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Morphodynamic analysis and identification of triggering mechanisms of flow-like landslides in the Trougoût torrential watershed (Rif, Morocco)

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ABSTRACT

Flow-like landslides represent a major natural hazard, particularly in mountainous environments where steep slopes and geodynamic processes increase risks. These gravitational phenomena can lead to significant human losses and substantial material damage, as demonstrated by the tragic event that occurred in 2019 near Asni, south of Marrakech. The Rif Mountain range in northern Morocco is characterized by highly rugged terrain resulting from complex tectonic processes, making the region particularly vulnerable to slope instability. This study focuses on the Trougoût region, located on the Mediterranean slope in the northwest of Driouch Province, and aims to identify the triggering mechanisms of flow-like landslides typical of the Trougoût torrential basin. The analysis is based on the visual interpretation of high-resolution images, combined with an assessment of geological, geotechnical, and hydrological factors, while integrating detailed morphodynamic mapping to better understand the dynamics of relief deformation. The results show that this region is particularly prone to slope instability due to the combined effects of rainfall, the mechanical behavior of rocks, and active tectonics. The morphodynamic analysis of landslides improves the understanding of complex gravitational phenomena in this region and proposes tailored strategies for geological risk management, ensuring the safety of infrastructure and local populations.

Keywords: flow-like landslides, morphodynamics, Atterberg limits, MBV, Trougoût, activity map, Rif-Morocco.

INTRODUCTION

Landslides represent a major natural hazard, particularly in mountainous regions. They can cause significant damage, both human and material, as evidenced by the tragedy in July 2019 near Asni, south of Marrakech, where a mudflow and rock debris buried a vehicle, resulting in 15 fatalities. These phenomena, often linked to seismic events such as the Al Haouz earthquake or intense rainfall, lead to destructive impacts on infrastructure and permanently alter the morphology of the terrain. In northern Morocco, the rugged relief of the Rif Mountain range, resulting from complex geological processes, promotes slope instability, which adds to the hydro-climatic risks affecting the entire country (Khaddari et al., 2023; El Idrissi et al., 2024; Rahoui et al., 2024). Rainfall, tectonic deformations, and earthquakes exacerbate these risks, making the region particularly vulnerable to landslides (Millier-Lacroix, 1968; Azzouz et al., 2002; Labriki, 2020).

Our current study focuses further north in the Rif Mountain range, on the Trougoût watershed, located in the northwest of Driouch Province on the Mediterranean coast, extending across the torrential slopes bordering the Nekor plain and Al Hoceima Bay to the east (Fig. 1). This region is prone to complex gravitational movements, typically slow-moving, occurring on moderate to steep slopes. These movements can take various forms, including landslides evolving into flows, known as "Earth flows" (e.g., Malet et al., 2004; Hungr et al., 2014; Carrière et al., 2018). These are continuous and progressive geological phenomena that can develop over long periods, ranging from a few months to several years (Dikau et al., 1996; Flageollet, 1996; Cruden and Varnes, 1996). Moreover, a thorough understanding of the mechanisms and processes driving these phenomena is essential for risk management and the safety of populations living in this region.

The main goal of this study is to investigate the triggering mechanisms of landslides by analyzing a representative case: the flow-like landslide of Takariast (Fig. 1c), situated on the northern slope of the Trougoût watershed. This research also involves the detection and mapping of landslides throughout the entire Trougoût watershed. As the first study of its kind in the region, it offers a valuable contribution to the evaluation of landslide risks in this highly vulnerable area. Such landslides are prevalent on this slope and play a crucial role in supplying sediment to torrents, with torrential rainfall being a primary triggering factor.

STUDY AREA

The study area encompasses several morphological units that constitute the Trougoût torrent, which is developed within the bedrock of the Ketama unit (Maurer, 1968). The torrent valley is characterized by steep, incised slopes and a rugged topography (Fig. 1). During episodes of intense rainfall, water rapidly flows through the watershed, significantly increasing the torrent's discharge. This leads to the

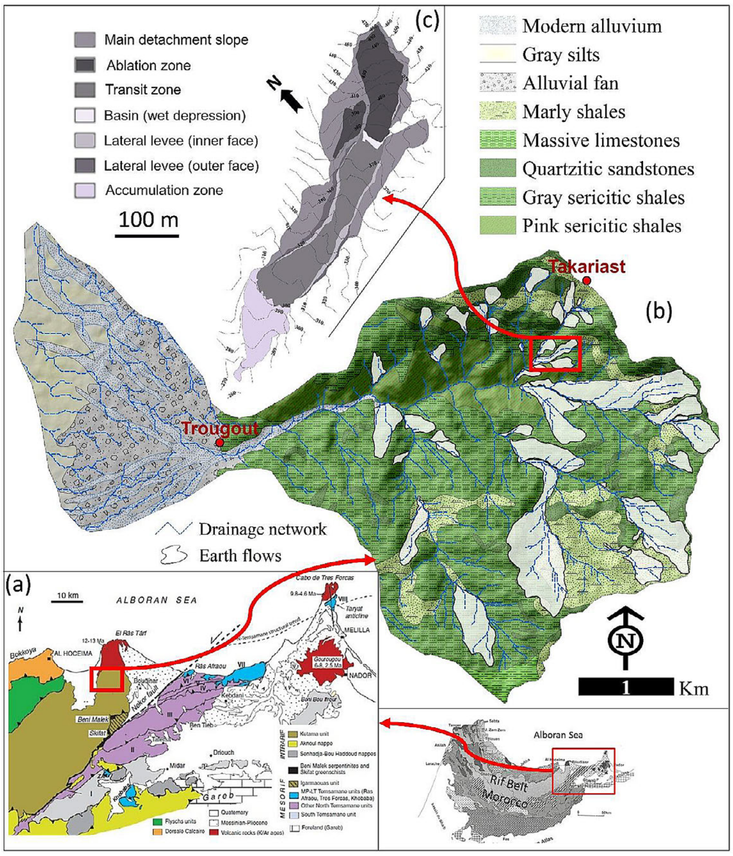

Figure 1. Geological and structural context of the Trougoût Watershed: (a) atructural map of the eastern Rif after Frizon de Lamotte (1985) and Negro et al. (2007), in Michard et al. (2007); (b) geological map of Trougoût (extracted from the geological maps of Al Hoceima (Choubert et al., 1984a) and Boudinar (Choubert et al., 1984b) at 1:50000 scale); (c) map of the Takariast flow-like landslide on the northern slope of the Trougoût Watershed

rapid formation of temporary streams and small gullies, which erode rock and clay materials along their paths. The low infiltration capacity of clayey soils exacerbates erosion along the banks, making clay walls unstable and prone to landslides when saturated. These processes result in rapid alterations to the watercourse. Torrential rains also contribute to the transport of substantial sediment loads into the torrent. As the torrent reaches the Nekor plain, its flow velocity decreases, reducing its capacity to transport sediments. Consequently, the transported materials are deposited, gradually forming a wide, fan-shaped alluvial cone.

Furthermore, the torrent, shaped within the deformed and thrust bedrock of the Ketama unit (Andrieux, 1971), is situated in close proximity to the Nekor fault (Fig. 1a), a major trans-Alboran strike-slip structure in the region (Morel, 1987; Meghraoui et al., 1996; Chalouan et al., 2006). To the north, the bedrock is overlain by lava intrusions and the terminal flow of the Neogene volcanism of Ras Tarf (Hernandez et al., 1987; Aït Brahim et al., 1990). To the east, the area is bounded by the post-nappe Boudinar basin, which formed during the Upper Miocene (Guillemin and Houzay, 1982; Barhoun and Wernli, 1999; Azdimousa et al., 2011), following the earliest volcanic activities (El Azzouzi et al., 2014). To the west, the area terminates in the Nekor plain, marked by the terminal lobe of the torrent. From a lithological perspective, two superimposed units can be distinguished (Fig. 1b):

- Beni Boû Yacoub Unit: This unit consists of marly schists from the Upper Cretaceous, interbedded with limestone bundles that transition into massive limestones of Jbel El Kama. It also includes mixed zones containing blocks of Jurassic limestone or dolomite, as well as marl-limestones from the Lower Cretaceous (Choubert et al., 1984).
- Ketama Unit: Composed primarily of gray to black sericitic schists from the Albian-Aptian, this unit exhibits a pink coloration along the abnormal contact with the Upper Cretaceous. Locally, it is characterized by an abundance of quartz-sandstones (Andrieux, 1971; Choubert et al., 1984).

METHODOLOGY

An integrated methodology was adopted to study the landslide in the Trougoût watershed, focusing on the geological characteristics, soil properties, local hydrology, and precipitation patterns, within the specific context of the Takariast flow-like landslide. This approach includes a morphodynamic analysis based on satellite imagery from the Google Earth database, correlated with observed precipitation variations between 2004 and 2023. Fieldwork was also conducted to identify the type and conditions of the movement, as well as to collect samples for the geotechnical characterization of unstable materials.

Role of precipitation and morphodynamic evolution of the landslide

Initially, a morpho-dynamic map was developed using geospatial data analysis from high-resolution satellite imagery provided by Google Earth, complemented by topographic and geological maps at a 1:50,000 scale. These data provided a detailed understanding of the terrain configuration and facilitated the identification of areas showing signs of ground movement. Remote sensing and photo-interpretation techniques were subsequently employed to map landslides across the watershed.

