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# Cut slope stability assessment along forest roads using the limit equilibrium approaches and Slide software

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**Abstract:** Calculating the factor of safety (*FS*) as slope stability factor is necessary to prevent environmental damage. Therefore, this paper aims to (*i*) calculate *FS* using the limit equilibrium approaches and Slide software and (*ii*) investigate the stability of slopes according to calculated *FS* (Janbu and Bishop methods) and status of different sites in the study area (Hyrcanian forest of Iran). Six landslides were selected along the forest road by a field survey. Landslide dimensions including length, width, and height were measured using meters. Slope gradients were measured using the Suunto clinometer. The Slide software was used to evaluate the stability analysis of slopes. According to laboratory tests on soil samples the average of the liquid limit was recorded as 58%. The results of the direct shear test showed that the rate of soil cohesion (*c*) and coefficient of friction angle (φ) decreased with an increase in moisture content. According to the results, the factors of safety for landslide sites (Sites 1–6) were calculated to be 1.3, 0.65, 0.76, 0.55, 1.19 and 1.51, respectively. These calculated *FS* can accurately determine the slope status in terms of slope stability. According to the software classification, the status of Site 1 is "susceptible to landside". Sites 2, 3 and 4 are "very high risk". Also, the status of Sites 5 and 6 are "high risk" and "stable", respectively. The instability of the slopes in studied sites is related to the drainage system (lack of culverts or ditches) as well as marlstone as bedrock. According to the calculated *FS* in different sites and comparison of the obtained results with the real conditions of sites, it can be concluded that the slope stability analysis in the Slide software is very accurate and it can be used to determine the factor of safety under different conditions in terms of morphology, hydrology and soil mechanics.

**Keywords:** bioengineering; reinforcement; road construction; soil erosion; stabilization

For well-engineered roads geometric design and alignments as well as road materials have carefully been selected (Petković, Potočnik 2018; Kadi et al. 2021). High bulk densities of pavement layers in forest roads can lead to the generation of surface runoff (Hearn, Hart 2011; Ran et al. 2018). Landslides occur after accumulating the surface runoff in the road body. Most of these landslides are shallow and occur in loose soil materials on steep slopes during rainfall (Pradhan, Kim 2020). The landslide involves downward and outward movements of materials due to a gravitational force by flowing, sliding and falling (Chen, Cui 2017). Frequent slope failure along natural and engineered slopes is of significance as it threatens the road safety, hampers the forest logging operations, and deteriorates the natural habitat (Leroueil 2001). One of the main ingredient stimulators of landslides is the road construction which is the basis for the large landslides by creating unstable trenches on both sides of the

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road, changing the waterway paths and clearing trees on the cut slope of road and removes the tree roots from the soil. Plant roots and vegetation can increase the mechanical reinforcement in slopes susceptible to landslide (Bordoni et al. 2016; Cohen, Schwarz 2017; Hosseini et al. 2017). This reinforcement can reduce the risk of shallow landslides and increase the slope stability. Forest area with denser canopy and understorey layers is considered less susceptible to landslides (Rajakumar et al. 2007; Peduzzi 2010). In recent years, many studies on the slope stability have been undertaken (Kainthola et al. 2015; Anbazhagan et al. 2017; Bushira et al. 2018). Chanmee et al. (2016) carried out research on the analysis and simulations of erosion protection designs using the Slide programs. Oh and Lu (2015) expanded the limit equilibrium and finite element methods using a generalized effective stress framework to calculate the slope stability factors. Ebrahimi et al. (2018) conducted a study to estimate the stability of slopes on the roads and the effect of tracing and nailing on soil stabilization. Bugday and Akay (2019) assessed different forest road alternatives in sensitive mountainous areas based on the Landslide Susceptibility Mapping (LSM). Calculating the factor of safety (*FS*) as slope stability factor is necessary to prevent risks and damage. Therefore, this paper aims to (*i*) calculate *FS* using the limit equilibrium approaches and Slide software and (*ii*) investigate the stability of slopes according to calculated *FS* and status of different sites in the study area.

## MATERIAL AND METHODS

**Study area.** This study was carried out in the northern forest of Iran (Figure 1). The climate of the studied area is affected by the Caspian Sea and its relative humidity is high throughout the year with an average of 80%. There is a deciduous forest in this area and the main woody species are oriental beech (*Fagus orientalis* Lipsky), European hornbeam (*Carpinus betulus* L.), Persian ironwood (*Parrotia persica* C.A. Mey) and black alder (*Alnus glutinosa* L.). In this region, the road network is used by forestry machinery and public transport. The elevation ranges from 180–875 m a.s.l. and average annual precipitation is 750 mm and the climate of the area is wet and cold. The stability of road cut slopes in the study area is related to poor drainage, marl bedrock and frequent intersection of roads with valley (usually seasonal waterways).

