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Advanced geospatial solutions for monitoring, modeling and understanding of landslides

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Abstract Landslide represents a geological event in which there is a sliding or shifting of soil, usually resulting from factors such as rainfall, earthquakes, erosion, changes in water levels, climate change, and/or human activities. Especially with the prevalent challenges of climate change, the risk of landslides becomes exceptionally high, emphasizing the need for response and preventive action in terms of crisis management. Humans strives for understanding, prediction, and preventive action to minimize potential hazards and damages from such risks. This paper demonstrates the description of advanced technologies, namely the integration of various technologies into unified automated systems, for effective monitoring, modeling, and understanding of landslides. By integrating these technologies, precise monitoring of geological changes, quick identification of potential hazards, and detailed modeling of relevant factors are enabled. An overview of the general approach to the architecture of monitoring systems will be provided, including the basic components of integrated geodetic and terrestrial radar sensors, as well as a practical example where such an approach has had necessary application.

Keywords monitoring, geodetic technologies, terrestrial radar, landslides.

Introduction

Landslides are one of the most dangerous and destructive natural hazards, capable of causing significant damage to the environment, economy, infrastructure, and human lives. The speed of landslide movement varies from slow material displacement in millimeters or centimeters per year to sudden avalanches of large volumes of debris (Pradhan, S. P. et al., 2019). To effectively manage the risks associated with the occurrence and activity of landslides in the short and long term, it is evident that data from various sources need to be combined and analyzed. Integrating data from different sources leads to the representation of parameters that control the event and contribute to the classification of their impact on the evolution of the phenomenon. Modern monitoring techniques can provide very precise and reliable data on deformations caused by soil displacement even in real-time. Furthermore, they enable increased speed, affordability, and overall quality of landslide monitoring. Viewed from the perspective of integrating different technologies, a holistic approach to landslide monitoring is often provided, enabling better understanding and adequate response to potential hazards. Scientific and technological advances in recent decades have made available the necessary tools for conducting monitoring, modeling, understanding, and mitigating landslide-related crisis events. Never before have scientific and practical communities had access to such a wide variety of powerful tools for monitoring and modeling landslides on different aspects. However, geoscientific understanding of landslide processes and mass movement remains crucial for the adequate interpretation of all collected results provided by monitoring and modeling tools, and for their use in designing mitigation measures (Corsini A, Borgatti L, (2019).

In this paper, the geodetic techniques will be mentioned in the review of data and information that they can provide. It is important to note that each techniques has its own advantages and limitations, which may be imposed by the area of interest itself, and thus each individual project requires a certain degree of personalization and optimization.

Monitoring system architecture

The common elements of a monitoring system typically include the structure (object, area of interest being monitored), sensors, data collection systems, mechanisms for data transmission and recording, data management tools, and tools for data interpretation and diagnosis (system identification, structural model updating, condition assessment, prediction of remaining parameters indicating future behavior). This concept is widely applied to various forms of crisis areas or objects, especially as countries worldwide face ever greater challenges of risk moments. Particularly when it comes to damages caused by geological phenomena, it is important to note that there are phases of increasing severity that require knowledge of the following characteristics:

- Determining the existence of damage to the environment affected by the crisis phenomenon,
- Locating damage,
- Identifying types of damage,
- Quantifying the severity of damage.

In these cases, signal processing and statistical classification are necessary to convert field sensor data into information about potential corrective and preventive measures.

The mentioned approach can be more simply characterized by four main components, which include monitoring sensors that generate raw measurements at defined intervals, a 24/7 power supply with backup power, a communication device to facilitate data transmission, and software for monitoring displacements and reporting movements. If the previous approach were narrowed down to a specific application and illustration in a landslide, various fields of interest that need to be included in the monitoring architecture would be considered. These can include: geotechnical sensors, geodetic instrumentation and automated monitoring instruments, meteorological sensors, data loggers, data transmission systems, data analysis software, management and diagnostic systems, warnings, deep learning, and prediction of future scenarios. Each monitoring project is different and unique, it means that monitoring solutions combine diversity and flexibility in adapting to project requirements, regardless of the environment or object requiring monitoring. Whether it is human activity or a natural process, proven solutions are needed to provide the highest level of safety, performance, and sustainability. In order to mitigate the landslide hazard, several landslide monitoring techniques have been developed over the last decades. Broadly, these can be categorized into remote sensing, photogrammetric, geodetic, geotechnical, geophysical, wireless sensor networks (WSN) and the Internet of Things (IoT) (Thirugnanam H, Uhlemann S, Reghunadh R, Ramesh M.V., Rangan V.P., 2022)

