. In particular, it has been found out that the TML technology was able to detect more than 70% of the slope areas, even if sometimes the presence of sub-vertical slopes beside the viaducts and vegetation hidden the areas of interest. Moreover, on average, 48% of the potential detachment zones were detected with a point density higher than the fixed threshold of 300 point/m² to identify the detachment of small blocks if surveys are carried out periodically. These values of the percentage of detected area and density of points demonstrate the effectiveness of the TML survey.

In terms of efficiency, it has been proved that the TML requires a lower amount of time (i.e. half a day) respect to a traditional static LiDAR survey (i.e. some days). In addition, the safety of the workers has been ensured without closing the traffic lane.

Then, by considering a rocky jutting wedge, it was possible to survey its surface, except for the sides that are not intercepted by the line of sight of the mobile LiDAR. This is a limitation of this methodology of survey: in fact, not recognizing these faces led to a wrong estimate of the rocky jutting wedge volume with respect to the evaluation from an on-site survey. Moreover, the geomechanical characterization of the planes forming the rocky wedge is limited due to the fact that sub-horizontal planes were not recognized because they were not visible to the scanner.

Therefore, from the current preliminary results, it has to be underlined that only the combination of TML with other survey techniques could better explore areas of the critical rock slopes. Alternatively, knowing that sub-vertical slopes may hide less inclined planes, these should be artificially included in the geomechanical characterization to select the rock volumes that require specific on-site surveys.

Moreover, only further repetitions of the TML will demonstrate whether it is a valid tool for identifying detachments, slope movements and, in general, for supporting the motorway operator in monitoring wide hazardous areas.

For further repetitions of the TML survey, the motorway operator could improve the environmental performance installing the LiDAR on an electric or hydrogen-powered

vehicle and, or on vehicles that are often required to transit along the slow lane of the motorway, such as trucks. In the latter case, the TML monitoring won't increase the amount of traffic along A22 highway.

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