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Landslide Risk Assessment Based on Real-Time Rainfall Data and Groundwater Fluctuation Modelling

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Damir Jagodic[1]*, Ahmed El Sayed[1] and Zlatan Talic[2]

[1]*International BURCH University, Faculty of Engineering, Natural and Medical Sciences, Bosnia and Herzegovina*

[2]*University of Zenica, Polytechnic Faculty, Bosnia and Herzegovina*

***Corresponding Author:** Damir Jagodic, International BURCH University, Faculty of Engineering, Natural and Medical Sciences, Bosnia and Herzegovina.

Abstract

This research focuses on assessing landslide risk triggered by rainfall through numerical modelling of groundwater level fluctuation and slope stability. The methodology is based on real-time field measurements and meteorological data obtained from hydrometeorological stations. The research methodology is structured into three main phases. The first phase involves defining the relationship between rainfall characteristics—such as intensity, cumulative precipitation, runoff coefficient, and soil permeability—and the corresponding change in groundwater level. The second phase consists of a detailed geotechnical model of the slope, with groundwater level as an input derived from the first phase. Slope stability calculation is performed using finite element software, where groundwater level is treated as a variable parameter. Groundwater elevation is determined so that global stability safety factor is equal to 1.0. Considering calculation results, goal of the paper is to help develop a predictive equation that links cumulative rainfall to groundwater level and slope stability.

Keywords: Landslide; Groundwater; Rainfall; FEM Analysis

Introduction

One of the most common natural hazards are landslides, mainly in areas with steep terrain, complex geology, and high rainfall. Rainfall variability is increasing with climate change, so rainfall-triggered landslides are becoming more frequent and intense [1]. The primary trigger of slope failures is rainfall, and many studies have proposed rainfall thresholds based on intensity - duration (ID) or event duration (ED) relationships as indicators of landslide activation [2, 3]. Even so, empirical thresholds often lack a physical explanation since parameters are defined using statistical methods.

The hydrological process linking rainfall to slope failure is the fluctuation of groundwater level, which changes groundwater pore pressures [4]. Groundwater level rise is reducing effective stresses and soil shear strength. In standard engineering practice, the groundwater level is treated as a constant, even though it varies over time. The goal of this study is to develop a predictive relationship connecting cumulative rainfall, groundwater level elevation, and factor of safety. A model like this can be used as an early-warning system and support geotechnical planning by integrating real-time meteorological data with site-specific parameters and stability modelling.

Literature Review

Both empirical and physically based methods have widely studied for landslides activated by rainfall. Empirical models typically rely on rainfall thresholds to estimate the likelihood of failure. For example, Caine [5] created one of the earliest and most influential ID thresholds, later expanded by Guzzetti et al. [2] and Peruccacci et al. [6] using large databases. The main problem with thresholds is that they often lack physical meaning and are site-specific. To overcome these limitations, researchers such as Segoni et al. [7] incorporated hydrological parameters, such as cumulative rainfall and soil moisture, to improve model behaviour. Aleotti [8] and Gariano and Guzzetti [1] emphasize the importance of hydrological precursors in refining the behaviour of thresholds.

Changes in groundwater level are recognized as a key parameter in slope instability. Research and analysis by Iverson [4] showed the role of transient infiltration and pore-pressure build-up in triggering failures. Bogaard and Greco [9], Reid and Iverson [10], and Baum et al. [11] concluded that rapid groundwater changes can critically reduce effective stresses, particularly in unsaturated soils. Several research papers have directly quantified rainfall-groundwater interactions, such as Saito et al. [12], who analysed the time lag between rainfall and groundwater rise, and Chinkulkijniwat et al. [13] developed functions relating groundwater response to rainfall and permeability. Gofar and Lee [14] and Wieczorek and Glade [15] observed similar relationships across diverse geomorphological settings.

