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LANDSLIDE RISK MANAGEMENT IN PRACTICE: PHASED MITIGATION USING THE OBSERVATIONAL METHOD

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Landslide risk management typically involves an initial assessment to characterize the phenomenon and a subsequent phase to design and implement safety measures. However, financial constraints and technical challenges often require a phased approach to optimize resource allocation. In such cases, the observational method provides a flexible approach, allowing for phased implementation of measures while monitoring their effectiveness over time. In this study we applied this strategy to the "Paradisi" landslide (Belluno, Italy), a rotational slide at the interface between moraine debris and the Belluno Flysch formation. The 115x200 m landslide involves nearly 200,000 m^3. Predisposing factors include poor geotechnical properties, high water content at the moraine-Flysch interface, and steep gradients, while intense winter precipitation triggers rapid mudflows along a central watercourse. Initial interventions addressed critical instabilities through slope reprofiling and shallow and medium-deep drainage systems. At the same time, monitoring systems - inclinometers and piezometers - tracked the slope behaviour. Subsequently, smart self-drilling composite anchors with optical fiber instrumentation were installed to stabilize the slope. Finally, the landslide toe was reinforced with a row of gabions spanning almost the entire width of the landslide. Drone-based photogrammetric periodic surveys complemented the monitoring efforts. This phased strategy allowed for iterative refinements, with each intervention evaluated based on observed residual movements and site conditions. The observational approach ensured that limited resources were effectively utilized. This strategy was applied not only to adaptively guide the phased course of action but also as a long-term framework to monitor future landslide evolution. This approach aims to assess the potential need for further risk mitigation phases, ensuring sustainable resource allocation and long-term site safety. The case study highlights the importance of integrating phased strategies with robust monitoring systems to optimize landslide risk management under resource constraints.

Keywords: phased risk management, observational method, slope stability, smart passive anchors, optical fibers.

1. Introduction

Italy is one of the European countries most exposed to hydrogeological risk due to its complex morphology and the geotechnical properties of its soils. Landslides in Italy encompass a wide variety of types, including slow viscous slides, rapid debris flows, deep-seated gravitational slope deformations, and complex movements. Identifying the specific type of instability, assessing its interactions with infrastructure and populations, and determining an effective risk mitigation strategy are highly challenging tasks. The situation is further exacerbated by the increasing frequency and intensity of triggering factors linked to climate change, which has heightened the risk of slope instabilities across the country. Local authorities face additional difficulties due to limited financial resources. Ambitious risk mitigation objectives often exceed available budgets, particularly given the large number of instabilities that require simultaneous management. This financial constraint makes it unlikely to achieve adequate safety margins for all identified landslides, especially in regions where intense rainfall during the rainy season triggers widespread slope failures. A pragmatic solution may lie in adopting the observational method, as outlined in European and Italian legislation. In the context of landslide risk mitigation, this approach involves a phased strategy where the effectiveness of each phase is assessed through monitoring, guiding subsequent interventions in an efficient manner. By integrating monitoring systems into stabilization measures, it is possible to define tolerable risk thresholds, ensuring continuous site surveillance and enabling timely reinforcements where and when necessary. This approach optimizes both the design of interventions and long-term territorial protection.

The observational method's adaptability makes it particularly valuable in managing landslides characterized by high geotechnical uncertainty. As highlighted by Calvello (2017), this method enables real-time adjustments to design and construction based on site observations. Moreover, phased interventions, as discussed by Brezzi et al. (2021), allow stabilization efforts to align with available resources while addressing the most critical safety concerns. This modular approach not only slows down slope movements but also provides opportunities to enhance safety over time, guided by improved site understanding and monitoring data. In summary, the observational method represents a cost-effective, adaptable framework for managing landslide risk, ensuring efficient allocation of resources and prioritizing safety in areas with significant hydrogeological challenges.

2. Description of the case study

The Paradisi landslide takes its name from the village of Paradisi, located in the municipality of *Ponte nelle Alpi*, province of Belluno (Italy). This landslide is classified as a complex movement due to distinct behaviors observed in its head and foot regions. At the head, the movement is predominantly rotational, occurring between the moraine cover and the alpine flysch, while at the foot, the movement is characterized by spalling lobes, distributed midway down the landslide slope. Among the various triggering factors, heavy winter rainfall played a key role, compounded by the lack of precipitation reabsorption through glaciation due to unusually high temperatures compared to the years before. Additionally, the presence of the Rio San Pietro stream in the center of the affected area fed the landslide, generating high-velocity mudflows that exacerbated instability. The instable volume is between 150,000 and 200,000 m³. Before stabilization efforts began, the landslide was moving at a significant rate of several cm/day, leading to the formation of visible fracture lines both upstream and downstream, affecting also the provincial road SP4 *"della Val Cantuna"*, rendering it impassable. The road's closure, combined with the hazard posed by the moving terrain toward the road, necessitated urgent intervention.

