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Application of digital technologies in landslide prediction, mapping, and monitoring

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Review Article

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Digital technologies applied to landslides
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Scoping review

Abstract

This paper presents a scoping review on the use of digital technologies for predicting, mapping, or continuously monitoring landslides on natural slopes. Articles and reviews published between 2001 and 2023 indexed by Scopus (Elsevier) were selected. The results showed that the number of publications involving this theme has been growing every year, with two periods of prominence: 2008-2010 and 2015-2021. China, Italy, India, USA and Taiwan are the five countries that published the most on the subject during the studied period. It was also found that remote sensing tools were the most used and showed strong stability, accompanied by artificial intelligence tools. Digital sensors have been widely used in Early Warning Systems, composing Wireless Sensors Network, monitoring terrain or climate variables. There is no doubt that digital technologies are extremely advantageous in relation to traditional technologies and that they already present themselves as a solution and confirm their trend of future consolidation.

1. Introduction

Mass movements on slopes, also called landslides, are movements of blocks of rock, soil, or debris that move down a slope due to natural influences, human-induced factors, or a combination of both. On a geological time scale, mass movements certainly will occur on slopes. These movements have become an object of international political and institutional interest because they are responsible for major socioeconomic impacts at a global level every year. (UNISDR, 2015; UNDRR, 2019).

In 1988, the Centre for Research on the Epidemiology Disasters (CRED) created the Emergency Events Database (EM-DAT) to gather data on adverse events of natural, biological, or industrial origin, including landslides. Using the EM-DAT data available until January 2023, it was found that landslides correspond to about 5.6% of all events reported worldwide between 1900-2022, causing damage of around US$ 23.4 billion, affecting approximately 14.8 million people and fatally hitting 72 thousand. However, it is important to highlight the existence of underreporting, which means that these numbers can be even higher. Figure 1 shows a graph with the number of people affected, injured or dead and the estimated cost of damage caused by landslides using data from 2001-2023 from the EM-DAT database.

In terms of measures for mitigating the effects caused by landslides, solutions can be grouped into two categories: i) structural measures and ii) non-structural measures (MCID/IPT, 2007; IG, 2009). Structural measures involve engineering solutions and can be exemplified by retaining walls, drainage systems, and urban infrastructure works. Conversely, non-structural measures are related to public policies, urban planning, and civil defense plans. These include solutions such as Monitoring Systems (SM), Early Warning Systems (EWS), and Susceptibility Maps (MCID/IPT, 2007; Kong et al., 2020). Non-structural measures indirectly mitigate the effects of landslides. They are less costly and have less impact on the environment compared to structural measures. They can also produce results as satisfactory as structural measures in preventing and mitigating the effects of landslides, especially in irregularly occupied risk areas in urban centers.

In the last decade, Digital Transformation (DX) has caused significant changes, from simple activities in society and economic activities to more complex applications, such as real-time monitoring of industrial and environmental procedures. The outcome of this process has been identified and named as the 4th Industrial Revolution or Industry 4.0 (Frank et al., 2019; Vial, 2019; Tortorella et al., 2020). Vial (2019) defined DX as a process aimed at institutional/social improvement that triggers significant changes through the combination of information, computing, communication, and connectivity technologies. This definition is the result of a review study that included 282 papers involving DX

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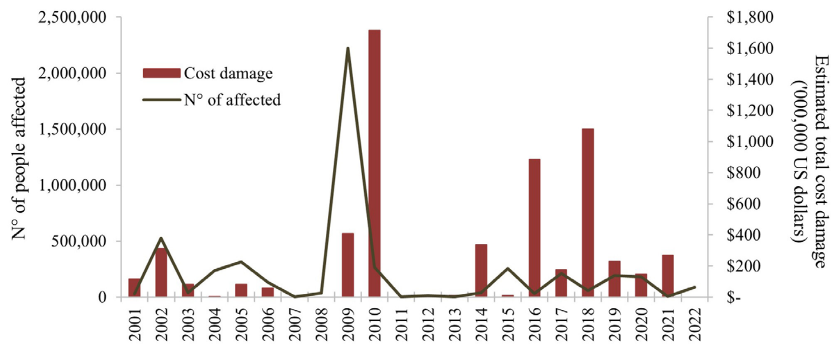

