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LANDSLIDES TRIGGERED BY INTENSE RAINFALL: NUMERICAL SIMULATION USING FLAC AND PRELIMINARY RISK CONSIDERATIONS FOR CULTURAL MONUMENTS

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ABSTRACT

This study investigates landslides in Zagora (Pelion, Greece) due to extreme rainfall of Storm Daniel (2023). More specifically, it deals with the failure mechanisms and their indirect impacts on nearby cultural monuments. Based on field observations, it appears that rapid saturation near the surface of the slopes increased water pressures in the pores and reduced the shear strength, causing their instability. The simulation was carried out through the FLAC 2D program, and it was shown that the results agree largely with the field observations. In this case, that is, that heavy rainfall destabilizes the slopes and disrupts access to cultural sites. In conclusion, the need for monitoring and achieving targeted stabilization measures in areas of high vulnerability is emphasized.

Keywords: landslides, slope stability, numerical simulation, geohazards, cultural heritage

INTRODUCTION

The rainfall during Storm Daniel in 2023 led to large-scale flooding in the Thessaly region of Greece. In addition to flooding, several landslides occurred in the surrounding area. Eastern Pelion was one of the areas most affected. In Zagora, where the terrain is characterized by steep slopes, several landslides were recorded. The proximity of the unstable slopes to cultural monuments, such as the Monastery of Agios Athanasios the Athonite and the Rigas Feraios School, created the conditions for initiating an investigation into these landslides. The main purpose of the investigation is to understand the failure mechanisms and protect these cultural monuments.

More specifically, the failure mechanisms of slopes are investigated through numerical simulation in the program (FLAC 2D). The program is based on the finite difference method. In addition, it is possible through the program to search how factors associated with precipitation, such as intensity and duration, affect slope stability.

Surface Landslides and Rainfall-Induced Activation Mechanisms

Landslides, through the displacement of geomaterials, can block waterways, disrupt traffic on road or rail networks, and generally cause extensive damage to the human-made environment. Furthermore, due to the sudden triggering and the absence of precursory phenomena, landslides are characterized as unpredictable hazards.
Before precipitation events, soil and rock materials are usually in an unsaturated state, a state that generally enhances slope stability due to matric suction.
The shear strength of unsaturated geomaterials depends mainly on two stress state variables: the effective stress and suction (Fredlund & Rahardjo, 1993; Peranić & Arbanas, 2020). The increase of the above variables leads to higher soil strength, as the effective stress compresses the soil skeleton, while suction plays an important role in the connection between the particles within the unsaturated zone.
During periods of rainfall, the effective stress usually changes only slightly, while suction decreases significantly, resulting in reduced shear strength. At the same time, depending on the soil permeability, water infiltration can create positive pore-water pressures. This is due to the formation of a sloping aquifer within the mass of the slope. The process reduces effective stress and can eventually lead to a landslide of the slope (Terzaghi, 1943).

Climatic Change and Its Impact on the Increased Frequency of Geohazards

Climate change is increasingly affecting hydrometeorological conditions, with noticeable effects in mountainous and semi-mountainous areas. In recent years, both the frequency and intensity of extreme weather events have increased, especially through short-duration and high-intensity rainfall events. Events that were previously considered rare now occur with increased frequency, even within the same year.
The accumulation of large volumes of water in short periods of time leads to supersaturation of the surface layers of the soil and a progressive reduction in their shear strength. Under these conditions, infiltration occurs at a rapid rate with a simultaneous increase in pore-water pressures. Effective stress decreases, resulting in the whole process being able to cause landslides or even soil liquefactionSteep slopes are particularly vulnerable to landslides and it is essential to monitor their stability.
Heavy rainfall often leads to floods, which increase erosion along the slopes. As a result, erosion reduces the stability of the slopes, favoring the conditions for failure. At the same time, the rise in water levels, reducing the active stresses and subsequently the shear strength of the soil. Therefore, it becomes possible to cause subsidence at the base of the slopes, contributing to the creation of structural failures.
The occurrence of geohazards is not limited to landslides. but also, to rock falls and mudflows. Areas of cultural importance are particularly exposed, as many structures are old and sensitive to soil deformation. For example, Civita di Bagnoregio in Italy (Margottini et al., 2013) is a well-known site where slope instability has been linked to moisture fluctuations.
In Greece, similar conditions are observed in mountainous areas such as Pelion, Meteora and Olympus. In these areas, several cultural structures are located on slopes that are generally vulnerable to hydrometeorological changes. The recent storms Daniel and Janus highlighted the sensitivity of such areas to geohazards.
A multifaceted package of measures is required to address the above challenges. In addition to conventional engineering measures such as drainage systems and retaining anchors, new ones are also required that aim to provide early warning of such phenomena. Monitoring systems are an example of such a system, as they can record in real time critical variables of slopes such as displacement, pore water pressures and soil saturation. At the same time, the combination of