Here it will be focused on reviewing and analyzing the application of geodetic solutions for landslide monitoring, with an approach to creating, combining, and integrating multidimensional approaches into tailored solutions adapted to specific project needs. In addition to the geodetic approach, certain projects also require integration with radar terrestrial systems and/or geotechnical sensors, leading to the creation of absolute or total monitoring approaches. Monitoring data from ground-based radars are used to give a holistic view of the unstable area. Remediation and early warning strategies are commonly based on continuous monitoring of the slope displacement which can give crucial information on the dynamics and evolution of the landslide (Eberhardt, E., Watson, A.D. and Loew, S., 2008). Integrating data from different sources is leading to the depiction of the eventcontrolling parameters and the delineation of their effect on the phenomenon's evolution (Botsialas K., Røvde V, Falomi A, Meloni F., Boldrini N Bellotti F., Leoni L., Coli N., 2021). Whether it is monitoring to provide information to experts for early warning of natural hazards such as landslides, seismic, and volcanic activity, information for potential fault prediction, or data after events for studies and better understanding, the hardware-software concept must be purposeful, compatible, and reliable. The priority is on monitoring real-time information, with automated report generation. Special reports with inverse velocity, hazard, and displacement maps, as well as speed limit checks, provide additional insight into mass land acceleration, increasing the risk of failure. Since components of geodetic monitoring can stem from various approaches, such as GNSS systems, LiDAR, InSAR, total stations, and leveling instruments, as well as photogrammetry, this paper will further explore one example of a system composed of a total station and a radar terrestrial system as key measuring equipment. The architecture is based on the concept of total monitoring developed by the companies Leica Geosystems AG and IDS GeoRadars.

Geodetic and radar monitoring architecture

The complexity of monitoring projects often lies in installation and configuration part of the monitoring project. This is often a cumbersome process, which requires special equipment and expertise. Another challenge is surely missing or low-quality data, a situation that significantly increases the risk of not capturing movements in critical moments. What could cause this? Basically anything from instrument issues, communication issues, power outages. In response to the identified risks and challenges, Leica Geosystems has developed a monitoring system based on Edge computing technology and networked communication.

IoT is the networking of smart objects, commonly referred to as things, enabling interoperability and intelligent communication with services and applications in the cloud using Internet standards. IoT facilitates the inclusion of everyday objects as virtual representations, where people and objects interact with each other as equals. Such inclusivity can provide greater penetration and understanding of the environment, aiding in addressing societal issues, including disaster monitoring and early warning, more effectively than before (Thirugnanam H, Uhlemann S, Reghunadh R, Ramesh M.V., Rangan V.P., 2022). Based on this rationale, the company Leica Geosystems has developed a monitoring system that relies on Edge technology within the IoT communication framework.

The latest technological advancements in the geodetic terestrical monitoring solution address potential issues to provide continuous and uninterrupted data flow, which in practice includes the Leica Nova TM60 total station for monitoring, the Leica ComBox60 communication device with built-in monitoring software, and Leica GeoMoS Edge, enabling autonomous functions and local data storage using "EdgeConnect" technology. This provides a secure IoT connection between field monitoring sensors and the office software Leica GeoMoS Monitor.

The Leica TM60 total station is designed with several characteristics specific to monitoring with automatic measurements, in variable environmental conditions, and over long distances. These innovations help ensure continuous, comprehensive data collection. Equipped with Leica Captivate software and ATRplus technology, the TM60 automatically adjusts measurement settings to current environmental conditions and ensures that targets are automatically measured at distances of up to 3,000 meters, much further than traditional total stations.

Additionally, ATRplus recognizes and rejects non-target reflections, such as headlights or sunlight, to focus on the correct tracking prisms. The TM60 is equipped with a Piezo-drive system for uninterrupted long-term operation, as well as a Leica PinPoint EDM rangefinder for distance measurement accuracy and an optional camera for inspection and remote positioning and photodocumentation. Another tracking-specific innovation with the TM60 is the AutoLearn application, which quickly detects, measures, and learns all targets in a defined area. Automatic point learning speeds up the initial setup of monitoring projects and the integration of additional prisms while eliminating human errors, thereby minimizing the risk of insufficient coverage of all planned measurement points.

