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ScienceDirect

Procedia Structural Integrity 62 (2024) 499–505

Structural Integrity Procedia

www.elsevier.com/locate/procedia

II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

Mobile Terrestrial LiDAR survey for rockfall risk management along a highway

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Abstract

In the alpine stretch, from Brenner to Bolzano (Northern Italy), the Highway A22 is exposed to rockfalls and protection structures must be progressively extended as new detachments are identified. This paper defines a procedure to manage the rockfall risk through periodic Mobile Terrestrial LiDAR surveys from a vehicle travelling along the highway. This type of survey requires the adoption of specific precautions to work safely without interrupting traffic on the highway, such as escorting the surveyors' vehicle using specific vehicles for mobile road works. Prior to a field trial, the potential effectiveness of a Mobile Terrestrial LiDAR survey was demonstrated through a GIS-based simulation. The simulation was performed for the most critical cliffs in a GRASS GIS environment with the support of Python scripts and the results were compared with those from a simulation of a static survey. Still working in a GIS environment, eight cliffs were identified as the most susceptible to rockfalls that may interfere with the infrastructures. The survey simulation revealed that a Mobile Terrestrial LiDAR survey has the potential to sense over 85% of the cliff area with a point density greater than 100 pts/m^2. Given these promising results, a trial survey was then carried out in April 2023 using the innovative mobile mapping system Trimble MX9. Half a day was sufficient to sense the rock slopes along a 30 km stretch of the motorway with a point density of up to 900 pts/m^2 for distances up to 150 m.

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10.1016/j.prostr.2024.09.071

Keywords: Mobile Terrestrial LiDAR; rockfall; highway; survey; monitoring; risk management

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1. Introduction

In the Eastern Alps of Italy, the European Route E45 leads from the Brenner Pass to Bolzano following the Isarco valley. In this sector, the E45 takes the national code A22 and runs in large part over viaducts, founded on top or at the base of talus slopes, and through tunnels. The Isarco valley has a typical U-shaped glacial profile, with rock slopes locally steeper than 70° where the valley is carved into volcanic rocks, i.e. the Permian ignimbrite and tuffs of the "Complesso vulcanico atesino" (Fenti et al., 1981; Bosellini, 1996). This makes rockfalls a major natural hazard in this area (Rete Civica Alto Adige, 2022) and a factor of risk for the A22, as they can damage its infrastructure and endanger its users.

To perform a quantitative hazard and risk assessment associated with rockfalls along the A22 and hence support the highway manager in the planning of a risk mitigation strategy, a cumulative probability distribution of the annual number of rockfall events and their volume should be defined (Mignelli et al., 2014 and Macciotta et al., 2015). Usually, rockfall occurrence databases include only events that have been recorded because the blocks impacted structures located along their trajectories or were of very large volume. Therefore, the probability of a rockfall impacting a structure could be overestimated, since the total number of rockfall events is underestimated. To overcome this problem, periodical surveys of the rock cliffs can be used to identify the detachment of rock blocks and estimate their volume, so to build a database of the temporal and spatial occurrence of rockfalls of a given volume by means of which obtaining a more significant cumulative probability distributions of events vs volume.

Periodical surveys aimed at identifying the source areas of rockfalls and assessing the volume of potentially unstable blocks have improved the reliability of rockfall analyses both at the regional (Lanfranconi et al., 2020) and site scale (Evans and Hungr, 1993), and should be carried out to design the protection works. Abellán et al. (2010) demonstrated that periodical surveys using a terrestrial LiDAR (Light Detection And Ranging) from a single station can recognize detachments of blocks with volumes as small as 10^{-3} m^3. During a 10-month study, the Authors carried out three surveys of a rock slope carving layers of marl, sandstone, silt and clay and were able to detect the centimetric deformations preceding a toppling event. Similarly, Kromer et al. (2015) monitored a rock slope with periodical LiDAR surveys and recognized rockfalls and deformations as precursor of the failure event. Weidner and Walton (2021) demonstrated the utility of terrestrial laser scanning in evaluating slope-mitigation measures in an objective way and Walton et al (2023) used terrestrial LiDAR to identify, forecast and mitigate a site-specific rockfall hazard.

