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Research Article

NUMERICAL INVESTIGATION OF RAINFALL-INDUCED SLOPE FAILURES THROUGH COUPLED FLUID–SOIL INTERACTION MODELING

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Abstract

This paper performs a detailed numerical analysis of slope instability that can be caused by precipitation using a full couple fluid-soil interacting model. The analyses are based on the formulation of the finite element with the usage of Richards equation to state the movements of water by means of unsaturated and saturated mediums. The three sandly materials were tested under condition of rainfall of 25, 50, 75 and 100mm h -1 and also at different storm duration durations to determine stability of the sand in different infiltration regimes. Findings prove that the factor of safety (FS) decreases in proportion to the intensity and duration of rainfall highlighting the importance of the pore-water pressure accumulation and suction depletion in triggering failure. The Toyoura sand was more stable, which is explained by the high permeability and high friction angle whereas Saigata and Ohto sand had lower stability because it had already failed at high rainfall intensity. The two-way hydro-mechanical methodology is good in capturing the elusive behavior of the pore pressure and the effective stress, with more accuracy than the uncoupled models. The results put the model in perspective of its ability to forecast rainfall led slope failures and its ability to help in making better slope designs and risks assessment.

Keywords: Fluid–Soil Interaction, Numerical Techniques, Rainfall-Induced Slope, Richards Equation, The safety factor.

1. INTRODUCTION

Rainfall is one of the weightiest influences to induction the landslide hazards. Founded on previous experimental and numerical studies [1]. In turn the landslides are causing in over of continuously drains money and infrastructure so that it represents the second most important natural disaster after earthquakes however some landslides due from human activities [2]. Rainwater may be leading to slope instability by penetration of water into a soil slope so that it may rise underground water level and soil weight and decline soil mechanical properties, The dual effects of soil (water) and gas(air) fluids over and within the soil lead to infiltration to rainfall of the slope which is represents a complex unsaturated escape process. There are more than one factor that influence on infiltration intensity of soil such slope boundary conditions, water-air viscosity and soil permeability [3]. During the process of infiltration of the rainfall, the water which is represent the liquid phase applies pressure on the gas phase represent by air within the soil, as the result in a jacking force that compete with the way of water drive. This singularity can cause a decline in the rate of infiltration of the rainfall because of the reduction that occurs in the gradient of the pressure of the water. These effects of air on the infiltration progression were detected and described in frequent studies. In studying the mechanism of landslides caused by rainfall and attempts to avoid them, in addition to physical modeling that simulates reality, numerical simulation methods are the most popular and widely used. They represent standard methods, especially the finite element method, in addition to other numerical methods and computational fluid dynamics. Many researchers have studied the deformation and seepage of unsaturated slopes during rainfall or after an earthquake. They have stated that earthquakes have a noteworthy impact on the slippage of slope surfaces affected by rain, which leads to an increase in the intensity of ground vibrations [4][5].It implements a coupled fluid soil interaction model within a single finite element framework 7the finite difference method wherein the soil is treated as a continuum [6]. The transport model (Richard 27s equation) integrates the soil water holding curvature, enabling the assessment of unsaturated saturated soil states, thereby facilitating the initiation and development of failure mechanisms. Rainfall is frequently the primary initiation of landslides in several areas of the world. Rainwater infiltration into a slope drives pore pressure development and alters suction in unsaturated zones, affecting the mechanical response of the soil and contributing to a loss of slope constancy. Finally, the coupled response of fluid flow and soil mechanics is critical to quantifying the activating of the slope that is induced by rainfall failures. The numerical investigation from the slope that is induced by rainfall instabilities through the coupled consideration of fluid–soil interaction is presented [7]. A fully coupled continuous approach with a non-isothermal multiphase model simulates single-phase and multiphase flow, unsaturated characteristic of the curves of soil-water, and variations of porousness with saturation and void relation. The constitutive response of the soil skeleton is captured with an elasto-plastic law, while hydro-mechanical coupling and the effects of volumetric changes on permeability are modeled through the adjustment of porosity. The primary impartial of this work is to examine the numerical assessment of triggering rainfall events by implementing the coupled fluid–soil interaction model into a computational framework. Stability of slopes exposed to complex rainfall infiltration patterns under various configurations is then investigated. The response of water saturated and unsaturated slopes subjected to different land slide triggering conditions is evaluated, and failure patterns for the slope that is induced by rainfall instability are identified.