Numerical models remain a central tool in applied research. Zhang et al. [16] investigated the importance of time-dependent pore pressure variation in slope stability modeling using coupled hydro-mechanical models. The application of physically based distributed models (TRIGRS) for the evaluation of slope stability, integrating rainfall and groundwater interaction, is presented in the research of Crosta and Frattini [17]. Similar research was conducted by Baum et al. [18], accounting for the variability of saturated conditions.

Research performed by Suljić [19] defines the relationships among rainfall input, runoff coefficients, and effective infiltration within a landfill body. A concept applicable to modelling groundwater rise on natural slopes. Jusić et al. [20] researched how infiltration-based stormwater systems influence groundwater recharge. Complementing this, Šuvalija et al. [21] underline how reduced infiltration due to urbanisation and intensified rainfall events alters groundwater regimes and increases hydrological hazards.

Research Design

The goal of the research paper is to link real-time rainfall data to groundwater level fluctuations that affect slope stability. This question arises from the identified research gap: previous studies describe rainfall-infiltration and groundwater processes but do not integrate them into a unified, real-time predictive framework.

The methodology is primarily quantitative, combining:

- Hydrological analysis of rainfall data, which mainly refers to cumulative precipitation,
- Groundwater modelling through correlation of rainfall and groundwater level elevation, and
- Numerical slope stability analysis using PLAXIS 2D with groundwater level as a variable input.

Qualitative field observations serve only as contextual support, while the core analysis relies on measurable hydrological and geotechnical data.

Results and Discussion of the Parametric Analysis

Groundwater level elevation and slope stability calculations are performed for the Curine Njive landslide on Trebević Mountain. The rainfall data used for calculation is from March 1 to March 20 (data obtained from the Federal Hydrometeorological Institute), during which approximately 180 mm of precipitation fell over 20 days. Also, this is the period of the highest landslide movements measured at the inclinometer IN-1. This event consisted of continuous moderate rainfall with several daily peaks exceeding 10 mm, coinciding with the observed acceleration in slope movement.

Results from the geological investigation showed that the soil profile consists of three distinct soil layers. The first layer is low-permeability weathered silty clay, the second is sandy siltstone with higher water permeability, and the third is a fractured bedrock layer considered impermeable for groundwater modelling. Key geotechnical parameters from field and laboratory tests, such as permeability, unit weight, and shear strength, are listed in the table below, as they directly influence infiltration behaviour and groundwater rise during rainfall events.

The sandy siltstone layer acts as a preferential flow path with a higher infiltration capacity than the low-permeability silty clay cap. Considering surface vegetation and moderate slope angle, a runoff coefficient C=0.4 is assumed.

Effective infiltration is calculated as:

$$I_{eff} = P_{cum} \cdot (1 - C) \quad (1)$$

For P_{cum} = 180 mm, and C = 0.4, we obtain:

$$I_{eff} = 180mm \cdot 0.6 = 108\ mm \quad (2)$$

Assuming steady-state vertical infiltration and saturated hydraulic conductivity of k = $5 \cdot 10^{-6}$ m/s, the infiltrated water level is calculated.

Using Darcy's law seepage velocity delay time is calculated for comparation with measured values.

$$Q = k \cdot I = 5 \cdot 10^{-6} \frac{m}{s} \quad (3)$$

$$V = \frac{q}{n} = \frac{5 \cdot 10^{-6}}{0.3} = 1.67 \cdot\ 10^{-5} \frac{m}{s} \quad (4)$$

Time for infiltration to reach the phreatic surface:

$$t_v = \frac{z}{v} = \frac{3.0m}{1.67x10^{-5}\frac{m}{s}} = 1.8\ x\ 10^5\ s = 2.1\ days \quad (5)$$

This corresponds closely to field observations where the groundwater level rise was detected 2-4 days after the rainfall event.

By linear approximation, a rainfall of 180 mm (after runoff losses) results in a 2.0 m rise of the water table. This groundwater level will be used for slope stability calculation.

$$\Delta h = f(P_{cum}) \rightarrow \Delta h = \alpha \cdot {P_c}^{*}{}_{um} \quad (6)$$

Where P_{cum}^* = 108 mm, α ≈ 2.0 / 108 ≈ 0.0185 m/mm.

