Challenges and limitations in geodetic monitoring of landslides, case-study of Viella (Pyrenees mountains) and La Valette (Southern Alps), France

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Abstract

To better understand the kinematics of landslides in mountainous areas, permanent GNSS receivers and reflectors monitored by an automated total station are sometimes installed. The challenge is to describe the surface displacements as accurately as possible with an adequate observation rate (from a few seconds to 1 or 2 hours or more). After a brief review of the methods and equipment used to reduce measurement errors, such as atmospheric refraction, instability of some reference points outside the sliding zone, etc., we describe the processing of terrestrial and GNSS data from two monitored landslides in the Pyrenees (Viella site) and the Southern Alps (La Valette site).

Keywords: landslide monitoring, total station, GNSS

1 Introduction

Landslides are common in the mountains, in the hills, and along high costs, where they can pose serious threats to the population, public and private properties, and the economy (e.g. Lombardo, 2021). To cope with the landslide problem and to mitigate the landslide damaging effects the size, geometry and geology of the landslides must be estimated at precise as possible and as continuous in time.

Different types of measurements are performed: terrestrial, air-borne and space-borne (Malet et al. 2016; Ferhat et al., 2018). Variations of the surface topography can be measured using repeated TLS, Terrestrial Laser Scanner measurements (e.g. landslide in Austria (Stumvoll et al., 2021)) or Ground-Based SAR Synthetic Aperture Radar (Handwerger et al., 2018). Repeated leveling data can show also slow motion such as at the Adroit landslide, Southern Alps, France (Ferhat et al., 2017). GPS and GNSS sensors have been installed on some landslides (Malet et al. 2002; Benoit et al. 2015), photogrammetric records may also be used (Travelletti et al., 2012; Strumpf et al., 2015). Geophysical measurements are key elements to better map the sub-surface of the landslides (e.g Hibert et al., 2012).

Triggered in 1982 and 2018 respectively, the La Valette and Viella landslides are both located in France on slopes above villages: Saint-Pons (Alpes-de-Haute-Provence) for La Valette and Viella (Hautes-Pyrenees) (Figure 1). They are therefore posing a threat to the communities in these villages. In order to put in place preventive measures to ensure safety downstream, observations are made by experts grouped together within the French Landslides Observatory OMIV, the *Observatoire Multidisciplinaire des Instabilités de Versant* (Malet et al. 2016, www.ano-omiv.cnrs.fr). Various geophysical and geodetic measurements (satellite images, LiDAR, GNSS, tacheometers) can be used for this purpose. Since 2019, a continuous monitoring system using an automated total station has been installed in the two study areas, with the aim of capturing daily landslide movements.

After a brief review of the methods and equipment used to reduce measurement errors, such as atmospheric refraction, instability of some reference points outside the sliding zone, etc., we describe the processing of terrestrial and GNSS data from two monitored landslides in the French Southern Alps (La Valette site) and in the French Pyrenees (Viella site, Figure 1).

Figure 1. Location of the La Valette and Viella landslides

2 La Valette landslide

The Valette landslide is located between the communes of Barcelonnette and Saint-Pons, in the Alpes-de-Haute-Provence département (Southern Alps in France). It extends from the north-east, at an altitude of 2,100 m, to the south-west, at an altitude of 1,300 m (Figures 1, 2 and 3). This phenomenon appeared in 1982, following heavy rainfall during the snowmelt and rainy season. The collapse of the upper part of the land led to an overload of material in the central area, which was mainly black marls. This overload gradually increased, causing slow instability that culminated in January 1988.

The landslide was triggered in March 1982 at the contact between these two main geological units. The deformation is attributed to the steep slopes and the increase in pore-fluid pressure resulting from the different hydraulic conductivities of the two geological units (Samyn et al., 2012). The landslide has been subject to numerous investigations using a variety of direct and indirect methods, such as remote sensing (terrestrial and airborne LiDAR), geotechnical analysis of samples recovered from boreholes, and geodetic measurements (e.g., extensometers, inclinometers, GPS), for the spatio-temporal assessment of surface de-formation (Raucoules et al., 2013; Malet et al., 2013; Travelletti et al., 2013).