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2. METHODOLOGY

Governing Equation (Richards Equation)

The common form of the Richards formula describes the transient drive of the water in both unsaturated saturated then regions of the soil. It states that the degree of alteration of volumetrical content of the water edness (signified by the Greek letter theta θ) with deference to time (t) is equal to the divergence of the product of the conduction from unsaturated hydraulic (k, which is the function of soil force, (ψ) and the gradient of the entire hydraulic head (H) [8][9].

Mathematically as following:-

$$\partial\theta/\partial t = \nabla\cdot (k(\psi)\ \nabla H) \quad \ldots\ldots\ldots\ldots\ldots 1$$

3. COUPLED HYDRO-MECHANICAL ANALYSIS

3.1. Governing Equations

3.1.1. Force Equilibrium

The force equilibrium equation is given as following:

$$\nabla\cdot \sigma + \rho\ b = 0 \quad \ldots\ldots\ldots\ldots\ldots 3$$

3.1.2. Mass Continuity of Water

$$\partial(nS)/\partial t + \nabla\cdot (\rho w v w) = 0 \quad \ldots\ldots\ldots\ldots 4$$

4. ANALYZING OF THE SLOP´S STABILITY

In Table (1) we were included analysis restrictions for the sensitivity and the constancy of the slope.

4.1. Numerical Techniques

Numerical modeling of coupled fluid–soil interaction systems usually adopts one of two fundamental approaches: an uncoupled, iterative scheme or a coupled approach. In the uncoupled scheme, the fluid transport equations are solved first and the resulting hydraulic parameters are input to a geomechanics analysis [9]. Conversely, the coupled approach solves the governing fluid flow and geomechanics equations simultaneously. At element level this leads to a coupled fluid-continuity and momentum-balance equation. At grid level the system yields the classical coupled matrix equations for coupled multi-phase flow and geomechanics. The uncoupled approach, while physically inconsistent, is widely utilized by computational platforms such as FLAC and is typically employed for coarse sensitivity studies with low computational effort [2][10]. Conversely, the coupled scheme offers enhanced simulation capabilities for transient response problems but entails increased numerical complexity and elevated computational demand.

4.2. Parameter Selection

Downloaded material was considered [3]. Parameters were set after reviewing published studies of the slope that is induced by rainfall failures [4][11]. Several cases were examined to clarify the influence of each parameter and identify effective countermeasure designs.

5. The Boundary Equilibrium Method

5.1. Interslice Shear Force

$$X = \lambda\ .fIS(x)\ .\ E \quad \ldots\ldots\ldots\ldots 5$$

5.2. Factors of Safety

5.2.1. Factor of Safety regarding Moment Equilibrium (Fsm)

$$FSm = [\Sigma\ \{c'.\beta slice.R + [N - u_a.\beta slice + (u_a - u_w).\beta slice.\tan(\varphi')].R\ .\ \tan(\varphi')\ \}]\ /\ [\Sigma\ W_x - \Sigma\ N_f] \quad \ldots\ldots\ldots\ldots 6$$

5.2.2. Factor of Safety (Force Equilibrium) (Fsf)

$$FSf = [\Sigma\ \{\ c'.\ \beta slice.\ \cos(\alpha) + [(N - u_a.\beta slice) + (u_a - u_w).\tan(\varphi')]\ .\ \tan(\varphi').\cos(\alpha slice)\ \}]\ /\ [\Sigma\ N.\sin(\alpha slice)] \quad \ldots\ldots\ldots\ldots\ldots 7$$

6. FLUID–SOIL INTERACTION

The method of assessing slope stability in presence of transient rainfall requires the proper description of the coupled fluidsoil system achieved by a completely integrated computational scheme. Parameters of constitutive correlations and hydraulic conductivity, chosen in accordance with the typology of a particular soil, have a considerable effect on whether the saturation condition of soil and the pressure in the pores are determined [1][13]. The bidirectional coupling approach allows simultaneous solving of fluid and solid equations of motion by exchanging information to occur at control-volume boundaries. The geometrical arrangement of the dug hole is shown as a column with some inclined surfaces of slops and rainfall infiltration is modeled with an exposed void at the top cover. Coupled fluidsoil interaction is used to carry out preliminary failure analyses, thus, forming uniform failure mechanisms in various loading configurations [2][12]. Under transient infiltration, the fluid–soil interaction model yields reliance predictions comparable to coupled seepage-stability analysis for shallow failure surfaces. Subsequently, constant-intensity rainfall induces instability during the rise of the pore water pressure ratio, whereas decaying-rainfall events trigger failure during the peak phase [14] (see table (2).