To explore the relationship between landslide dynamics and precipitation in the region, a morpho-dynamic analysis was conducted on the unstable site of Takariast. This analysis was based on a series of Google Earth images covering the period 2004–2023 and precipitation data extracted from the NASA Power platform for the same period. The results enabled the reconstruction of terrain deformation evolution and the identification of key geomorphological features associated with landslides (scarps, cracks, tension fissures, soil deformations). Finally, an activity map was produced to represent the density of fractures and tension cracks. This map provides a precise visualization of active landslide zones, distinguishing areas with significant movements from those with potential instability.

Field data collection

Field data collection for the Takariast landslide study involved direct field observations, geological surveys, and sample collection. These methods provided valuable data on the materials involved in the landslide, interpretation of the movement type, and mapping of the geological structure and morpho-dynamic features of the site. These data are crucial for a thorough analysis of the landslide and a better understanding of its mechanisms. Direct field observations were made to explain the type of movement. We meticulously studied morphological features, paying particular attention to cracks, soil deformations, subsidence, and material accumulations. Observing the movement form helped determine the landslide dynamics, direction and speed of displacement, as well as tension and shear zones.

Geotechnical characterization of unstable materials

As part of this study, three samples were collected (see location on Figure 7) to evaluate the behavior of materials involved in the landslide in relation to water and to estimate the clay content by analyzing parameters such as grain size distribution, Atterberg limits, and methylene blue value (MBV). Grain size analysis was performed using a series of sieves to separate different soil fractions. The three soil samples were sieved, and the weights of the different fractions were measured. This analysis allowed us to quantify the particle size distribution and estimate the clay content in the soil. Atterberg limits were determined to assess the soil's behavior in relation to water, including the liquid limit and plastic limit. The liquid limit represents the moisture content at which the soil transitions from a plastic to a liquid state (Mitchell and Soga, 2005), while the plastic limit corresponds to the moisture content at which the soil loses its plasticity. By measuring the moisture content at which these transitions occur, we can evaluate the soil's plasticity and sensitivity to water. MBV tests were conducted according to the French standard NF P 94-068 to determine the specific surface area of clay particles (Hang and Brindley, 1970; Santamarina et al., 2002) and to serve as an indicator of clay content in the soil. This test involves adding a methylene blue solution to the soil and measuring the amount absorbed by the clay particles. The higher the clay content, the greater the amount of methylene blue absorbed. Consequently, the MBV will help estimate the content of swelling clays such as montmorillonites (Chen et al., 1999) and assess their influence on soil behavior, particularly in terms of deformation, permeability, and compressibility.

RESULTS

Morphodynamic evolution of the landslide

Landslide morphology

The morphology of a landslide is a key indicator for characterizing its dynamics, internal mechanisms, and interactions with the underlying substrate (Varnes et al., 1996; Flageollet, 1989; Hungr et al., 2014). Detailed analysis of the satellite image (Fig. 2) reveals that the Takariast landslide exhibits a quasi-viscous dynamic, moving along a pre-existing failure surface and deforming continuously. This morphology reflects a response to gravitational stresses and the geomechanical properties of the mobilized materials (Labriki et al., 2016; Labriki, 2020; Taj et al., 2024). The landslide can be subdivided into three distinct morpho-functional entities:

- Upstream (source zone) – the ablation zone, or source zone, is characterized by a main scarp with a distinct crown-like morphology, indicative of a major initial rupture in the materials. This configuration suggests a rotational or translational nature of the landslide. The presence of open tension cracks reflects shear deformation mechanisms induced by gravitational stresses. The accumulation of debris at the base of this main scarp indicates gravitational collapse, likely linked to hydromechanical conditions and a loss of cohesion in the geological formations.
- Intermediate (transport zone) – the transport zone manifests as a narrow, elongated corridor, approximately 200 meters long and no more than 60 meters wide. This section is dominated by slow gravitational flow kinematics, where the mobilized material moves along a relatively intact sliding surface. The geometry of this zone is strongly influenced by local slope variations, which condition and direct the propagation of movement.
- Downstream (accumulation zone) – the accumulation zone is characterized by a widened terminal lobe, marked by the accumulation of heterogeneous debris comprising materials of varying sizes. The slope gradually becomes less steep but terminates in an abrupt front with an inclination ranging between 20° and 30°, reflecting a decrease in kinetic energy and a marked slowdown in flow dynamics. The observed morphological structures, such as compression ridges and frontal bulges, testify to the final compressive stresses and the progressive deceleration of the mobilized materials, typical of accumulation lobes in flow-like landslides.

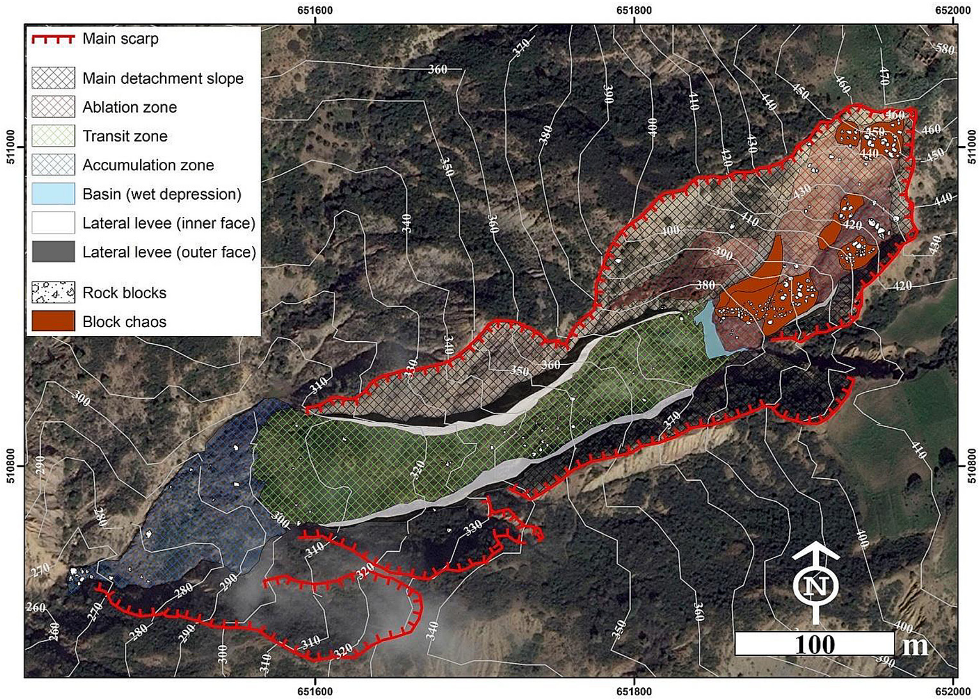

Figure 2. Morphology of the Takariast landslide based on photo-interpretation of a high-resolution Google Earth image dated March 16, 2014: This Figure illustrates the distinct morphological features of the Takariast landslide, as identified through the analysis of a high-resolution satellite image. The photo-interpretation highlights key elements such as the main scarp, tension cracks, transport corridor, and the terminal accumulation lobe, providing a comprehensive overview of the landslide's structure and dynamics

Collectively, these morphological entities illustrate the kinematics of the landslide and its morpho-dynamic evolution. The tension and traction cracks, compression ridges, and rounded lobes with lateral and frontal bulges observed align with the descriptions of Flageollet (1989) and Baum et al. (2003). These structures result from a complex interaction between the rheological characteristics of the materials, the geometry of the sliding surface, and the gravitational stresses imposed on the system.

Correlation between acceleration periods and precipitation

The analysis of precipitation data and the evolution of the Takariast flow-like landslide highlights a direct relationship between rainfall events and the mechanisms of destabilization, reactivation, and progressive deformation of the landslide body (Fig. 3 et 4). Between 2004 and 2006, low precipitation levels maintained a general state of stability. The landslide remained latent or inactive, with limited signs of erosion and intact vegetation cover in the source zone. These conditions indicate that, despite a topography prone to instability, the absence of prolonged saturation contributed to soil cohesion and shear resistance, preventing any notable reactivation.