Figure 1. Number of people affected by mass movements per year and their estimated total cost damage adjusted in millions of US dollars caused by the movements.

as a central theme. Traditionally observed in the industrial, technology and information systems environment, mainly due to the digitalization of its processes, products, and organizational strategies (Frank et al., 2019; Nambisan et al., 2019; Tortorella et al., 2020; Vial, 2019), DX is not limited to these fields of application. It also extends to everyday applications in urban centers, enabling the application of the concept of Smart Cities.

The concept of a Smart City was introduced in the 1990s to incorporate solutions based on advanced information and communication technologies into urban planning, and it was closely associated with Digital Transformation. Bellini et al. (2022) highlight that the Internet of Things (IoT) represents one of the main drivers and facilitators of smart innovation and sustainable development linked to the evolution of Smart Cities. IoT is a fundamental part of the digitalization of devices, in addition to the incorporation of Artificial Intelligence (AI) tools, which make data processing more feasible in the face of high acquisition rates that place Smart Cities on the scale of big data.

It is common sense that the Environment is qualified as one of the domains of interest of Smart Cities (Sharif & Pokharel, 2022; Bellini et al., 2022). The monitoring and mapping of susceptibility, danger, and risk of damages events of hydro-geological origin fits in the context of interest of Smart Cities and have suffered the effects of Digital Transformation in recent years (Santos et al., 2020). Several studies have sought to improve the tools and methods for monitoring and managing the risk of movements on slopes. From the point of view of mapping and predicting movements on slopes, Artificial Intelligence tools have been the flagship that leads the advancement of major research and applications (Wang et al., 2019; Bragagnolo et al., 2020; Huang et al., 2020; Catani, 2021; Rodrigues et al., 2021), while the originally digital instruments or the digitalization of traditional instruments are being the main tools for improvement of slope monitoring methods (Giogetti et al., 2016; El Moulat et al., 2018; Mei et al., 2020; Ruzza et al., 2020; Giri et al., 2022; Otero et al., 2022; Marino et al., 2023).

Within the context of IoT, these digital instruments operate interconnected by the same wireless network and transmit data to the same storage center. In recent years, there has been a growth in the amount of use of low-cost sensors and transmitter devices, seeking to reduce the cost of IoT solutions for monitoring movements on slopes. Low-cost sensors have been integrated into so-called Early Warning Systems, composing Wireless Sensors Networks. Sensors are usually used to measure rainfall indices, soil moisture content, seismic vibration, and angular variations (Ruzza et al., 2020; Bagwari et al., 2022; Thirugnanam et al., 2022; Lau et al., 2023; Marino et al., 2023).

As for the use of Artificial Intelligence, Machine Learning has been widely used for prediction or mapping landslides. Machine Learning is a method of data analysis that uses algorithms that seek to simulate human thinking, which would make the machine capable of making decisions based on a set of validated data that would train the algorithm (supervised learning) or discovering patterns in input data using different types of techniques to generate output data (unsupervised learning) (Sreelakshmi et al., 2022; Collini et al., 2022) Deep Learning is a subgroup of Machine Learning, which seeks to simulate, in greater depth, the action of an artificial neural network (Baghbani et al., 2022; Tehrani et al., 2022).

Another alternative to traditional methods for monitoring, remote sensing has also been widely used for mapping areas susceptible to landslides and monitoring movements on natural slopes. Remote sensing uses satellites, radars, and on-board technology to acquire information about a specific area or object. Synthetic aperture radar (SAR) and its variations, light detection and ranging (LiDAR), airborne laser scanning (ALS) are major examples of remote sensing techniques (Thirugnanam et al., 2022).

This paper presents a scoping review of the effects of incorporating new technologies and the DX on natural slope monitoring. It characterizes the process through publications on the subject between 2001-2023, identifying characteristics such as the number of publications over the years, recurrence of keywords used, geographical distribution of the first authors, using Scopus (Elsevier) as a study source. Section 2 presents the methodology protocol applied in the review. Section 3 presents the results obtained and discusses the observations. Section 4 concludes this work.

