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Sensitivity Analysis of Effective Factors in Hillslopes Instability; A Case Study of Javanrud Region, Kermanshah Province

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ABSTRACT

Aims Evaluating the factors affecting the mass movement and recognizing the regions sensitive to landslide are vital for planning, performing the construction projects, and providing proper management solutions in sensitive regions. The aim of the present study was to investigate the stability of the hillslope using the Stability Index Mapping (SINMAP) model to recognize the most important factor in causing the landslide by one-time sensitivity analysis method.

Materials & Methods In the experimental research, the studied area included several watersheds in Javanrud, Kermanshah Province, Iran. Sensitivity analysis was performed for slope angle, internal friction angle, depth of soil, hydraulic conductivity, saturated storage ratio and rainfall. Accordingly, each of the mentioned parameters was changed by 10% to 75% compared to their initial value, assuming that other parameters remain constant. Then, the safety factor (FS) for each variation and the ratio of safety factor variations to initial FS were calculated.

Findings The slope angle was the most important effective factor in causing the landslide in this region. The Second and the third factors were internal friction angle and saturated storage ratio, respectively.

Conclusion The slope angle is the most important factor in causing the instability in all hillslopes, as where this factor is reduced by 20%, FS initial value increased by twice. After slope angle, soil internal friction angle has the highest importance, which shows a direct relationship with factor of safety. It means that, as this angle increase, stability of the hillslopes will also increase.

Keywords Landslide; Hillslope Instability; Sensitivity Analysis; SINMAP Model

CITATION LINKS

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Introduction

Shallow landslides are considered the most important geomorphologic phenomenon in the mountainous parts of the world. They always cause death and many financial and economic losses in residential areas all over the world [1]. Many types of research have been conducted by geotechnical engineers, geologists, and hydrologists given the importance of this phenomenon in construction projects, and various models have been introduced for predicting landslide hazards, such as empirical models, statistical models, and physically based models [2]. Physically based models are often based on limit equilibrium concept based on physical laws related to tensile and resistance forces. Their result is a safety factor, which is the quantitative value of hillslope stability. Most of the physically based models comprise hydrological and geomechanical models, and they can be divided into steady state and dynamic model [3]. In steady state models, landslides are evaluated based on the combination of stability analyses of hillslope (Infinite slope method), assuming that groundwater level is constant and parallel to bedrock [4, 5]. Compared to steady-state models, dynamic models which are used for spatial-temporal evaluation of hydrology and hillslope stability, the processes such as rainfall patterns and changes in groundwater level are numerically modeled and they integrate with infiltration models and hillslope stability analysis [6]. Most of these models have been developed by integrating hillslope stability analysis (Infinite slope method) and hydrological models and they are able to evaluate the landslides resulting from hydrological conditions [7-9]. Physically based model of Stability Index Mapping (SINMAP) was used in this research to analyze the hillslope stability of the whole region and to determine the safety factor. This model has been developed based on a numerical model of infinite slope stability.

Many types of research have been carried out with regard to landslide using the physically based model of SINMAP [10-12]. These researches used the SINMAP model to investigate the different factors affecting the occurrence of landslides in various regions and spatial distribution map of landslide prepared [13-15]. The safety factor is usually calculated for one hillslope to evaluate its stability using certain values of geotechnical properties of the soil and geometric parameters of hillslope [16]. In fact, each factor has a wide range of values and these values influence the stability of hillslope, hence, geotechnical properties of hillslope always include some degree of uncertainty in simulations. This uncertainty reduces our trust in findings and output of the model. Thus, model sensitivity analysis is required to identify sensitive factors (Factors with a significant impact on model results) and to recognize the behavior of the model to various parameters [17].