Figure 1. Landslide sites in study area (Mazandaran, Iran)

**Methods**

**Limit equilibrium approaches.** Limit equilibrium analysis methods (LEMs) belong to the basic approaches to slope stability analyses. LEMs based on massive analysis or slices investigate a possible slippery mass at the top of the assumed slip surface, and the polyhedral force vector closure or incurring moments in equilibrium state which are capable to be utilized in static and dynamic conditions for two-dimensional and three-dimensional space (Azarafza et al. 2021). If these polyhedral forces are closed and all assumptions/requirements are provided, this implies that the mass is in equilibrium and that the analysis is valid. The basis of all these methods is the comparison of stresses, moments and resistance forces during mass movement relative to tensions, moments and destructive forces [Equation (1)]. Slide is a 2D and 3D slope stability program for evaluating the safety factor of non-circular and circular failure surfaces using limit equilibrium methods in soil slopes (Nagendran et al. 2019). Slide is simple to use, and complex models can be created and analysed easily and quickly.

$$FS = \frac{\sum \text{Resistance forces or moments}}{\sum \text{Destructive forces or moments}} \tag{1}$$

where:

*FS* – factor of safety.

**Field survey and software modelling.** Six landslides along the forest road were selected by a field survey. Landslide dimensions including length, width, and height were measured using meters.

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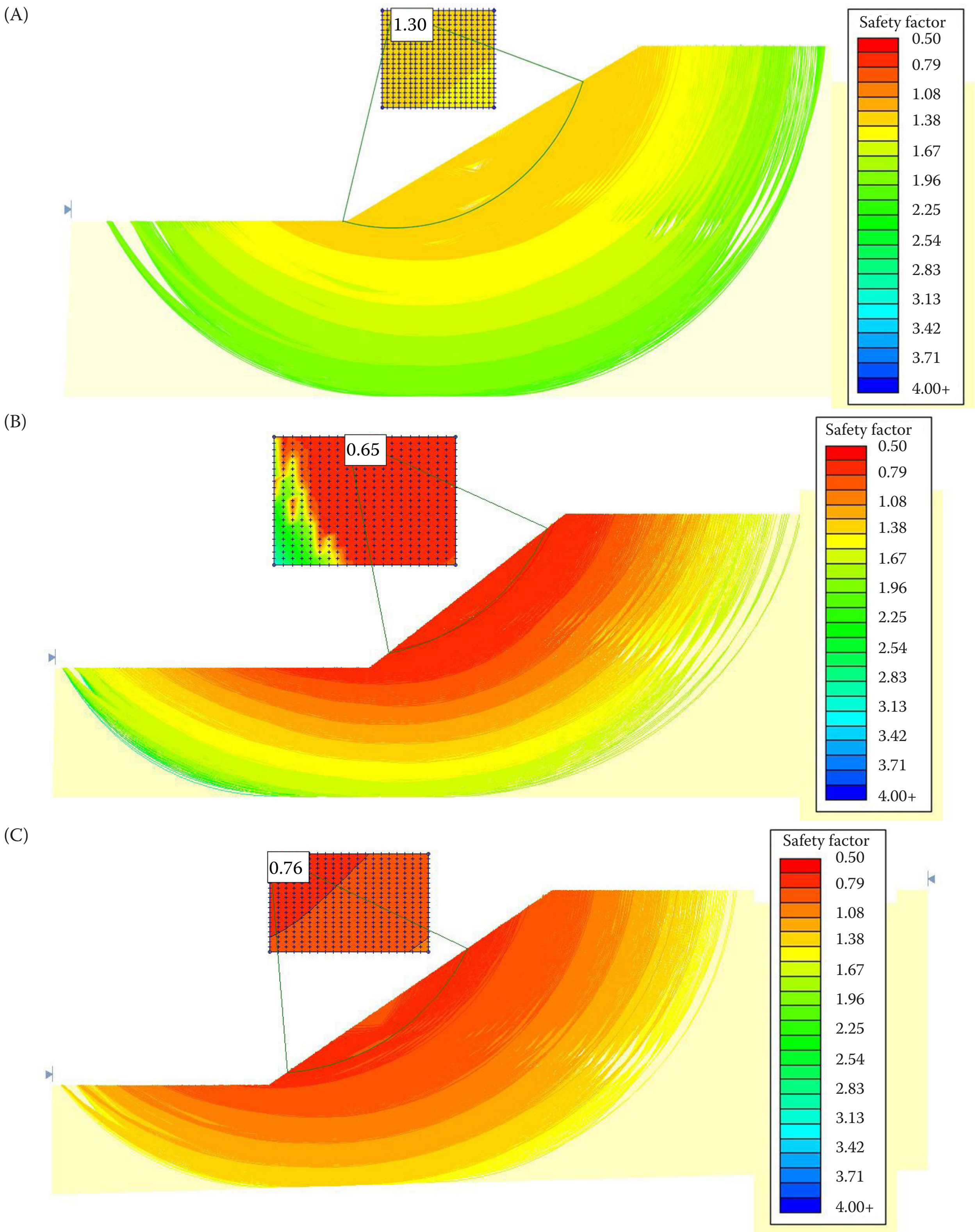