satellite data and on-site measurements can contribute to identify critical areas. Furthermore, the development of predictive models integrating meteorological and geotechnical data is considered important for determining the probability of landslides. The above models must also utilize data on rainfall intensity, duration and changes in soil saturation.
In summary, the protection of cultural heritage and related infrastructures for integrated risk management strategies. These include hazard mapping and systematic geohazard assessment, preventive interventions and early warning planning. Through the implementation of the above measures, the possibility of reducing the impact of geohazards and improving the resilience of culturally important areas is provided.

Case Study: Zagora, Pelion (Greece, 2023)

Storm Daniel caused widespread and severe damage, with Zagora being among the most affected areas. The landslide activity was mainly caused by high rainfall during the event. According to data from the Zagora meteorological station (LGG3) of the National Observatory of Athens, the total rainfall between 4 and 7 September reached 1095 mm. The highest daily total was recorded on 5 September (759 mm), after a significant rainfall phase had also followed on 4 September (134 mm). It should be emphasized that these values are among the highest ever recorded at a national level. As such, they contributed to the rapid increase in water resource pressures and the subsequent slope failure examined in this study.
In Zagora, the damage affected both the natural environment and the local infrastructure. The landslides caused landslides, leading to rock falls, the transport of debris and the deposition of large volumes of mud and worn material on roads, residential areas and agricultural lands. Consequently, significant sections of the road network were damaged or remained inaccessible for long periods of time. At the same time, small bridges and other technical structures were destroyed due to the strong hydraulic action and erosion caused by the flowing water.subsequent slope failure modeled in this study.

Figure 1: *Damage caused in Zagora by landslides due to heavy rainfall*

The geomorphological characteristics of the area played a significant role in the occurrence of the damage. Zagora is characterized by steep terrain, steep slopes and geological formations with a high degree of surface weathering. The soil masses, consisting mainly of colluvial deposits and weathered metamorphic rocks, exhibit low cohesion and high sensitivity to changes in saturation. Under normal conditions, many slopes are already close to their ultimate stability. The rapid increase in soil saturation during the storm reduced the shear strength, causing the slope to fail. The geomorphology of the area favored the flow of water through streams in deep canyons, increasing the velocity and subsequent erosion.

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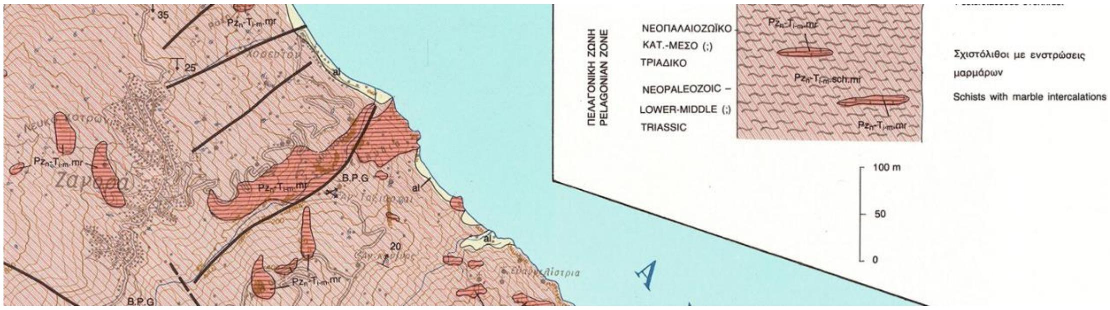