Sensitivity analysis is an interactive process adopted to simulate hillslope instability realistically and to determine the impact of various factors on the safety factor. It determines which of the input parameters is vital to evaluate the hillslope stability and which of the input parameters is less important in this regard [18]. In the sensitivity analysis of the safety factor, values are calculated for parameters using the lower limit and upper limit [19]. In a sensitivity analysis, change of a parameter at one time is the common method to recognize the impact of this process on the output [20]. This approach is seemingly a logical approach since any observed change in the output is clearly resulting from the change of the factor selected. In addition, by changing a factor at one time, all other factors can be stabilized compared to baseline or central values [21]. The one-time approach is the most common method, in which an input parameter is selectively changed to evaluate its impact on the target function [22]. Any input data might be changed with a certain value (eg. 10 or 20%) [23]. Change of input parameters of the model is common to find the optimal values in hydrological modeling [24, 25]. This method needs to be based on physical reasoning and includes only sensitive parameters (Parameters with a certain impact on the model result) [26, 27].

Hillslope instability, such as a landslide, is one of the complex processes in Javanrud located in the Northwest of folded Zagros as this phenomenon leads to the demolition of forest lands, farms, and pastures of the region. In addition, it is considered a threat to road traffic [28]. Hence, investigating the factors affecting mass movements and recognizing the regions sensitive to landslide are essential for planning, performing construction projects, and roviding appropriate management solutions in sensitive areas.

The aim of the present study was to investigate the stability of the hillslope using the SINMAP model to recognize the most important factor in causing the landslide by one-time sensitivity analysis method.

Materials and Methods

This study is experimental.

Study area: The study area included several watersheds in Javanrud, Kermanshah Province, Iran including the watersheds of Zalan, Lileh, Bazan, and Safi Abad. Geographical coordinates of the area are between 34° 39' to 56' 34° north latitude and 10' 46° to 36' 46° Eastern longitude in Northwest of Iran (Figure 1). The area is a mountainous region topographically with a height difference between 1,000 and 2,708m. The average annual temperature in this region is 15.6°C and the average annual rainfall is almost 600mm. In terms of geological structure, the region can be divided into highlighted mountainous units and hill lands. The type of geological formations of the mountainous units is limestone with gray marl (Sarvak Formation) along with the sequence of clay limes to gray limes and black shale (Grove Formation). The type of hill lands in the middle part of the region is Gurpi formation, including shale and gray marl, and in the east of the region, it includes Kermanshah Radiolarites (Figure 1). Based on the geological map, it could be stated that two Gurpi formations and Kermanshah Radiolarite provide the condition for landslide occurrence in this area.

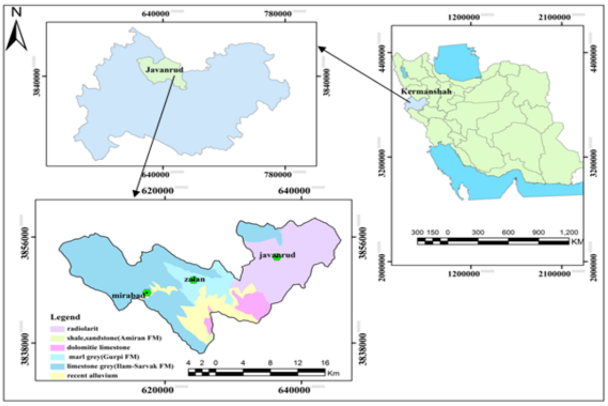

Figure 1) Geographical and Geological map of the Javanrud region

Methodology: Field studies and laboratory methods were used to conduct the research and achieve the desired data with regard to studied parameters, including geomorphologic and hydrological properties and soil mechanics of the study hillslope. 1:50,000 Topography maps of Javanrud region, 1:100,000 geological maps, 1:55,000 aerial photos, Google Earth satellite images, Global Positioning System (GPS), 20m digital elevation model, Arc GIS 10.3 and MATLAB 2016 Software were used in the current research.

