الجمهورية الجزائرية الديمقراطية الشعبية
Republique Algériènne Démocratique et Populaire
وزارة التعليم العالي والبحث العلمي
Ministère de l'Enseignement Superieur et de la Rechérche Scientifique
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Institut des Mines
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Département des Mines et Géotechnologie

MEMOIRE

Présenté pour l'obtention d'un master académique en:
Filière : Génie Minier
Option : Géotechnique

Development of a landslide control Tool

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Année universitaire 2024/2025

ملخص

تُعتبر الانزلاقات الأرضية من أخطر الظواهر الجيوتقنية التي تهدد الأرواح والبنية التحتية، خاصة في المناطق ذات التضاريس المعقدة والتربة غير المستقرة. يهدف هذا العمل إلى تطوير أداة ذكية لمراقبة والتحكم في الانزلاقات الأرضية في الزمن الحقيقي، اعتمادًا على مقاربة تكنولوجية متكاملة ومنخفضة التكلفة. يبدأ البحث بمراجعة شاملة للأدبيات العلمية المتعلقة بآليات الانزلاق وأنواعه وأسبابه وطرق تقييم المخاطر، مع التركيز على قيم الإزاحة وتأثير منسوب المياه الجوفية. كما تم تحليل مختلف تقنيات المراقبة، بما في ذلك الاستشعار عن بعد، وأجهزة القياس الميدانية، وأنظمة الإنذار المبكر. وتتمثل المساهمة الأساسية لهذا العمل في التصميم المفاهيمي ومراحل تطوير نموذج أولي ذكي قادر على جمع وتحليل البيانات البيئية والجيوتقنية وإصدار تنبيهات عند تجاوز حدود الاستقرار. يهدف هذا النظام إلى تقليل مخاطر الانزلاقات الأرضية وتوفير حل عملي قابل للتطبيق في المناطق ذات الإمكانيات المحدودة.

كلمات مفتاحية: الانزلاقات الأرضية، استقرار المنحدرات، المراقبة ، الإنذار المبكر، المخاطر الجيوتقنية

Abstact

Landslides represent one of the most dangerous geotechnical hazards, causing significant human, economic, and environmental losses, particularly in areas with complex geology and steep slopes. This work focuses on the development of a real-time landslide monitoring and control tool based on an integrated and low-cost technological approach. The study begins with a comprehensive review of landslide mechanisms, classifications, triggering factors, and risk assessment methods, with particular emphasis on displacement-based criteria and groundwater influence. Various monitoring techniques are analyzed, including remote sensing methods (InSAR, optical imagery, LiDAR), in-situ instrumentation, and early warning systems. The core contribution of this research lies in the conceptual design and development process of an intelligent monitoring prototype capable of collecting environmental and geomechanical data, processing them in real time, and issuing alerts when instability thresholds are exceeded. The proposed approach aims to provide an effective, adaptable, and economically feasible solution for landslide risk mitigation, especially in regions with limited technical and financial resources.

Keywords: Landslides, Slope stability, Monitoring systems, Early warning, Geotechnical risk.

Résumé

Les glissements de terrain constituent l’un des aléas géotechniques les plus dangereux, entraînant des pertes humaines, économiques et environnementales importantes, notamment dans les zones à topographie complexe et à sols instables. Ce travail porte sur le développement d’un outil de surveillance et de contrôle des glissements de terrain en temps réel, basé sur une approche technologique intégrée et à faible coût. L’étude débute par une revue approfondie de la littérature concernant les mécanismes, les types, les causes et les méthodes d’évaluation du risque des glissements, en mettant l’accent sur les déplacements et l’influence du niveau des eaux souterraines. Les principales techniques de surveillance sont ensuite analysées, incluant la télédétection, l’instrumentation in situ et les systèmes d’alerte précoce. L’apport principal de ce travail réside dans la conception et le processus de développement d’un prototype intelligent capable de collecter, analyser et transmettre des données en temps réel afin de détecter les signes précurseurs d’instabilité. Cette solution vise une application efficace et adaptée aux contextes à ressources limitées.

Mots-clés : Glissement de terrain, Stabilité des pentes, Surveillance, Alerte précoce, Risque géotechnique.

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General Introduction

Landslides are among the most hazardous geological phenomena that threaten soil stability and infrastructure, often causing significant human and material losses—especially in regions with complex terrain or unstable soils. These events occur when ground masses lose equilibrium and slide down slopes due to natural factors such as heavy rainfall, earthquakes, and erosion, or due to human interventions like excavation, uncontrolled urban development, and improper land use. Therefore, understanding landslides and analyzing slope stability is a fundamental concern in geotechnical engineering.

Earthworks such as cuttings, fills, and embankments, as well as natural slopes, are of great concern for geotechnical engineers and researchers alike. Slope failure often results in dramatic, destructive, and sometimes fatal consequences. Numerous methods of stability calculation have been proposed, yet most agree on defining a global safety factor through which slope stability is assessed and ensured.

Our main objective in this work is to develop a tool to control land slides in real time using relevant technologies. This work is composed of three partes:

- In the first part we presented a literature review on landslides;

- In the second part we presented the different techniques of landslides monitoring;

- In the third part we presented the conceptual part of the present work.

Chapter 1: Literature Review on landslides

1.Introduction

Landslides are one of the most serious natural disasters that threaten human life and property, especially in mountainous areas or with steep slopes. This phenomenon has been of great interest to researchers and scientists, especially in view of climate changes and increased human interventions in the environment. This chapter deals with a presentation of the most prominent studies and previous research related to landslides, focusing on their causes, types, forecasting methods, monitoring and early warning methods.

2.Slope stability

2.1.Definition of Landslides

Landslides are gravitational movements of a mass of soil whose volume can range from a few tens of m^3 to several tens of millions of m3. The thickness of the slip can vary from a few meters to several tens of meters while their surface can reach a few km^2. There is therefore an extreme variability of landslides from the one that can lead to a closure of a road to the one that completely modifies the topography of a site. These landslides can be terrestrial or underwater. Traces of sliding have also been discovered on Mars.