For such reasons, repeated periodical surveys with terrestrial LiDAR can be part of the rockfall-hazard mitigation strategies for linear transportation infrastructures. In the case of the A22, one option involves carrying out the LiDAR surveys statically from one or more fixed stations. However, this would imply installing and operating the laser scanner at different locations on the emergency lane, exposing the surveyors to the danger associated with the passage of heavy vehicles on the adjacent slow lane. An alternative method to reduce such danger, involves using a mobile terrestrial LiDAR mounted on a vehicle (Lim et al., 2013) that travels along the emergency or slow lane escorted by a pilot car for mobile road works from the highway manager.

This paper describes the analyses and activities carried out before, during and after the trial mobile terrestrial LiDAR survey: the identification of the areas susceptible to rockfalls that might interact with the A22 highway (between the 58 and 72 km markers) and are therefore worth to be surveyed; a GIS-based simulation of the potential effectiveness of a mobile terrestrial LiDAR survey to identify detachments and evaluate block volumes; and, finally, the actual execution of the mobile LiDAR survey.

2. Analyses before surveying

2.1. Classification and characterization of the A22 highway elements

To assess the vulnerability to rockfalls of the exposed elements, which is necessary to assess risk (Fell et al. 2008), the highway infrastructure was classified into three types using GIS analyses (Ferro et al., 2023): (1) tunnel, (2) viaduct and (3) open-sky, ground-supported road. The locations of the tunnel were obtained from a shapefile freely available from Rete Civica Alto Adige (2022), while viaducts and stretches of open-sky, ground-supported road were distinguished based on the distance H between the ground and the roadway. Values of H greater than 2.5 m were associated with viaducts, lower values with open-sky, ground-supported road. For the viaducts, the positions of the piers were also represented in QGIS. This analysis showed that 55% of the 15 km length of the A22 highway between the 58-km and 72-km markers, runs on viaducts, 13% in tunnels and 32% consists of open-sky, ground-supported road.

2.2. Rockfall risk identification and rating along A22

Rockfalls susceptibility was analysed using two different statistical models, Frequency Ratio and Weight of Evidence, which provided values for the Landslide Susceptibility Index (LSI) and Contrast (C), respectively (Ferro et al., 2023). These models were trained with 75% of the rockfalls events included in the Italian landslide inventory database (IFFI Project, 2012) for the period 1993-2020 and were validated using the remaining 25% of the events. Assuming lithology of the bedrock, land cover and slope gradient as contributing factors, the statistical models recognized 55 rockfall source areas, with higher LSI and C, which were assumed as the most susceptible to rockfalls.

The hazard of each area was assessed with reference to two block sizes: small blocks with a reference diameter of 0.5 m, and large blocks with a reference diameter of 2 m. It was assumed that the events recorded in the IFFI database involved only large rock blocks. Therefore, the corresponding frequency of occurrence was attributed to blocks with diameter of 2 m. The frequency relative to small blocks with diameter of 0.5 m was estimated using the frequency-magnitude relationship proposed by Corominas and Moya (2008). As a result, four classes of frequency of occurrence were defined from very low to very high, for blocks with diameters of both 0.5 and 2 m.