The steps of this research can be summarized in this way as follow:

Selecting the hillslopes in the area: Map of landslide distribution of the area was prepared first using satellite images, aerial photos, and field visits, to measure the effective factors in the considered hillslopes. After identifying the sliding points in the study area, their position was identified using the GPS, and finally, these points were transferred to the base map of the area by using the Arc GIS 10.3 software. During the fieldwork, 12 different hillslopes were recognized; 5 stable slopes (without landslide) and 7 unstable slopes (Existence of landslide). They were numbered 1-12. Slopes1 through 5 were stable and 6 through 12 were unstable (Figure 2).

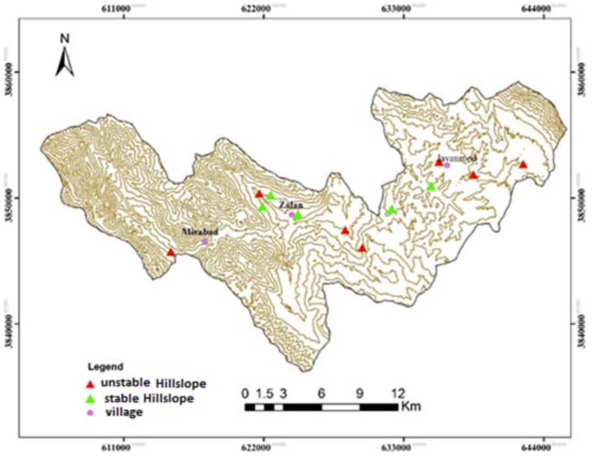

Figure 2) Distribution map of sliding points in the study area

After selecting the sample slopes, the necessary parameters were evaluated as follows:

1) Determining and measuring the factors needed to run the model

2) Determining the geometrical variables of hillslopes: The morphological and topographic variables such as moderate slope (β), the upstream area of hillslope (A), width of hillslope (w), and the length of hillslope were determined from topographical map, digital elevation model (With resolution of 20m), satellite images, and GIS 10.3 software. Field measurements and field tools such as manual

and laser meter and caliber were used to increase the accuracy

3) Determining soil geomechanical parameters: Laboratory methods were used to measure the variables related to geomechanical properties of the soil, including soil dry density (γd), soil wet density (γt), hydraulic conductivity (Ks), internal friction angle (φ), soil cohesion (C), and soil porosity. According to the laboratory expert, the core cutter was impossible to use because the soil was grained, so for the laboratory analysis, 50kg soils from a depth of 75cm to 1m from each hillslope were taken. The parameters of soil internal friction angle and soil cohesion were measured using direct cutting test. Hydraulic conductivity coefficient or permeability coefficient was measured by using the load falling method. Dry density of soil (γd) and a wet density of soil (γt) were measured by the test of soil humidity content and porosity percentage was measured by using actual and apparent density based on the standard ASTM-C127-128 (American Society for Testing and Materials) in soil mechanics laboratory.

4) Determining root cohesion values: Keeping in mind the end goal is to recognize the impact of root cohesion on the applied model, in the wake of determining the utilization of each slope (Wood, pasture, cultivated, arid), Kayastha [29] classification were utilized (Table1).

5) Determining the rainfall rate: The information of rain gauge stations near to studied sliding points of the study area was used to determine the rainfall parameters. The maximum rate of 24-hour rainfall was considered for a period of 20-year for each hillslope. The data were collected from 4 precipitation stations of Meteorological Organization and Ministry of Energy (Table 2).

These stations were used because of their vicinity to the landslides (Figure 3). The maximum precipitation values in 24 hours were obtained according to the daily precipitation data using the interpolation method.