Figure 1. Chambonource landslide: SAGE

3. Types of landslides

In low-relief areas, landslides occur as cut-and-fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, the collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. The most common types of landslides are described as follows [1].

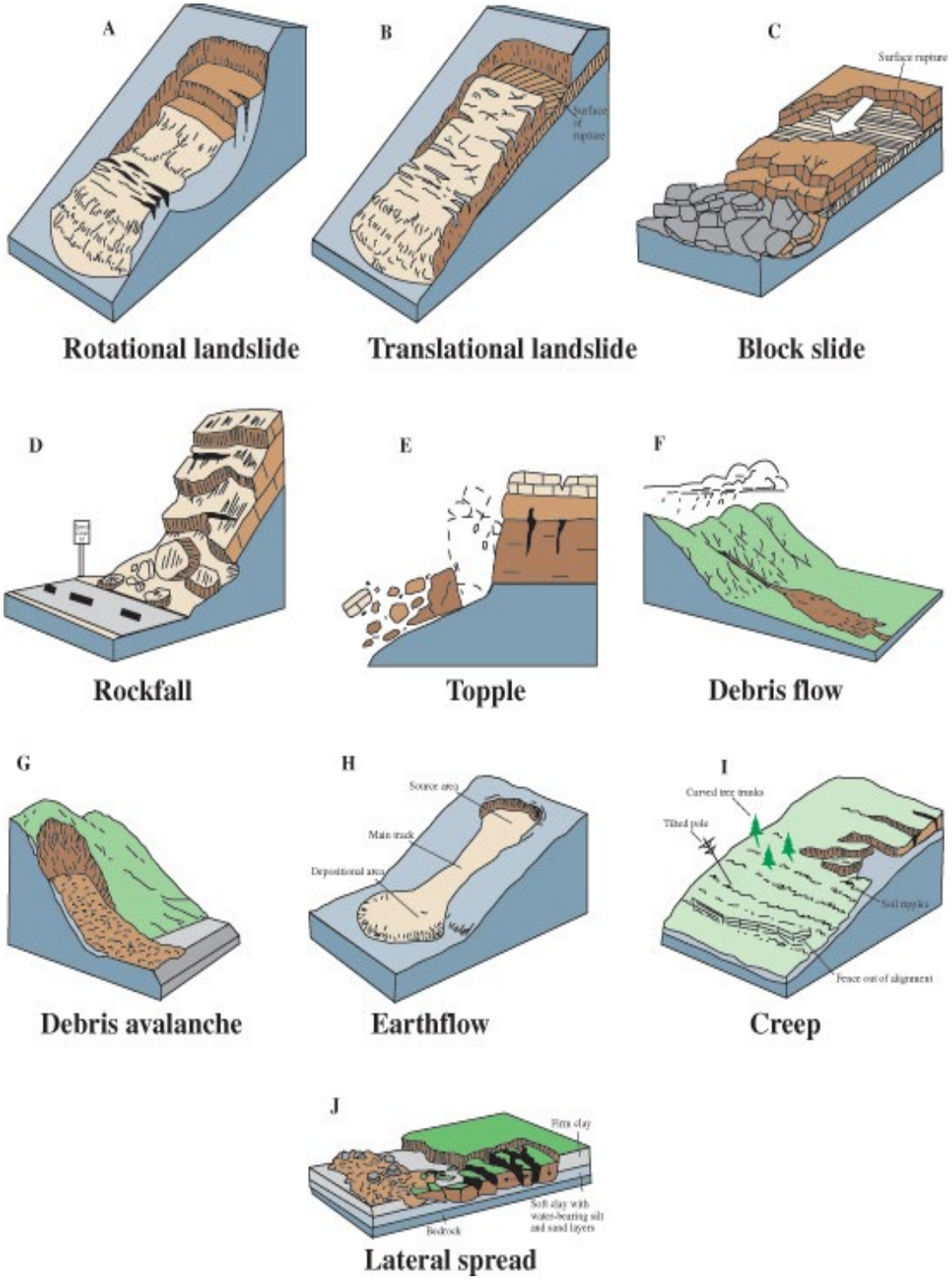


Figure 2. Major types of landslides [1].

Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where a distinct zone of weakness separates the slide material from the more stable underlying material. The two major types of slides are rotational slides and translational slides [2]:

3.1.Rotational slide

This is a slide in which the rupture surface is curved concavely upward, and the slide movement is roughly rotational about an axis parallel to the ground surface and transverse across the slide.

3.2.Translational slide

In this type of slide, the landslide mass moves along a roughly planar surface with slight rotation or backward tilting. A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass.

3.3. Planar landslide

Planar slip refers to movement along a flat surface, such as a layer or constructed surface. This type of slip often occurs in environments where there are layers of rocks that fracture along a straight shear plane, which can take different positions. It can result in slip occurring on the side or foot of a slope [3].

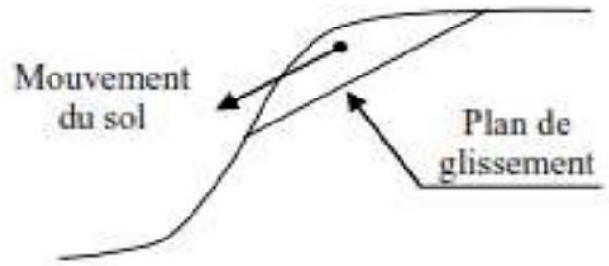


Figure 3. Planer landslide.



Figure 4. Planar Landslide in the "El Martello basin" of Rio Blanco.