The rockfall trajectories for the blocks of 0.5 m and 2 m that might detach from the 55 most critical rockfall source areas were simulated using RocPro3D software (2022). The number of possible detachment points and associated trajectories were varied based on the extension of the potential rockfall source areas (from a minimum of 1000 for a potential source area <4000 m^2 to a maximum of 2500 for a potential source area >20000 m^2). The points where the trajectories intersected the viaduct piers or artificial tunnels, or where the rockfall bounce height was higher than the A22 roadway were computed for the 0.5 m and 2 m diameter scenarios by GIS-based spatial intersections (Ferro et al., 2023). The simulated impacts with the piers and artificial tunnels were classified in terms of impact energy and affected surface and ranked into different physical vulnerability and risk levels accordingly. The impacts between the road surface and the bouncing blocks were assigned maximum vulnerability and risk, since the rock blocks falling on the road may hit vehicles. Of the 55 rockfalls source areas, 8 were identified as the highest-risk sources of rockfalls and should be surveyed by LiDAR (Fig. 1).

2.3. Simulation of the potential effectiveness and efficiency of the survey

A mobile survey from a vehicle moving along a highway requires the infrastructure manager to adopt the safety precautions required to not expose the surveyors to danger. Therefore, prior to the LiDAR survey, a simulation of the effectiveness and efficiency of the mobile survey was carried out to avoid unnecessary organizational efforts. Such a simulation can be performed, for example, using GIS software tools to calculate the percentage of potential sensed area respect the total source area and the potential point density. For this study, it was performed in GRASS GIS environment (GRASS, 2020) with the support of Python scripts (Ferro et al., 2023), assuming a RIEGL VUX-1HA laser scanner. The simulation showed that more than 85% of the area sloping more than 70° could be sensed, more than 70% of which characterised by a point density larger than 400 points/m^2 and almost all of it with a point density larger than 100 points/m^2.

3. Mobile Terrestrial LiDAR Survey

The field survey was carried out along the two directions of the A22 stretch between Bolzano Nord and Chiusa (about 30 km), using a vehicle-mounted solution for mobile mapping. This solution is able to acquire simultaneously images and geometric data from two oriented laser scanners providing, in a short time, a large amount of high-quality data.

a) b) c) d)

Fig. 1. a) Selected cliffs to survey; b) GNSS measurement of materialized Ground Control Point; c) example of MX9 laser scanners rear image with the relative data acquired (d).

3.1. Instrumentation

The technology used in this pilot project was developed by Trimble, a technology provider specialized in geospatial data capture and processing solutions. The data were collected using the Trimble MX9 system, which is composed of two laser scanners. Each scanner is able to collect up to 1.8 million points per second, has a range of more than 400 m and can take advantage of a range of cameras for enriching the data set with high-quality imagery. This solution is designed to operate at speeds of up to 110 km/h and incorporates high-precision Inertial Motion Unit (IMU) and Global Navigation Satellite System (GNSS) receivers.

Although the mobile mapping system relies on the IMU and GNSS technologies for the collection of georeferenced, high-quality data, Ground Control Points (GCPs) were measured using an independent high-end full constellation and multi-frequency GNSS receiver. Knowing the location of these points with high accuracy and precision (at the cm level) allowed the vehicle trajectory to be validated or corrected in the case of a failure of the onboard GNSS receivers or unexpected behaviour of the IMU. About 300 GCPs were collected covering the length of the highway where the rock slopes of interest were located.

3.2. Procedure

At first, GCPs were materialized along the emergency lane of the highway (Fig. 1b). Pre-analysis work identified 63 GCPs to be surveyed along the two directions of the A22 stretch. As these points had to be easily recognizable within the point cloud obtained by mobile mapping, the asphalt was marked using a specific stencil and a tracer spray that would allow the identification of the point detected by the GNSS technology. The position of the center of these marks was then measured using the Trimble GNSS solution, acquiring 180 epochs at 1 Hz.

Then the mobile mapping survey was carried out by driving the vehicle at an average speed of 30-35 km/h. The survey was repeated to ensure a better detectability of the geometric features of the rock walls adjacent to the infrastructure (the laser beam emitted by the sensors is projected towards the rear of the vehicle, "drawing" the trajectory visible in Fig. 1c and d) and to obtain a particularly high point cloud density (900 pts/m^2 at a distance of about 150 m). The instrument was set to maximize the covered distance and point density. As these two parameters are inversely proportional, one first lap was carried out with low range and high sampling frequency (1800 kHz per

LiDAR) and a second one with high range and low sampling frequency (1000 kHz). Overall, 4 runs raw data were carried out, two per direction.