Fig. 1 Evolution of the Paradisi Landslide through the years

The evident fracturing of the provincial road was the only sign indicating the presence of landslide movements. For this reason, it was necessary to enhance the understanding of the phenomenon as much as possible, identifying the main kinematics and the primary instability factors, to guide the risk mitigation strategy given a limited available economic budget. Given budget constraints, full-scale stabilization was not feasible in a single phase. Instead, a stepwise approach was adopted, prioritizing measures that maximized cost-effectiveness while maintaining safety. The observational method played a key role from the outset. Initial geotechnical investigations helped identify the primary instability factors, guiding early interventions. Monitoring systems, including inclinometers and piezometers, continuously assessed slope behavior, informing subsequent decisions. Such data make it possible to control the progress of the work and update the design in the early stages, enabling timely and precise adaptation to the actual site conditions. Two distinct behaviors were recognized in the landslide body: in the upper part, rotational sliding predominates along the interface between the moraine cover and the Flysch Alpino layer, both characterized by poor mechanical properties; in the lower part, the movement is dominated by shearing lobes distributed mid-slope. It was also noted that the instability was primarily attributed to an increase in rainfall events not offset by glaciation, which facilitated water infiltration into the fractures of the Flysch, a particularly vulnerable material, causing the soil to assume a state with characteristics similar to those of a liquid. Therefore, the slope stabilization had to address both the management of the landslide's hydraulic regime, aiming to reduce the amount of water circulating within the slope, and the improvement of the soil's mechanical properties through the use of distributed reinforcements.

3. Design and execution of interventions

The intervention program for the stabilization of the slope aimed to optimize the outcome, while accounting for a limited budget. It was both necessary and strategic to address the regulation of surface and mid-depth water flows. Drainage systems, in general, help reduce pore water pressures in the soil, thereby increasing effective stresses and, consequently, shear strength. However, water regulation alone may not be sufficient for long-term landslide stabilization. Delayed maintenance of drainage systems or the accumulation of small deformations over extended periods can significantly reduce the effectiveness of the intervention. Therefore, it was deemed strategic to complement a mitigation measure focused on hydraulic regulation with a mechanical intervention aimed at enhancing the soil's shear strength properties through distributed reinforcement. To optimize these interventions, the project also included a preliminary phase dedicated to reshaping the slope.

During each phase, as well as during the intervals between them, the slope was continuously monitored. Five boreholes were equipped with piezometric and inclinometric instruments between 2019 and 2021, prior to the start of the stabilization works. Additionally, some MASW *(Multichannel Analysis of Surface Waves)* and seismic tomography surveys were conducted to deepen the understanding of the site. In March 2022, following the completion of the re-profiling, an ERT *(Electrical Resistivity Tomography)* survey campaign was carried out. Further 4 boreholes with SPT tests were subsequently drilled to enhance the understanding of the position of the slip surfaces and better identify the volumes involved. The boreholes were also equipped with inclinometric and piezometric probes. Monitoring was essential to assess the evolution of the slope's kinematics, evaluate the effectiveness of each stage, and adjust the design of interventions planned for subsequent stages if necessary. The operations are detailed in the following.