Inclinometer measurements from 20 March indicate soil sliding, and given the rainfall in the period before the measurements, it can be clearly concluded that the landslide was caused by a rise in groundwater level due to rainfall. PLAXIS 2D simulations show that slope collapse (FS = 1.0) occurs when the groundwater level rises to -6.0 m, an increase of approximately 2.0 m from the measured groundwater level of -8.0 m. The geomechanical parameters used in the analysis and the adopted groundwater level of -6.0 m are summarized in the table below.

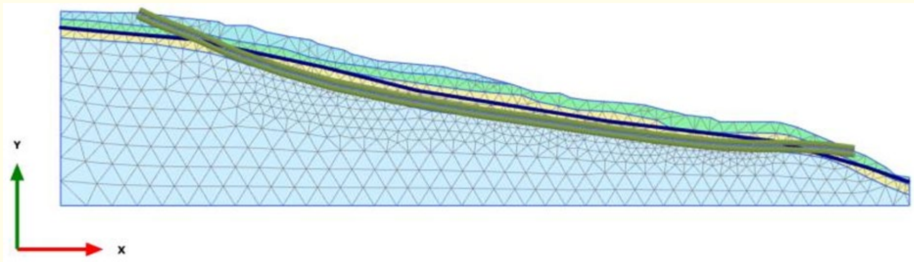

Figure 1: FEM Model in Plaxis 2D.

Identification		Fill material	Silty Clay	Sandy Siltstone	Siltstone	Sliding Surface
Identification number		1	2	3	4	5
Drainage type		Drained	Drained	Drained	Drained	Drained
Colour						
γ_{unsat}	kN/m³	20.00	19.00	20.00	21.00	20.00
γ_{sat}	kN/m³	20.00	19.00	20.00	21.00	20.00
E	kN/m²	20.00E3	10.00E3	40.00E3	60.00E3	10.00E3
ν (nu)		0.3000	0.3000	0.3000	0.3000	0.3000
G	kN/m²	7692	3846	15.38E3	23.08E3	3846
E_{oed}	kN/m²	26.92E3	13.46E3	53.85E3	80.77E3	13.46E3
c_{ref}	kN/m²	1.000	16.00	15.00	25.00	1.000
φ (phi)	°	30.00	19.00	22.00	30.00	12.00
k_x	m/day	0.864	0.00864	0.432	0.000	0.432
ky	m/day	0.864	0.00864	0.432	0.000	0.432

Table 1: Geomechanical soil parameters.

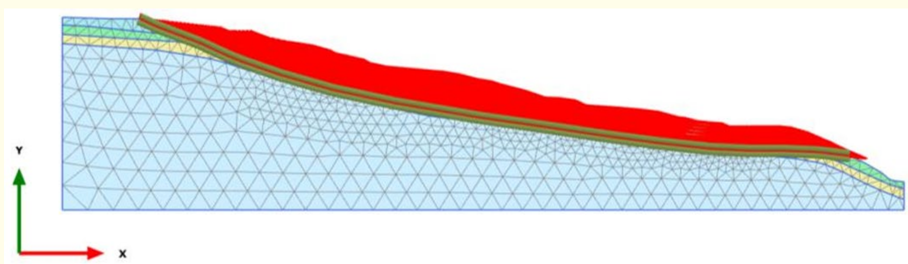

Figure 2: Critical sliding surface. FS = 1,0.