6.1. Hydraulic Conductivity

Hydraulic conductivity constitutes a fundamental input for the slope that is induced by rainfall failure analysis [19][15]. Two different approaches exist to define hydraulic conductivity k(θ), namely, from the soil water retention curve (SWRC) or from experimental data [16][18]. Since a coupled hydro-mechanical formulation with suction-dependent soil stiffness and strength properties is exploited, the methodology developed by is here implemented, which allows defining the hydraulic conductivity function independently of the SWRC. When a permeability function k(ψ):-

$$k\ oj(\theta) = k(\psi) \quad \ldots\ldots\ldots 8$$

Soil layers for which experimental k(ψ) data are unavailable can be reproduced by means of an analytical function and the Rigby method to invert the SWRC[16][17]. However, the most suitable option remains the direct use of the experimentally-based formulation, especially for slope materials governed either by enhanced permeability phenomena or with a poorly defined SWRC. Soil water retention curves for all materials are likewise derived by applying the inverted retention model.

Table 1. The parameters are used for analyzing sensitivity and the stability of the slope

Parameter	Symbol / Variable	Value / Range	Unit	Description
Method	–	Bishop-like slice method	–	Simplified slope stability method
Number of slices	nslices	20	–	Discretization for Bishop method
Failure criterion	–	FS < 1.0	–	Indicates slope failure
Hydraulic conductivity multiplier	k_mult	0.5–1.5	×k	Sensitivity range for k
Friction angle deviation	Δφ	−5 to +5	°	Sensitivity range for φ
Minimum factor of safety	FSmin	–	–	Lowest computed FS
Time to failure	t_failure	–	hr	Time when FS < 1.0

Table 2.Public Experiential Constants and Soil-Water Limits

Parameter	Symbol / Variable	Value	Unit	Description
Remaining water content	θr	0.045	–	Minimum volumetrically content of water
Saturated water content	θs	0.43	–	Maximum volumetrically content of water
Hole-connectivity parameter	l	0.5	–	Empirical constant
Cohesion	c	0 (default)	kPa	Cohesion used in FS computation
Suction-friction angle	φb	15	°	Contribution from matric suction

Table 3. Geotechnical parameters of three soils types that used in the present study

Soil Type	γ (kN.m^{-3})	φ	k (m.s^{-1})	α (1/m)	n (–)	m = 1−1/n
Toyoura Sand	16.0	37	1.19×10^{-5}	3.8	2.80	0.64
Saigata Sand	17.0	32	1.79×10^{-5}	3.5	2.65	0.62
Ohto Sand	17.4	31	1.25×10^{-5}	3.2	2.55	0.61

Table 4.The mesh and slope geometry conditions

Parameter	Symbol / Variable	Value / Range	Unit	Description
Slope angle	θ	25°, 30°, 35°	degrees	Inclination of the slope surface
Slope height	H	10	m	Vertical height of the slope
Slope length	L	20	m	Horizontal projection of the slope
Slope depth	D	15	m	Vertical computational domain depth
Number of nodes= (x-direction)	nx	80	–	Grid point at x-direction
Number of node=(z-direction)	nz	50	–	Grid point at z-direction
Grid spacing (x)	Δx	20 / (80–1)	m	Computed automatically
Grid spacing (z)	Δz	15 / (50–1)	m	Computed automatically

Table 5.The simulation condition of the rainfall

Parameter	Symbol / Variable	Value / Range	Unit	Description
Rainfall intensity	I	25, 50, 75, 100	mm/hr	Applied rainfall rate
Rainfall duration	td	12, 24, 36, 48	hr	Duration of rainfall event
Rainfall pattern	–	constant / increasing / decreasing / sinusoidal	–	Temporal variation type
Total simulation time	Ttotal	72	hr	Duration of full simulation
Time step	Δt	0.2	hr	Numerical integration step size

6.2. Soil Properties

Soil properties significantly influence the extent of slope failure under rainfall infiltration. In the simulations, specific weight, friction angle, and permeability are fixed; cohesion c and saturation degree r are set as functions of the volumetrical content of the water (θ/θs) [2][20].The geotechnical parameters of the three soils types that are used in the current studycan be found in the table (3). The relationships are expressed as:

$c = 10^{(3 - 5 (\theta/\theta s))}$

$r = (\theta/\theta s)^{1/2}$

The three sand types utilized in the study are characterized by their specific weight, friction angle, and permeability as follows:

- Toyoura sand:

$\sigma = 16.0$ kN m^{-3}, $\phi = 37°$, $k = 1.19\times10^{-5}$ m s^{-1}……………..9

Saigata sand: $\sigma = 17.0$ kN m m^{-3}, $\phi = 32°$, $k = 1.79\times10^{-5}$ m s^{-1}

- Ohto sand: $\sigma = 17.4$ kN m m^{-3}, $\phi = 31°$, $k = 1.25\times10^{-5}$m.s^{-1}

7. SIMULATION SCENARIOS

7.1. Mesh Configuration and Slope Geometry

All mesh configuration and the geometry conditions of the slope are presented in table (4).