2. Scoping review protocol

2.1 Review protocol

Review objectives:

i. To characterize the effects of incorporating new technologies for monitoring natural slopes.
ii. To present the gradual growth of the theme throughout the 21st century.
iii. Identify the main features caused by the Digital Transformation in slope mapping, prediction, and monitoring.

PICOC strategy adopted:

- P (Population): Articles written in the English language, published in scientific journals within the Scopus bases (Elsevier).
- I (Intervention): Digital Transformation in slope monitoring, geotechnical instrumentation on slopes, the use of IoT, Big Data and AI as tools for slopes monitoring and warning.
- C (Comparison): Concepts, application limitations of new technologies and spatial distribution of researchers.
- O (Outcome): Evolution of the theme over the last two decades, the regionalization of publications, AI tools and instruments used.
- C (Context): Geological disasters, slope movements and risk assessment.

Research questions:

1. How has the use of digital solutions advanced in the geotechnical environment with a focus on predicting and monitoring movements in natural slopes?
2. What remote sensing, photogrammetry and geodetic tools have been most used?
3. What artificial intelligence tools have been most used?
4. What digital sensors have been most used?
5. Considering the affiliation country of the first author, what are the main countries that are researching and publishing on the subject?

Criteria adopted for acceptance of documents in the review:

- Real case application using IoT, AI, Early Warning System, Remote Sensing, Optical Fibre, MEMS or similar.
- Laboratory simulation using IoT, AI, Optical Fibre, MEMS or similar.
- Monitoring and inspection with UAV, radar, satellites or similar
- State-of-the-art reviews

Criteria adopted for rejection:

- Duplicate
- Outside scope of the review

Search string:

The search was restricted to articles that met the following conditions: i) articles and reviews published between 2001 and May 4, 2023, ii) written in English, iii) in the final stage iv) that contained in the title, abstract or keywords the set of words contained in the groups 'Phenomenon', 'Activity' and 'Tools' shown in Figure 2.

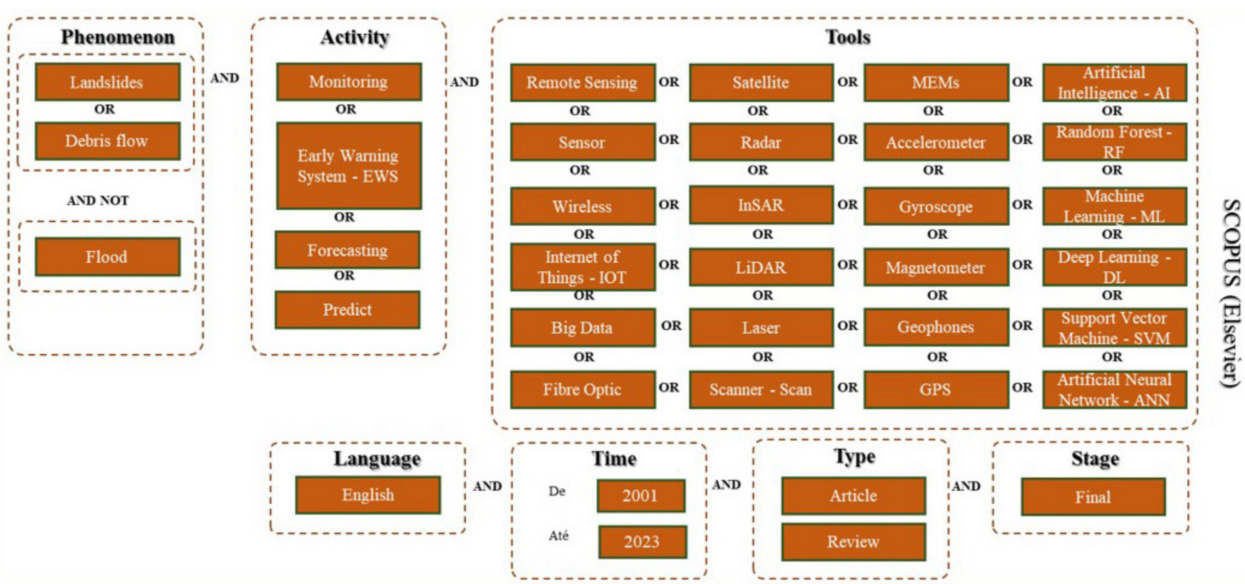

Figure 2. Considerations for constructing the search string.