The exceptional torrential rains of October 24, 2008, had major impacts on the Trougoût region (Fig. 3), as evidenced by the testimonies of the local population. These intense rainfall events caused extreme flooding in the Trougoût plain (Fig. 3, b1 and b3) and triggered several landslides, the most significant of which was the Takariast landslide. Additionally, basal erosion led to the collapse of several cliff banks (Fig. 3, b2), further increasing the instability of the terrain. An analysis of satellite images between 2007 and 2009 reveals a notable change in the image from September 21, 2009 (Fig. 4), marked by the collapse of the summit portion and the reactivation of the Takariast landslide, confirming earlier testimonies. This period includes the 2008 rainfall episode, which saturated the soils and generated hydraulic overload, drastically reducing the shear strength of the materials and triggering gravitational instability. Regressive erosion, facilitated by a ravine located at the foot of the ablation zone, played a critical role in the initiation and propagation of the landslide, a phenomenon also observed on the left bank of the Trougoût valley

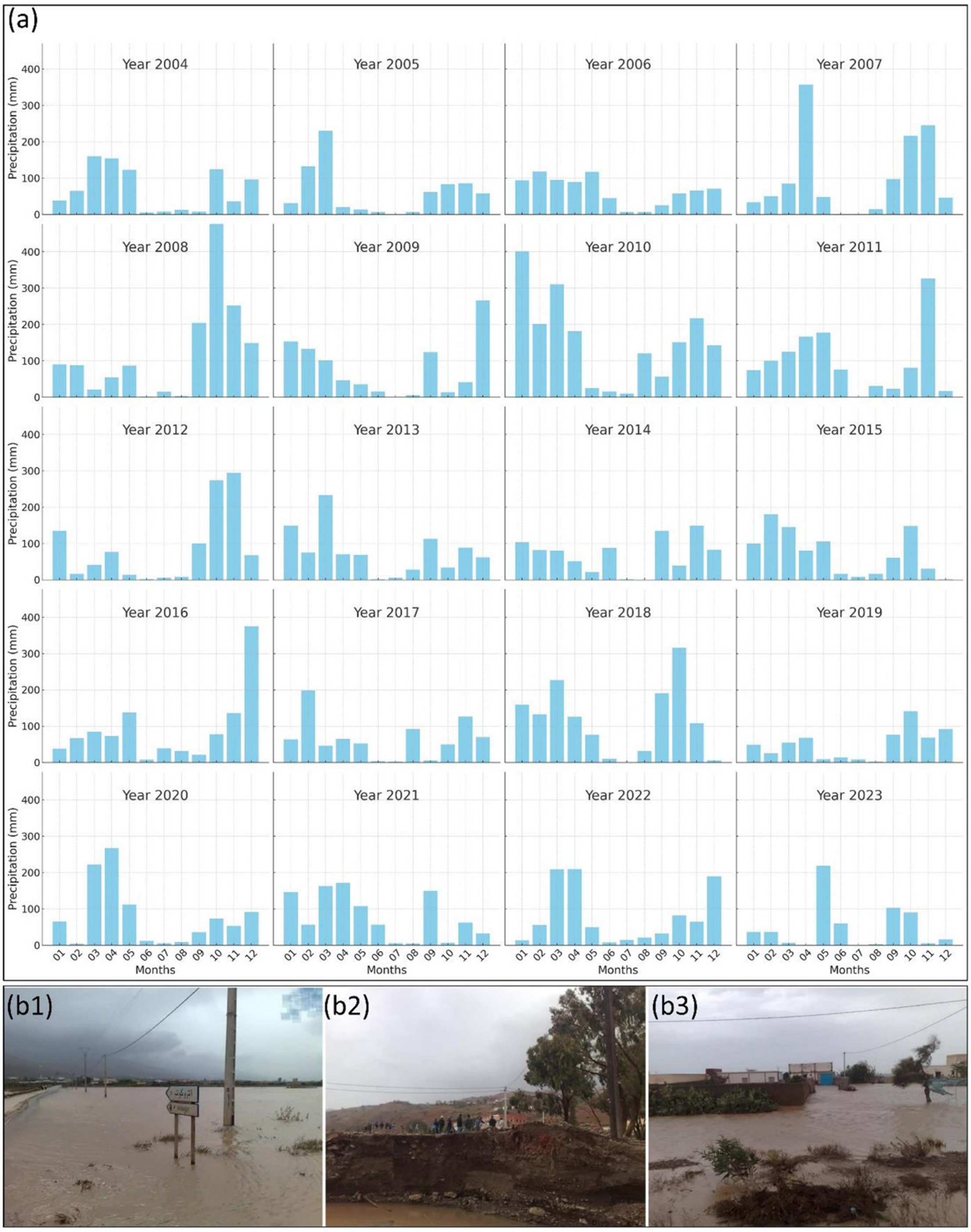

Figure 3. Annual precipitation trends in the Takariast landslide area between 2004 and 2023 (Precipitation data downloaded from https://power.larc.nasa.gov/data-access-viewer/, accessed in April 2024). (a) Annual precipitation trends; (b1) Flooding in the Trougoût plain; (b2) Bank erosion on the left bank of the Trougoût valley; (b3) Flood level in the village of Trougoût

(Fig. 3, b2). The reactivation of the landslide is further confirmed by the absence of vegetation in the source area, indicating recent disturbance.

Between 2010 and 2012, precipitation was more moderate compared to the previous period but sufficient to maintain active landslide movement in a fragile geomorphological context. The formation of wet depressions, fed by lateral gullies, as well as the appearance of lateral ridges and tension cracks, reflect progressive deformation associated with prolonged saturation episodes. These observations indicate a period of hydromechanical adjustment, where soils remained sensitive to water accumulation, promoting slow but continuous displacements.

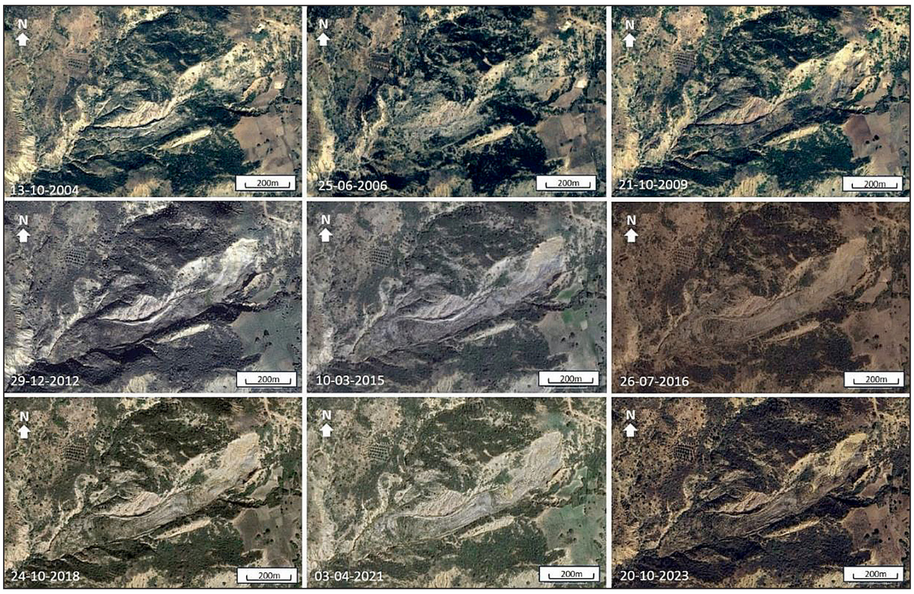

Figure 4. Google earth images showing different stages of the Takariast landslide evolution between 2004 and 2023

The period 2013–2015, relatively dry, saw a decrease in precipitation, limiting the effects of prolonged saturation. Nevertheless, sporadic rainfall events maintained moderate activity, as evidenced by the development of cracks in the landslide body, reflecting the propagation of internal stresses likely linked to cycles of rewetting and drying. These processes highlight that, even during periods of reduced precipitation, the soil's hydraulic memory and structural imbalances inherited from previous phases can sustain a certain level of activity.

In contrast, between 2016 and 2018, intense and frequent precipitation once again saturated the soils to a critical point, leading to more pronounced reactivation of deformation processes. The appearance of folds in the surface layers, chevron structures, and compression fractures at the frontal bulge indicate local shortening and increased compressive stresses. These mechanisms are characteristic of an active landslide under the influence of high pore pressures, exacerbated by the soil's low drainage capacity.

Finally, during the period 2019–2023, a slight decrease in precipitation was observed, but the landslide continued to exhibit accelerations during wet periods and slowdowns during dry periods, illustrating a creep behavior controlled by hydrological variations. This relative stabilization of the landslide edges, combined with slow but persistent movement, reflects a state of progressive adjustment where displaced materials equilibrate under moderate gravitational and hydrological stresses.

Hydrological configuration of the site

The landslide is located within the schist formations of the Ketama unit, overlain by a thick layer of superficial deposits and slope debris. Water sources in the area are scarce, with some points corresponding to resurgences fed by the infiltration of runoff water, often associated with perched aquifers in the superficial formations. However, water is abundant within the landslide body, particularly in two wetland areas. The first is located at the base of the ablation zone, forming a depression fed by runoff water from a gully that cuts through the superficial formations on the right side. The second is situated downstream, created by the accumulation of flow deposits in the gully bordering the landslide on the left side, where these deposits obstruct the circulation and flow of rainwater (Fig. 5).

The hydrogeological configuration of the slope is complex and directly contributes to the landslide dynamics. Gravitational movements generate shear fractures and tension cracks, the extent of which can be accentuated during dry periods due to material shrinkage. This network of cracks, particularly dense within the moving mass, facilitates significant infiltration of rainwater into the flow materials. This infiltration alters the mechanical properties of the materials, increasing their instability and susceptibility to sliding.

