ISSN: *2717-7696*
Research Article
Vol; 3, Issue; 2, pp. 49-57, 2022
DOI: 10.48053/turkgeo.1062245
Journal homepage:
https://dergipark.org.tr/en/pub/turkgeo

Parametric Analysis of Factors Affecting the Rainfall Induced Slope Stability

Furkan Veli Özçelik *[*1], **Murat Ergenokon Selçuk** [1]

[1]*Yıldız Technical University, Civil Engineering Faculty, Civil Engineering Department, Istanbul, Turkey*

Keywords
Slope stability
Rainfall infiltration
Unsaturated soil
Shear strength

ABSTRACT

Slope failures are one of the most vital problems in geotechnical engineering applications which may cause damage both in human life and financial. Slope failures are frequently observed especially in regions where rainfall is high. The most important factor affecting slope stabilities is rainfall infiltration. It is known that infilled soils are generally unsaturated soil. Therefore, the analysis of infill slopes should be performed within the scope of unsaturated soil mechanics. Rainfall infiltration causes the groundwater level to rise, which reduces the shear strength of the soil causing slope instability. In this study, the effect of rainfall intensity, rainfall duration, soil permeability, groundwater level, cohesion of soil, internal friction angle of the soil, and slope angle of the slope on the slope stability were analyzed parametrically by using GEOSTUDIO software. The infiltration analyses were performed using Seep/w module and factor of safety number of unsaturated soil slope were determined using Morgenstern method of Slope/w module of GEOSTUDIO software. Furthermore, different factor of safety numbers was found for each analysis along with the interpretation of the parameters effecting the slope stability. The results obtained in the present investigation showed that the rainfall intensity affects the stability of the slope. It was determined that there existed a non-linear relationship between rainfall intensity and safety number. As the rainfall intensity increases, the negative pore water pressure in the soil decreases nonlinearly, and the factor of safety number of the slope similarly decreases by 10% relative to the initial condition. When the rainfall duration change was taken into account, it was found that short time-heavy rainfalls affected the slope stability more than long time-low density rainfalls. Moreover, slope angle significantly influenced slope stability. It was observed that when the slope angle increased from 40° to 50°, factor of safety number decreased by 18.34%.

1. INTRODUCTION

Slope stability problems are among the common problems in geotechnical engineering applications. For many years, natural or artificial slopes have been of special interest to the geotechnical engineers. The effect of rainfall is one of the most significant factors affecting slope stability. Landslides on unsaturated soils usually occur during heavy rainy seasons. In other words, slope failures are triggered by the effect of rainfall. Many natural events, climatic and geological conditions have shown to trigger slope stability. Some of the factors affecting slope stability are slope of the slope, moisture content, pore water pressure change. In order to understand the effects of infiltration on unsaturated soil, its effect on slope stability must be studied. Several numerical and theoretical studies have been carried out on slopes under the effect of rainfall and reported in the literature.

The slope failures that occurred in Hong Kong and attempts to address the likely causes of these failures investigated by (Au, 1998). The author reported that the soils that were largely non-cohesive, steep terrain and intensive development were typical, slope failures frequently occurred, where intense rainfall in Hong Kong. Even though the impact of rainstorms on failures had not to be understood completely yet. Au, (1998) observed that rainfall intensity, areal extent, position and duration of the rainstorm had direct effects on the slope failure events.

* **Corresponding Author**

*(ozcelikfv@gmail.com) ORCID ID 0000-0002-1989-6957
(meselcuk@yildiz.edu.tr) ORCID ID 0000-0003-1890-7965

Received: 24/01/2022; Accepted: 25/08/2022

Cite this article

Özçelik F.V., & Selçuk M.E. (2022). Parametric analysis of factors affecting the rainfall induced slope stability. Turkish Journal of Geosciences 3(2), 49-57.

Rainfall induced landslides on partially saturated soil slopes were investigated by using the 2011 Umyeonsan landslides at the center of Seoul, Korea by (Jeong et al., 2017). The comprehensive investigation results in the mountainous area showed that the landslide activity is mainly related to rainfall and soil characteristics, slope and vegetation. Numerical analysis was also carried out to confirm the influence of these factors on the occurrence of landslides. Special attention is paid to rainfall infiltration analysis to determine the depth of the wet zone damaged by shallow and deep slopes of watershed-scale landslides. The simulation results were in good agreement with the investigation results, indicating that the method is suitable for the simulation of unsaturated soil landslides

Wang et al. (2020) studied the stability of a three-layer heterogeneous slope based on the generalized limit equilibrium method. The results showed that the stability of the slope decreased with the increase of rainfall intensity until it is destroyed. The safety factor of the slope was the lowest for a period of time after the rain stops. This situation implied that slopes are more susceptible to damage. With the increase of rainfall, the seepage field and stress field of the slope have undergone significant changes, which eventually makes the slope unstable. Consequently, the slope is considerably tended to landslides. Hence, we have to pay attention to monitoring the safety of slopes during rainstorms and for a period after the rainfall stops.