2.2 Results database

Following the considerations indicated in Figure 2 and described in the previous topic, 2,674 documents were obtained, of which 1,615 were classified as accepted. However, of these, 211 documents lacked some information, be it the country of origin of the publication, source and/or keywords. To maintain a regular analysis of the data, only documents with complete information were admitted, resulting, therefore, in a database with 1,404 articles.

3. Analysis and results

3.1 General observations

By observing Figure 3, clearly use of new technologies as a tool for prediction, forecasting or continuous monitoring of slope stability presents a strong trend growth in the number of publications each year. Analyzing the values individually, note that there is a first strong increase in the number of publications between 2008 and 2010, where the number came close to quadrupling in two years, with oscillations in the following years, but maintaining a certain stability, returning to show growth trend from 2015, with highlights for the period between 2019 and 2021, contemplating the Covid-19 pandemic period, which exceeded the first hundred publications per year and doubled the number in two years. The decrease in the number of publications made in 2022, which was unexpected compared to that of 2021, shows that the resumption of post-pandemic activities directly interfered with the publication process. This should be considered for 2023.

Detailing the contribution of each country in the number of publications considering the affiliation of the first author, Figure 4 presents the individual contribution of the top 5. From the graph, it is evident that China and Italy accompanied the first growth between 2008 and 2010, and remained close until 2008, when China assumed the absolute leadership of annual individual publications. Altogether, the five countries have a total of 902 publications, which represents 64.3% of the total publications surveyed in this study. Of these publications, 494 are attributed to China, 226 to Italy, 80 to India, 58 to USA and 44 to Taiwan. The Figure 5 shows a choropleth map with all the countries identified in this research, revealing a total of 64 countries.

The keywords synthesized in Figure 6 enable a global vision on the interest of researchers. Figure 6a presents the term Landslide as the most frequent phenomenon and the terms Monitoring, Susceptibility as activities of greatest

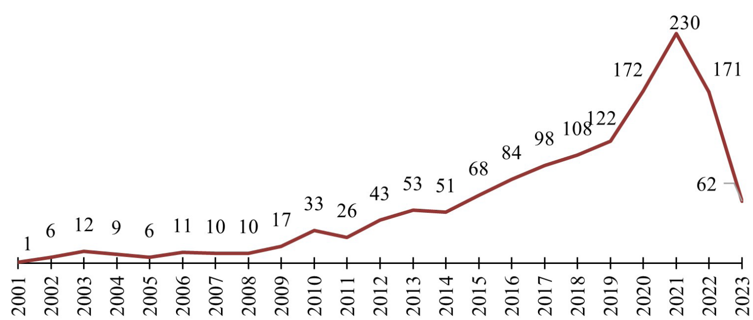

Figure 3. Number of publications per year about digital technologies applied to mass movements on natural slopes from 2001 to May 4, 2023.

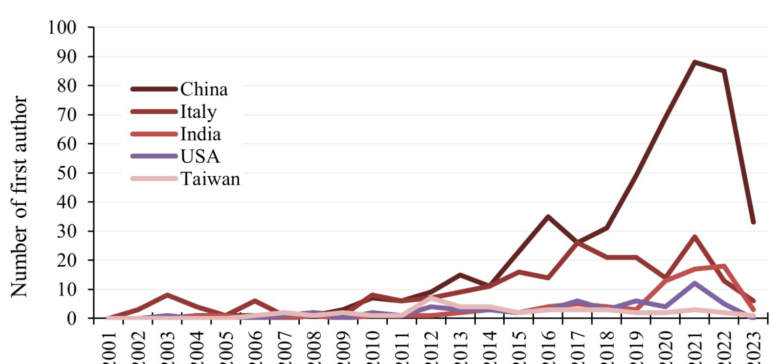

Figure 4. Number of first authors by country affiliation declared in each publication.