The specialized monitoring software, GeoMoS Monitor, acts as a server and can be installed on a personal computer or a virtual machine. Depending on project requirements and security standards, connectivity to field devices is achieved either via EdgeConnect cloud technology or within the local area network (LAN). Since various factors can disrupt this connection, it's crucial that field components can operate autonomously without a continuous connection to the office software. This is achieved through GeoMoS Edge, a data collection software component embedded in Leica M-Com communication devices. Utilizing EdgeComputing technology, GeoMoS Edge executes a measurement cycle pre-configured in GeoMoS Monitor, calculates the quality of raw measurement data, initiates repeated measurements, and delivers data to GeoMoS Monitor. With the Leica ComBox60, measurement cycles proceed uninterrupted based on the last available configuration, even during power and/or communication outages. This is possible due to the internal battery, which serves as a secondary power source and can supply power to monitoring sensors for hours or even days depending on the measurement frequency. These measurements are stored locally until communication with the server is reestablished, eliminating gaps in data.

Experience shows that transferring measurements from the field to the office is a critical step in the monitoring process, and therefore, the monitoring system must provide a quality solution in this regard. Data transmission protocols must meet the highest security requirements due to the sensitivity of monitoring data and the overall security of the server's local network. However, robust security measures involving complex IT configurations often require a significant amount of time and money. On the other hand, EdgeConnect technology simplifies this process while maintaining the necessary security levels. The integrated GeoMoS Edge enables a secure IoT connection in the cloud between the field and the office. EdgeConnect's "smart" procedure manages communication between GeoMoS Monitor and Leica M-Com communication devices using standard, open HTTPS ports, enabling configuration without additional IT modifications. Once connected, GeoMoS Monitor takes ownership of the device, making data loss, tampering, or theft impossible. The user has full control over the device and can transfer it from one project to another, simultaneously removing IT complexity from monitoring installation, reducing costs, and significantly shortening the time to start the monitoring phase.

One advantage of such a monitoring solution structure is the provided autonomous control over hardware and software, with the ultimate goal of ensuring data completeness and reliable information about movements in the monitored area. Another advantage is the possibility of integration with radar or geotechnical sensors into a unified solution. From radar devices to crack gauges, each instrument or sensor adds value to the solution if used correctly. In most monitoring projects, the integration of at least two technologies will generally be applied. Configuration, measurement, and data acquisition can be very simple but also time-consuming if automated solutions are not available. This may involve many complex cables or data logging solutions. However, the data they provide is highly valuable for analysis; therefore, the primary goal of the solution involves a wireless network that integrates measurement data from various sensors, avoiding complex cable installations and applying automated readings with wireless transport.

In the context of landslide applications, the role of ground-based radar systems is recognized in practice, among which the Hydra-G device stands out as part of the IDS Hydra family, comprising rapid monitoring radars designed for early warning and real-time measurement of submillimeter displacements. With a scanning range of up to 800 meters, the system employs advanced radar technology with high precision and resolution, relying on ArcSAR (rotation of the system around its centre point) technology that provides spatial resolution in centimeters and delivers updated displacement information every 30 seconds. Additionally, there is an optical and infrared HD camera enabling real-time visual inspection of monitored areas. Data obtained from radar scanning are further projected onto a 3D model of the scene, formed using built-in laser technology. The leading Hydra Guardian software offers a simple yet enhanced tool for visualization and interpretation of radar data, as well as analysis of trends in structural and slope movements. Furthermore, SurfScan serves as specialized software for analyzing real displacements and deformations.

The combination of radar and geodetic monitoring for landslides involves integrating data from radar-based systems, with traditional geodetic monitoring techniques like total stations and GNSS. This integrated approach allows for a more comprehensive understanding of landslide behavior, including detecting surface deformations and movements over time with high spatial resolution provided by radar systems, while also providing precise positioning and monitoring of key points using geodetic instruments. By combining radar and geodetic monitoring, researchers and engineers can gain insights into the dynamics of landslides, identify potential risks, and implement effective mitigation measures.