Karabulut, (2019) investigated the effects of rainfall infiltration into the soil on a high embankment slope built under unsaturated soil conditions on the stability by numerical analysis. The material parameters were determined from the laboratory tests performed on soil samples taken from the field after the embankment was built and from the ground-water characteristic curve. Pour water pressure changes were determined by using the SEEP / W module of the GEOSTUDIO software for the case of the seepage of rainfall into the slope, and the stability of the slope was investigated with the SLOPE / W module. Karabulut, (2019) observed that the change of groundwater level in unsaturated soils affects the shear strength of the soils. With the increase of the groundwater level, the number of safeties has decreased due to the shear strength of the soil. Furthermore, Karabulut, (2019) observed that rainfall intensity played an important role in slope stability, especially on unsaturated soils. Shear strength of the slope decreases with the increase of monthly rainfall intensity. However, in soils with low permeability, it was observed that the increase in the intensity of rainfall did not significantly change the slope stability, as the rainfall did not cause a significant increase in pore water pressures due to the inability of the rainfall to penetrate into the soil.

In this paper, parametric analyses of the factors affecting the rainfall induced slope stability were performed by GEOSTUDIO software. Hereby, factor of safety changes and percent decreases relative to the initial value were presented.

2. UNSATURATED SOIL MECHANICS

In classical soil mechanics applications, the conditions where the soil has positive pore water pressure are taken into account. However, in unsaturated soils, conditions where the pore water pressure is negative are taken into consideration. Soils are classified according to the water content in them as well as the size of the void that forms them. If the voids of the soils are completely filled with water, such soils are called saturated soils. If the voids are filled with a small amount of water, such soils are also called unsaturated soils (Önalp and Arel, 2013).

2.1. Suction Stress

It is known that in unsaturated soils, soil suction is related to the free energy of ground water. Matric and osmotic suction are components of this free energy. Total soil suction is obtaining by summing up the two basic components, matric and osmotic suction components (Karabulut, 2019).

$$\psi=(ua-uw)+\pi(\text{kPa}) \quad (2.1)$$

Where;

π = Osmotic suction (kPa), ua = Pore air pressure (kPa), uw = Pore water pressure (kPa), ψ = Total suction(kPa)

2.2. Soil Water Characteristic Curve

Soil-water characteristic curve (SWCC) is a considerable concept in determining unsaturated soil properties. Soil-water characteristic curve is generally defined as the relationship between soil water content and suction. Unsaturated soil properties can be determined by using soil water characteristic curve and saturated soil properties. In this case, the soil-water characteristic curve must be accurately estimated or measured and interpreted (Fredlund, 2012).

2.3. Shear Strength in Unsaturated Soils

The safety of many engineering structures depends on the strength of the soil that have located. Bearing capacity, lateral soil pressure, and slope stability are geotechnical applications depending on the shear strength of the soil. It is substantial to determine the shear strength of unsaturated soils because unsaturated soils are often used in the construction of engineering structures. It is also substantial to determine the changes in shear strength that may occur due to water infiltration in unsaturated soils (Fredlund, 2012).

The shear strength of unsaturated soils can be expressed in independent stress state variables. Any two of the stress state variables can be used for the shear strength equation. Equation (2.2) is obtained by using the (σ-ua) and (ua-uw) stress variables (Fredlund, 2012).

$$\tau = c' + (\sigma - ua)\ tan\phi' + (ua - uw) + tan\phi^{b} \quad (2.2)$$

Where, (σ-ua) refers to the effective normal stress, (ua-uw) matric suction, and (ϕ_b) the angle that indicates the amount of increase in shear strength due to matric suction.

Vanapalli 1996, proposed equation (2.3) by developing a physical model to obtain the shear strength of the unsaturated soil by defining the change of the water area at different saturation degrees along a soil-water characteristic curve. By this equation, shear strength can be determined for each desired matric suction change (Tetik, 2020).

$$\tau = c' + (\sigma n - ua)\ tan\phi' + (ua - uw)\ [(tan\phi')\ (\Theta - \Theta r / \Theta s - \Theta r)] \quad (2.3)$$

Where, ϴ, ϴr, ϴs refers to the volumetric water content, residual volumetric, water content and saturated volumetric water content respectively.

3. MATERIAL PROPERTIES

Soil parameters to be used in this study quoted from Aslan Fidan, (2017). Aslan Fidan, (2017) has worked around Veysel Karani Pond planned to be built in Veysel Karani Town of Baykan District of Siirt Province.

Within the scope of the field study of the Aslan, research wells were dug in six different locations in the study area in order to examine the geology of the region and to take samples for the necessary experiments.

3.1. Index and Physical Properties of the Soil

Determining the saturated and unsaturated parameters of the soil for slope stability analysis under the effect of rainfall infiltration of unsaturated soil is necessary. For this reason, the index and physical properties and shear resistance parameters of the examined clay soil were determined by routine laboratory experiments (Table 1). The unsaturated parameters of the soil were obtained by determining the soil-water characteristic curve by performing the filter paper test (Aslan Fidan, 2017).