For unconfined aquifer conditions, groundwater level rise can be calculated.

$$\Delta h = \frac{I_{eff}}{S_y} = \frac{0.108}{0.054} = 2.0m \qquad (7)$$

Using the parameters shown in this paper, an equation relating groundwater rise (Δh) to cumulative rainfall is derived and shown below.

$$\Delta h = \frac{1-C}{S_y} \cdot P_{cum} \qquad (8)$$

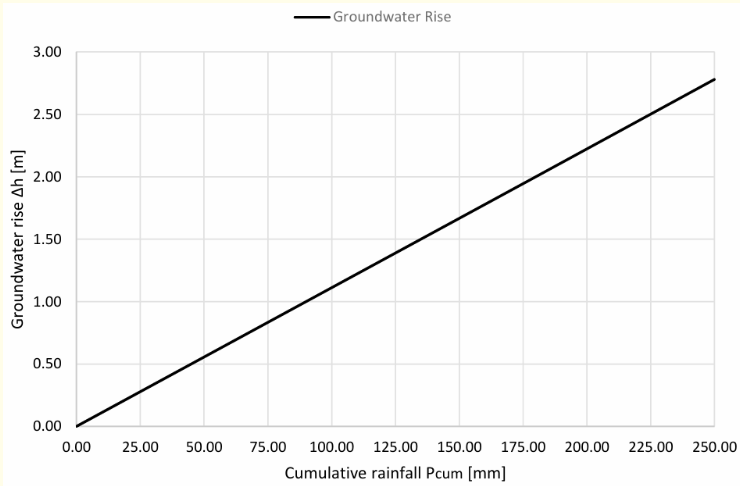

Figure 3: Cumulative rainfall – Groundwater level rise chart.

Combining these findings, a preliminary relationship is proposed for the Curine Njive site:

- Rainfall exceeding 100 mm within a 10-15 day period results in effective infiltration >60 mm.
- This results in a water table rise of>1.0-1.5 m, depending on soil permeability.
- If water table approaches -6.0 m (based on Plaxis FS = 1.0), slope instability is likely to initiate.

The parametric analysis confirms a clear quantitative relationship between cumulative rainfall, groundwater rise, and resulting slope stability, directly addressing the study's research question. By comparing precipitation amounts and the inclinometer displacements recorded in the sliding body over the same time period, it can be clearly concluded that the rise in groundwater level caused the movement of the sliding mass. This behaviour is consistent with Suljić [19], who showed that cumulative rainfall—after adjusting for runoff—directly governs changes in the internal water level.

Analysis of the calculation results indicates that the terrain's geological structure significantly influenced the accumulation of water in the soil. The slow flow of water through the surface sandy clay layer of low water permeability delayed the infiltration of water into the soil, while the high water permeability of the sandy siltstone layer enabled the rapid spread of infiltrating water, accumulating in this layer. This interpretation aligns with the research of Jusić et al. [20] and Šuvalija et al. [21], who found that groundwater flow and soil permeability have the most significant impact on groundwater location and quantity in the soil.

Applying the calculated groundwater level increase of 2.0m, setting the groundwater level at a depth of 6.0m, yields a slope safety factor approximately equal to 1.0, which is consistent with field measurements and events. In this way, it is also numerically demonstrated that the increase in groundwater level triggered the landslide.

Ultimately, the results show that if the terrain's geological structure and soil hydrogeological characteristics are known, it is possible to link precipitation intensity to groundwater level and, therefore, to the stability of the landslide. In this sense, the study effectively bridges the research gap by integrating hydrological, hydrogeological, and geotechnical processes into a unified, predictive landslide assessment system.

Conclusion

This research demonstrates that landslide analysis is possible using real-time hydrological parameters and groundwater-level calculations based on them. As mentioned in the paper, most landslide analyses are performed for static groundwater levels, without accounting for fluctuations in groundwater levels driven by hydrological and hydrogeological parameters. This approach leads to a more precise assessment of landslide risk because it also accounts for variations in groundwater levels driven by actual cumulative rainfall.

In the Curine Njive landslide, this approach proved very precise, as analytical and numerical calculations closely matched field-measured values, confirming that landslide risk can be reliably estimated using this model.

The paper also established a linear relationship between cumulative rainfall and groundwater level, which can be used to predict future groundwater levels from cumulative precipitation over a given period.

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