Figure 2. Graphic simulation of landslides and investigation of slope stability status at (A) Site 1; (B) Site 2; (C) Site 3

Slope gradient were measured using a Suunto clinometer (Suunto, Finland). The Slide software (Version 6.020, 2012) was used to evaluate the stability analysis of slopes (Figures 2 and 3). For this purpose, the "Add External Boundary" command was used to design slope geometry. Then the soil

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layers were separated using the "Add Materials Boundary" command. Using the "Define Materials" command, soil type and specifications such as soil moisture, cohesion and internal friction angle were entered into the software. Slope stability was calculated by considering the circular type of slip and

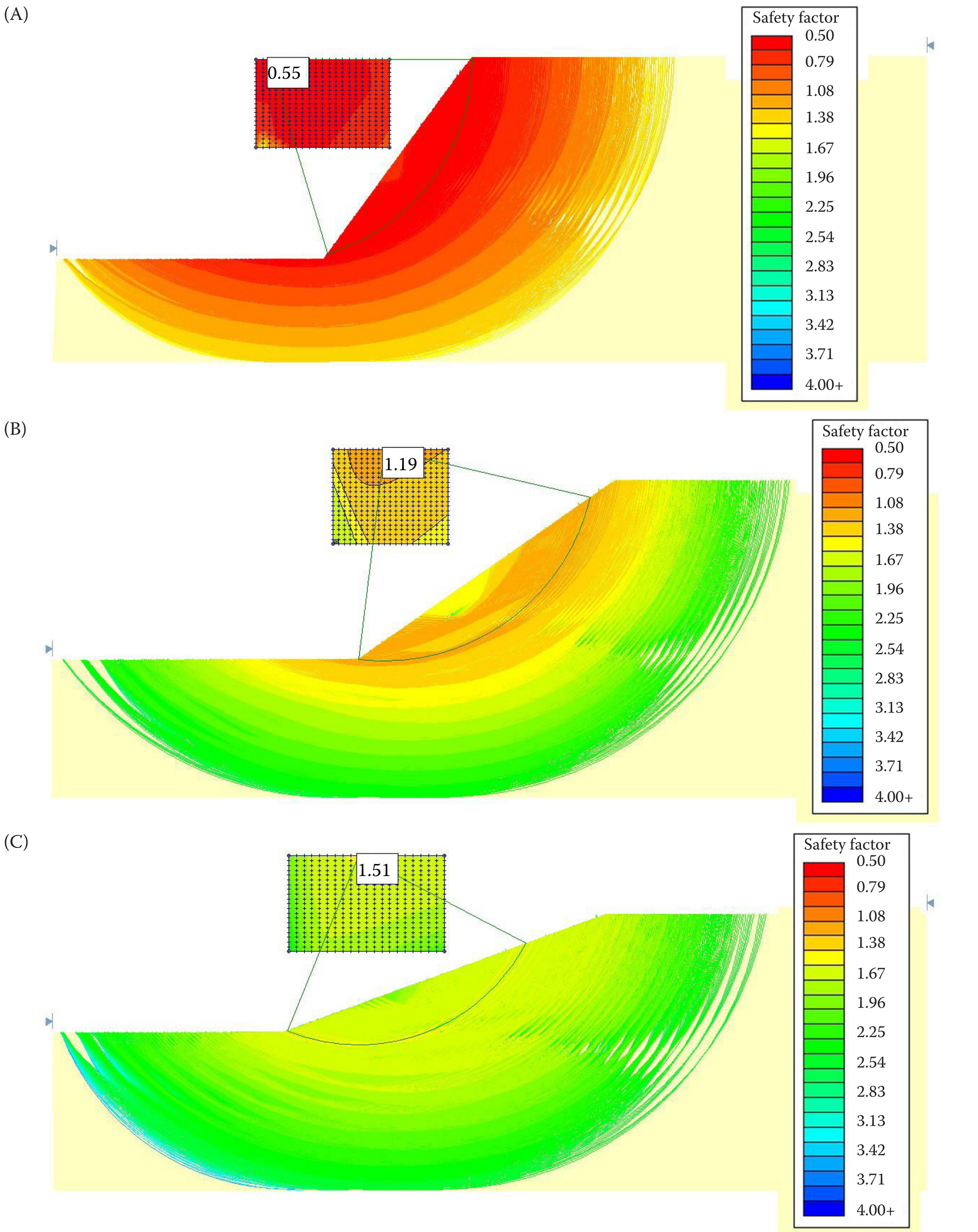


Figure 3. Graphic simulation of landslides and investigation of slope stability status at (A) Site 4; (B) Site 5; (C) Site 6

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graphic shapes of slip surfaces were used to analyse the results. The stability of the slope was evaluated based on the factor of safety. If the factor of safety is < 1, the risk of landslide is very high, for 1 to 1.25 the risk of landslide is high, 1.25 to 1.5 is susceptible to landslide, and more than 1.5 the slope has a stable condition in terms of stability.

**Soil mechanical tests.** To investigate the mechanical condition of the soil, samples were taken from the top and bottom of the slope as well as different soil layers in landslide sites. Soil mechanical tests including soil texture, coefficient of curvature, coefficient of uniformity, Atterberg limits (ASTM D 2166) and uniaxial compressive strength test (ASTM D 2166) were done in a soil mechanics laboratory. In order to analyse the slope stability a direct shear test was used to calculate the cohesion and coefficient of the friction angle of soil**.**

## RESULTS AND DISCUSSION

According to the unified soil classification system (USCS) studied soils were classified in the SW class (well graded sand). However, a soil sample was classified as SP (poorly graded sand). The high *Cu* (coefficient of uniformity) values in studied soil samples indicate a good condition of the soil aggregate size. The results of the Atterberg limits test showed that the soil liquid limit was high in the landslide sites. So that the average of the soil liquid limit was recorded as 58% (Table 1). The results of the direct shear test showed that the rate of soil cohesion (*c*) and coefficient of friction angle (ϕ) decreased with an increase in moisture content (Table 2).