Table 1. Index and Physical Properties of the Soil

Soil Index/Physical Properties	Change Interval
Natural Water Content (%)	21.37-25.83
Liquid Limit (%)	22.62-62.15
Plastic Limit (%)	15.74-26.51
Plasticity Index (%)	6.88-35.64
#4 sieve remaining (%)	0.16-48.74
#200 sieve passing (%)	31.25-90.05
Specific Gravity	2.72-2.75
Natural Unit Volume Weight (KN/m^3)	18.35-20.11
Permeability Coefficient (m/sec)	$1x10^{-7}$-$6x10^{-7}$

3.2. Soil Water Characteristic Curve

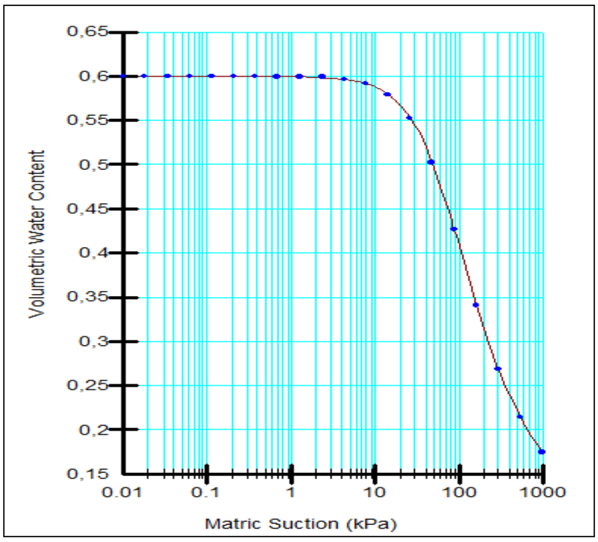

Figure 1. SWCC of the soil sample (Aslan Fidan, 2017)

One of the required input parameters for a transient analysis is the volumetric water content function. Since it can sometimes be difficult or time consuming to obtain a volumetric water content function, it may be of benefit to be able to develop an estimation of the volumetric water content function using either a closed-form solution that requires user-specified curve-fitting parameters, or to use a predictive method that uses a measured grain-size distribution curve. Seep/w module has several methods available to develop a volumetric water content function. One is to estimate a Data point function using a predictive method based on grain size, in which closed form equations based on known curve fit parameters. The soil-water characteristic curve obtained with the Data-Point Suction option in the Seep/w module of GEOSTUDIO software is shown in Figure 1.

3.3. Shear Resistance Parameters

Aslan Fidan, (2017) determined the total shear strength parameters required for slope stability analysis by unconsolidated-undrained triaxial pressure test (UU), and effective shear strength parameters by consolidated-undrained triaxial pressure test (CU). According to the triaxial pressure tests (UU-CU), the shear resistance parameters of ophiolite clay are shown in Table 2.

Table 2. Shear resistance parameters of the soil (Aslan Fidan, 2017)

Total Cohesion c (kPa)	Total Internal Friction Angle, ϕ (°)	Effective Cohesion, (kPa)	Effective Internal Friction Angle, ϕ' (°)
66,87	12,4	15	14

4. METHODOLOGY

In the scope of this paper, GEOSTUDIO software was used which is a package software developed to provide solutions to geotechnical problems. There are eight different modules in the program: Slope/w, Sigma/w, Seep/w, Quake/w, Temp/w, Ctran/w, Air/w, Vadose/w. Each module is designed to solve different problems (GEOSLOPE, 2012).

4.1. Seep/w Module

The SEEP module provides numerical modelling of water flows in saturated and unsaturated soils. Advantages of numerical modelling over physical modelling; It can be listed as providing the solution of complex problems in a short time, modelling many different situations during the analysis, obtaining the results in every desired location at the end of the analysis, taking into account more boundary conditions (GEOSLOPE, 2015). There are lots of different analysis options in Seep Module. Within the scope of this study, transient seepage analysis will be used. Transient seepage analysis can be defined as a constantly changing situation. In order to obtain the change occurring at the end of the period determined in the transient seepage analysis, the pore water pressures of the soil at the beginning of the analysis should be introduced to the soil as the initial condition.

4.2. Slope/w Module

The SLOPE module provides the safety number of slope stability to be obtained by limit-equilibrium analysis methods. Morgenstern-Price, Spencer, Bishop, Janbu, Sarma, Lowre-Karaifath limit-balance methods can be used in the software. (GEOSLOPE, 2012) In this study, the Morgenstern-Price method was preferred as the limit-equilibrium method. Morgenstern and Price, (1965) developed a method similar to the Spencer method, but they allowed for various user-specified interslice force functions. Constant, Half-sine, Trapezoidal, Data-point specified are the interslice functions available in Slope/w for use with the Morgenstern-Price method (GEOSLOPE, 2012). Selecting the constant function makes the Morgenstern-Price method identical to the Spencer method. In this study, Morgenstern-Price analysis with a half-sine function was used due to considering both interslice shear and normal forces. Simpler methods that do not include all interslice forces and do not satisfy all equations of equilibrium sometimes can err on the unsafe side. In summary, the Morgenstern-Price method:

- Considers both shear and normal interslice forces,
- Satisfies both moment and force equilibrium, and
- Allows for a variety of user-selected interslice force function (GEOSLOPE, 2012).