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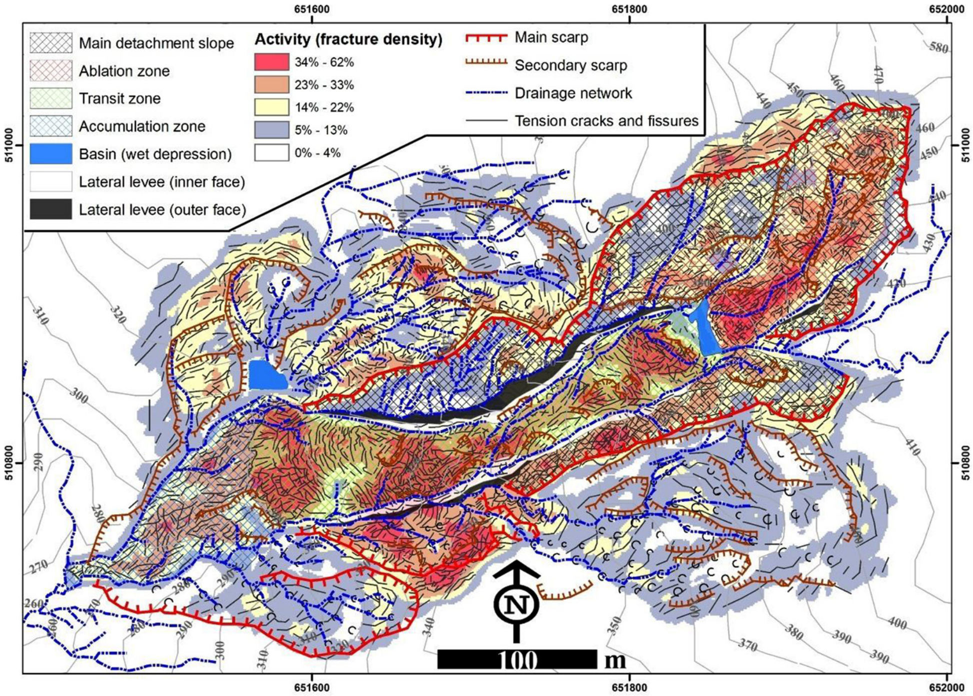

Figure 5. Activity map of the Takariast flow-like landslide showing evolution trends, crack distribution, hydrographic network, and the presence of two wetland depressions

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Analysis of field data

Superficial formations

Colluvium represents the most widespread superficial formation in the studied slope. It results from the gradual accumulation of pedological materials, weathering products, and loose rocks detached from the upper parts of the slope (Fig. 6a). These materials, transported primarily by gravity and runoff over short distances along the steepest slope lines, can also be mobilized as mudflows during sudden downpours or torrential rains. Depending on the climatic conditions that led to their formation, colluvium retains some characteristics of the source materials, while the alternation of fine and coarse layers observed in these slope deposits highlights the predominant role of intense precipitation in their genesis (Fig. 6b).

Furthermore, this area shows evidence of past landslide activity, as indicated by the presence of chaotic deposits overlying the gray schist formations of the Ketama unit (Fig. 6c). These deposits are interpreted as the product of gradual accumulations resulting from landslides in adjacent slopes. Ancient deposits associated with flow-like landslides appear to have filled a pre-existing irregular topography, reflecting a complex slope evolution over time.

Geology of the source zone

The source zone of the landslide is characterized by a main scarp approximately 80 meters high, composed of Upper Cretaceous marly schists belonging to the Beni Boû Yacoub unit (Fig. 7). These formations overlie the Ketama unit, which

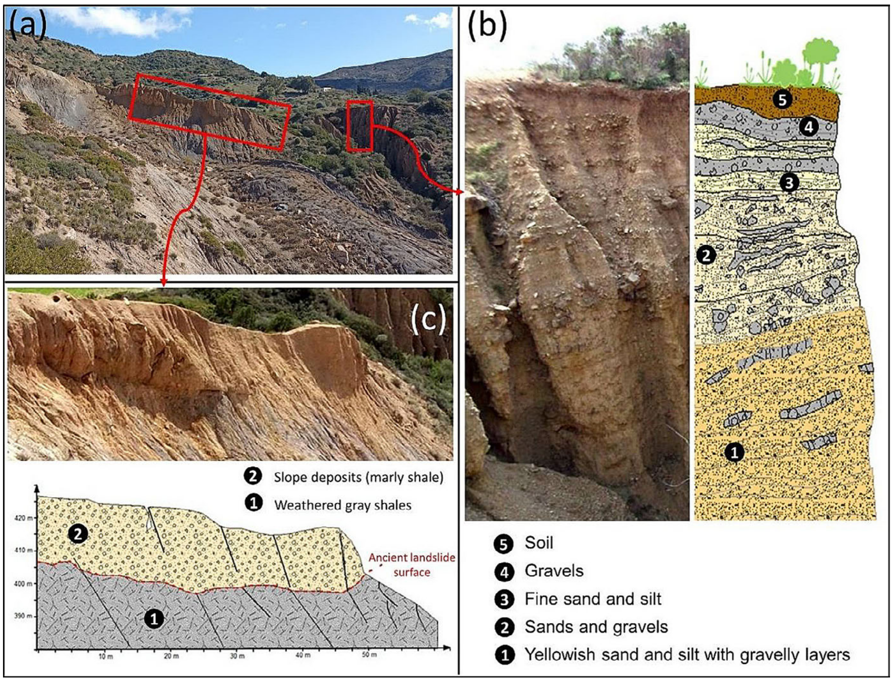

Figure 6. Analysis and interpretation of field data: (a) Photograph showing the abundance of superficial formations on the slope of the Takariast flow-like landslide; (b) View and interpretive diagram illustrating the different layers constituting the superficial formations on this slope; (c) Photograph and interpretive cross-section showing the boundary between ancient gravitational deposits and the bedrock

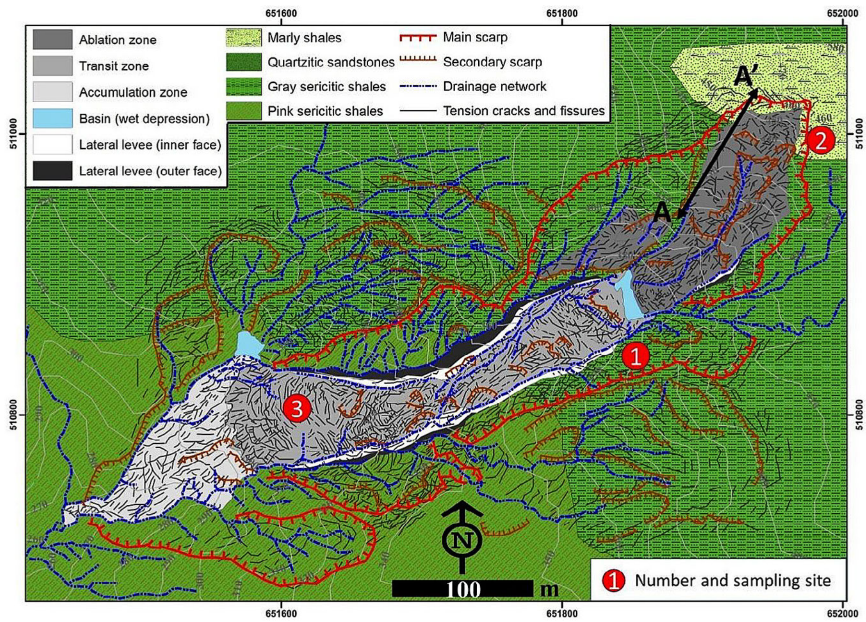

Figure 7. Morphostructural map of the Takariast landslide, illustrating the relationship between the landslide's evolution and the underlying geological formations. The map highlights key features such as the main scarp, tension cracks, transport zones, and accumulation lobes, as well as the distribution of geological units

consists of gray sericitic schists from the Albian-Aptian, interbedded with sandstone-quartzite layers (Fig. 8). A clear difference in mechanical competence is observed between the rock facies, directly influencing the landslide dynamics.

In the upper section, the marly schists appear highly weathered and fractured, making them particularly vulnerable to gravitational processes. In the intermediate section, the sandstone-quartzite layers exhibit marked fracture schistosity,

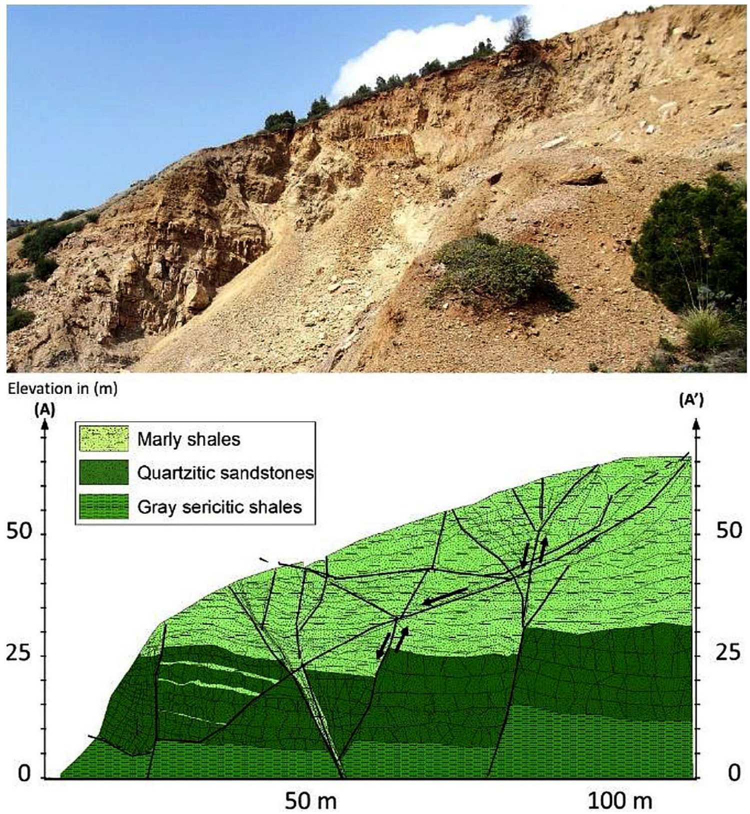

Figure 8. Photograph and interpretive cross-section of the detachment niche (see location on figure 7). This figure combines a photograph and an interpretive cross-section of the detachment niche, the area where the landslide initiated. The image highlights the intense fracturing observed in the rock formations. The interpretive cross-section illustrates how these fractures, along with the structural and lithological characteristics of the site, contribute to the instability of the slope

increasing their susceptibility to deformation under stress. At the base of the scarp, the sericitic schists show a high concentration of tectonic deformations, indicating significant structural anisotropy, which further weakens this unstable slope. The alignment of microstructures and minerals, a direct consequence of metamorphism, influences the overall behavior of the rock mass. Observations at different scales reveal advanced material fatigue, largely attributed to shearing along schistosity planes, further enhancing the instability of the landslide's source zone.