Table 1) Root cohesion values for different land uses

Land usage	Root cohesion (KN/m^2)
Farm lands	1
Wood lands	8
Rural and construction area	0
Shrubs and bare hills	1

Table 2) Maximum rainfall from the studied stations

Station name	Maximum rainfall
Banchaleh	80
Javanrud	80
zalan	86
Dehrash	100
Mirabad	50.3

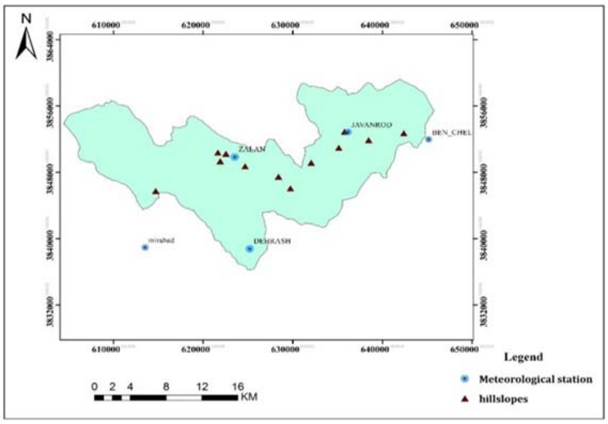

Figure 3) Location distribution of the meteorological stations in the studied area

Implementing the SINMAP model: This model simulates the non-stabling components such as gravity and stabilizing components such as friction force and soil cohesion of hillslope on a fracture surface. Using the input data such as slope angle, the area of the watershed, soil properties (Strength) and climatic properties (Hydrologic humidity), the land is classified based on the level of the stability. Each of the parameters is expressed on a cell network to be calculable in numerical calculations of the software [30].

The main output of this model is in fact Stability Index (SI), which by using this index; the software performed the land stability classification based on stability level at the surface of each cell of the network. Considering the factor of safety (FS), stability or non-stability of hillslopes can be predicted. Topography-dependent variables are automatically extracted from a digital elevation model. Other input variables have one type of uncertainty. Therefore, they can be defined as upper and lower limits or hillslope in the software. Based on the infinite slope method, the factor of safety (FS) is defined as follows [1, 2, 7, 8]:

$$Fs = \mathrm{C} + \mathrm{coc}(\beta) \times (1 - \mathrm{W} \times \mathrm{r}) \times \tan(\varphi) / \sin(\theta) \text{ (Equation 1)}$$

Where C is total soil cohesion including the soil and root (KN.m^{-2}), calculated by Equation 2. The lower and upper limits of cohesion were considered to be 0 and 25 (kN.m^{-2}), respectively, given the soil mechanics data. The default values of internal friction angle (φ) were also 30 and 45 degrees, respectively, for the lower and upper boundaries. In addition, the default value of soil density was considered to be 10%, given soil porosity in soil mechanics laboratory data. This value suggests that humidity boundary is between regions with low humidity and regions with a tendency to humid.

$\mathrm{C} = (\mathrm{Cr} + \mathrm{Cs})/(\mathrm{h} \times \mathrm{g} \times \mathrm{ps})$ (Equation 2)

Where β is the slope angle (%), h is groundwater height, Ps is the soil density (g.m^{-3}k), and g is gravity acceleration (9.81m.s^{-1}). W is the relative humidity obtained from Equation 3:

$\mathrm{W} = \min[\frac{\mathrm{Ra}}{\mathrm{Tsin}(\beta)}, 1]$(Equation 3)

Where R is rainfall (mm.day^{-1}), a is an upstream area of hillslope (m^2) and T is soil transmissivity calculated using Equation 4. The R/T parameter is the value related ratio of transfer to harvest, which is 2000 and 3000 meters for the downstream and upstream boundaries, respectively. In fact, R is an effective recharge for a critical period of humid weather, which might result in the landslide process.

$\mathrm{T} = \mathrm{K} \times \mathrm{d}$ (Equation 4)

Where K is hydraulic conductivity (m/h) and d is the depth of soil (m).

Performing the sensitivity analysis

Sensitivity analysis involves 4 steps as follow:

1) Selecting the real range of values for each input variable

2) Calculating the basic safety factor using the median values for all variables

3) Changing each input variable in line with the range of its values, while the other variable is assumed to be constant, and calculating the new safety factor for each input variable that has been changed.