5. ANALYSIS AND EVALUATIONS

In this study, same slope geometry which has 10 m height, and 40° slope angle were used. In the analyses, all other parameters were kept constant, except for the parameter whose effect of change was examined. Rainfall intensities were also investigated using the actual rainfall data of the study area.

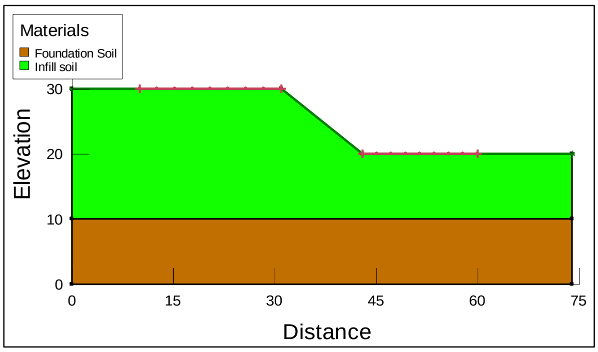

Figure 1. Slope model and Initial ground water table

5.1. Effect of Rainfall Intensity on Slope Stability

The effect of rainfall intensity on slope stability was investigated in unsaturated soil. At the initial conditions factor of safety was found as 1.75.

In the analyses, the monthly total rainfall amounts were converted into rainfall intensity. Safety numbers were obtained for three different monthly rainfall intensities: 300 mm, 500 mm, and 700 mm. Considering the groundwater level and pore water pressures after rainfall effect; Slope stability analyses were performed using unsaturated shear resistance parameters. Factor of safety values were found as 1.70, 1.64, and 1.59, respectively.

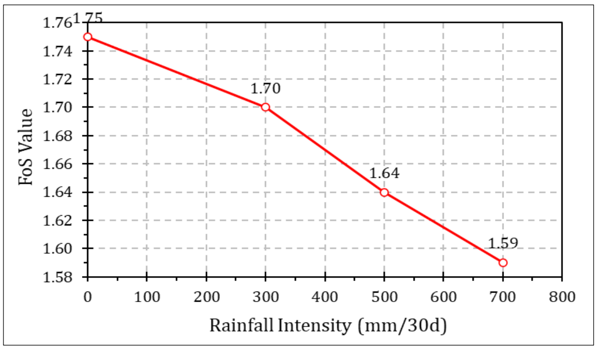

Figure 2. FoS value / Rainfall intensity graph

It was observed that the factor of safety number decreased while the rainfall intensity increased. In the Figure 3, the change in the factor of safety number depending on the rainfall intensity is seen clearly. Additionally, in Figure 4, percent decreases in the factor of safety number relative to the initial condition were shown. As it is seen in the Figure 4, 3.20%, 6.16%, and 9.08% decreases in the factor of safety number relative to the initial condition were observed under 300mm/30d, 500mm/30d and 700mm/30d of rainfall, respectively.

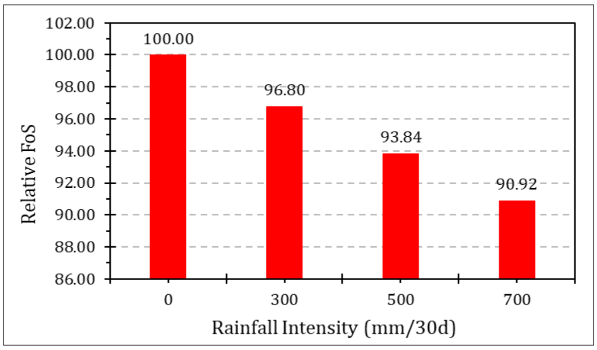

Figure 3. Percent FoS decreases relative to the initial value, depending on rainfall intensity

5.2. Effect of Rainfall Duration on Slope Stability

In order to see the effect of rainfall duration, the same amount of rainfall (300mm) was defined at different times as 3 days, 30 days, and 60 days.

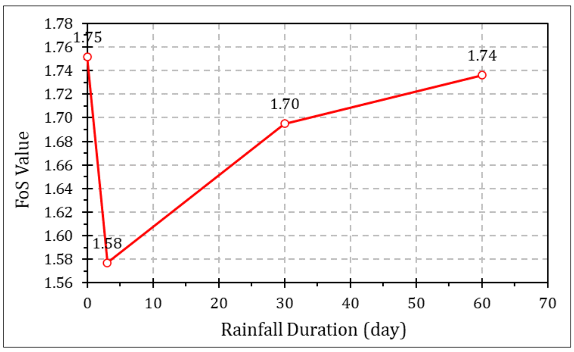

Figure 4. Factor of safety values after 300mm/3d, 300mm/30d, and 300mm/60d rainfall

As seen in the Figure 5, short time-heavy rainfalls affecting the slope stability more than long time-low density rainfalls. Additionally, in Figure 6, percent decreases in the factor of safety number relative to the initial condition were shown. As presented in the Figure 6, 9.99%, 3.25%, and 0.91% decreases in the factor of safety number relative to the initial condition were observed under 300mm/3d, 300mm/30d and 300mm/60d of rainfall, respectively. These results can be explained with the rapid decrease of the negative pore water pressure in the unsaturated soil.