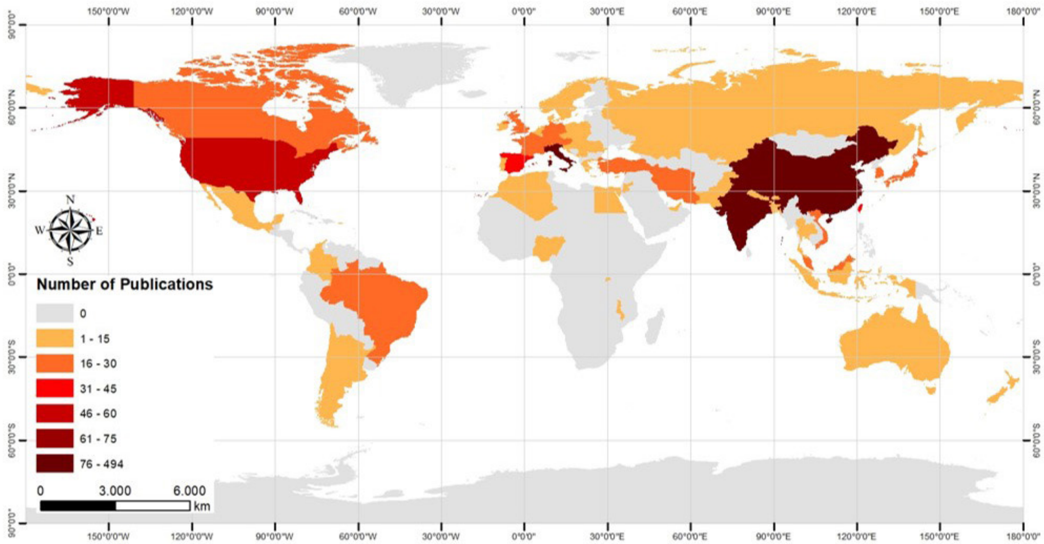

Figure 5. Choropleth map with geographical distribution of the first authors.

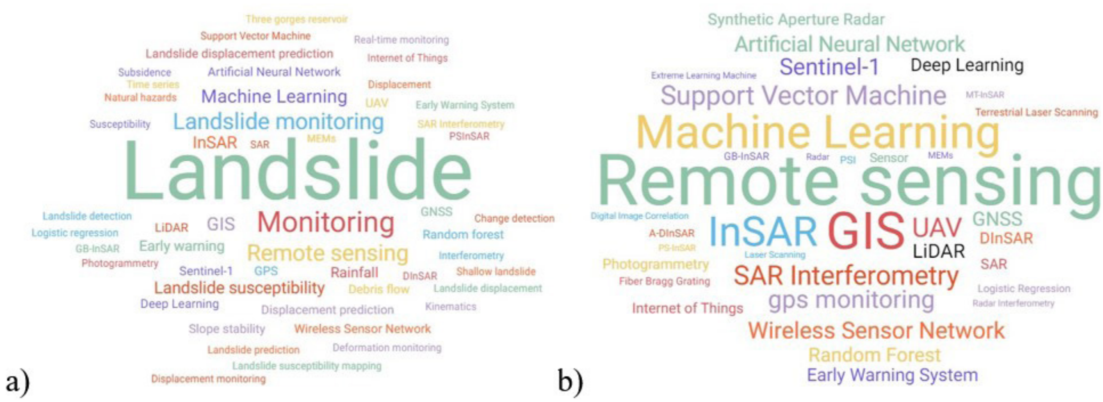

Figure 6. Keyword clouds with a) global and b) tools keywords.

interest for application of the methods. As for the group of tools, Remote Sensing and Machine Learning had greater expression, as well as their respective tools such as SAR and its variations, LiDAR, UAV for Remote Sensing and Support Vector Machine, Artificial Neural Network and Random Forest for Machine Learning.