Figure 2: *Geological map of the study area (Zagora, Mt. Pelion) (IGME, 1988).*

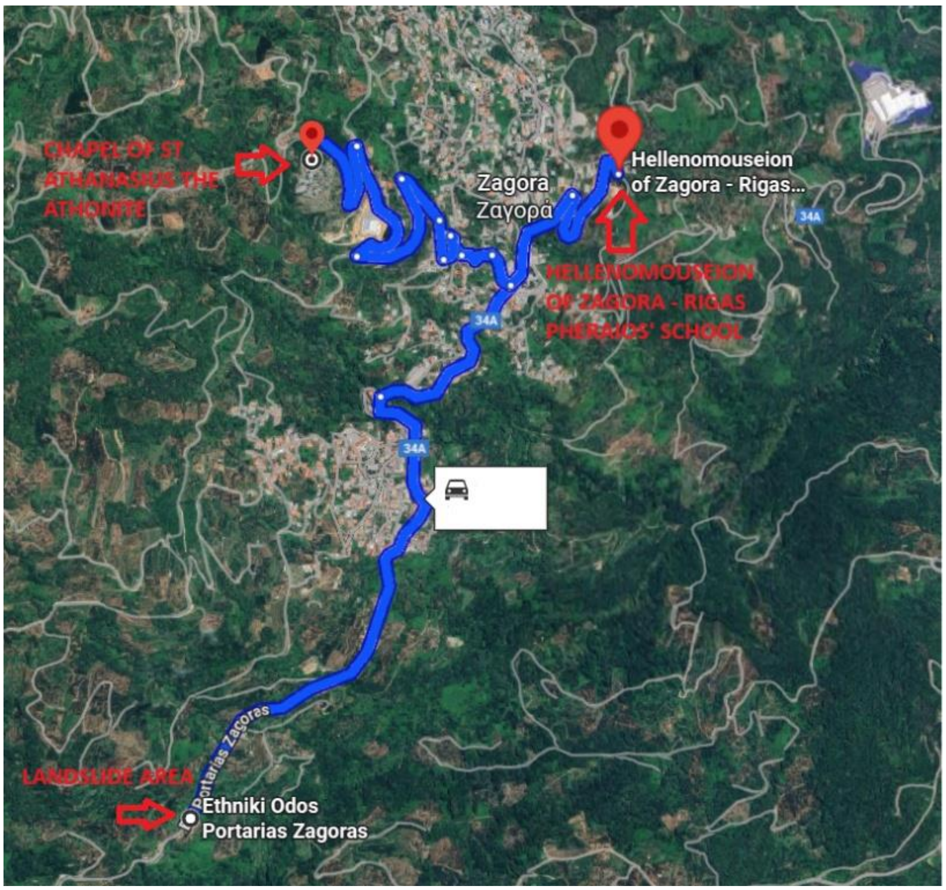

Figure 3: *Distances of the landslide area with the church of* Saint Athanasius Athonitis *(4 km) & Rigas Feraios School (3 km)*

The effects of Storm Daniel affected two important cultural monuments in Zagora - the historic Rigas Feraios School and the Monastery of Agios Athanasios Athonites. The damage was indirect, and related to the loss of access to these sites. For this reason, the slope stability assessment is being carried out on a critical section of the main road network related to these sites.

The landslides that occurred caused extensive damage, effectively isolating the monuments. As a result, visitor access and the operation of maintenance or emergency services were significantly limited. The location of these cultural sites on steep terrain highlights the need for systematic monitoring and targeted mitigation measures to ensure their protection.

Numerical Simulation of the Slope Using FLAC

FLAC is a numerical simulation tool based on the finite difference method (Itasca, 2023). It can analyze the mechanical behavior of geomaterials after user-defined loading conditions. In particular, the ability to analyze under conditions of partial saturation of geomaterials makes it suitable for the study of landslide processes.

In this case, emphasis was placed on the reduction of the soil shear strength due to the increase in pore-water pressures during the evolution of rainfall.