The first stage of post-processing consisted of a trajectory correction. The GNSS receivers mounted on the Trimble MX9 Mobile Mapping system collected positioning and heading data in Single Point Positioning mode (SPP). In this situation, the positioning RMS magnitude cannot be less than a few meters. Hence, the acquired raw GNSS observations were post-processed in differential positioning mode (DPM) to lower the RMS to the cm level. The nearest, continuously operating South Tirol Positioning Service station (Bolzano) was selected as the base station. The PPK (Post Processed Kinematics) trajectory was used to produce a first point cloud of the sensed area. The PPK trajectory was characterized by an average RMS of approximately 2.5 cm and 3.5 cm (East-North and Up respectively). Then, The GCPs that were clearly recognizable within the point cloud (and with precise DPM GNSS coordinates) were marked in the point cloud and used as fixed positions for a second step trajectory correction which led the car track to lay precisely on some of the GNSS surveyed GCPs. In fact, a GCPs registration was applied on the dataset, choosing 39 (22 on the North direction and 17 on the South direction, those closer to the interested rockfaces) out of the 61 GCPs sprayed on the asphalt – 32 on the North direction and 29 on the opposite side of the highway - as fixed positions for the trajectory correction. For these points, the GNSS-surveyed and the LiDAR-recorded coordinates will end up in a perfect overlay, so no RMS will be shown. In addition, 12 GNSS GCPs have been used as constrained positions so that they were involved in the registration. The latter, together with the remaining points, were also used as CP (Check Points) for the validation of the recording procedure. As a result, the global shift of the point cloud measured on the point pairs was on average 50 mm on the plane and 71 on the height and, considering only the validation points, the average RMS ended up being 25 mm on the plane and 38 mm on the Z-axis. The registration procedure was performed only on the high frequency runs trajectories. At this point, a second point cloud was produced, and the low-frequency runs have been automatically adapted, with the best geometric overlay, over the more precise GCP-corrected trajectory with a “Run-to-Run" procedure. These steps led to the extraction of the final complete point cloud, composed of both the high-range/low-frequency and low-range/high-frequency raw data.

The field survey phases required the presence of two operators. While the materialization of the GCPs took one workday, the actual survey using mobile technology took only half a day or one hour per 30 km lap. The post-processing required a single operator and took one workday.

3.3. Preliminary results

Thanks to the technology used and the knowledge and technical support provided by the Spektra Team (the Italian Trimble dealer), the results from the LiDAR survey showed how mobile mapping technology can be used for geotechnical engineering monitoring applications.

The workflow used, despite its ease of implementation and speed of execution, provided high-quality data with very dense point cloud (900 pts/m^2 at a distance of about 150 m - Fig. 2) and limited the positional uncertainties, of the same order of magnitude of the GNSS+IMU+GCPs derived trajectory.

The results from the GCP trajectory correction showed that the RMS remains in the same order of magnitude as the pure onboard navigation unit (GNSS+IMU) of the Trimble MX9 Mobile Mapping system. Therefore, in term of accuracy, using only the mobile mapping system provides state of the art accuracy in terms of GNSS measurements. On the other hand, global shifts show that, when absolute precision is required, the integration of GCPs is unavoidable.

For the survey of rock slopes, Mobile Mapping is then considered a good solution in terms of effectiveness and since the dense RMS values remains within acceptable thresholds whether GCP is used or not, and using the RunToRun procedure, a “geometric best-fit” overlap of scans taken at different times can always be performed in order to see time related changes on the observed facades. Final point cloud density can be easily controlled by survey speed and number of passes without requiring over expected efforts.