4) Displaying of the results as a relative percentage

By sensitivity analysis of variables, it was tried to determine the most important factor affecting the landslides in the region. Sensitivity analysis was performed on variables of soil depth (D), rainfall (N), hydraulic conductivity (Ks), soil internal friction angle ($\emptyset$), slope angle (β) and saturation humidity storage (σ).

In each step of sensitivity analysis, the value of the mentioned variables (Other variables remain constant) increases and reduces by 10% to 75%, compared to their initial value. FS of each of these changes and then, the ratio of safety factor variations to the initial safety factor were calculated. By calculating the new safety factor for each of the variables, the changed input was plotted in a chart as a percentage for each hillslope. The variable having the highest safety factor variations (Having a higher slope in the chart) is regarded as to the most important factor.

After obtaining the parameters required for computing the safety factor (FS) of hillslope including laboratory, topographical and hydrological parameters, these variables were placed in the mentioned model to stability analysis of the hillslope and Fs values for each hillslope were calculated in the MATLAB 2016 software.

Findings

The greatest percentage of changes in safety factor was related to slope angle, which was approximately 130%.

The hillslopes with a factor of safety more than 1, were in low vulnerability class and non-stable hillslopes of the studied area, having a factor of safety lower than 1, were placed in very high vulnerability class (Table 3).

Most of the hillslopes with safety factor less than 1 (Hillslopes 6, 7, 8, and 9) had higher saturation storage value compared to stable hillslopes (Table 3).

Saturation storage coefficient and rainfall rate in most of the hillslopes had full overlap and sometimes close overlap with each other, however, in the hillslope 1, these two parameters had a significant difference, so that in this hillslope, the impact of saturation storage and slope of its changes was higher compared to the rainfall rate.

The internal friction angle of unstable hillslopes was usually more than 30 degrees (Table 3).

By performing the sensitivity analysis accordingly, each of the mentioned variables, the line slope of the gradient parameter of hillslopes was more than that of other variables, so the most effective factor involved in the landslide phenomenon of the region was identified (Diagram 1; Table 4).

The lowest line slope in the plotted charts related to cohesion coefficient suggested the low impact of this factor on the instability of hillslopes compared to other variables.

Table 3) Parameters for determining factor of safety in hillslopes

Hillslopes	Average slope (%)	Cohesion (kgcm^{-2})	Internal friction angle (Degree)	Permeability coefficient (ms^{-1})	Soil saturation density (kgm^{-3})	Maximum 24-hour rainfall (mmday^{-1})	Soil depth (M)	Safety factor (FS)
1	22	0.08	34	4.98×10-6	2744	86	1	2.05
2	17	0.01	31	3.18×10-8	2544	86	1	1.63
3	33	0.08	29	2.21×10-9	1892	86	1	1.24
4	34	0.01	26	6.24×10-4	2502	86	1	1.35
5	31	0.06	32	4.38×10-8	2466	80	1.2	1.14
6	46	0.03	26	2.2×10-9	2603	50	1.1	0.68
7	37	0.04	28	6.3×10-8	2636	80	1.2	0.91
8	46	0.05	25	7.1×10-9	2672	86	1	0.11
9	32	0	29	1.18×10-7	2755	100	0.7	0.73
10	23	0.03	22	2.2×10-6	2176	100	0.7	0.93
11	23	0.07	23	7.12×10-8	2374	86	1.2	0.99
12	15	0.02	20	1.2×10-7	2511	80	1.2	1