The geometry of the slope, approximately 30 m high and 60 m long (Figure 4), consists of a layer of loamy sand to sandy silt overlying the weathered, low-permeability shale. The upper horizontal section represents the road infrastructure. The numerical field was discretized using a regular grid, with local densification near the slope surface in order to improve the stress representation. In addition, this method achieves a more accurate recording of the pore pressure change during the simulation. (Wolff, 1989).

The mechanical boundary conditions include a rigid base and lateral boundary restraint in the horizontal direction. The slope surface and the road surface remain mechanically free. The soil behavior was modeled using the Mohr-Coulomb failure criterion.

A completely dry state would lead to immediate instability. Therefore, partial saturation was introduced to better represent the field conditions. The initial state is defined by a matric suction of 58 kPa, corresponding to a degree of saturation of 0.49. The degree of saturation is maintained by a constant prior infiltration rate of 84 mm/month.

Figure 4: *Illustration of the slope upstream and downstream of the road network (left). Illustration of the slope simulation in the FLAC program (right)*

***Table 1**: Soil properties and fluid properties*

Property	Value	Property	Value
Dry density of soil, ρ_d (Kg/m^3)	2000	Water density, ρ_w (Kg/m^3)	1000
Drained bulk modulus, K_d (MPa)	15	Air density, ρ_a (Kg/m^3)	0
Shear modulus, G (MPa)	69.3	Van Genuchten parameter α	0.3
Drained cohesion, c' (kPa)	0	Van Genuchten parameter b	0
Drained friction angle, φ' (°)	31	Van Genuchten parameter, air-pressure value P_o (MPa)	0.012
Soil porosity, n	0.33	Water bulk modulus, K_w (MPa)	1.0
Mobility coefficient, k (m^2/(Pa·s))	10^{-9}	Air bulk modulus, K_a (MPa)	1.0

The coupled numerical simulation for Storm Daniel (Figures 5-6) shows that the slope reaches failure under the applied extreme rainfall conditions. A significant cause of the failure is the redistribution of pore-water pressures within the soil mass.
The post-event analysis (Figure 6) shows a clear reduction in matric suction, especially in the near-surface zones (faster saturation). At the same time, the pore-water pressures at the soil surface decrease to about 10 kPa, while the degree of saturation increases to about 0.90.
This transition from partially saturated to nearly saturated conditions together with the loss of shear strength associated with suction appears to be the main failure mechanism of the slope in the simulation.

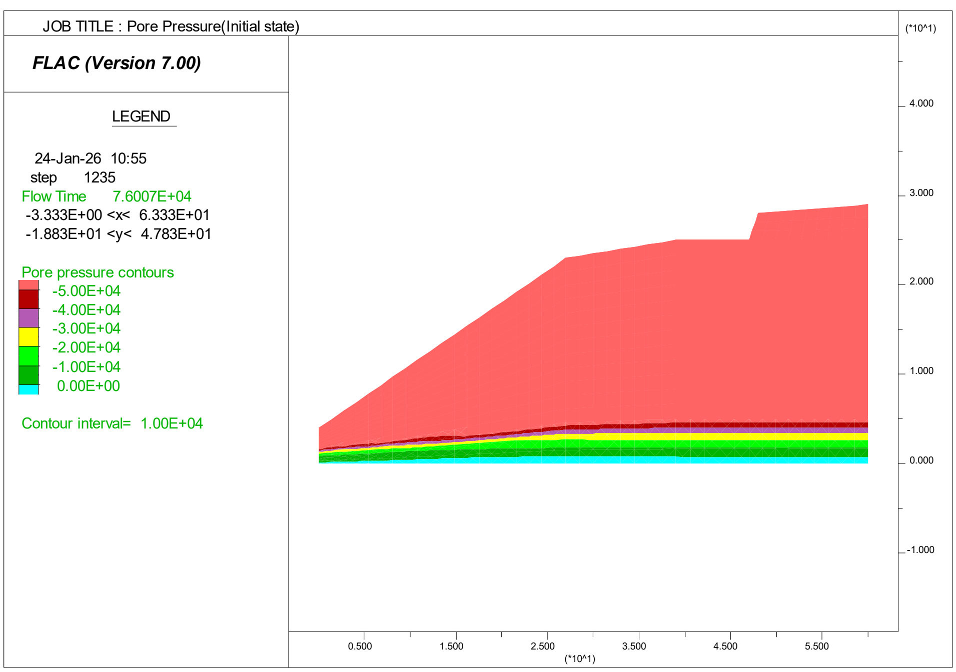

Figure 5: Initial pore pressure distribution (prior to the heavy rainfall event).