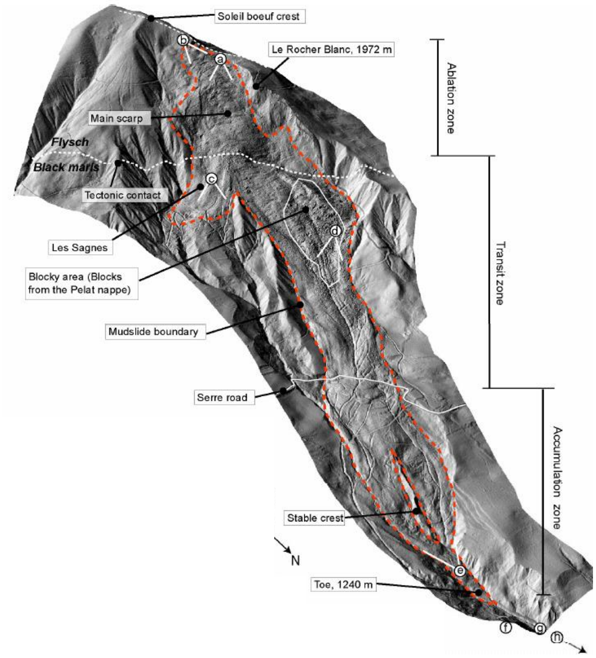

Figure 2. The La Valette landslide and the ablation, transit and accumulation zones. The stable crest in the accumulation zone

3 Total station monitoring the La Valette landslide

To monitor the 54 targets located on the La Valette landslide, a permanent total station (Trimble S9 DR HP, 1”, Long Range) has been installed (Figure 4). Observations of these targets are performed every 1 to 3 hours, depending on the acquisition protocol since September 2019 (Figures 5 and 6).

The targets are distributed along the whole landslide with a higher density in the lower zone which is supposed to be more susceptible to accelerate and because it is closer to the inhabited area downstream (Figures 5 and 6). Figure 5 presents the relative position of the 54 targets from the total station. The closest target is at a horizontal distance of 343 m and the furthest at 2230 m. The differences in height vary from -48 m to 675 m. Because of the long distances and the high height variations, air temperature and pressure change creating variations of atmospheric refraction. In a standard model, air temperature T decreases in the troposphere almost linearly with height h according to $dT/dh = -0.0055^{o}\ C.m^{-1}$ (Torge & Muller, 2001).

Figure 3. The La Valette landslide as seen from the hut hosting the permanent total station and the nearby GNSS pillar (France)

4 Viella landslide

The Viella landslide, located in the Hautes-Pyrénées region of the French Pyrenees, has significantly impacted the local community and infrastructure (Figure 1). The village of Viella, situated west of Luz-Saint-Sauveur in the Bastan Valley, has experienced multiple landslide events over the years, with notable incidents in 1898 and 2018 (Figure 6).

In 1898, a substantial rock collapse on the northern face of the Crête de Couret resulted in a scree cone covering approximately 5 to 6 hectares, extending to about 950 meters above sea level. The estimated volume of displaced material ranged between 600,000 and 1 million cubic meters. This event led to observable landslide activity between the scree cone and the village, affecting nearby structures (pyrmove.eu).

More recently, in February 2018, after a period of heavy rainfall, approximately 250,000 cubic meters of shale material shifted, partially overlaying the existing scree cone. This reactivation of the landslide adversely affected the lower slope, causing damage to buildings and roadways, including the RD918 route leading to the Col du Tourmalet, a popular tourist destination. It's important to note that a significant flood in the Bastan River in June 2013 had previously eroded the base of the slope, potentially compromising its stability prior to the 2018 landslide (pyrmove.eu).

Figure 4. Permanent automated total station Trimble S9 Long Range on the pillar at the monitoring site at La Valette landslide (France)

In response to these events, extensive studies have been conducted to better understand the landslide's dynamics. Geotechnical and geophysical investigations, along with piezometric measurements, have been implemented to monitor the slope's behavior. Findings indicate that the landslide comprises various active zones with slip surfaces at depths ranging from 10 to 54 meters. The slope's composition includes unstructured shale blocks from previous collapses, while the underlying bedrock remains unaffected by recent movements. Additionally, preferential water flow paths have been identified, often aligning with deeper slip surfaces (pyrmove.eu).