Manifestations of instability

The instability features observed in the Takariast flow-like landslide reflect a complex dynamic (Fig. 9a). In the source zone, tension cracks, following the circular shape of the main rupture zone (Fig. 9e), indicate deformation forces associated with gravitational stresses. These cracks are accompanied by the disintegration of marly and sericitic schists, as well as the mechanical fragmentation of sandstone-quartzite layers, generating debris accumulations at the base of this zone (Fig. 9d). Along the edges of the main landslide body, vertical shear zones, marked by striations aligned with the gravitational movement (Fig. 9a), testify to the frictional forces between the displaced materials and the stable terrain. These zones are associated with lateral compression ridges, reflecting the accumulation of lateral stresses in the peripheral materials of the flow (Fig. 9b).

The internal body of the flow, composed of heterogeneous materials, is characterized by intrinsic instability and slow displacement strongly influenced by variations in hydrological conditions (Fig. 9c). Although it does not exhibit marked shear zones like the edges, tension cracks and folds indicate a differentiated response to fluctuations in pore pressures and gravitational stresses. These internal structures reflect an alternation between phases of acceleration, favored by water saturation, and periods of slowdown corresponding to the gradual dissipation of stresses.

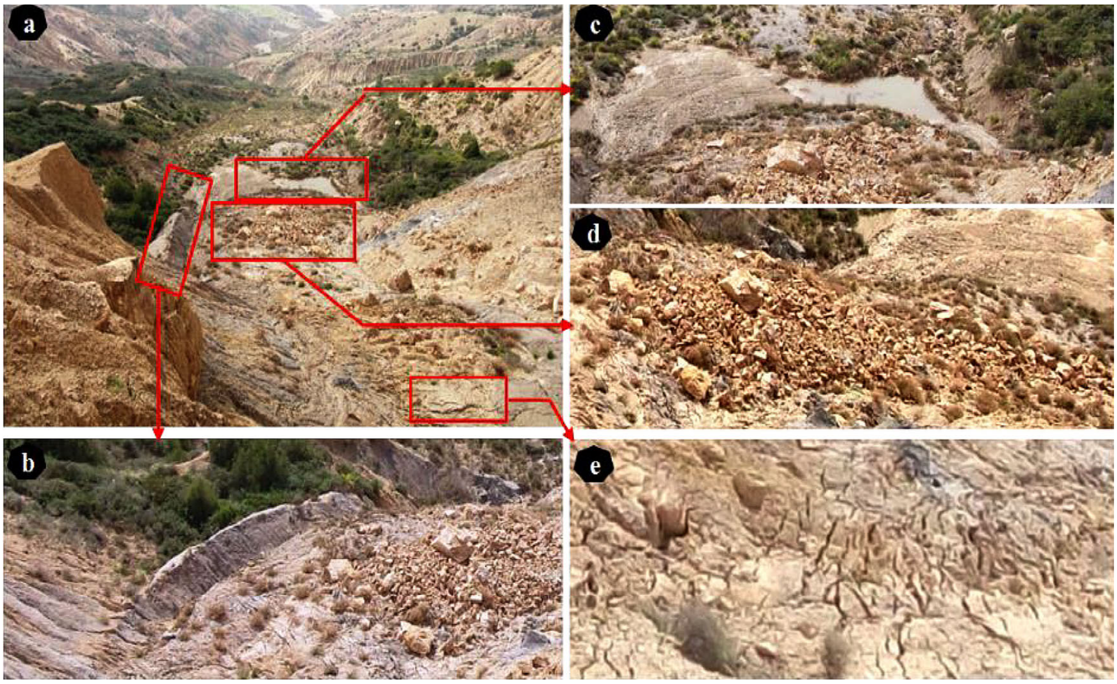

Figure 9. Instability features along the Takariast flow-like landslide: (a) Top-down view of the Takariast landslide: (b) Lateral compression ridge; (c) Wetland area; (d) Debris accumulation; (e) Tension cracks

Geotechnical characterization

Grain size analysis

The grain size analyses of the materials involved in the Takariast flow-like landslide reveal differentiated properties that significantly influence their hydromechanical behavior. The sericitic schist sample (Sample 1, Fig. 10, Table 1) exhibits a grain size distribution dominated by coarse particles, with over 97% of grains larger than 31.5 mm and a limited proportion of fine fraction (<0.08 mm) reaching 18.3%. This distribution results in high permeability and facilitates rapid drainage, limiting generalized pore pressures. However, stress concentrations can form along stratification planes under partial saturation conditions.

In contrast, the marly schist sample (Sample 2, Fig. 10, Table 1) shows a grain size distribution marked by a distinct inflection at 16 mm, followed by a significant proportion of fine particles, representing 44.8% of the mass. This distribution promotes low permeability and high-water retention capacity, leading to elevated pore pressures under saturated conditions. This reduces effective

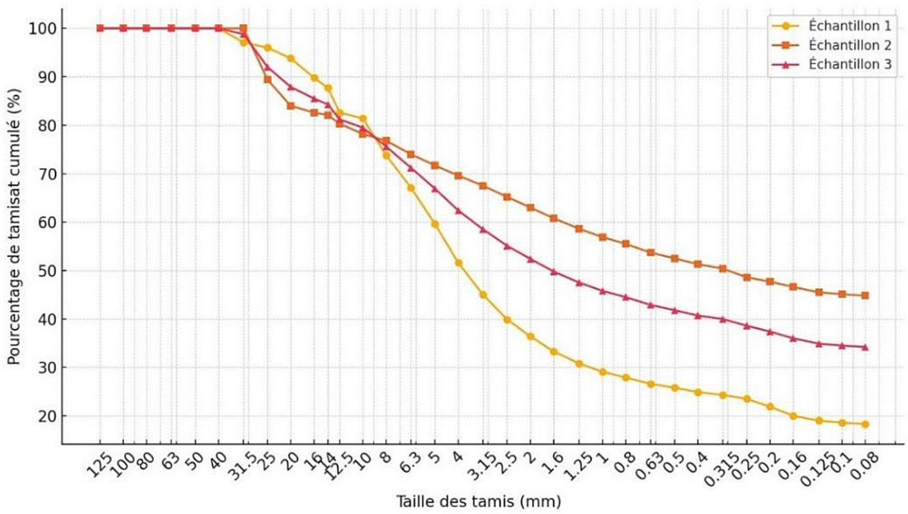

Figure 10. Grain size distribution curves of the three samples collected from the unstable Takariast site

Table 1. Summary of the geotechnical characteristics of the three samples collected from the unstable site of Takariast

Sample	Fine fraction	Liquid limit (LL) in (%)	Plastic limit (PL) in (%)	Plasticity index (PI)	MBV
1	18.3 %	43	23	20	0.63
2	44,8 %	39	27	12	1,31
3	34,2 %	40.4	25.6	14.8	1.072

stress and favors creep mechanisms, increasing susceptibility to sliding in these zones.

The sample taken from the landslide body (Sample 3, Fig. 10, Table 1) exhibits an intermediate grain size distribution, with a fine fraction proportion of 34.2% and a more homogeneous grain size transition. This configuration reflects a balance between plasticity and rigidity, limiting sudden deformations while allowing progressive and coherent movements. Moderate permeability promotes controlled water infiltration, explaining the observed water accumulation in the wetland depression during torrential rainfall events.

These results highlight the critical role of grain size properties in regulating flow-like landslide processes. They directly influence permeability, water retention, and deformation mechanisms under external stresses and varying hydrological conditions.