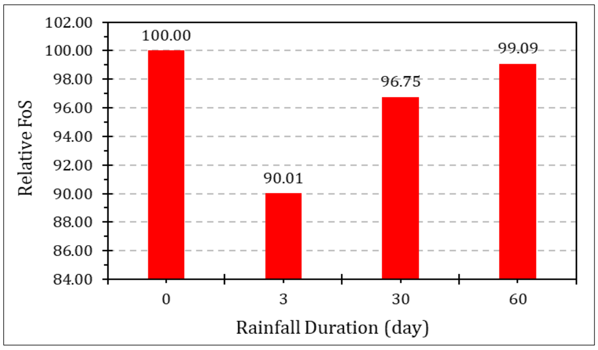

Figure 5. Percent FoS decreases relative to the initial value, depending on rainfall durations

5.3. Effect of Soil Permeability on Slope Stability

In this part, the effects of soil permeability on rainfall infiltration and consequently slope stability were investigated. Using different permeability values in the analyses, safety numbers were obtained after 300mm/30d rainfall. The permeability values which are used in the analyses are k1=5*10-5, k2=1x10-6, and k3=5x10-7m/sec.

In the Figure 7, the factor of safety changes while permeability of the soil decreases was presented. Additionally, in Figure 8, percent decreases in the factor of safety number relative to the k1(5.10-5m/sec) result were shown. As it is seen in the Figure 8, 6.48%, and 9.61% decrease in the factor of safety number relative to the k1 result (1.76) were observed under 300mm/30d rainfall. This situation can be explained by the relationship between infiltration and drainage. In soils with very high permeability (ks> 10-4 m/sec), rapid drainage occurs simultaneously with infiltration and therefore pore water pressure does not rise. Due to this reason the factor of safety number not to be affected much by infiltration. On soils with intermediate permeability (10-4 m/s - 10-7 m/s) infiltration-drainage balance gains importance. As the permeability decreases in this range, accordingly the safety number decreases.

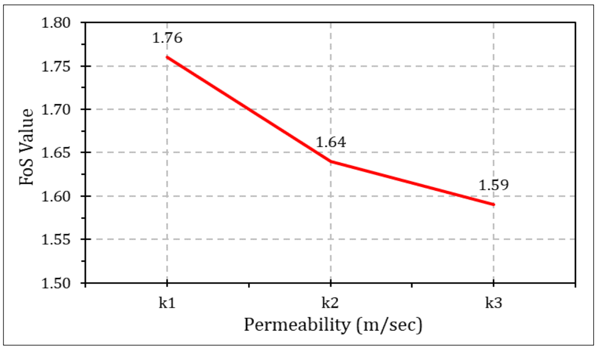

Figure 6. FoS number / Permeability graph

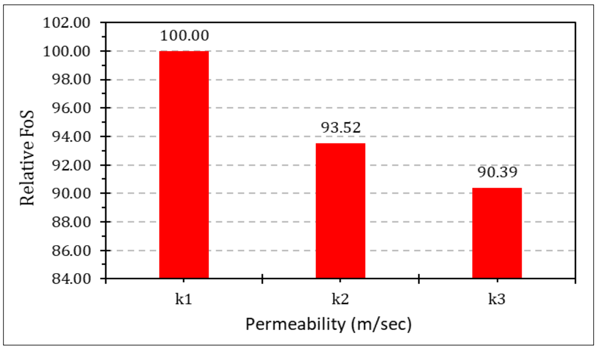

Figure 7. Percent FoS decreases relative to the first value, depending on the permeability

5.4. Effect of the Ground Water Table Change on Slope Stability

One of the noteworthy effects of rainfall is the change in groundwater level. A rise in the groundwater level may occur after rainfall, depending on the decrease in the negative pore water pressure (matric suction) of the soil, the shear strength that before rainfall of the soil decreases.

In this analysis, factor of safety numbers was obtained for 3 different groundwater levels in which, 16 m, 18 m, and 20 m above the lowest point of the slope model, in no rainfall conditions.