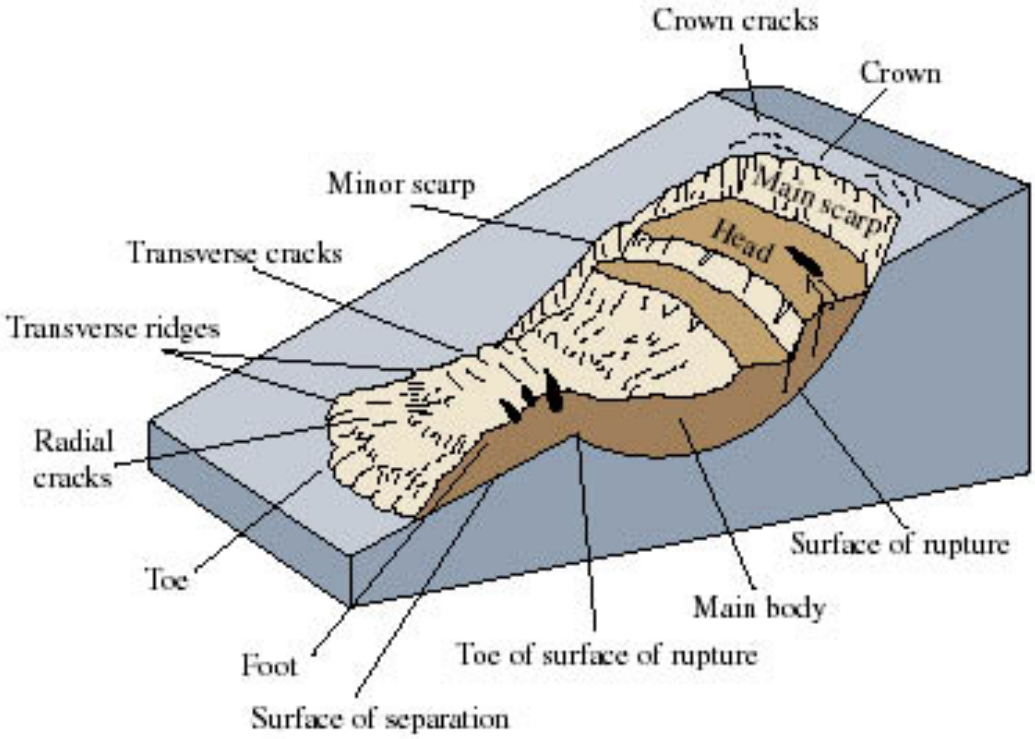


Figure 5. Rotational landslide.

3.4. Circular or rotational slide

In this movement case, the sliding surfaces are more or less circular. A clear starting zone and bead generally characterize the movements; the front is more or less pronounced, and the internal restructuring depends on the nature of the ground and the importance of the movement. It mainly occurs on loose ground and homogeneous rock, not very cohesive or very split [4].



Figure 6. Rotational landslide (La Conchita, coastal region of Southern California. Landslide and land flow in 1995).

3.5. Any Landslide (random)

The movement is very similar to the previous one in its external pace. However, the vertical section of the sliding surface is irregularly shaped.

It is often a combination of the two previous cases. According to a random shear plane, breaks are usually caused by translational motion and occur in heterogeneous deposits [5].

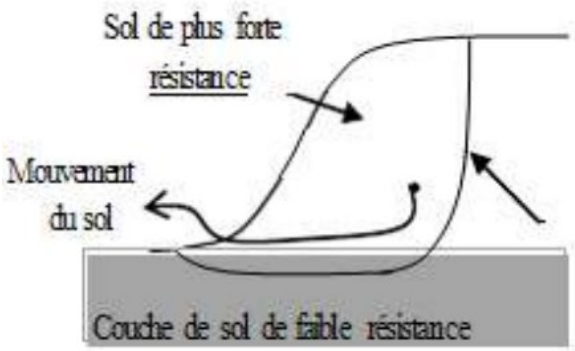


Figure 7. Any Landslide.



Figure 8. Any landslide (U.S. geological core log).

4.Landslide causes

The main cause of landslides is the effect of gravity on the weakening material that makes up the sloped terrain.

While some landslides occur slowly over time (e.g., a few meters of land movement per month), the most damaging landslides occur suddenly following heavy rainfall earthquakes. That was the case in the last extremely deadly mudslide in the continental United States. The 2014 mudslide killed 43 people and destroyed 49 homes and other structures.

Part of an unstable mound collapsed, throwing dirt and debris south across the North Fork of the Stillaguamish River and engulfing a rural community. Before the landslide, the Oso area, about 55 miles northeast of Seattle, had experienced heavy rain over 45 days, with some sources receiving up to 261 % of normal levels [1].

4.1. Geological causes [1]

a. Weak or sensitive materials
b. Weathered materials
c. Sheared, jointed, or fissured materials
d. Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)
e. Contrast in permeability and/or stiffness of materials

4.2. Morphological causes [1]

a. Tectonic or volcanic uplift
b. Glacial rebound
c. Fluvial, wave, or glacial erosion of slope toe or lateral margins
d. Subterranean erosion (solution, piping)
e. Deposition loading slope or its crest
f. Vegetation removal (by fire, drought)
g. Thawing
h. Freeze-and-thaw weathering
i. Shrink-and-swell weathering

4.3. Human causes [1]

a. Excavation of slope or its toe
b. Loading of slope or its crest
c. Drawdown (of reservoirs)
d. Deforestation
e. Irrigation
f. Mining
g. Artificial vibration
h. Water leakage from utilities

5.Risk Assessment according to the Displacement Values

5.1.Low Displacement (< 5 mm/year)

Risk: very low.

Characteristics: the movements are slow and are usually associated with minor natural processes or internal modifications of the soil.

Impact: little or no impact on infrastructure or security.

Measurements: regular monitoring to detect any acceleration.

5.2.Moderate Displacement (5-20 mm/year)

Risk: Medium

Characteristics: Moderate displacements can indicate increasing instability, often influenced by external factors such as rainfall or groundwater fluctuations.

Impact: Increased risk for small infrastructure or rural areas.

Measures: Implementation of drainage systems and strengthening of sensitive areas.

5.3.High Displacement (20-100 mm/year)

Risk: High.

Characteristics: Rapid movements signal significant instability, often triggered by major events such as intense rains, earthquakes or human activities.

Impact: Significant damage to infrastructure and threat to human security.