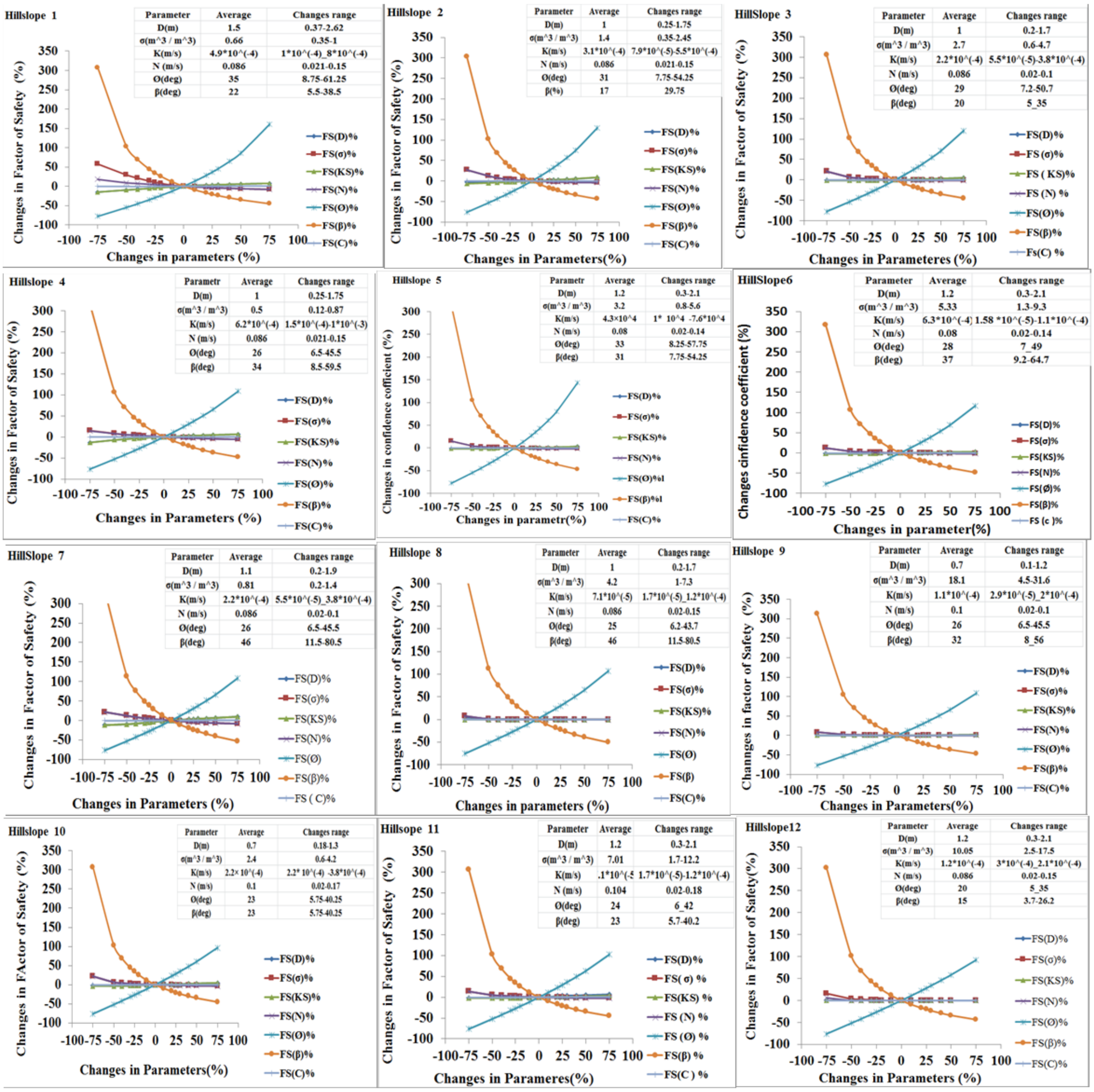

Diagram 1) Sensitivity analysis of effective parameters in hillslope instability; The negative slope of line related to this factor in charts illustrates the relationship between the slope gradient and the factor of safety of the natural hillslopes