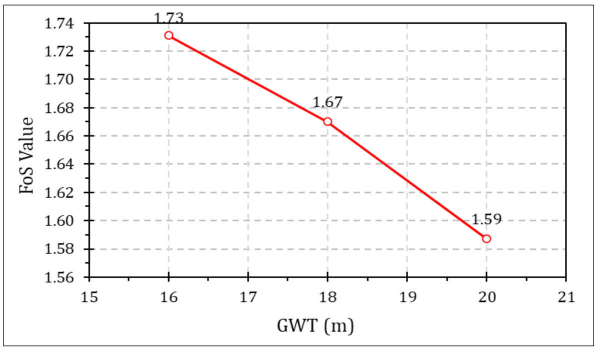

Figure 8. The change in the FoS values depending on GWT

As it is seen in the Figure 9, when the ground water table increase, factor of safety values decreases as well due to decrease in the matric suction. Additionally, in Figure 10, percent decreases in the factor of safety number relative to the lowest GWT (16m) result were shown. 1.14%, 4.57%, and 9.14% decreases in the factor of safety number relative to initial value were observed.

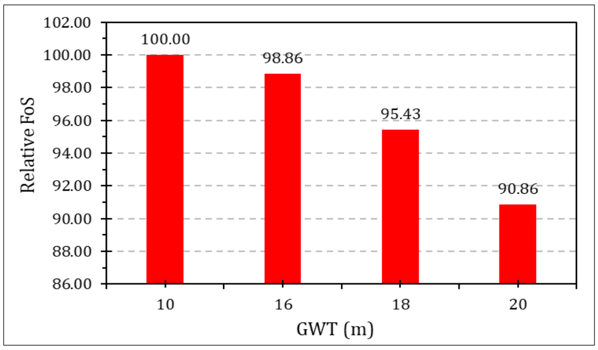

Figure 9. Percent FoS decreases relative to the initial value, depending on the GWT

5.5. Effect of Cohesion(c) on Slope Stability

In the analyses, the effect of the cohesion parameter on the slope stability was observed. Except cohesion, other parameters were kept constant in the analysis. Different factor of safety values was obtained for three different effective cohesion values of the unsaturated fill soil which are 15, 13 and 11(kPa).

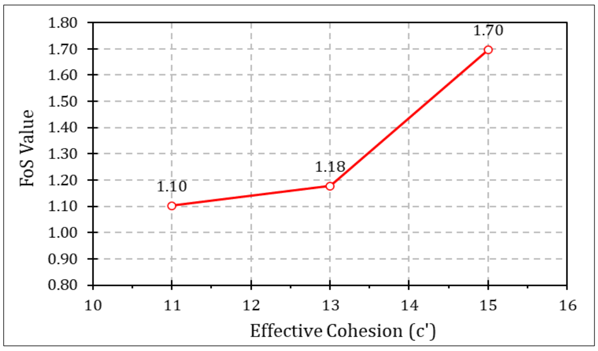

Figure 10. The change in the FoS values for different cohesion values

It is clearly seen in the Figure 11 that FoS increases with the increase in the effective cohesion. Additionally, in the Figure 12percent decreases in the factor of safety number relative to the initial FoS value (1.75) were shown. 2.86%, 32.57%, and 37.14% decreases in the factor of safety number relative to the initial FoS value were observed. In order to evaluate the results, we can say that cohesion is a considerable soil parameter that affects the stability because the safety number was significantly reduced with a small reduction in cohesion.

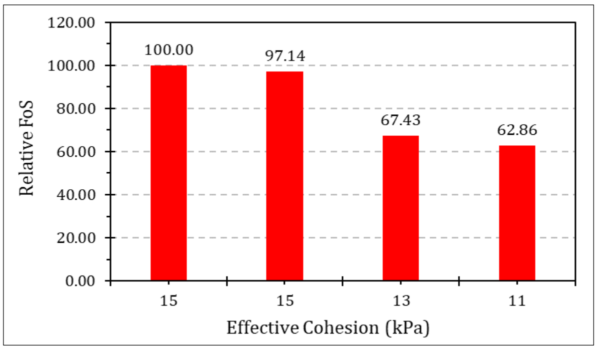

Figure 11. Percent FoS decreases relative to the initial value, depending on the effective cohesion

5.6. Effect of Internal Friction Angle on Slope Stability

In this analyses, effect of the internal friction angle in unsaturated soil on slope stability was investigated. Different factor of safety values was obtained for three different effective internal friction values of the unsaturated fill soil which are 14°, 12° and 10°. For these different internal friction angles, different ϕ_b values were calculated. The ϕ_b values calculated as 8.82°, 7.31°, and 6.08° for 14°, 12°, and 10° internal friction angles, respectively. Then, the new angles were used for each analysis.