7.2. Rainfall Patterns

Rainfall patterns influence the occurrence of the slope that is induced by rainfall failures by affecting the generation of pressure of pore-water, which compromises these stability of the slope [21]. To accurately reproduce rainfall infiltration, a variety of time-dependent rainfall scenarios are considered. Generally, infiltration acts on a slope as infiltration cycles. The ×-th infiltration cycle occurs within the time interval [ts, te], where ts and te are the starting and ending times of the cycle, respectively. The time domain [ts, te] is divided into m periods and the starting and ending times of the i-th period are denoted by ti−1 and ti, respectively, with ts ≡ t0 < t1 < · · · < tm ≡ te. Within the i-th period, the rainfall intensity varies from Ri−1 to Ri. The simulation condition of the rainfall are included in the table (5).

7.3. Slope Configurations

Shioi and Zhang et al. established that slope failures depend on failures in rock masses or soils with weak layers. These weak layers are of two types: a single sliding plane and translational shear failure in parallel weak layers. Any of these failure modes may be triggered in mountain slopes due to rainfall infiltration. Consequently, the deepest failure plane or slip surface can develop along weak layers of soil or rock having a relatively lower undrained shear removal that has been fully soaked by wet infiltration. Kamai et al. and Kakogiannou et al. clarified that the identification of slip surfaces is the most challenging problem in the estimation of slop´s stability and the evaluation of failure extent.

8. RESULTS AND DISCUSSION

The coupled hydro -mechanical simulations were performed on slopes of Toyoura Sand under varying intensities of rainfall (25mm.h^{-1}, 50mm.h^{-1}, 75mm.h^{-1} and 100 mm.h^{-1}) and at a length of time of the rainfall (maximum 72 hours). The outcomes, which were presented in figure 1, display how the Factor of Safety (FS) variationsby time. This analysis displays that the intensity of the rainfall and the duration of infiltration have a very close connection to slope stability.

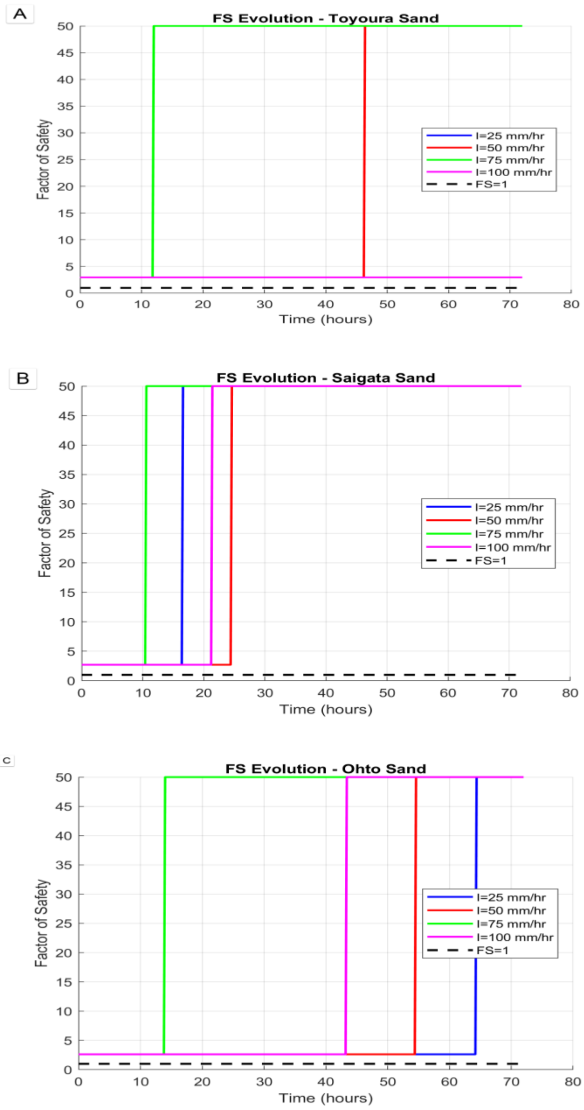

Figure (1). The plotting the safety factor variations through the time for: (A) Toyoura Sand, (B) Saigata Sand and (C) Ohto sand