Case study

For practical application of the solution described here, a case study conducted by Leica Geosystems and InfoTop will be presented, focusing on a landslide of toxic mass from a slope landfill as an example. The example will depict monitoring after a landslide occurred due to the intense movement of several thousand meters of material from the landfill on the slope. This event took place in northern Spain, and despite the material damage caused by blocking traffic on the highway, it also claimed two human lives Fig.1. The primary task was to carry out remediation and cleaning of the mass while preemptively responding to any potential further movements.

Fig 1. The Landslides slope

The landslide dragged thousands of cubic meters of material - some of them toxic and flammable - from the landfill, which occupied an area 30 meters wide and about four meters high (Fig2).

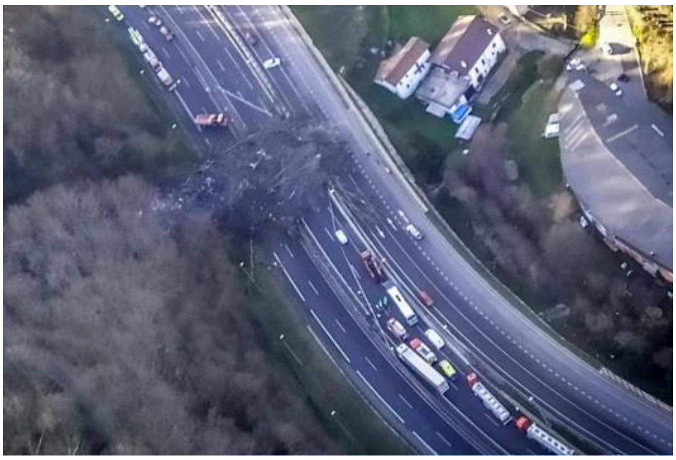

Fig.2. landslide mass

Emergency services needed to quickly assess the stability of the slopes to initiate rescue operations. They were working in a hazardous and unstable environment and required an alert system to notify them if the waste material shifted again. It was a challenging installation. Due to the hazards on-site, the monitoring system had to be completely remote, without manual measurements. It could only be installed within 400 - 800 meters of the landslide, and more importantly, it had to operate 24/7 without operator presence. In terms of speed, the data collected by the system had to be automatically processed, with reports generated and sent to stakeholders for interpretation. For coordination with the distributed team, data had to be accessible from anywhere. Ultimately, the monitoring system had to be configured to send real-time alerts to technicians via SMS and email.

Faced with these conditions, an automated monitoring solution was implemented, combining total stations with radar. Two Leica Nova TS60 total stations were installed, with mobile communication provided by a Leica ComGate10 router using 4G technology via a virtual private network (VPN). The total stations conducted measurements using a series of over 100 prisms placed in the field. Positioned on concrete pillars, one total station was placed next to the radar, while the other was positioned in an area near the landfill to measure prisms not visible from the first station. The measurements were then managed by the Leica GeoMoS software installed on a virtual cloud infrastructure, Fig 3.

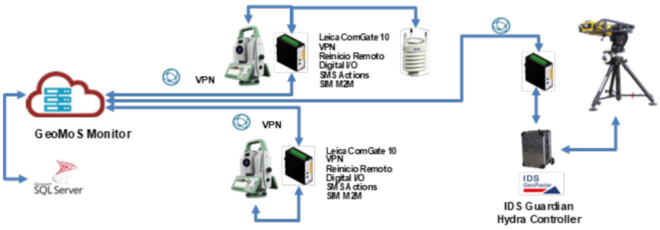

Fig.3. Architecture of monitoring system

In addition, an IDS HYDRA-G – remote sensing monitoring system based on radar technology – was installed to give a continuous measurement sweep. With 120 degrees of coverage horizontally and 30 degrees vertically, this covered most of the danger zone, except for areas hidden by vegetation. Designed for early warning and real-time measurements of sub-millimetric displacements in cut-slopes, the HYDRA-G provided real-time data of movements, transmitted to the IDS Guardian software for interpretation and alarm management, Fig4, Fig 5.