The proposed procedure could be made even more effective by using fixed GCPs along the motorway. Its efficiency is demonstrated by the survey speed and the ease in post-processing compared to traditional survey procedures.

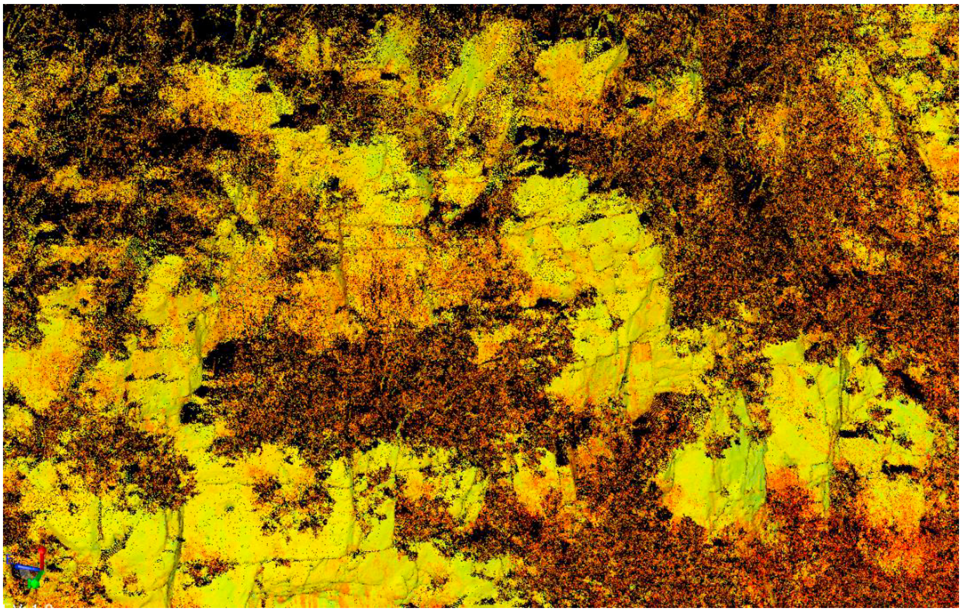

Fig. 2. Point cloud of a portion of a rock slope of interest, colorized by return energy intensity.

3.4. Safety

The survey procedure was planned carefully by the highway manager, Autostrada del Brennero S.p.A., to allow the surveyors and highway personnel to work safely, while minimizing traffic disruption and risk to road users. The surveyors' vehicle was equipped with a specific sign and flashing lights to improve its visibility, and was supported by specific mobile work vehicles for signaling and protection.

4. Conclusions

Mobile terrestrial LiDAR surveying was found to be efficient, with 120 km of highway covered in half a day, and effective, with point density up to 900 pts/m^2 at a 150 m distance. The materialization of the GCPs was more expensive, as it required an entire workday. Therefore, in view of performing periodic Mobile terrestrial LiDAR surveys, it is appropriate to provide for a permanent materialization of the GPCs. The survey confirmed the results from the preliminarily GIS-based simulation, which therefore proved to be an effective tool for the preliminary assessment of the effectiveness of a Mobile terrestrial LiDAR survey of critical rock walls. In this way, the Mobile terrestrial LiDAR survey and the preparatory activities for the materialization of the GCPs and those necessary to ensure the safety conditions of the surveyors can be carried out only after a preliminary assessment of the potential effectiveness of the survey.

Further analyses of the survey data will be carried out to better investigate the effectiveness of Mobile Terrestrial LiDAR compared with, for example, static surveys.

Funding

This research was funded by Autostrada del Brennero S.p.A (Brenner Autobahn AG) and partly by MUR PON R&I 2014-2020 Program (project MITIGO, ARS01_00964).

Data Availability Statement

The data are not publicly available due to legal agreements between the research institutions and Autostrada del Brennero S.p.A (Brenner Autobahn AG).

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