Measures: Early warning systems, evacuation of areas at risk, stabilization work.

5.4.Very High Displacement (>100 mm/year)

Risk: Very high.

Features: The movements are fast and critical, indicating an imminent or ongoing slip. Impact: Serious risks to human lives and massive destruction of infrastructure.

Measures: Immediate evacuation, emergency intervention to stabilize the terrain.

Methods Used to Assess the Risk :

Models such as the simplified model based on the Newmark displacement make it possible to calculate the probability of a slip as a function of the cumulative displacement and the geological parameters.

For example The displacement is broken down in terms of trend (internal factors), periodicity (external factors such as rain), and random terms (unpredictable factors such as wind or earthquakes). Tools such as kinetic energy indicators and their rate make it possible to identify the critical stages before a slip [5-7].

5 .4.1. (Displacement) to assess the degree of severity of landslides and determine warning levels

The Newmark displacement model is one of the popular tools in this field, as it connects seismic ground acceleration and possible displacement of slopes.MDPI Classification of risk levels based on displacement:

* Displacement of less than 5 cm: indicates low risk.

* Displacement between 5 and 15 cm: indicates moderate risk.

* Displacement between 15 and 30 cm: indicates a high risk.

* Displacement greater than 30 cm: indicates a very high risk

5 .4.2.The Newmark displacement model (Newmark's Method for Displacement)

Is one of the mathematical models that is used to analyze the behavior of structures under the influence of dynamic loads, such as earthquakes or other vibrations. It was developed by William David Newmark in 1959, and is considered one of the basic methods used in the analysis of the dynamic response of structures.

The concept of the new mark model of displacement: The new mark model focuses on the movement or displacement of objects (such as buildings, dams, soil, or other structures) when subjected to dynamic forces.

It is used to calculate the time response of structures based on dynamic equations of motion.

The model is mainly based on the method of time differences (Time Stepping Method) and is used to determine the acceleration, velocity, displacement of structures under the influence of external forces.

The basics of the new mark model: This model is considered a numerical approximation for solving the equations of motion of structural systems under dynamic influences.

It is based on the concept of dividing time into small periods and identifying dynamic variables in each time interval.

6. Steps to determine the degree of risk

The skidability of the slope depends on the physical and environmental characteristics :

* **Geological factors**: soil type, petrology, Geological fractures and faults.

* **Terrain morphology**: steep slopes, relative relief, topographic differences.

* **Hydrological conditions:** the presence of groundwater, soil saturation, natural or artificial drainage.

* **Vegetation cover**: loss of vegetation cover (deforestation) reduces the stability of sols23. 2. Analysis of triggers Slips are often triggered by certain events :

* **Intense or prolonged rains**: increased pore water pressure and saturation of sols13.

* **Earthquakes**: cause vibrations that reduce the cohesion of materials.

* **Human activities**: excavations, constructions on unstable slopes or deforestation.

* **Erosion**: by rivers or coastal waves that weaken the base of the cliffs . [11]

7. groundwater level

7.1. What is the high groundwater level

Groundwater is water that is located under the surface of the earth in porous layers of rocks or soil. The groundwater level is influenced by several factors such as the amount of precipitation, evaporation, and the volume of human consumption of water. A high groundwater level means an increase in the water level in these layers, which can lead to several environmental and geological problems [9].

7.2. Causes of high groundwater level [10]

1. Heavy rains: when large amounts of rain fall, part of the water seeps into the ground, raising the groundwater level.
2. Low groundwater extraction rate: in some areas, reducing groundwater withdrawal (such as stopping pumping water from Wells) causes the groundwater level to rise.
3. Increased surface water: in areas near rivers or lakes, a rise in the surface water level can lead to an increase in the groundwater level due to the overlap between surface and groundwater.
4. Changes in soil properties: such as the presence of layers of clay that may trap water in the upper layers, causing the water level to rise

7.3 How does a high groundwater level affect a landslide

1. Reducing soil cohesion: when the groundwater level rises, the soil is saturated with water, which leads to a decrease in cohesion between soil particles. That's because water creates internal pressure in the soil (porous water pressure), which reduces friction between soil grains and increases the likelihood of soil slipping. Waterlogged soils become less able to resist forces that may lead to collapse, such as excess weight or vibrations.

2. Increased hydrostatic pressure: the rise in the groundwater level leads to an increase in hydrostatic pressure (water pressure inside the ground pores). In cases where the hill or slope is weak or unstable, such pressure can lead to landslides, especially if the water level rises rapidly.

3. The occurrence of the phenomenon of "fluidity" or "liquefaction": in some soils, such as wet clay or waterlogged sand, a high groundwater level can cause the phenomenon of liquefaction. This happens when the soil becomes unable to withstand excess weight due to its waterlogging, which causes it to turn into a semi-liquid state, and this increases the risk of sudden landslides.

4. Effect on clay soils: clay soils tend to absorb water easily. When the groundwater level rises in these soils, the clay becomes saturated with water, which leads to a decrease in its strength and increases the risk of slipping. When increasing the hydrostatic pressure inside such saturated soil, a landslide may occur.[9]

5. Effect on sandy soils: in sandy soils, the pores are better able to drain water compared to clay soils. But if there is a large amount of water in the deep sand layers, this can lead to the formation of unstable layers that may slip when subjected to additional stress, such as an increase in weight or vibrations.

6. Increased erosion: a high groundwater level can increase the erosion process in the soil. When water saturates the soil, the soil becomes more susceptible to erosion due to the movement of water through the soil layers, which can lead to cracking or collapse of the Earth in some places.

7.4. Some studies indicate specific values of groundwater level rise associated with an increased risk of landslides

* Gradual increase in the groundwater level: in a study conducted in Slovakia, **elevations of up to 25 cm per day** were recorded in periods of heavy rainfall, which led to an increased risk of landslides

* Greater rises in the groundwater level: at the Batu higao open-pit mine in Indonesia, analyzes have shown that **a 70-meter increase in the groundwater level** may lower **the safety coefficient below 1.2**, indicating an unstable situation and an increased risk of a landslide.