Landslides occur when gravitational and other types of shear stresses within a slope exceed the shear strength. The risk of landslides in steep slopes increases due to the force of soil weight and surcharge. In Site 2 (Figure 2B), the risk of landslides is very high due to the high weight of the soil as a surcharge. In many studies, the destructive effect of surcharge on slope stability was investigated and in all studies, soil weight and surcharge were considered very important (Imani Kalehsar et al. 2021; Masi et al. 2021). Lotfalian et al. (2019) showed that with increasing age of alder trees from 7 years to 15 years, the additional root cohesion increased. Also, with the increase of the age of trees to 20 years the amount of root cohesion slightly decreased. So, the overall slope stability factor decreases due to an increase in surcharge pressure. The results of this study are in agreement with the results of other researchers (Lotfalian et al. 2019; Imani Kalehsar et al. 2021; Masi et al. 2021). According to the calculated *FS* in Site 2 (Figure 2B), the limit equilibrium approaches in the Slide software can be used to predict the landslide risk. So that landslides have occurred in this area and the factor of safety presented in Table 3 can confirm this issue. In this area, the type of pavement layer is asphalt. Water penetrated to the roadbed due to lack of drainage. So that with increasing soil moisture content the probability of landslides increases. The resistance factors of soil are extremely affected by the water and pore pressure of soil. When the soil is saturated, the coefficient of internal friction and ultimately the shear strength of the soil decrease. Numerous studies have reported the negative effects of water under the road body (Borga et al. 2004; Harabinová 2017). According to Table 3, the *FS* for this region was calculated to be 1.3. This number indicates that this area is susceptible to landslides and landslides will occur in the future. In Site 5 (Figure 3B) due to the existence of blocked pipe culverts, the cut

Table 1. Geometric design of slopes and mechanical characteristics of soil in different sites

| Site number | Slope (degrees) | Dimension (m) | | | *PL* (%) | *LL* (%) | *Cu* | *Cc* | USCS |
|---|---|---|---|---|---|---|---|---|---|
| | | length | width | height | | | | | |
| 1 | 29 | 40.0 | 13.5 | 15.0 | 39 | 62 | 13.18 | 0.68 | SP |
| 2 | 38 | 60.0 | 30.0 | 18.0 | 29 | 57 | 6.34 | 2.48 | SW |
| 3 | 34 | 50.0 | 15.0 | 17.5 | 33 | 62 | 8.53 | 2.31 | |
| 4 | 54 | 24.0 | 20.0 | 10.5 | 29 | 61 | 7.94 | 2.44 | |
| 5 | 35 | 30.0 | 15.0 | 12.5 | 28 | 52 | 8.53 | 2.31 | |
| 6 | 20 | 25.0 | 24.0 | 9.0 | 24 | 48 | 12.11 | 2.51 | SW–SC |