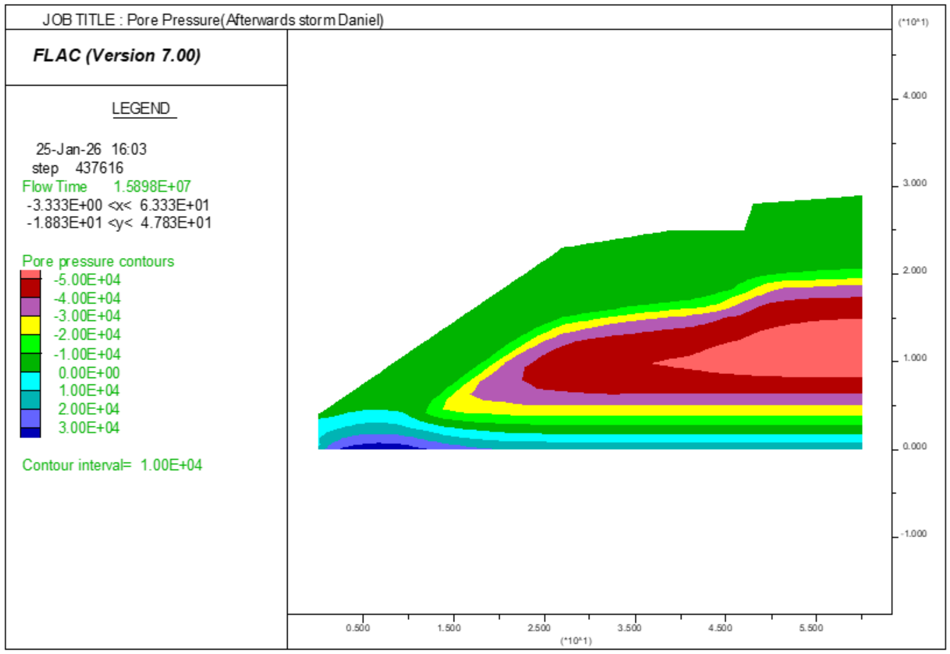

Figure 6: *Pore pressure distribution after Storm Daniel***.**

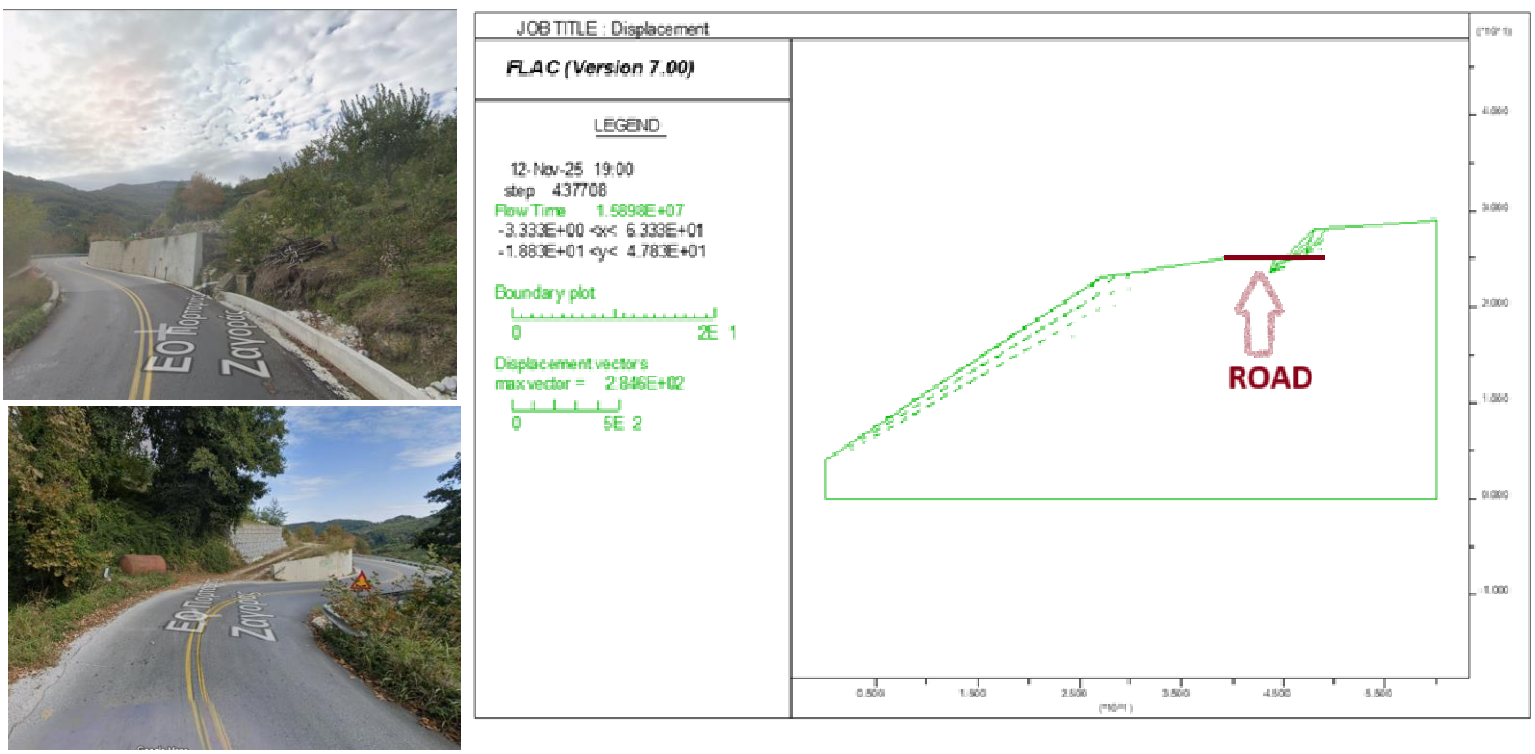

Figure 7: *Illustration of the slope geometry upstream and downstream of the road network (left). Numerical simulation results from FLAC 2D showing the displacement vectors after Storm Daniel (right). A distinct circular failure surface is observed, which intersects the road section at the crest of the slope and leads to significant disruption of accessibility.*

As shown in Figure 7, the displacement vectors define the development of a sliding surface that intersects the upper, nearly horizontal part of the slope. This specific failure mode affects the stability of the road network, which functions as the main access route to the specific cultural monuments in the area.

IMPACT ON CULTURAL HERITAGE MONUMENTS

The simulation highlights the indirect impact of the landslide on the monuments due to the cut-off of access to them. The wider area also requires further investigation as the displacement of geomaterial may lead to differential settlements or foundation displacements of the nearest building infrastructure. To mitigate these risks, the use of real-time monitoring systems is considered essential. These systems can record critical variables such as soil saturation, displacements and subsidence. At the same time, the implementation of conventional engineering measures, such as drainage systems and slope stabilization works, is recommended. These measures include gabion structures and retaining walls.

CONCLUSIONS

This study examined a landslide event on a section of the Zagora Road in Pelion, Greece, which was caused by the extreme rainfall of Storm Daniel. The simulation results indicated that the main reason for the slope failure was the increase in pore water pressure. The increase in pressure resulted in a decrease in the shear strength of the slope. The failure caused the road network to be cut off and two local cultural sites to be disconnected from it. In this way, the indirect impact of the landslide on local cultural monuments was highlighted. The results of this study highlight the need for a holistic approach to the management of geohazards and landslides in particular. Emphasis should be placed on promoting continuous monitoring measures and implementing conventional slope stabilization measures. Rapidly changing climatic conditions necessitate the above actions.

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