It is important to note that these values are highly dependent on the local conditions of each site, including geological and hydrological characteristics. Therefore, it is always advisable to monitor groundwater levels and regularly assess the stability of slopes in landslide-prone areas

Examples from field studies

1. Region of Slovenia (collapse of Šumljak): o daily average elevation: elevations in some wells ranged **from 3 to 3.6 meters in response to daily rainfall**. o impact: this rapid rise in the groundwater level increased the instability of the slope, accelerating the landslide.

2**. Lubya district, Slovakia**: o daily rise rate: record a rise of **up to 25 cm per day** in periods of heavy rainfall. o effect: increased pore pressure on the potential slip surface, which contributed to the reactivation of the landslide.

3. **Reunion Island,** Indian Ocean (grand Ilet collapse): o daily rise rate: a rapid rise in the groundwater level that **occurs in less than a day after heavy rains**. o effect: an acceleration in the movement of the landslide is associated with an increase in the groundwater level. **[8] [9] [10] [11]**

8. Conclusion

Previous literature shows that landslides are a complex phenomenon caused by the interference of natural and anthropogenic factors, requiring a thorough understanding of the interactions between geological characteristics, environmental conditions and human practices. The methods of monitoring and forecasting have developed significantly, especially with the introduction of remote sensing technologies, precise positioning systems, and intelligent sensors. Despite this progress, there are still knowledge and application gaps, especially in rural areas or with limited infrastructure. Therefore, there is a need to create low-cost technical solutions, which can be easily integrated within local contexts, and provide a continuous monitoring and early warning capability

Chapter 2: Landslide Monitoring: Methods, Instrumentation and Techniques

1.Introduction

Introduction Landslide monitoring is the cornerstone of effective early warning systems and the reduction of their catastrophic risks. The success of monitoring depends on understanding the mechanisms of occurrence of collapses (eg: sliding, falling, flow) and the selection of appropriate methods and techniques for detecting primary (pre-failure) movements and monitoring developments in vulnerable areas. This separation requires a clever combination of modern technologies and traditional field observation.

2.Monitoring objectives

2.1.Early detection: identification of movement initiation or acceleration before catastrophic collapse [13].

2.2. Stability assessment: monitoring the behavior of slopes at risk over time and under the influence of stimuli (rain, earthquakes, human activities) [10].

2.3. Verification of prediction models: calibration and development of computer models for predicting avalanches [7].

2.4.Evaluation of the effectiveness of installation measures: monitoring the performance of installed Engineering Structures for slopes [12].

2.5.Providing data for early warning: feeding the alarm systems with data in a timely manner [13].

3.Methods and techniques of remote monitoring (Remote Sensing)

3.1.Satellite-Based space remote sensing: (InSAR-Interferometric Synthetic Aperture Radar)

Principle: it measures minute changes in the distance of the Earth's surface from the satellite (on the order of millimeters/year) using the interference of radar waves from two or more surveys of the same area at different times. Technologies: PSInSAR (permanent points), SBAS (serial monitoring), DInSAR (differential).

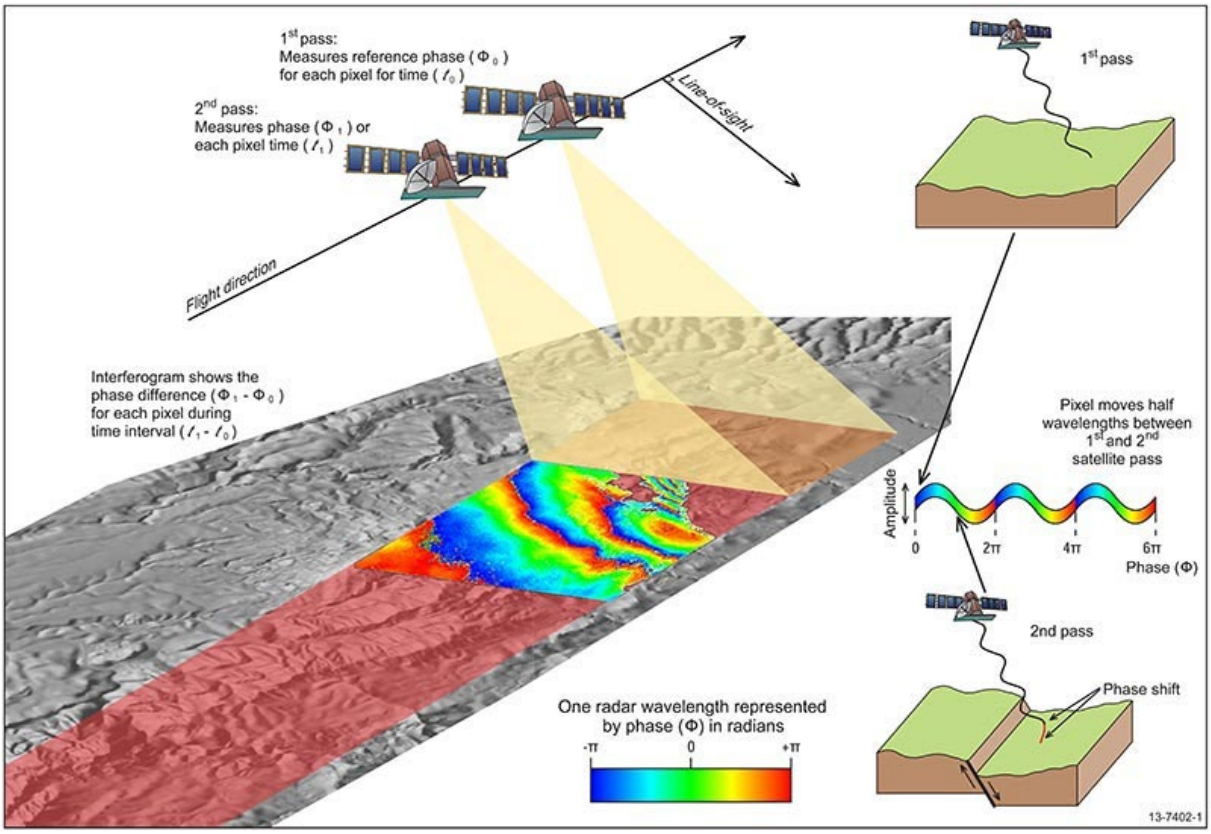


Figure 9: Two SAR images of the same area are acquired at different times.