In the word cloud containing only tools and your groups, it is possible to verify that the tools that work with image acquisition and processing are the most common tools to use. Associated to this fact, the Artificial Intelligence tools, led by the Machine Learning and Deep Learning tool groups are among the main ones adopted. These tools can be used both to optimize image processing, to generate susceptibility, hazard, or risk maps, to identify slope movement patterns or even to identify temporal changes. Moreover, AI tools are fundamental for processing data collected at high acquisition rates of data and stored at Big Data scale, obtained by solutions associated with the Internet of Things.

These high acquisition rates can be exemplified by the Wireless Sensors Network (WSN), also present in Figure 6b. Depending on the duration of monitoring and the acquisition rate, the monitoring system may enter the big data storage scale, raising the level of processing, where it is necessary to use AI tools that carry out filtering processes, identify patterns and use part of the results as a validation set, performing the function of "teaching" the machine what is and that is not of interest to the user, and can be applied to predict events in monitoring and alert systems, or even to evaluate changes in the stability of monitored elements.

Figure 7 shows the journals that published the most about the use of new technologies. It is easy to see that the listed journals are within the context of geology or sensors

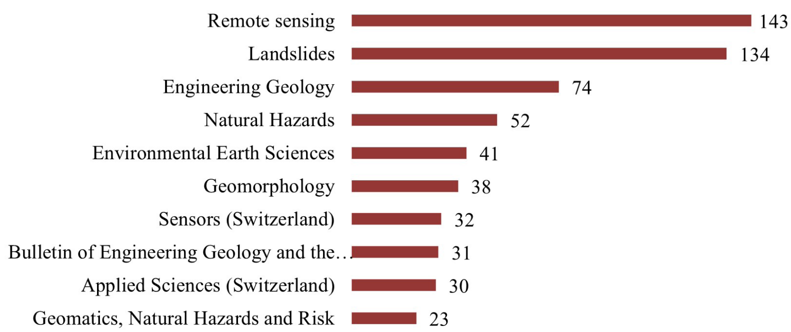

Figure 7. List of the top 10 academic journals that published the most about the theme.

and applied technology, not appearing traditional geotechnical journals. With the study, it was observed that these traditional geotechnical journals have focused their publications either on the application of methods and tools for slope stability analysis or on proposals for solutions applied to the stabilization or containment of movements, with only a small part of the publications focused on methods of movement investigation.

3.2 Answering the research questions

A. How has the use of digital solutions advanced in the geotechnical environment with a focus on predicting and monitoring movements in natural slopes?

The use of new technologies driven by the Digital Transformation began its process slowly between 2001 and 2008, with significant increase in the number of publications between 2008 and 2010. In this first stage, the use of GIS tools predominated for processing data obtained by satellites, radars, or GPS, with strong image processing steps. Initial studies on inertial sensors with wireless transmission and fibre optic applications began to be carried out. From 2010 onwards, in addition to the continuity of GIS, satellite and radar tools, studies on early warning systems were intensified, accompanied by wireless sensor networks and real-time monitoring, and AI for motion prediction and image processing. From 2016, tools such as UAV, IoT, and AI gained greater prominence, still accompanied by GIS, satellite and radar tools, with AI applications for predicting movements, preparing susceptibility maps and processing remotely acquired data at high rates acquisition process, enabling real-time monitoring.

B. What remote sensing, photogrammetry and geodetic tools have been most used?

An expressive presence in the papers evaluated in this research, the most cited tools were:

- Satellite Sentinel-1
- Synthetic Aperture Radar (SAR)
- Interferometric SAR (InSAR)
- Diferencial InSAR (DInSAR)
- Ground Based InSAR (GB-SAR)
- Unmanned Aerial Vehicle (UAV)
- Light Detection and Ranging (LiDAR)
- Global Position System (GPS)

C. What artificial intelligence tools have been most used?

It was observed that Machine Learning and Deep Learning algorithms that work with supervised learning were preferred over unsupervised learning. Below are listed the three tools that were most cited:

- Support Vector Machine (SVM)
- Random Forest (RF)
- Artificial Neural Network (ANN)

D. What digital sensors have been most used?

The digital sensors have been incorporated into Early Warning Systems (EWS), composing the Wireless Sensor Networks. Among the usual sensors, the use of:

- Accelerometer
- Barometer
- Gyroscope
- Soil moisture
- Geophone
- Temperature/humidity
- Optical fibre
- Strain gauge

E. Considering the affiliation country of the first author, what are the main countries that are researching and publishing on the subject?