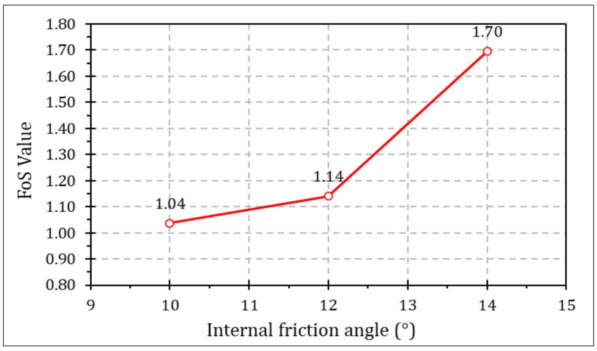

Figure 12. FoS number depending on internal friction angle

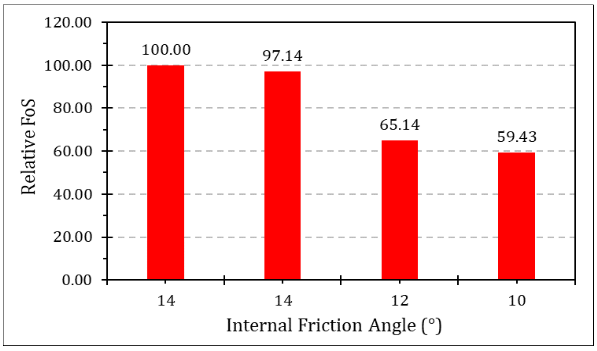

Figure 13. Percent FoS decreases relative to the initial value, depending on internal friction angle

In the Figure 13, it is seen that as the internal friction angle increases, the FoS values increases as well. Additionally, in the Figure 14, percent decreases in the factor of safety number relative to the initial FoS value were shown. 2.86%, 34.86%, and 40.57% decreases in the factor of safety number relative to the initial FoS value were observed.

5.7. Effect of Slope Angle on Slope Stability

In these analyses, only effect of slope angle change on slope stability was investigated. During the previous analyses slope angle was 40°. This angle was increased from 40° to 45° and 50°. At the initial conditions, FoS values obtained as 1.75, 1.59, and 1.44 for 40°, 45°, and 50° slope angles, respectively. As seen in the Figure 15, after 300mm/30d rainfall, FoS values were obtained as 1.69, 1.54, and 1.38 for 40°, 45°, and 50° slope angles, respectively.

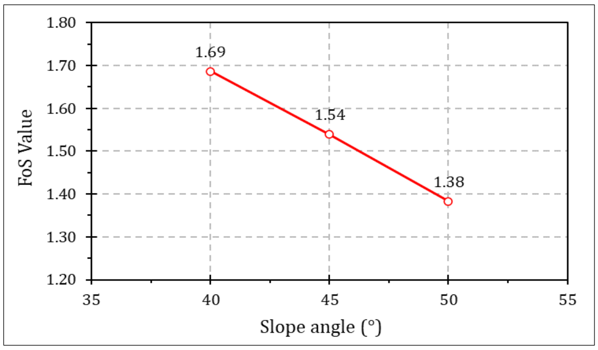

Figure 14. FoS values depending on slope angle

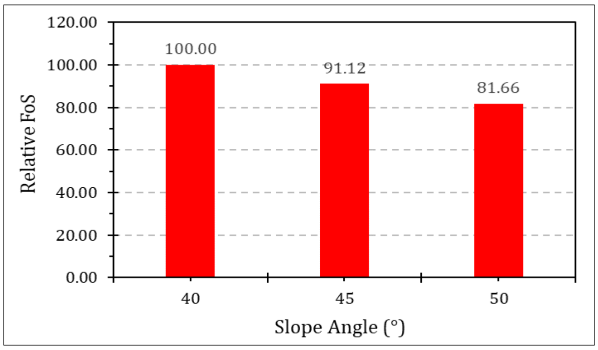

Figure 15. Percent FoS decreases relative to the first value, depending on slope angle

In the Figure 15, it is obviously seen that FoS values decreases as slope angle increases. For this reason, it can be said that slope angle is a significant factor on slope stabilities especially in rainy areas. Additionally, in the Figure 16, percent decreases in the factor of safety number relative to the FoS value of the 40° of slope angle were shown. 8.88%, and 18.34% decrease in the factor of safety number relative to the FoS value of the 40° of slope angle were observed.

6. CONCLUSION

The results showed that the rainfall intensity affects the stability of the slope significantly. Non-linear relationship between rainfall intensity and safety number was determined. As presented in the Table 3, while the rainfall intensity increases, the negative pore water pressure in the soil decreases nonlinearly, and consequently the factor of safety number of the slope similarly decreases.

Table 3. Rainfall intensity analysis results

Rainfall Intensity (mm/day)	FoS Value at Initial Condition	FoS Values After Rainfall	Percent Decrease Relative to Initial Condition
300		1.70	3.20
500	1.75	1.64	6.16
700		1.59	9.08

When the effects of rainfall duration on infiltration and accordingly slope stability were examined, it was seen that short-term heavy rainfall was more effective than long-term but relatively low-intensity rainfall. As seen in the Table 4, when 300 mm of rainfall fell on the soil in 3 days, a considerable decrease in the number of safeties were observed. These results can be explained with the rapid decrease of the negative pore water pressure in the unsaturated soil.