Features: wide coverage, high accuracy in measuring vertical/horizontal displacements, ability to monitor remote/hazardous areas.

Challenges: sensitivity to dense vegetation and weather changes, a relatively long traffic cycle for some.

Devices: satellites such as Sentinel-1 (ESA), COSMO-SkyMed (ASI), TerraSAR-X (DLR).

3.2.Optical & Multispectral/Hyperspectral

Principle: detection of topographic changes, new cracks, erosion of the sides, change of land cover and vegetation characteristics that may indicate instability.

Pairwise comparison (Image Correlation) techniques such as Co-registration of Optically Sensed Images and Correlation (COSI-Corr) are used to measure horizontal offsets.

Satellites: WorldView, Pleiades, SPOT, Landsat [13].

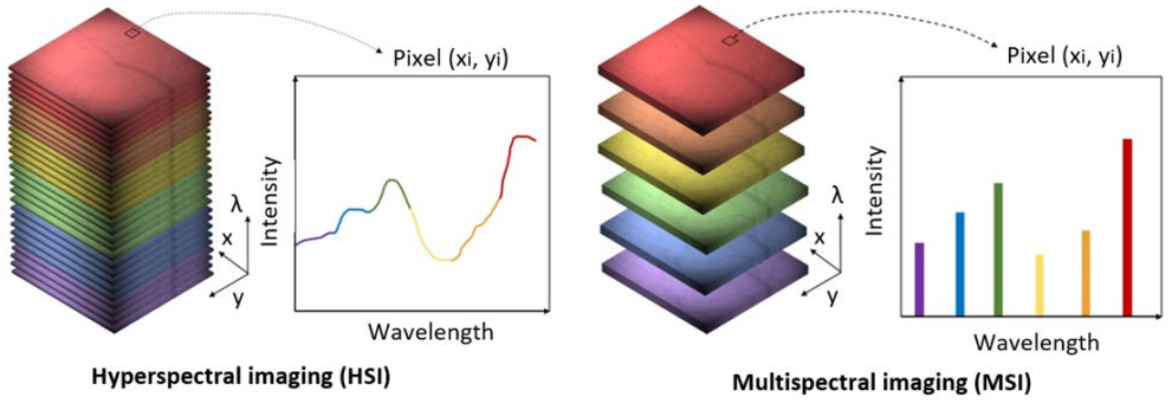


Figure 10. Comparison of spectral imaging (HSI) and multispectral imaging (MSI).

3.3.Aerial/trajectory remote sensing (Airborne/Drone-Based)

3.3.1.Laser scanning (LiDAR-Light Detection and Ranging)

Principle: generate high-precision digital elevation models (DEMs) using laser pulses from an airplane or drone.

Comparison of DEMs models at different times reveals such subtle topographic changes (up to centimeters) as surface deformations, displacement of masses, accumulation of debris.

Features: partial penetration of vegetation (especially terrestrial LiDAR - TLS), very high spatial resolution.

Devices: aircraft/drones mounted laser scanners (e.g. Riegl, Leica) [16].

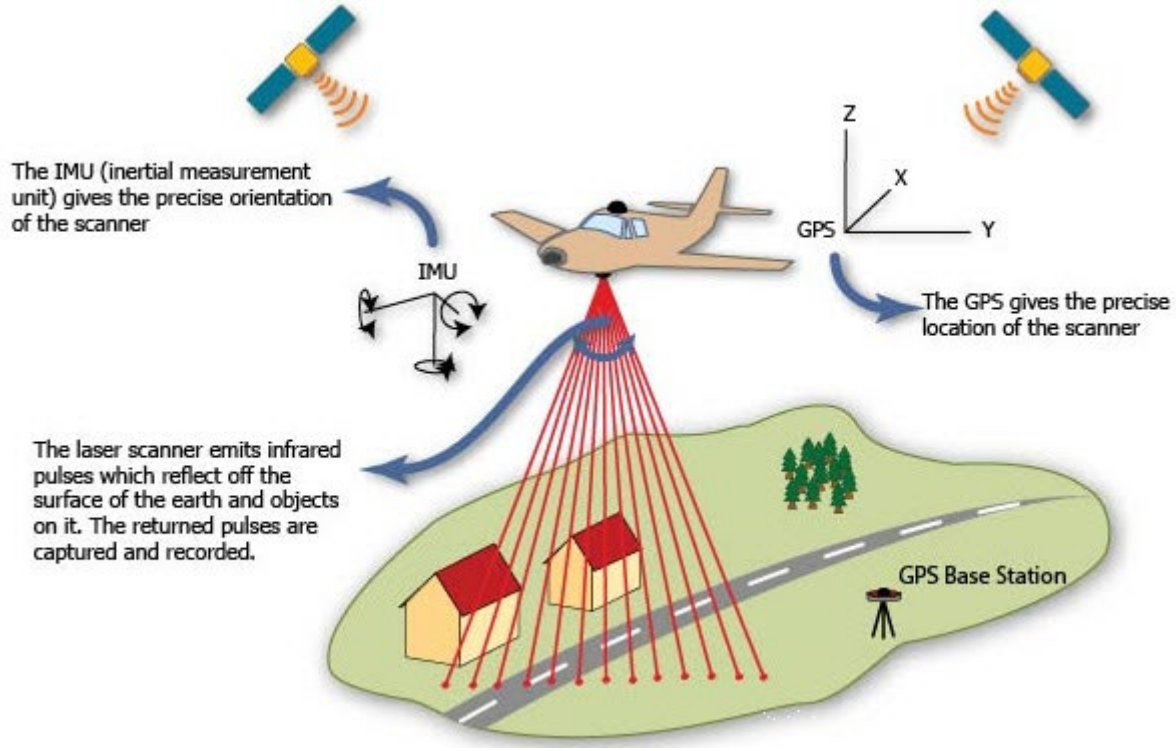


Figure11. Light Detection and Ranging System.