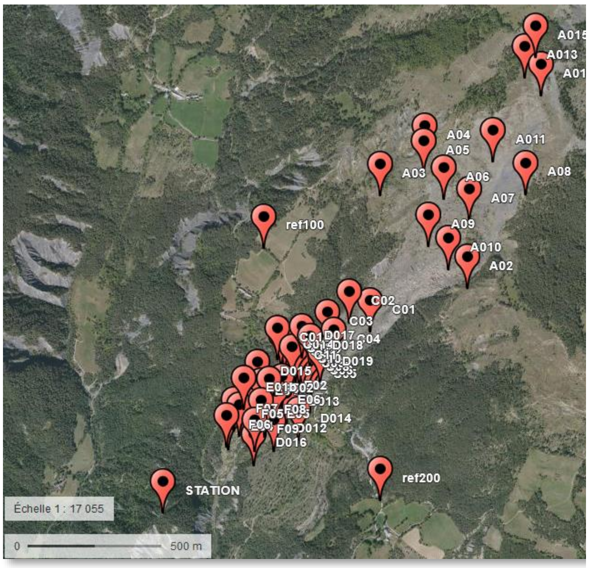

Figure 5. Map of reflectors at the La Valette landslide (France). Reflectors at high elevation with letter A are in the ablation zone (Ferhat et al., 2020).

Figure 6. Reflectors on the central part and location of the stable crest at the La Valette landslide (France)

To enhance landslide risk management in the Pyrenees, the European PYRMOVE project was initiated. This initiative aims to develop and implement cross-border tools for forecasting and managing landslide hazards. The project focuses on improving emergency response strategies and establishing monitoring and warning systems to facilitate preventive measures. The Viella landslide serves as one of the key study sites within this project, providing valuable insights into landslide behavior and risk mitigation (brgm.fr).

Figure 7. Viella landslide in August 2020 (France)

Ongoing monitoring and research are crucial for understanding the factors contributing to the Viella landslide and for developing effective strategies to protect the local population and infrastructure from future events.

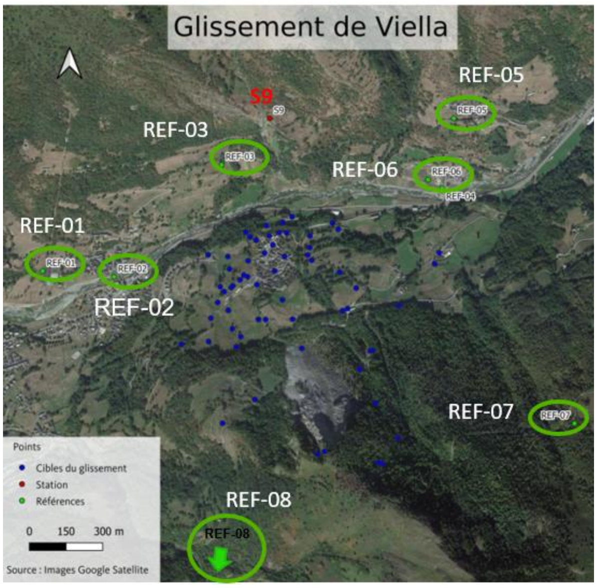

Figure 8. Location of the Trimble S9 total station (in red), the references (REF#, green circle) and the targets (in blue) at Viella landslide, Pyrenees mountains (FR)

5 Atmospheric effects on total station measurements

The atmospheric effects on geodetic observations place a limit on their accuracy. The simple approaches - using end point meteorological measurements for electronic distance measurement EDM reductions and the coefficient of refraction in trigonometric heighting - are effective for surveys of low or intermediate accuracy (Rüeger, 1999). When higher accuracy is needed, improvements can be found by adopting an atmospheric model which corresponds more closely to the real atmosphere, or using atmospheric dispersion, by using an instrument equipped with two or more colors (Angus-Leppan, 1979).

Figure 9. Permanent automated total station Trimble S9 Long Range on the pillar at the monitoring site at Viella landslide (FR)

The total station provides three measurements: horizontal angles, vertical angles and slope distances. Each of these measures is affected differently by the lower part of the atmosphere. In theory, Electromagnetic Distance measurements must be corrected with an integration of the refractive index over the entire wave path (Rueger, 1990) from air temperature, air pressure and air humidity. In practice, simplified methods based on endpoint measurements are usually adopted (Rueger, 1990).

Horizontal angles are less affected by the horizontal temperature gradients of the lower atmosphere (Moritz, 1961). These horizontal temperature gradients are usually very small compared to the vertical temperature gradients because the lower layer of the atmosphere is vertically stratified. The main effect is then the vertical deviation of a sight as illustrated on Figure 5.