Table 4. Rainfall duration analyses results

Rainfall Duration (day)	FoS Value at Initial Condition	FoS Values After Rainfall (300mm)	Percent Decrease Relative to Initial Condition
3		1.58	9.99
30	1.75	1.70	3.25
60		1.74	0.91

It was further observed by different permeability analyses that when permeability decreased, the number of safeties also decreased. The analyses results are presented in the Table 5. This observation can be explained by the relationship between infiltration and drainage. In soils with very high permeability (ks> 10^{-4} m/sec), rapid drainage occurs simultaneously with infiltration and therefore pore water pressure does not rise. On soils with intermediate permeability (10^{-4} m/s -10^{-7} m/s) infiltration-drainage balance gains importance. As the permeability decreases in this range, accordingly the safety number decreases.

Table 2. Permeability analyses results

Soil Permeability (m/sec)	FoS Value at Initial Condition	FoS Values After Rainfall (300mm)	Percent Decrease Relative to Initial Condition
$5x10^{-5}$		1.76	0
$1x10^{-6}$	1.75	1.64	6.48
$5x10^{-7}$		1.59	9.61

Likewise, it has been observed that the shear strength of the soil decreases, thus the safety number decreases with the rise of the groundwater level. When the initial conditions were examined, it was observed that as the groundwater level increased, the safety number decreased compared to the initial conditions due to the decrease in the matric suction values of the soil.

Table 3. GWT analyses results

Ground Water Table (m)	FoS Value at Initial Condition	FoS Values in no rainfall Condition	Percent Decrease Relative to Initial Condition
16		1.73	1.14
18	1.75	1.67	4.57
20		1.59	9.14

Furthermore, soil cohesion on slope stability was evaluated, and it was found that the shear strength of the soil decreases markedly with the reduction of the cohesion. Hence, factor of safety decreased. As presented in the Table 7, 32.57%, and 37.14% decreases which are remarkable decreases in accordance with other parameters, observed with the reduction of effective cohesion value.

Table 4. Effective cohesion analyses results

Effective Cohesion (c') (kPa)	FoS Value at Initial Condition	FoS Values After rainfall (300mm/day)	Percent Decrease Relative to Initial Condition
15		1.70	2.86
13	1.75	1.18	32.57
11		1.10	37.14

When the internal friction angle effect was evaluated. It has been found that the shear strength of the soil decreases with the reduction of the internal friction angle. Similar to the effective cohesion analyses results, 34.86% and 40.57% decreases seen due to reduction of internal friction angle value.

Table 5. Internal friction angle analyses results

Internal Friction Angle (°)	FoS Value at Initial Condition	FoS Values After rainfall (300mm/day)	Percent Decrease Relative to Initial Condition
14		1.70	2.86
12	1.75	1.14	34.86
10		1.04	40.57

Slope angle has a key role on slope stability. When the slope angle increased, it has been obtained that factor of safety decreased. Therefore, slope angle determinations must be done carefully on the related projects. In the Table 9, factor of safety changes and percent decreases relative to the 40° slope angle value is given. As seen in the Table 9, 8.88% and 18.34% decrements were observed due to 5° and 10° increments of the slope angle value.

Table 6. Slope angle of slope analyses results

Slope Angle of Slope (°)	FoS Values After rainfall (300mm/day)	Percent Decrease Relative to 40° Slope Angle
40	1.69	0
45	1.54	8.88
50	1.38	18.34

When the results of all analyses were evaluated, it was seen that the results were consistent with other studies in the literature.

Author Contributions

Furkan Veli Özçelik: Conceptualization, Methodology, Software. **Murat Ergenokon Selçuk:** Supervision, Reviewing, and Guiding.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

Aslan Fidan, A. (2017). Doygun olmayan koşullarda yağış infiltrasyonu etkisindeki şevlerin stabilite analizi. (MSc thesis). Dicle University, Diyarbakır, Turkey (in Turkish).

Au, S.W.C. (1998). Rain-induced slope instability in Hong Kong. *Engineering Geology*, 51(1), 1-36.

Fredlund, D.G. (2012). Unsaturated soil mechanics in engineering practice. *Journal of geotechnical and geoenvironmental engineering*, 132(3), 286-321.

GEOSLOPE (2012). Stability Modeling with Slope/w. Canada.

GEOSLOPE (2015). Seepage Modeling with Seep/w.

Jeong, S., Lee, K., & Kim, J. (2017). Analysis of Rainfall-Induced Landslide on Unsaturated Soil Slopes. *Sustainability*, 9(7), 1280.

Karabulut, B. (2019). Yağış ile Sızmanın Şevlerin Stabilitesine Etkisi . (MSc thesis). Yıldız Technical University, İstanbul, Turkey (in Turkish).

Önalp, A., & Arel, E. (2013). Geoteknik bilgisi I zeminler ve mekaniği çözümlü problemlerle. Birsen Yayınevi, İstanbul, 461.

Tetik, A. (2020). Yağış etkisi altındaki şevlerin stabilite analizi (MSc thesis). Manisa. Celal Bayar University, Manisa, Turkey (in Turkish).

Wang, Y., Chai, J., Cao, J., Qin, Y., Xu, Z., & Zhang, X. (2020). Effects of seepage on a three-layered slope and its stability analysis under rainfall conditions. *Natural Hazards*, 102(3), 1269-1278.