A total of 64 countries were identified that published at least one publication on the subject. The top 5 positions are occupied China (1st), Italy (2nd), United States of America (3rd), India (4th) and Taiwan (5th), which together represent 65.3% of the total number of publications between 2001-2023.

3.3 Advantages over the traditional methods

- Decreased visits to field monitoring sites.
- The short response time of digitalized instruments.
- The possibility of monitoring readings in real time and remotely.

- The possibility of investigation a greater number of variables at the same instrumentation point, or even different types of measurements at different depths.
- The combination of more than one technological solution in the same monitoring program.

3.4 Projecting the future from the past and present observing

One can expect:

- The continued use of satellites, radars, and on-board technologies, in addition to the increased use of (UAV) for mapping and surface monitoring.
- The digitalization of traditional instruments or, even, the adaptation of new technologies to play the roles of these instruments.
- Greater scope and depth of application of Artificial Intelligence tools, going beyond prediction or simples signal processing.
- Integration of warning systems managed by government agencies, fed in real time by instruments installed in the field.

4. Conclusions

This work conducted a scoping review that presents a study on the effects of incorporating new technologies for monitoring natural slopes. The process was characterized based on publications carried out between 2001-2023 on the subject.

The conclusions can be summarized as follows:

- The use of new technologies applied for predicting, mapping or continuous monitoring slopes shows a strong growth trend, despite the visible decrease in the number of post-pandemic publications.
- The topic grew slowly between 2001 and 2008, with a significant increase between 2008 and 2010, when the number of publications almost quadrupled. As of 2015, the theme again showed a sharp growth trend, with emphasis on the period between 2019 and 2021, with coincided with the Covid-19 pandemic. During this period, publications surpassed the first hundred and doubled in two years.
- China and Italy lead the number of publications on the subject. Until 2018, the two countries were close in the number of publications. From then on, China assumed the absolute leadership of annual individual publications. India, United States, and Taiwan follow as the countries that published the on the subject.
- The journals that have published the most on the subject are linked to geology or sensors and applied technologies.
- It was found that the most recurrent instruments used are satellite imagery or radar and on-board technologies, associated with GIS tools. Instruments for localized use, such as inertial sensors and fibre optics, had their applications intensified from 2010 onwards, mainly for use in monitoring and warning systems.
- The most cited remote sensing, photogrammetry or geodesic tools were: Sentinel-1, SAR, InSAR, DInSAR, GB-InSAR, UAV, LiDAR, GPS.
- It was observed that Machine Learning and Deep Learning algorithms that work with supervised learning were preferred over unsupervised learning.
- The main Artificial Intelligence tools that are being used are: Support Vector Machine, Artificial Neural Network and Random Forest.
- The digital sensors have been incorporated into Early Warning Systems (EWS), composing the Wireless Sensor Networks. Among the most usual sensors, were cited: accelerometer, barometer, gyroscope, soil moisture, geophone, temperature/humidity, optical fibre and strain gauge.
- There is no doubt that the digital technologies driven by the Digital Transformation are already a reality in slope geotechnics, presenting themselves as a present solution and confirming a strong trend towards future consolidation. Studies involving these and new tools should be encouraged in our researchers' centers and the already known use should be improved for possible large-scale applications, favoring the sectors, security, and regional and national economic development.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Gabriel Raykson Matos Brasil de Araújo: conceptualization, methodology, data curation, visualization, software, writing – original draft. Alessandra Cristina Corsi: conceptualization, methodology, visualization, supervision, project administration, funding acquisition, writing – review & editing. Eduardo Soares de Macedo: conceptualization, methodology, supervision, project administration, funding acquisition. Marcos Massao

Futai: conceptualization, methodology, supervision, project administration, funding acquisition, writing – review & editing.

Data availability

The datasets generated analysed in the course of the current study are available from the corresponding author upon request.

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