Since the FS was approximately steady during the course of the simulation at a low rate of rainfall (25 mm /h -1), it indicates that the slope behavior was also constant and that the pore-pressure accumulation was also minimal. This result validates the fact that when the infiltration rate is low the soil possesses sufficient suction to sustain stability. On the other hand, a more significant rise in FS was demonstrated when the moderate intensity (50mmhr-1) was attained, which is an indication of a transient numerical stiffening with a sharp change of unsaturated states into saturated ones [21]. At an intensity of 75mm/hours, the onset of failure was sooner, approximately at 10 hours, which was a sign of considerable decrease in suction and the creation of a balanced water table. At the high-intensity case (100 mm/hr -1), the FS was almost 3.0 which indicates the state of near-saturated condition due to rather large scale of friction angle (37 °) of Toyoura Sand (See Figure 1).

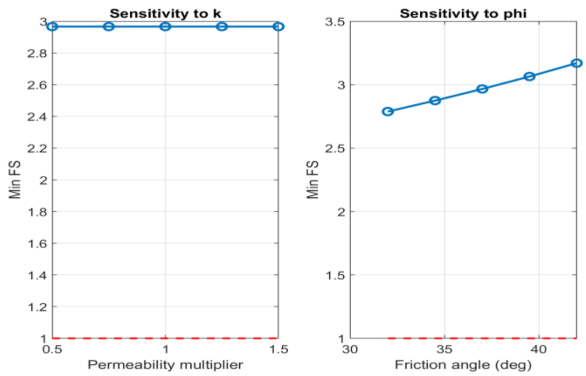

Figure 2.The figure shows a sensitivity analysis of slope stability of Toyoura Sand in terms of two important soil parameters permeability and friction angle

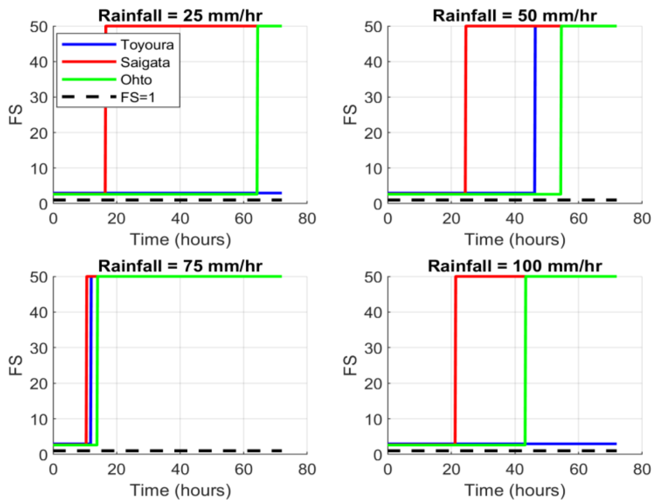

Figure 2. Safety factor is introduced as the function of time (in hours) on three diverse types of soils southern Toyoura, Saigata, and Ohto soil at four different rain intensities (25, 50, 75 and 100 mm/hr)

All in all it was found that Toyoura Sand is stable to all simulated levels of rainfall and that FS is always larger than 1.0. However, time taken to achieve conditions leading to critical is less with the higher the strength of the rainfall, which supports the direct relationship between the infiltration rate, suction loss, and effective stress reduction. The success of the transient hydro-mechanical coupling in capturing the development of pore pressure and the consequent changes in the stress field in the slope was successful thereby reinforcing the use of the coupled approach over uncoupled approaches especially in short duration, high intensity events of rainfall when a hydraulic and mechanical process takes place simultaneously (See figure 2 and 3).

9. Conclusion

The numerical analysis showed how the rainfall intensity impacted the slope stability based on coupled fluid-soil interaction model. The Toyoura Sand, with high permeability and internal friction, demonstrated stable behavior with all the rainful situations dedicated to it and ensured the ratio of the safety values were in range ratio of safety indicating the critical level. The level of safety reduces with the intensity and time of infiltration as a result of minimal matric suction. The coupled hydro-mechanical model is effective in the evolution of the temporary coupling of the build-up of hole pressures and a decrease in shear strength. The intensive rainfall hastens the stability development, but does not necessarily cause failure in the coarse-grained mixtures, including the Toyoura Sand. The finite element model gives true to life predictions of slope behaviour acting upon the rainfalls confirming its practical abilities in prediction of risk assessment and slope designs optimization. Experimental validation of the numerical results under controlled infiltration conditions with controlled infiltration conditions as well as comparison with finer-grained soils should be included in the future work to gauge the generality of the numerical results.

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