The atterberg limits and methylene blue value (MBV)

The geotechnical analyses of samples from the area affected by the slow earthflow landslide reveal complex deformation mechanisms closely linked to the physico-chemical properties of the materials (Table 1). The sericitic schist (sample 1) exhibits a high plasticity index (PI = 20) and a relatively low methylene blue value (MBV = 0.63), reflecting moderate clay activity dominated by minerals such as sericite. This material, although showing marked plasticity, is characterized by a low cation exchange capacity, limiting its swelling potential but remaining particularly sensitive to water saturation. This property, combined with the material's schistosity, promotes progressive shear failure. The marly schists (sample 2), on the other hand, display a moderate plasticity index (PI = 12) and a high MBV (1.31), suggesting strong clay activity dominated by expansive phases such as smectites or illites. This composition makes them highly sensitive to hydrological cycles, with a tendency to swell in saturated conditions and to crack due to desiccation, leading to a significant reduction in cohesion and shear strength.

The landslide body (sample 3), composed of slowly displaced materials, exhibits intermediate plasticity (PI = 14.8) and moderate clay activity (MBV = 1.072). This mixture of fine particles and rock fragments has sufficient cohesion to limit rapid flow, but its susceptibility to progressive deformation under gravitational stresses makes it prone to slow creep. These properties, combined with persistent saturation, promote poor drainage capacity and an increase in pore water pressures, which are critical mechanisms in the initiation and dynamics of the slow earthflow.

The data collectively highlight the predominant role of hydrological cycles in the instability of the materials. Water infiltration reduces shear strength, particularly in the marly schists and the landslide body, and amplifies progressive deformations. The properties of the sericitic schists, although less active, act as structural weak zones facilitating stress concentration. This interaction between the intrinsic properties of the materials and hydrogeological conditions is a determining factor in the dynamics of the slow earthflow. These results underscore the importance of managing both groundwater and surface water to limit the propagation of such gravitational phenomena.

DISCUSSION

The Trougoût watershed, located in the Rif Mountain range of Morocco, is a privileged site for studying the mechanisms of flow-like landslides (Fig. 11). These movements, characterized by a fluid and progressive dynamics, are initiated through a circular sliding model guided by pre-existing structural discontinuities, such as stratification and fracturing in sericitic and marly schists (Giordan et al., 2013; Bertello et al., 2018). Flow-like landslides in this region are strongly influenced by hydrological cycles and the geotechnical properties of the materials. Prolonged soil saturation, combined with toe erosion through undercutting, triggers movements that evolve through three distinct phases: initiation, evolution, and propagation.

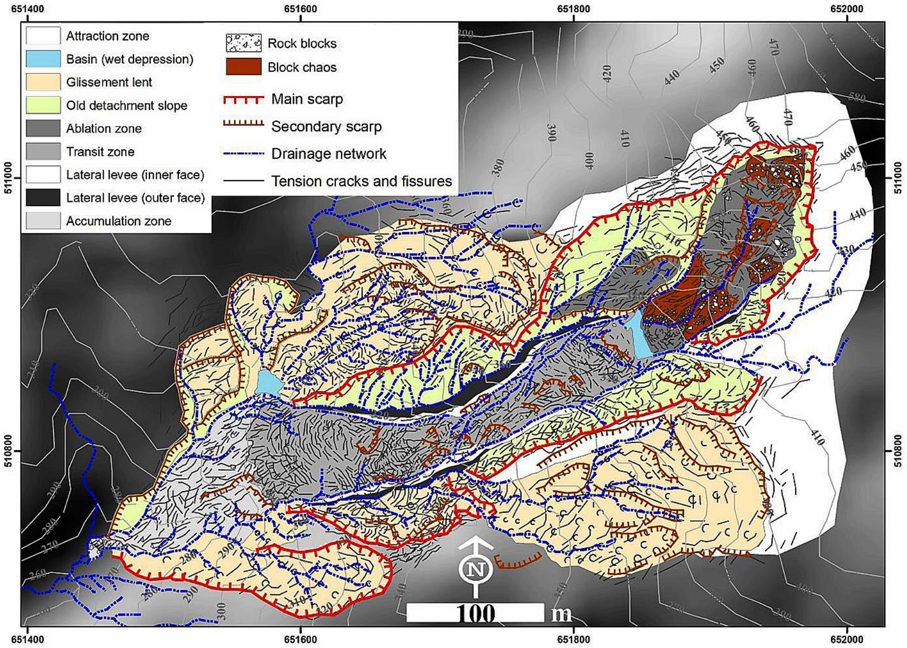

Figure 11. Morphodynamic map of the Takariast flow-like landslide (Labriki, 2020): This map illustrates a comprehensive overview of the processes driving the landslide, from initial detachment to final deposition, and is essential for assessing risks and managing landslide impacts in the region

These phases are conditioned by complex interactions between local morphology, water saturation, and the intrinsic properties of the materials (Tavenas et al., 1983; Hungr et al., 2014).

- Initiation (Fig. 12 A) – the initiation phase of the Takariast landslide is primarily controlled by two key factors: prolonged soil saturation and toe erosion through undercutting (Tavenas et al., 1983). Saturation leads to a significant increase in pore water pressures, reducing effective normal stresses and promoting material fluidization (Iverson, 1997, 2005). In marly schists, which are rich in expansive clay minerals such as montmorillonite, this sensitivity to water infiltration is particularly pronounced (Chen et al., 1999). Water infiltration through a dense network of fractures also activates creep mechanisms and gravitational deformation, as observed by Van Asch et al. (1984) and Travelletti et al. (2013). These conditions enable the retrogression of the main scarp, progressively expanding the source area and altering the slope morphology.
- Evolution (Fig. 12 B) – during the evolution phase, a gradual transition from sliding to slow flow occurs, influenced by repeated hydrological cycles (wetting/drying). These cycles redistribute internal stresses and progressively adjust the materials within the landslide body (Picarelli et al., 2004). The main body of the landslide, with a moderate plasticity index (IP = 14.8), acts as a moderator of the overall dynamics due to its moderate permeability and controlled drainage capacity (Mainsant et al., 2012; Coussot, 2005). This behavior is described by viscoplastic rheological laws (Coussot and Piau, 1994; Malet et al., 2005), reflecting a subtle balance between pore water pressures and the intrinsic resistance of the materials.
- Propagation (Fig. 12 C) – the propagation phase is characterized by the downslope migration of mobilized materials, sustained by persistent saturation and regressive erosion. The presence of gullies at the base of ablation zones amplifies material fluidization (Hungr et al., 2014). Wet zones within the landslide body act as local hydraulic reservoirs, enhancing the effects of prolonged saturation and increasing the soil's susceptibility to sporadic reactivations (Zerathe et al., 2016; Fiolleau et al., 2021). Hydrological cycles regulate the transitions between sliding and slow flow, particularly by inducing variations in critical stresses proportional to water content (Locat and Demers, 1988; Hungr et al., 2014).

Geotechnical properties of materials, particularly their plasticity index and permeability, play

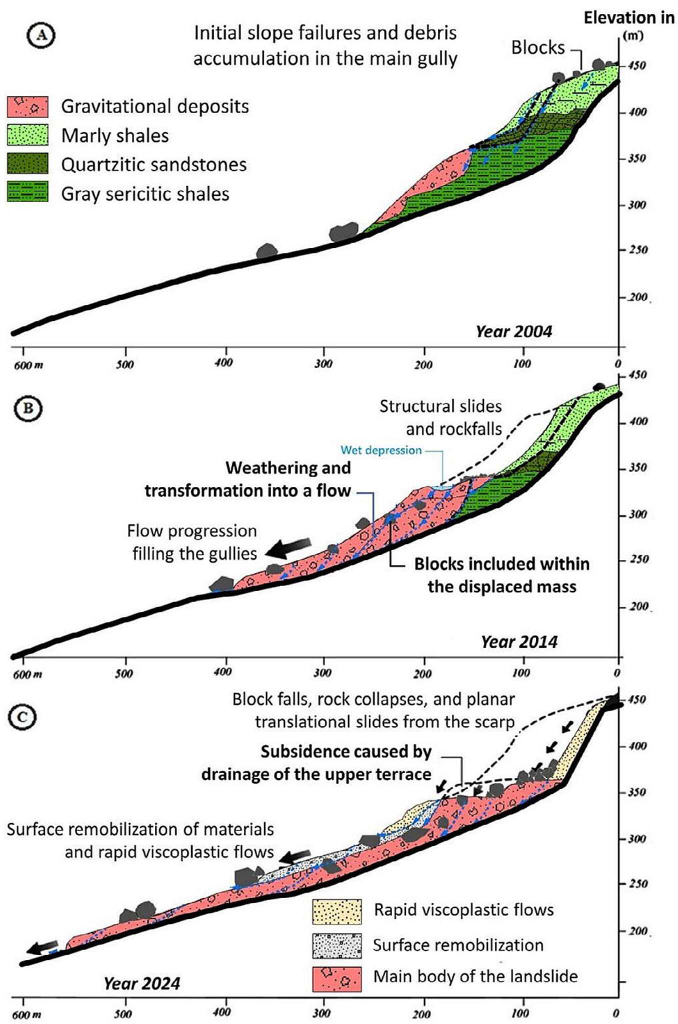

Figure 12. Conceptual model of the Takariast flow-like landslide evolution: This figure illustrates the evolution of the Takariast landslide from 2004 to 2024, showing initial slope failures, debris accumulation, and transformation into a flow. Key processes include block falls, rock collapses, and rapid viscoplastic flows driven by surface remobilization. The model highlights the role of weathering, gravitational forces, and hydrological changes in landslide dynamics. It provides insights into the progression and mechanisms of the landslide over two decades

a key role in the dynamics of flow-like landslides. Marly schists, with their high clay activity (MBV = 1.31, where MBV represents the clay activity index), are particularly sensitive to wetting and drying cycles, promoting the progressive fluidization of materials (Chen et al., 1999; Hungr et al., 2014). In contrast, sericitic schists, with their coarse-grained texture and low clay activity (MBV = 0.63), limit swelling effects but remain vulnerable to progressive shearing along schistosity planes, especially under partial saturation (Picarelli et al., 2004). Hydrological cycles also influence the internal reorganization of materials, profoundly altering local slope morphology. The presence of wet zones within the landslide acts as a hydraulic reservoir, accentuating the effects of prolonged saturation and increasing the soil's sensitivity to sporadic reactivations (Zerathe et al., 2016; Fiolleau et al., 2021).