Fig.4. Combination setup radar technology and geodetic technology

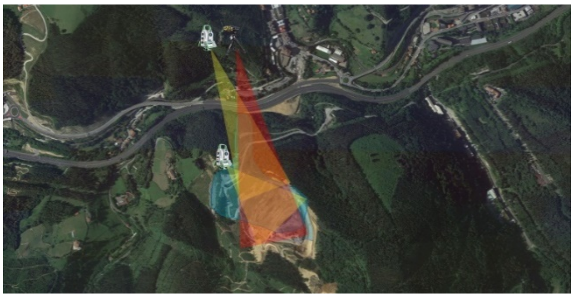

Fig 5. coverage of the landslide with total stations and radar system

The radar system allowed movements to be identified across hectares in seconds by comparing consecutive measurements through interferometry (the interference of waves) over a large distance range, detecting movements of ±0.1mm at up to 800m. While highly sensitive, it can only monitor within its line of sight. Not all areas of the landslide allowed radar measurement due to its inclination and parts being hidden by vegetation.

Therefore, multiple total stations covered any blind spots and measured prisms in both the radar coverage and shadowed areas. The prism data helped the engineers and geologists understand each area's true movement, building an exact picture of the 3D movements taking place. Geodetic measurements are a prerequisite for ensuring geotechnical safety by monitoring the impassibility of not exceeding the critical states defined for the slopes of the landfill, they make it possible to monitor the uniformity of settlement of the facility, and on their basis it is possible to model the directions of future displacements and deformations of the facility, which are of fundamental importance in planning the target land management after completion of reclamation works. Geodetic data also provide information on the dimensions, surface area and volume of the facility and their variability over time, (Pasternak, G. 2022). These highly complementary technologies provided a combination of speed from radar detection with reliable spatial information on the movements via total station measurements. Leica Geosystems and IDS GeoRadar technology and software form Hexagon Geosystems' monitoring solution.

The Leica GeoMoS and IDS Guardian data processing software allowed experts to automate the system so that the data could be instantly and remotely shared with specialists for interpretation. GeoMoS Now! is web interface that made it possible for the geologists to analyse the situation from any location, 24/7. The system was also configured with a series of real-time alerts that sent warnings immediately if the configured thresholds were exceeded.

Conclusions

Monitoring techniques are of paramount importance, especially when there is a need to predict landslide events and thus allow time for safe evacuation with early warning signs indicating failures in monitoring unstable slopes. Additionally, monitoring facilitates the study of various mitigation techniques and the effectiveness of soil stabilization, enabling geological or geotechnical experts to accurately model slope deformations, thereby protecting people and infrastructure with minimal disruption. Projects present unique challenges, and different hardware-software solutions are applied according to their needs. Besides the example described in this paper, monitoring requirements may necessitate the use of other technologies, where following list provides examples of components that have justified practical application in monitoring various types of geohazards.

Leica Geosystems solutions:

- Leica MS60 MultiStation for 3D measurement, imaging & scanning
- Leica ComBox60 power & communications controller with GeoMoS Edge
- Leica GeoMoS Monitor data acquisition & computation software
- Leica GeoMoS Now! data analysis & visualisation software / service
- Leica Geosystems AS11 / GM30 GNSS absolute 3D monitoring
- Leica GPR112 monitoring prisms measuring 3D structural displacements
- Leica GMX910 smart antenna tracking position via post-processing & GNSS Spider
- Remote image capture / live video stream of embankment via TPS telescope camera
- Remote detection of surface deformation using fully automated 3D laser patch scanning technology via MS60 and GeoMoS
- Leica VADASE for rapid autonomous GNSS displacement onboard GM30

Integrated 3rd party solutions:

- Wireless smart data hub for geotechnical sensors
- Geotechnical sensor data import into Leica GeoMoS via AnyData
- Wireless tilt sensors to monitor slope
- Wireless interface with locally connected water level sensor / IPI / borehole extensometers
- Wireless sensor tilt measurement for verticality of wall

Interferometric Radar solutions:

- IBIS-FM EVO,
- HYDRA-G,
- IBIS-FS,
- RockSpot

Monitoring is necessary to report dangerous events in hazardous areas by providing measurement information as early as possible when a landslide occurs, to inform about the magnitude of movement so that every danger can be immediately assessed. Landslides can block, damage, or destroy transportation links and critical infrastructure, besides endangering lives. Therefore, an automatic early warning system is essential to provide information for mitigating the risks of such hazards. Pre/post-event records are crucial for aiding in understanding why landslides occur. Additionally, during remediation, it is essential to have as realistic supervision of the event as possible to measure subsequent movements and future monitoring of soil collapse.

Monitoring provides real-time information on slope movements and enables fact-based decision-making, facilitating swift and crucial decisions to ensure the highest level of safety and effective risk management.

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