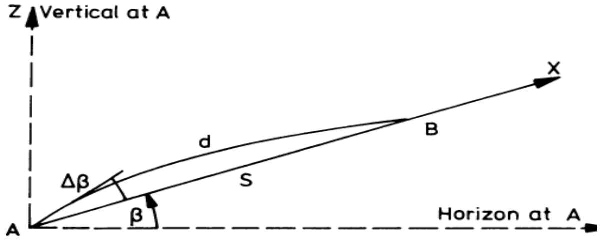

Figure 10. Wath path d and cord s due to vertical atmospheric refraction between point A to B. (Angus-Leppan, 1979)

A rigorous method to estimate vertical refraction would require vertical temperature profiles along the sight between the total station and the target observed. Given the order of displacement at the La Valette landslide, few centimeters are required on the accuracy of the position of more distant targets (> 2.3 km). Instead of deploying meteorological sensors, we use references to estimate changes in vertical angle and slope distance measurements to apply these changes as corrections on measurements performed on targets located on the sliding zone. Again, the horizontal angle is supposed to be not largely affected by the refraction of the lower part of the atmosphere.

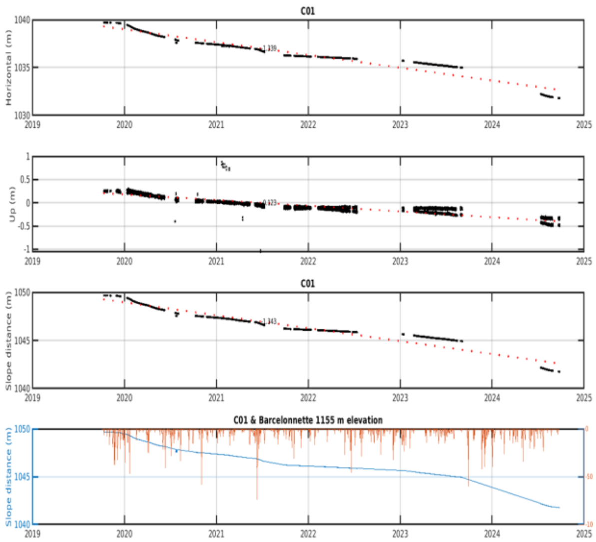

Figure 11. Horizontal and vertical displacements, slope distances from the total station to C01 and precipitation (mm) for the C01 prism at the La Valette landslide (France) for the period September 2019 to August 2024

6 Results on the motion of these landslides

The sliding zone of the La Valette is equipped with 55 reflectors located mainly in the accumulation zone. As an example, figure 11 shows the displacement of the C01 prism located in the transition zone (Figure 12). Two time series of positions of reflectors are computed: a rapid solution for the longest period, i.e. September 2019 to August 2024 and a more precise one for January 2021 to March 2023. A horizontal velocity of 1.35 m/year is observed for C01 during the period September 2019 to August 2024 (Figure 11). Vertical velocity is only 12.3 cm/year (Figure 11).

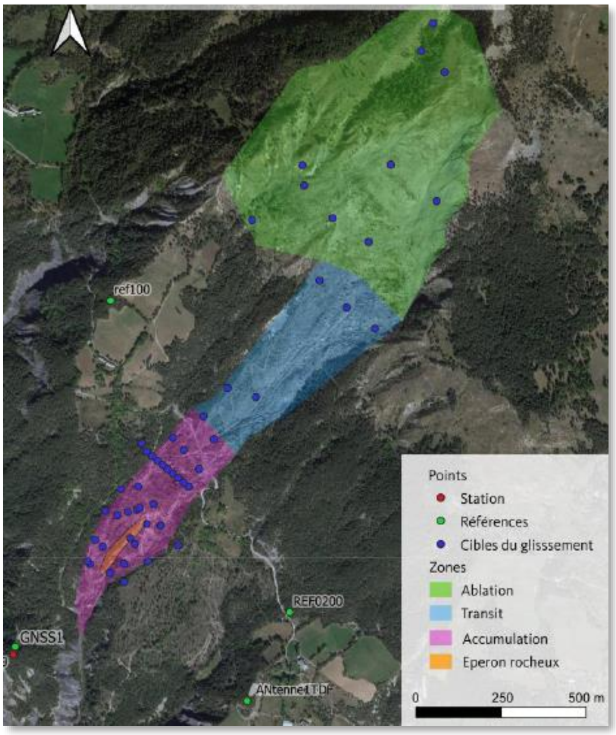

Figure 12. Location of the Trimble S9 total station (in red), along with the GNSS pillar (GNSS1), and the 55 prisms (in blue) at the La Valette landslide (France) (Louvier, 2023)

The ablation zone is equipped with reflectors whose names start with the letter A (Figure 13). The reflectors on top of the crest (A013, A014 and A015) show no displacement or very little displacement (Figure 13). In the steep slope of the ablation no reflectors are installed because of its rapid motion. In the ablation zone, horizontal velocities vary from 1.0 to 2.8 m/year (Figure 13).