The Takariast landslide shares similarities with other flow-like landslides documented in various geological contexts. For example, in the Apennines, landslides are often triggered by pre-existing structural discontinuities and intense hydrological cycles (Giordan et al., 2013; Bertello et al., 2018). In the Alps, movements are influenced by the presence of glaciers and snowmelt, which increase soil saturation (Mainsant et al., 2012; Fiolleau et al., 2021). In the Andes, flow-like landslides are often associated with extreme climatic conditions and high seismic activity (Zerathe et al., 2016). These comparisons highlight the importance of local factors, such as lithology, structure, and climate, in landslide dynamics.

CONCLUSIONS

This study highlights the critical role of geotechnical properties and hydrological cycles in the dynamics of flow-like landslides, as exemplified by the Takariast landslide in the Trougoût watershed. The results demonstrate that materials with high clay activity, such as marly schists, are particularly sensitive to water saturation, leading to reduced shear strength and increased deformation. In contrast, sericitic schists, with lower clay activity, exhibit limited swelling but remain prone to progressive shear failure. The landslide body, with intermediate properties, plays a moderating role, facilitating slow creep under persistent saturation.

The study underscores the importance of understanding flow-like landslides, which pose significant risks to infrastructure and communities. By elucidating the mechanisms of retrogression, fluidization, and pore pressure dynamics, this research contributes to improved landslide prediction and management. These findings emphasize the need for proactive measures, such as controlling water infiltration and stabilizing slopes, to mitigate the impacts of flow-like landslides in geologically complex regions like the Rif Mountain range.

REFERENCES

1. Aït Brahim, L., & Chotin, P. (1990). Oriental Moroccan Neogene volcanism and strike-slip faulting. *Journal of African Earth Sciences (Middle East), 11*(3), 273–280.
2. Andrieux, J. (1971). *La structure du Rif central. Etude des relations entre la tectonique de compression et les nappes de glissements dans un tronçon de la chaîne alpine*. Notes & Mémoires, Service de la Géologie, Maroc, n° 235, 155 p.
3. Azdimousa, A., Jabaloy, A., Asebriy, L., Booth-Rea, G., Bourgois, J., Rezqui, H., Aït Brahim, L. (2011). Rif oriental. In A. Michard, O. Saddiqi, A. Chalouan, E. Rjimati, & A. Mouttaqi (Eds.), *Nouveaux Guides géologiques et miniers du Maroc/ New Geological and Mining Guidebooks of Morocco* (pp. 91–118). Notes et Mémoires du Service géologique du Maroc, n°s 556–564.
4. Azzouz, O., El Fellah, B., Chalouan, A. (2002). Processus de glissement dans le Massif de Bokoya (Rif interne, Maroc): exemple de Cala Bonita. *Bulletin de l'Institut scientifique, Section Sciences de la Terre, 24*, 33–40.
5. Barhoun, N., & Wernli, R. (1999). Biostratigraphie du Mio-Pliocène du bassin de Boudinar par les foraminifères planctoniques (Rif nord-oriental, Maroc). *Revue de Paléobiologie, 18*, 491–508.
6. Baum, R. L., Messerich, J., & Fleming, R. W. (1998). Surface deformation as a guide to kinematics and three-dimensional shape of slow-moving, clay-rich landslides, Honolulu, Hawaii. *Environmental & Engineering Geoscience, 4*(3), 283–306. https://doi.org/10.2113/gseegeosci.iv.3.283
7. Bertello, L., Berti, M., Castellaro, S., & Squarzoni, G. (2018). Dynamics of an active earthflow inferred from surface wave monitoring. *Journal of Geophysical Research: Earth Surface, 123*(9), 1811–1834. https://doi.org/10.1029/2017JF004233
8. Carrière, S. R., Jongmans, D., Chambon, G., et al. (2018). Rheological properties of clayey soils originating from flow-like landslides. *Landslides, 15*(8), 1615–1630. https://doi.org/10.1007/s10346-018-0972-6
9. Chalouan, A., Galindo-Zaldivar, J., Akil, M., Marin, C., Chabli, A., Ruano, P., Bargach, K., De Galdeano, C. S., Benmakhlouf, M., Ahmamou, M., & Gourari, L. (2006). Tectonic wedge escape in the southwestern front of the Rif Cordillera (Morocco). In G. Moratti & A. Chalouan (Eds.), *Tectonics of the Western Mediterranean and North Africa* (pp. 101–118). Geological Society Publishing House.
10. Chen, G., Pan, J., Han, B., & Yan, H. (1999). Adsorption of methylene blue on montmorillonite. *Journal of Dispersion Science and Technology, 20*(4), 1179–1187. https://doi.org/10.1080/01932699908943843
11. Choubert, G., Faure-Muret, A., Mourier, T., et al. (1984a). *Carte géologique du Rif au 1/50000, feuille d'Al Hoceima*. Notes Mém. Serv. Géol. Maroc., 302.
12. Choubert, G., Faure-Muret, A., Hilali, E. A., Houzay, J. P., de Lamotte, D. F. (1984b). *Carte géologique du Rif au 1/50.000, feuille Boudinar*. Notes Mém. Serv. Géol. Maroc., 299.
13. Coltorti, M., & Tognaccini, S. (2019). The gravitational landscape of Montespertoli (Valdelsa Basin, Tuscany, Italy): state of activity and characteristics of complex landslides. *Geomorphology, 340*, 129–142. https://doi.org/10.1016/j.geomorph.2019.04.030
14. Coussot, P. (2005). *Rheometry of pastes, suspensions, and granular materials.* Wiley Online Library.
15. Coussot, P., & Piau, J. M. (1994). On the behavior of fine mud suspensions. *Rheologica Acta, 33*(3), 175–184.
16. Cruden, D. M., & Varnes, D. J. (1996). Landslide types and processes. In A. K. Turner & R. L. Shuster (Eds.), *Landslides: Investigation and mitigation* (pp. 36–75). Transportation Research Board, Special Report 247.
17. Dikau, R., Brunsden, D., Schrott, L., & Ibsen, M.-L. (Eds.). (1996). *Landslide recognition: Identification,*

movement, and causes. Wiley.