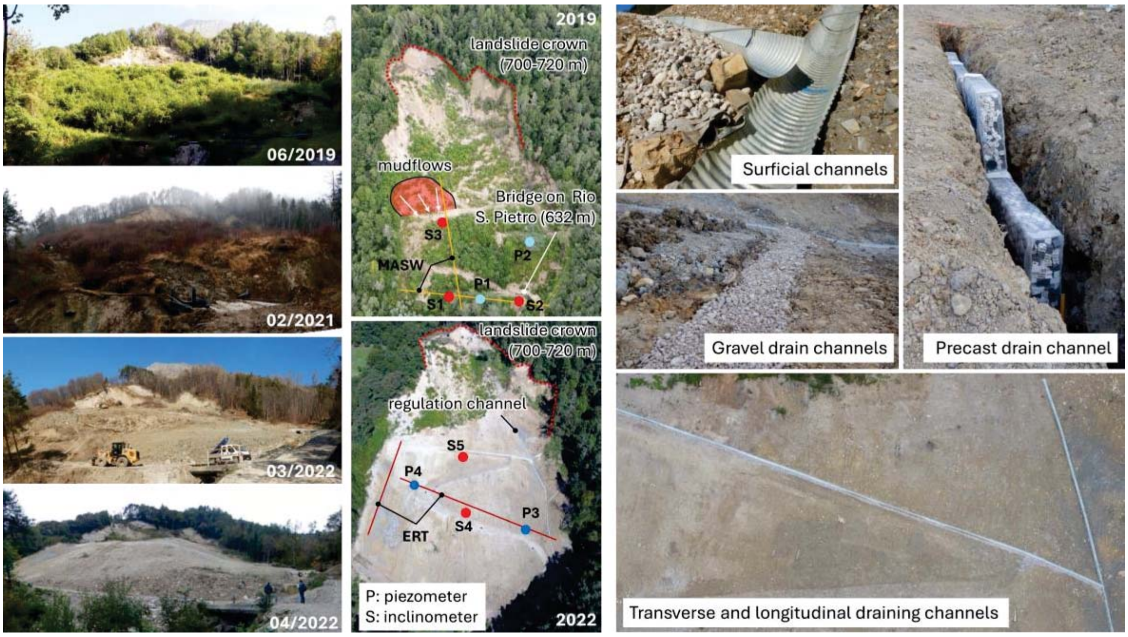

Fig. 2 First phases interventions: reshape and drainage system realization

1. Site Accessibility Restoration – The access road, damaged by initial movements, was repaired to facilitate intervention. **2. Slope Reprofiling and Drainage Implementation** – Approximately 23,000 m³ of material was firstly removed to reshape the slope (Fig. 2). Then, to prevent water runoff, hydraulic bypasses were constructed around the landslide, followed by the reconstruction of the drainage network using prefabricated drainage trenches and channels. The new slope configuration enabled additional monitoring and piezometer installations, strategic tools to determine how to proceed in the next steps. **3. Monitoring-Guided Stabilization** – Continuous data collection refined the intervention strategy, ensuring that additional measures were implemented only when justified. The inclinometer results indicated a significant reduction in slope movements; however, the landslide remained active, necessitating further actions. **4. Smart Passive Anchors** – To enhance slope stability, 42 floating passive anchors were installed in rows, with 3 instrumented using fiber-optic sensors for real-time deformation monitoring. The collected data enabled the precise confirm the efficacy of the location and number of anchors designed. In this context, passive floating anchors (Brezzi et al., 2021) emerged as a cost-effective solution. While these anchors rely on slope movement to activate their stabilizing response and provide lower resistance compared to traditional active anchors, they are simple and quick to install, leading to substantial cost savings. Typically, they are installed in rows with a spacing equal to 3 times their diameter. However, due to budget constraints, the spacing was doubled, resulting in a total of 42 bars 30 m long distributed across 5 rows (Fig 3). Continuous monitoring of movements was particularly crucial in this scenario, as it allowed for the assessment of whether the number of anchors was sufficient to stabilize the slope. The intervention adhered to the observational method, maintaining flexibility for additional reinforcements with traditional spacing, should they become necessary.

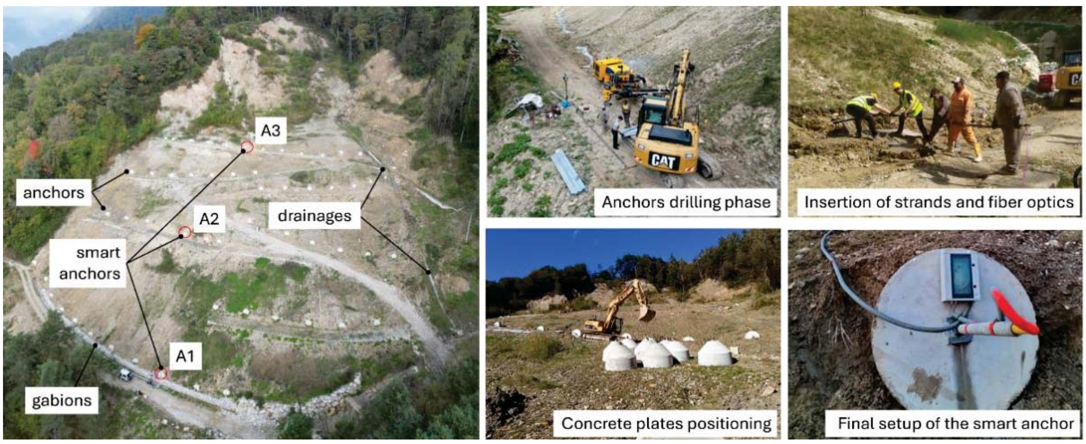

Fig. 3 Site overview with installed anchors, drilling and anchors installation, followed by fiber optic placement and setup