3.3.2.Digital aerial photography and photogrammetry

The principle: using multiple overlapping images taken from different angles (often by drones) to reconstruct a three-dimensional model (3D point Cloud or Mesh) of the surface.

Comparison of models over time reveals changes.

Related software: Agisoft Metashape, Pix4D, OpenDroneMap. Advantages: relatively lower cost than LiDAR, ease and speed of replication, rich visual data. [16]

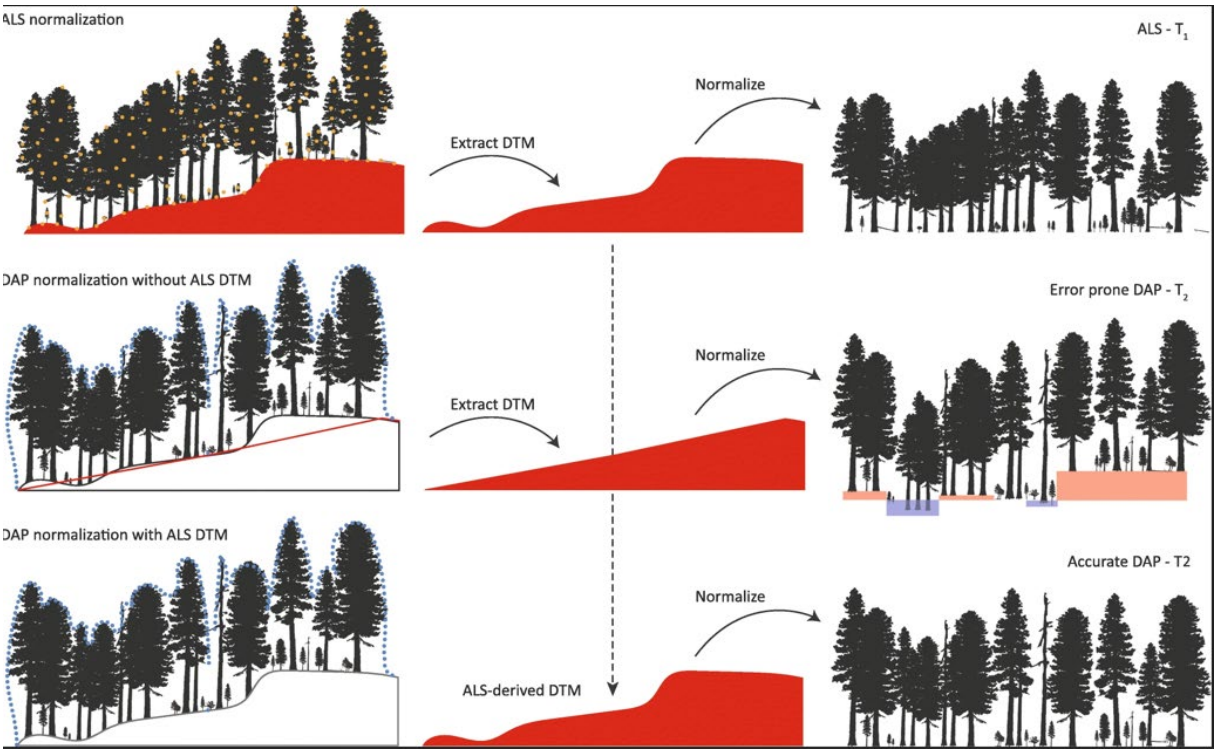


Figure 12. Digital Aerial Photogrammetry for Updating Area-Based Forest Inventories: A Review of Opportunities, Challenges, and Future Directions.

4.Field devices and systems (In-Situ Monitoring)

4.1. Movement and Displacement Monitoring (Displacement Monitoring):

4.1.1.inclinometer

Principle: measurement of changes in the angle of inclination inside a vertical (or horizontal) hole passing through the potential shear zone.

It measures the deep movement of the slope [9] [13].

There are different types: Manual (periodic manual reading), In-Place (stationary sensors connected to a recording device), MEMS (multi-axis precision sensors).



Figure 13. Inclinometer.

4.1.2.deviation scale (Extensometer)

Principle: measure the change in the distance between two fixation points (one in a stable area, the other in a moving area) across cracks or shear zones.

There are different types: Wire (Wire), Rod (Rod), Laser (Laser), wire vibration (Vibrating Wire) [10].

4.1.3.Rain sensor

Principle: detect precipitation, measure its intensity and quantity.

Importance in monitoring landslides: rains are the most common catalyst for landslides, especially when the soil is saturated with water, which increases its weight and reduces its cohesion. Precipitation monitoring is essential for early warning models [9] [14].

4.1.4.Sensitive to soil moisture

Function: measure the moisture content or water content inside the soil.

Importance in monitoring slips: high soil moisture directly increases the likelihood of collapse, as it leads to a decrease in cohesion forces between soil particles and an increase in pore pressure, which weakens shear resistance [9].

4.1.5.accelerometer.

Function: measurement of vibrations and precise movements (vibrations) in the ground or structures.

Importance in slip monitoring: capable of detecting light ground vibrations and minute movements that may precede or accompany the onset of a landslide, providing sensitive data for early warning [13].

4.1.6.Distance Sensor

Function: measuring the distance to the surface of the soil or earth (measuring the change in the surface level).

Importance in slip monitoring: it is used to observe sudden or gradual changes in the height of the surface or to measure openings in cracks, which may indicate a subsidence or the beginning of a sliding movement.

4.1.7.measure of intra-soil pressure-piezometer

Function: measurement of water pressure inside pores (pore water Pressure) in soil or rock layers. **Importance in monitoring slips**: porous pressure inside the soil is the most decisive factor affecting the stability of slopes; its height reduces the effective pressure and stress between soil grains, which significantly weakens shear resistance and raises the risk of slipping, especially after rains.