18. El Azzouzi, M., Bellon, H., Coutelle, A., & Rehault, J.-P. (2014). Miocene magmatism and tectonics within the Peri-Alboran orogen (western Mediterranean). *Journal of Geodynamics, 77*, 171–185.
19. El Idrissi, S., Zerdeb, O., Labriki, A., Mehdioui, S., El Omari, M., Chakiri, S., & Inekach, S. (2024). Diachronic Study of the North Atlantic Coast of Morocco between Larache and Moulay Bousselham: A Geometric Approach. *Ecological Engineering & Environmental Technology, 25*(6), 90–103. https://doi.org/10.12912/27197050/186683
20. Fiolleau, S., Jongmans, D., Bièvre, G., et al. (2021). Multi-method investigation of mass transfer mechanisms in a retrogressive clayey landslide (Harmalière, French Alps). *Landslides, 18*(8), 1981–2000. https://doi.org/10.1007/s10346-021-01639-z
21. Flageollet, J. C. (1989). *Les mouvements de terrain et leur prévention*. Masson.
22. Flageollet, J.-C. (1996). The time dimension in the study of mass movements. *Geomorphology, 15*(3–4), 185–190.
23. Frizon de Lamotte, D. (1985). *La structure du Rif Oriental (Maroc). Rôle de la tectonique longitudinale et rôle des fluides*. Thèse de Doctorat d'État, Université Pierre et Marie Curie, Paris VI.
24. Giordan, D., Allasia, P., Manconi, A., Baldo, M., Santangelo, M., Cardinali, M., Corazza, A., Albanese, V., Lollino, G., & Guzetti, F. (2013). Morphological and kinematic evolution of a large earthflow: the Montaguto landslide, southern Italy. *Geomorphology, 187*, 61–79. https://doi.org/10.1016/j.geomorph.2012.12.035
25. Guillemin, M., & Houzay, J.-P. (1982). Le Néogène post-nappes et le Quaternaire du Rif nord-oriental (Maroc): stratigraphie et tectonique des bassins de Melilla, du Kert, de Boudinar et du piedmont des Kebdana. *Notes et Mémoires du Service Géologique du Maroc, 314*, 7–238.
26. Gunn, D. A., Chambers, J. E., Hobbs, P. R. N., Ford, J. R., Wilkinson, P. B., Jenkins, G. O., & Merritt, A. (2013). Rapid observations to guide the design of systems for long-term monitoring of a complex landslide in the Upper Lias clays of North Yorkshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology, 46*(3), 323–336. https://doi.org/10.1144/qjegh2011-028
27. Hang, P. T., & Brindley, G. W. (1970). Methylene blue absorption by clay minerals. Determination of surface areas and cation exchange capacities (clay-organic studies XVIII). *Clays and Clay Minerals, 18*(4), 203–212. https://doi.org/10.1346/CCMN.1970.0180404
28. Hernandez, J., Lauzière, F. D., Bolze, J., Bordet, P. (1987). Le magmatisme néogène bético-rifain et le couloir de décrochement trans-Alboran. *Bulletin de la Société géologique de France, 8*(3), 257–267.
29. Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. *Landslides, 11*(2), 167–194. https://doi.org/10.1007/s10346-013-0436-y
30. Iverson, R. M. (1997). The physics of debris flows. *Reviews of Geophysics, 35*(3), 245–296.
31. Iverson, R. M. (2005). Regulation of landslide motion by dilatancy and pore pressure feedback. *Journal of Geophysical Research: Earth Surface, 110*(F2).
32. Khaddari, A., Jari, A., Chakiri, S., El Hadi, H., Labriki, A., Hajaj, S., et al. (2023). A Comparative Analysis of Analytical Hierarchy Process and Fuzzy Logic Modeling in Flood Susceptibility Mapping in the Assaka Watershed, Morocco. *Journal of Ecological Engineering, 24*(8), 62–83. https://doi.org/10.12911/22998993/165958
33. Kohv, M., Talviste, P., Hang, T., Kalm, V., & Rosentau, A. (2009). Slope stability and landslides in proglacial varved clays of western Estonia. *Geomorphology, 106*(3–4), 315–323. https://doi.org/10.1016/j.geomorph.2008.11.013
34. Labriki, A. (2020). Analyse morphodynamique, géomécanique et modélisation volumique des instabilités des versants méditerranéens entre Ras Tarf et El Jebha (Rif, Maroc) (Thèse de doctorat). Université Ibn Tofail, Faculté des Sciences, Kénitra, 249 pages.
35. Labriki A., Chakiri S., Nouaim W. et al. (2016). Etude géotechnique et modélisation volumique des zones instables ; processus d'effondrement de la falaise adjacente à la voie de contournement du port d'Al Hoceima (Rif, Maroc). European Scientific Journal (ESJ), 13(9), 251–265. http://dx.doi.org/10.19044/esj.2017. v13n9p251
36. Labriki, A., Chakiri, S., Razoki, B., Bejjaji, Z., Hmidi, F. E., Rassou, K. K. (2019). L'évolution géo-mécanique du massif paléozoïque de la klippe tectonique d'Al Hoceima (Rif, Maroc) par l'analyse des figures d'instabilité et l'interprétation des données géotechniques. *Bulletin de l'Institut Scientifique, Section Sciences de la Terre, 41*, 13–23. http://www.israbat.ac.ma/wp-content/uploads/2019/12/Lakbiri_2019.pdf
37. Lacroix, P., Bièvre, G., Pathier, E., Kniess, U., Jongmans, D. (2018). Use of Sentinel-2 images for the detection of precursory motions before landslide failures. *Remote Sensing of Environment, 215*, 507–516. https://doi.org/10.1016/j.rse.2018.03.042
38. Locat, J., Demers, D. (1988). Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays. *Canadian Geotechnical Journal, 25*(4), 799–806.
39. Maquaire, O., Malet, J.-P., Remaître, A., Locat, J., Klotz, S., Guillon, J. (2003). Instability conditions

of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette basin, South East France. *Engineering Geology, 70*(1–2), 109–130.

40. Mainsant, G., Jongmans, D., Chambon, G., Larose, E., Baillet, L. (2012). Shear-wave velocity as an indicator for rheological changes in clay materials: lessons from laboratory experiments. *Geophysical Research Letters, 39*(19).
41. Malet, J.-P., Maquaire, O., Locat, J., et al. (2004). Assessing debris flow hazards associated with slow moving landslides: methodology and numerical analyses. *Landslides, 1*(2), 83–90. https://doi.org/10.1007/s10346-003-0005-x
42. Malet, J.-P., Laigle, D., Remaître, A., & Maquaire, O. (2005). Triggering conditions and mobility of debris flows associated to complex earthflows. *Geomorphology, 66*(1–4), 215–235.
43. Margaa, Kh. (1994). *Essai de cartographie des risques naturels : application à l'aménagement de la région d'Al Hoceïma*. Thèse de Doctorat, Université de Franche-Comté, Besançon, France.
44. Maurer, G. (1968). *Les montagnes du Rif central ; étude géomorphologique*. Travaux de l'Institut Scientifique, série Géologie & Géographie physique, 14, Rabat.
45. Meghraoui, M., Morel, J. L., Andrieux, J., & Dahmani, M. (1996). Pliocene and quaternary tectonics of the Tell-Rif mountains and Alboran Sea, a complex zone of continent convergence. *Bulletin de la Société Géologique de France, 167*(2), 141–157.
46. Michard, A., Frizon de Lamotte, D., & Negro, F. (2007). Serpentinite units and metamorphism in the External Maghrebides: Arguments for an intracontinental suture in the African paleomargin (Morocco, Algeria). *Revista de la Sociedad Geológica de España, 20*(3–4), 173–185.
47. Millies-Lacroix, A. (1968). Les glissements de terrains. Présentation d'une carte prévisionnelle des mouvements de masse dans le Rif (Maroc septentrional). *Mines et Géologie, 27*, 45–55.
48. Mitchell, J. K., & Soga, K. (2005). *Fundamentals of soil behavior* (3rd ed.). John Wiley & Sons.
49. Morel, J.-L. (1987). Evolution récente de l'orogène rifain et de son avant-pays depuis la fin de la mise en place des nappes (Rif, Maroc).
50. Negro, F., Agard, P., Goffé, B., Saddiqi, O. (2007). Tectonic and metamorphic evolution of the Temsamane units, External Rif (northern Morocco). Implications for the evolution of the Rif and the Betic-Rif arc. *Journal of the Geological Society, London, 164*(5), 824–842.
51. Picarelli, L., Russo, C. (2004). Mechanics of slow active landslides and interaction with manmade works. In W. A. Lacerda, M. Ehrlich, S. A. B. Fontoura, & A. S. F. Sayao (Eds.), *Landslides. Evaluation & Stabilization, 9th International Symposium on Landslides* (pp. 1141–1176). A.A. Balkema.
52. Rahoui, H., Labriki, A., Bejjaji, Z., Chakiri, S. (2024). Impact of Climate Conditions on the Water Potential of the River Ansegmir Watershed (Morocco). *Ecological Engineering & Environmental Technology, 25*(10), 107–117. https://doi.org/10.12912/27197050/191362
53. Santamarina, J. C., Klein, K. A., Wang, Y. H., Prencke, E. (2002). Specific surface: determination and relevance. *Canadian Geotechnical Journal, 39*(1), 233–241. https://doi.org/10.1139/t01-077
54. Taj, B., Mastere, M., Benzougagh, B., El Hilali, M., Sassioui, S., El Fellah, B. (2024). Geotechnical Prospects and Electrical Tomography to Study Slope Instability in the Rif Alboran Sea Shoreline on The Mediterranean By-Road (Northern Morocco). Ecological Engineering & Environmental Technology, 25(1), 138-151. https://doi.org/10.12912/27197050/174340
55. Tavenas, F., Flon, P., Leroueil, S., Lebuis, J. (1983). Remolding energy and risk of slide retrogression in sensitive clays. In *Proceedings of the symposium on slopes on soft clays, Linköping, Sweden* (pp. 423–454). SGI report.
56. Travelletti, J., Malet, J.-P., Samyn, K., et al. (2013). Control of landslide retrogression by discontinuities: evidence by the integration of airborne- and ground-based geophysical information. *Landslides, 10*(1), 37–54. https://doi.org/10.1007/s10346-011-0310-8
57. van Asch, T. W. J., Malet, J.-P., Bogaard, T. A. (2009). The effect of groundwater fluctuations on the velocity pattern of slow-moving landslides. *Natural Hazards and Earth System Sciences, 9*(3), 739–749. https://doi.org/10.5194/nhess-9-739-2009
58. Van Asch, T. W. J., Brinkhorst, W. H., Buist, H. J., & Vessem, P. V. (1984). The development of landslides by retrogressive failure in varved clays. *Zeitschrift für Geomorphologie, Supplementband, 4*, 165–181.
59. Varnes, D. J., Savage, W. (Eds.). (1996). *The Slumgullion earth flow: a large-scale natural laboratory*. U.S. Geological Survey Bulletin 2130.
60. Zerathe, S., Lacroix, P., Jongmans, D., Marino, J., Taipe, E., Wathelet, M., Pari, W., Smoll, L. F., Norabuena, E., Guillier, B., Tatard, L. (2016). Morphology, structure and kinematics of a rainfall controlled slow-moving Andean landslide, Peru. *Earth Surface Processes and Landforms, 41*(11), 1477–1493. https://doi.org/10.1002/esp.3913