*PL* – plastic limit; *LL* – liquid limit; *Cu* – coefficient of uniformity; *Cc* – coefficient of curvature; USCS – Unified Soil Classification System; SP – poorly graded sand; SW – well graded sand; SC –clayey sand

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Table 2. Cohesion and internal friction angle of the soil in different percentages of saturation

| Saturation (%) | Coefficient of the friction angle (ϕ) | Cohesion (*c*; kPa) |
|---|---|---|
| 2.37 | 33.1 | 20 |
| 2.04 | 26.9 | 40 |
| 1.79 | 19.5 | 60 |
| 1.36 | 18.3 | 80 |
| 1.21 | 15.4 | 100 |

slope of road has been severely eroded. The accumulation of litter and tree branches can block the pipe inlet. Many studies have shown that seasonal culvert inspections must be performed at a certain time interval (Jin et al. 2010; Mount et al. 2011). So that runoff can destroy the road body. This issue was confirmed in this study. Soil mechanical tests showed that the studied soil is in good condition in terms of granulation. According to the results of Atterberg limits and soil moisture content, it can be understood that the soil has absorbed a lot of water and is unstable due to high humidity. According to the results, the internal friction angle of the soil and the soil cohesion decreased with an increase in moisture content. Since the soil shear strength is affected by cohesion between soil particles and coefficient of friction angle, this issue can change the soil shear strength. In Sites 3 (Figure 2C) and 4 (Figure 3A), shallow landslides have occurred. The main reasons for landslide in this area were steep slope and the presence of marlstone as bedrock. Marlstone does not allow water to penetrate to the lower layers of soil by creating an impermeable layer. Marl soil is one of the problematic soils in terms of road design and construction. Numerous studies have shown its negative impact on the quality of road construction (Cerdà 1996; Alonso et al. 2015; Kostić et al. 2016). So it is better to identify negative points during the initial design of forest roads. If the construction of forest road is necessary and if there is not any other access point, it is better to stabilize these areas. The traffic of forest machinery can cause shallow landslides after accumulating runoff in the roadbed. Road maintenance projects should be performed regularly, since some segments of roads are built where the bedrock type is marlstone. In the study area, the type of shallow landslides is circular and they occur due to the traffic load of forest machinery on the roadway with low stability. According to Table 3, the slope stability analysis shows that these slopes are completely unstable. The reduction of the factor of safety in these slopes is related with steep slope, high humidity and with a decrease in soil cohesion and internal friction angle due to water saturation.

Table 3. Calculated factor of safety for different slopes and status of different sites

| Site number | Area (m$^2$) | $FS_{\text{Bishop}}$ | $FS_{\text{Janbu}}$ | Status |
|---|---|---|---|---|
| 1 | 1 160 | 1.41 | 1.30 | susceptible to landside |
| 2 | 1 800 | 0.68 | 0.65 | very high risk /occurred |
| 3 | 750 | 0.81 | 0.76 | |
| 4 | 480 | 0.59 | 0.55 | |
| 5 | 450 | 1.29 | 1.19 | high risk |
| 6 | 600 | 1.68 | 1.51 | stable |

*FS* – factor of safety

## CONCLUSION

According to the calculated *FS* in different sites and comparison of the obtained results with the real conditions of sites, it can be concluded that the slope stability analysis in the Slide software is very accurate and it can be used to determine the factor of safety under different conditions in terms of morphology, hydrology and soil mechanics. So that in studied sites the rate of calculated *FS* using this model corresponds to real conditions of the site. To improve the models, it is better to use the meteorological data of the region as well as hydrological studies to calculate coefficients related to the soil piezometric pressure. Construction and maintenance of forest roads can affect the rates of shallow landslides. The geometric design of forest roads such as slope of trenches, clearing limits and right of way must be designed according to the standards. The use of high-quality materials in road construction projects and seasonal visits can reduce the number of shallow landslides. In order to decrease the occurrence of shallow landslides the soil bioengineering techniques can be used to improve the soil condition. Timber haulage and machine traffic are

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the main causes of road damage. So the excessive load of forestry machinery on forest roads should be minimum, especially during the rainy seasons of the year.

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