As stated, to enhance the monitoring system, 3 of the anchors were instrumented with optical fibers (Cola et al., 2019; Brezzi et al., 2023), enabling real-time deformation monitoring along their entire depth. This approach provided valuable insights into the effectiveness of the stabilization system. Notably, the instrumented anchors were strategically placed across 3 different rows, facilitating a detailed analysis of the ongoing kinematics and ensuring accurate control of the slope's stability. **5. Final Adjustments and Long-Term Monitoring** – Ongoing observations determine whether further reinforcements are required, preventing unnecessary expenditures on premature stabilization efforts. When the slope is deemed sufficiently stable, restoration of the damaged areas and the redevelopment of the road infrastructure can proceed. Planned activities also include the reconstruction and reinforcement of the containment of the Rio San Pietro, a crucial intervention to prevent the entry of additional volumes of water into the landslide body, thus contributing to ensuring the long-term stability of the slope. Continuous monitoring of both the landslide and the anchors will allow for the assessment of whether additional safety measures for the slope are needed, such as implementing further floating anchors, new drainage systems, or other measures, only where necessary. This approach enables the economic investment for slope stabilization to be spread over time and optimizes available resources by adapting the intervention plan to the actual site conditions as they evolve with the measures already implemented.

4. Monitoring results and conclusions

For nearly a year following the completion of steps 1-4, all inclinometers on-site recorded extremely limited movements, measuring less than a few centimetres per year. It may be of interest to present the measurements obtained from the optical fibers installed in the 3 anchors, referred to as A1, A2, and A3.

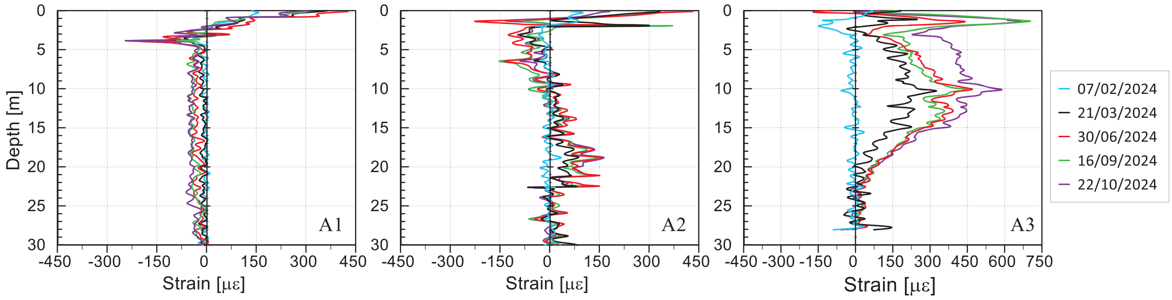

Fig. 4 Results of the monitoring of anchors through optical fibers (*reference reading 18/01/2024*)

A preliminary observation concerns the limited magnitude of deformations measured in all 3 anchors, confirming the temporary stability of the slope. Anchor A1, at the toe of the landslide, shows almost unchanged data from January to October 2024. Similarly, anchor A2, at the centre of the slope, exhibits very minor strains. Between 15 and 22 meters in depth, a slight tensile state is observed, suggesting a probable initial activation of the bar at the slip surface. Anchor A3, in the uppermost row, behaves differently. Activation of the bar is observed, propagating from the surface to nearly 20 meters in depth. Multiple small-scale mudflows were observed interacting with this anchor, completely covering the conical concrete plate. These mudflows appear to have induced bar activation by exerting a pullout effect. The measurements remain preliminary but primarily serve to confirm, in alignment with inclinometer readings, the effectiveness of the implemented risk mitigation system.

The Paradisi landslide case clearly demonstrates the application of the observational method in the context of landslide risk mitigation through the use of various techniques. This approach allows stabilization measures to be implemented in phases, ensuring a cost-effective allocation of resources over time, while maintaining flexibility to adapt interventions based on evolving site conditions. The ability to proceed incrementally enables public authorities to distribute economic investments across different fiscal periods, avoiding excessive upfront costs. Simultaneously, the observational method ensures that decisions are continuously refined based on real-time monitoring, optimizing the selection of the most appropriate stabilization measures. This case study highlights the crucial role of a phased strategy in balancing financial constraints with effective risk reduction, ultimately enhancing long-term land protection.

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