Table 4) Range of percentage of changes in Factor of Safety

Variable	Range of variations in safety factor	Mean percentage of variations
Soil depth (D)	4.9_ (-3.5)	0.66
Saturation storage (σ)	16.36_(-2.56)	6.89
Hydraulic conductivity (Ks)	5.72_(-2.61)	1.5
Internal friction angle ($\emptyset$)	112.13_(-76.46)	17.83
Slope angle (β)	317.8_(-46.86)	135.48
Cohesion (C)	0.245_(-0.24)	0.0008

Discussion

The aim of the present study was to investigate the stability of the hillslope using the SINMAP model to recognize the most important factor in causing the landslide by one-time sensitivity analysis method.

The hillslopes of Javanrud region in the studied area are sensitive to slippery movements, proved by numerous landslides. Because of the complications related to the mechanism of occurrence of landslides, the present study attempts to investigate the stability of hillslopes using the SINMAP model and to recognize the most important factor in causing the landslide in this region by one-time sensitivity analysis method.

According to the findings of sensitivity analysis, the line slope of the slope angle of hillslopes was more than that of other variables. In one hillslope with specific and constant properties, when slope percentage increased, the impact of destructive forces also increased and the values of reinforcing and stabilizing forces of the mass reduced. Thus, the increased slope can increase the shear stresses of the hillslope [30]. The significant and strong role of this factor where slope gradient is reduced is well known so that by increasing this factor by 20%, FS value will increase by 200% (Twice that the initial value). The negative slope of line related to this factor in charts illustrates the relationship between the slope gradient and the factor of safety of the natural hillslopes. Given the findings obtained by calculating the safety factor, hillslopes having the factor of safety of more than 1 were placed in low vulnerability class and the slope angle had mainly less than 30% and unstable hillslopes had such a slope greater than 35%.

According to the result of the present research, the greatest percentage of changes in safety factor was related to slope angle, which was approximately 130%. Although the slope angle is effective in any instability, it should be mentioned that hillslope geometry can also effect on hydrological processes [3, 4] and then due to this process (Saturated storage ratio), FS decreased. This means that the slope angle affected on instability twofold.

Another important factor involved in landslides in the region is the soil internal friction angle, specified as the second factor in all hillslopes. This factor showed a direct relationship with the factor of safety. It means that as this angle increased, the stability of hillslopes also increased. According to the findings, the internal friction angle of unstable hillslopes was usually more than 30 degrees. After the slope angle, this factor showed the highest percentage of changes in the FS, which is about 18%.

Other factors that can be seen in sensitivity analysis charts and have the greatest impact are related to the hydrological parameters of the hillslope, including saturation storage coefficient and rate of the rainfall. With respect to the hillslope hydrologic issue, water infiltrated resulting from rainfall in the hillslope increases the level of pore pressure, reduces the soil suction, and increases the soil unit weight. This decreases soil shear strength and makes the hillslope susceptible to landslide [31]. Thus, the most important section in examining the landslide is its hydrological section, so that change in value and threshold of rainfall in the region can cause a change in landslide initiation. The role of rainfall in a landslide is revealed through subsurface flow and relative humidity of the hillslope (W). Thus, the relative humidity is determined after determining the soil morphological and mechanical parameters in each hillslope. The impact of these two factors in decreasing conditions results in an increased factor of safety.

Based on the obtained results, most of the hillslopes with safety factor less than 1 (hillslopes 6, 7, 8, and 9) had higher saturation storage value compared to stable hillslopes. Saturation storage coefficient and rainfall rate in most of the hillslopes had full overlap and sometimes close overlap with each other. However, in the hillslope 1, these two parameters had a significant difference, so that in this hillslope, the impact of saturation storage and slope of its changes was higher compared to the rainfall rate. This point is due to low level of saturation storage of this hillslope compared to other hillslopes. The impact of these two factors had been applied in decreasing conditions, resulting in an increased factor of safety.