4.1.8.deformation sensor (Strain Gauge)

Function: measurement of tensile, compressive, or slight changes in length within rocks, soil, or supporting structures (e.g. retaining walls or pillars).

Importance in slip monitoring: it is used to monitor deformations, microcracks and stress changes within materials, mechanical structural changes that often precede the actual collapse by a period, providing a valuable warning indicator [13].

5.Early warning systems

Modern early warning systems are based on the integration of previous devices with real-time data analysis software.

It usually consists of: A central control unit (e.g. ESP32): collects and processes data from sensors. Wireless communication system (Wi-Fi, LoRa, GSM): for data transfer to the control center or the cloud.

Warning System (sirens, SMS messages, light signals): activates when the specified limit values are exceeded. Such systems are especially used in communities near mountain slopes or seismically active sites [14].

6.Challenges in landslide monitoring

Despite the availability of technologies, there are real difficulties, including: The high cost of devices in some advanced systems. Lack of network coverage in remote areas. Continuous maintenance of sensors exposed to weather factors. Manage and analyze huge amounts of live data. The difficulty of predicting sudden avalanches, especially on non-cohesive soils [7].

7.Conclusion

It is clear from the presentation that landslide monitoring is based on a wide technical integration that combines field observation, advanced measuring devices, communication technologies, and predictive analysis tools. Early warning systems based on live data and Intelligent Analysis are an essential tool for Risk Reduction. Despite infrastructure and cost challenges, open-source and low-cost solutions, are promising for application in resource-limited environments, provided that they are designed with engineering care and based on a thorough geological understanding of the target area.

Chapter 3 :Tool Development Process

1.Introduction

This chapter focuses on the presentation of the general steps that were followed during the development of the proposed instrument for monitoring landslides, based on innovative electronic and environmental technologies. Due to the innovative nature of this work and the researcher's quest to legally protect it by filing a patent, the development stages will be presented in general without going into technical details.

2. Conceptual design

Stage Work on the project began with the identification of the basic functional objectives of the instrument, taking into account the type of information required for early monitoring of landslide indicators. This stage was based on the review of scientific literature, geological and technical reports, as well as the analysis of traditional and modern monitoring systems. The initial concept was based on the idea of developing a low-cost integrated unit, based on reading and analyzing a set of environmental and geomechanical data, and sending alerts when unusual behavior is detected. The design also took into account the requirements of the target use environment, which often includes rugged or remote areas, which necessitated the need for the tool to be resistant to environmental conditions, low energy consumption, and scalable in the future.

3.The stage of selection of components

After determining the variables that are supposed to be monitored, the passage was made to the selection of the appropriate hardware components. This process included a comparative evaluation of several sensors, communication modules, and microcontrollers, with the aim of reaching a balanced combination in terms of performance, stability, and price. Compatibility between components, programmability, accuracy, measurement range, and real response time were also taken into account. At this stage some parts or utilities were also developed internally in an ad hoc manner, adapted to the system requirements.

4 .Prototype development stage

The prototype was assembled in an experimental development environment, using a programmable control panel to facilitate initial tests. During this phase, preliminary tests were carried out in a simulated reality environment, using auxiliary materials and systems. The stability of the performance, the ability of the system to respond in real time, and the continuity of uninterrupted data transmission have been tested. A data Logging system is also included to monitor the performance of the sensor and its outputs over a specified period of time.

5.Calibration and optimization phase

This stage was an essential step towards achieving accuracy and reliability. A series of calibration tests were carried out under various conditions, comparing the readings generated by the developed sensor with known reference readings (standard references). Calibration was carried out, and the resulting data were analyzed using statistical tools to determine the level of deviation and bias in the readings. Based on the calibration results, some adjustments were made to the module's code, the places of connection of components were reviewed, and some internal environmental factors were adjusted to ensure stable performance in variable conditions.

6.Conclusion

This chapter formed an accurate stage narrative of the process of developing an intelligent monitoring tool dedicated to the early prediction of landslides. An integrated methodology of theoretical planning, technical selection, design, calibration, and testing was followed, within a scientific and realistic vision that takes into account environmental and logistical constraints. The results of this work are promising and open up wide prospects for practical application in the fields of geotechnical safety and early warning‹

General conclusion

The first three chapters of this research dealt with the theoretical and applied framework for the development of a system aimed at early monitoring of landslides, starting from a review of the scientific literature, passing through a review of the most prominent methods and techniques adopted globally in this field, up to a systematic presentation of the stages of development of the proposed tool.

Firstly, the concept of landslides and their natural and anthropogenic causes were highlighted, along with the economic, social and environmental consequences they have, especially in areas with sensitive topography or weak infrastructure. The various scientific references also reviewed the complexity of the phenomenon and the increasing need for technical solutions to cope with the challenges of early monitoring.

Then, the various methods of landslide monitoring were analyzed, including traditional methods such as optical survey and geological analysis, modern technologies such as remote sensing, GNSS systems, InSAR technologies, as well as built-in sensors and early warning systems based on the Internet of Things (IoT). The analysis has shown that the integration of these methods, along with the development of low-cost smart tools, represents a promising direction for increasing monitoring accuracy and improving response time.

Finally, the general course that was followed in the design and development of the tool for the project was presented. This included conceptual design, component selection, prototype construction, calibration, and initial field testing. We focused on presenting the stages systematically without disclosing sensitive details, taking into account the intellectual property protection procedures related to the developer's sensitivity. The technical and logistical challenges that were dealt with during the development process were also documented, the overcoming of which will later be a decisive factor in improving the tool's operability and manufacturability.

Based on what has been reviewed, it can be said that the work at its initial theoretical and technical stages forms a solid foundation towards the development of a reliable and effective tool in the field of early warning of landslides. The transition to the evaluation and field analysis phases will later be a key point for determining the efficiency of the system and the feasibility of its deployment in various environments with high Geological Hazard.

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