The profile with reflectors' letters C in the accumulation shows a quite continuous velocity of 0.10 m/year. Reflectors C015 and C05B on the edge of this profile exhibit no displacement (Figure 14). A stable rocky crest in the lower part shows no displacement. The section located on the right side of this stable crest is moving with velocities of 0.10 m/year (Figure 14).

Figure 13. Horizontal velocities (m/year) for the period 2021 to March 2023 at the La Valette landslide (France). Grid is every 0.2 km

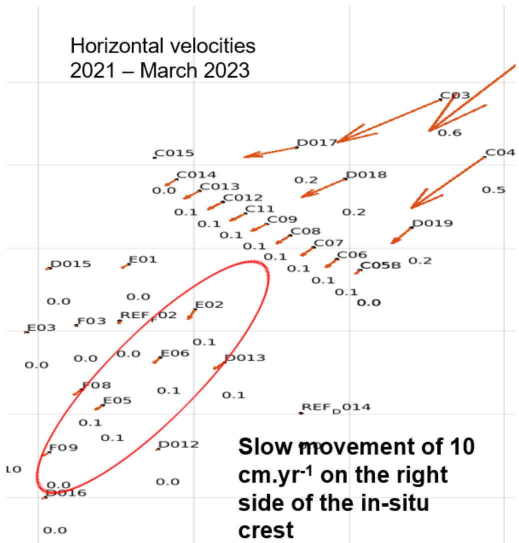

Figure 14. 2021-2023 velocity vectors and magnitude (m/yr) of the lower part of the La Valette landslide (France).

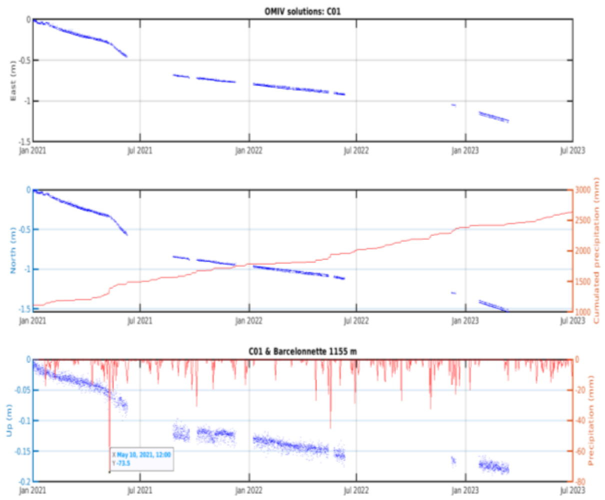

Figure 15. Displacements ENU (in meters) with precipitations and cumulated precipitations (mm) for January 2021 – March 2023 of the C01 prism at the La Valette landslide (France)

Hourly measurements enable the observations acceleration of the C01 prism initiated on May 10, 2021, related to a peak of cumulated precipitation (Figure 15).

Same type of observations can be made at the Viella landslide. Figure 16 illustrates the velocity vectors for the period September 2023 to August 2024.

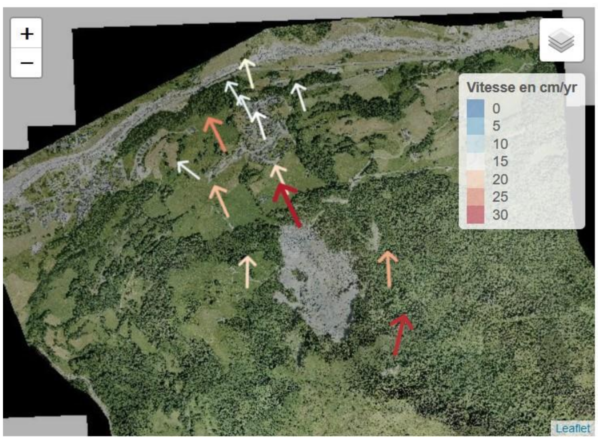

Figure 16. Velocity vectors in m/year for reflectors in the Viella landslide (France) September 2023 to August 2024

7 Conclusion

Geodetic monitoring of the La Valette and Viella landslides (France) using an automated total station has provided displacements, velocities and acceleration of some reflectors. The processing of angles and distances of such long sight requires at least a mitigation of atmospheric refraction effects. Vertical angles and slope distances performed by the total station are corrected using measurements at references. Given the magnitude of displacements for such landslides, this simple correction has proven to be enough sufficient. Slow motion of surface is observed for the lower part of the La Valette landslide. The ablation zone at the top of the landslide exhibits the largest displacements.

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