Hydraulic conductivity (*ks*) is one of the hydrodynamic properties of soils, that plays the vital role in water and salts movement and transfer in soil, estimating the value of subsurface flows under various hydraulic conditions, the stability of soil structures, and soil mechanics. Reduction in hydraulic conductivity up to twice in comparison to its initial value will result in an increase in the factor of safety (FS) by up to 30%. According to the result of the present research, an increase or reduction in soil hydraulic coefficient showed no significant changes in the factor of safety (FS), so that in hillslopes (8 and 12), safety factor did not change. Increase in the value of saturation humidity index from 1 means that saturation humidity content is equal with total saturation capacity of the hillslope and in conclusion surface flow is formed. The mean changes in the factor of safety for this factor are about 1.5%. Soil cohesion coefficient depends on grain diameter, size and the type of soil minerals. As size or diameter of grains is smaller, water absorption capacity and the created cohesion will be greater and vice versa.

An increase or reduction in soil cohesion in most of the hillslopes did not change the value of factor of safety in the studied hillslopes. In some hillslopes, the obtained factor of safety did not change compared to the initial factor of safety, so that the lowest line slope in the plotted charts belonged to this factor, indicating the low impact of this factor on the instability of the studied hillslopes compared to other variables, it was due to the low cohesion of most of the soils in the study area. Coarse-grained soil texture in these hillslopes, which is the type of regullite resulting from decomposition of shale and marl rocks of Gurpi and radiolarite formations under cold and humid climates conditions with abundant rainfall, causes very low cohesion and increased internal friction angle factor. This parameter has the lowest coefficient of changes and the mean coefficient of its changes is less than 1% and at the level of 0.001%.

In this research due to the complexity of behavior of hillslope in nature, the physically based model was used for the stability analysis of the studied hillslopes. It was tried to calculate the factor of safety for each hillslope considering the geomechanical parameters of soil and the topographical properties. Then, a sensitivity analysis was used to investigate the sensitive parameters and determining the most important factor.

Due to the effect of slope angle on hydrological processes in hillslopes [3, 5], it should be emphasized that the triggering factor in hillslope instability is infiltrated water of rainfall [2, 3]. In fact, topographic characteristics of hillslopes effect on the hydrological behavior of hillslopes. In the conducted sensitivity analysis, safety factor variations related to the increase or decrease of cohesion parameter were negligible and even unchanged, so that the lowest line slope in the plotted charts belonged to the cohesion factor. It suggests the low impact of this factor in the instability of studied hillslopes compared to other variables, it is because of low cohesion of most of the soils in the studied area.

The limitations of this research include the following:

These models are not able to predict landslides caused by artificial factors. Also, vegetation status is not well considered in these models. The tree overload effect on the stability amount of the hillslope is also an important factor that should be considered in subsequent studies.

It is suggested that the model should be used for different regions. The results and the model parameters sensitivity under different conditions (Climatic, soil characteristics, topographic, etc.) should be measured. It is also suggested that in order to determine the instability of the hillslope using these models, for the marginal slopes of the road (Affected by the human factor) changes are introduced and developed, and human parameters are analyzed along with the natural factors.

Conclusion

The SINMAP model can be used for stability analysis of the hillslopes and determining the most important factor in causing the landslide in this region. The slope angle is the most important factor in causing the instability in all hillslopes, as where this factor is reduced by 20%, FS initial value increased by twice. After slope angle, soil internal friction angle has the highest importance, which shows a direct relationship with the factor of safety. It means that, as this angle increase, the stability of the hillslopes will also increase.

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Authors' Contribution: Zarei P. (First author), Introduction author/ Original researcher/ Statistical analyst/ Discussion author (50%); Talebi A. (Second author), Methodologist/ Original researcher (40%); Alaie Taleghani M. (Third author), Methodologist/ Assistant researcher (10%)

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