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RESEARCH PAPER

Investigating the reactivation potential of an old huge dormant landslide adjacent to the Miyaneh-Ardabil railway, Iran

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Abstract
In this study, the possibility of reactivation of an undetected dormant landslide whose reactivation can be very risky for a railway bridge is investigated. Landslide #370 is a huge dormant landslide that occurred in the chainage of 370 km of the Miyaneh-Ardabil railway which is under construction in the Northwestern part of Iran. The big Bridge #12 of this railway is located in the vicinity of the landslide's toe. Besides, this landslide is adjacent to Shahriar Dam Lake. Therefore, there are concerns about the possibility of landslide reactivation and the effects of these activities on two adjacent projects. Due to factors such as ground perturbation performed during the construction of the railway and access road to the dam site, the rising water level of the dam lake to a level very close to the landslide toe, high seismicity of the region, and high seasonal precipitations, it is essential to investigate the possibility of reactivation of this major landslide. The above factors can all work to reduce the safety factor of this old landslide. Therefore, in this study, an attempt has been made to investigate the effect of the temporal change of influencing factors on landslide stability and provide solutions to reduce the risk of landslide reactivation. Both limit equilibrium and numerical methods were employed to evaluate the stability conditions of this huge landslide in the future. The results of the performed studies indicate that due to the occurrence of a long/heavy rainfall and/or a large earthquake in the surrounding areas, the safety factor along the identified failure surface will decrease and this reduction will be enough to bring the landslide to a critical situation. So, risk reduction methods must be designed and implemented to prevent a tragic event.

Keywords: Dormant old landslide; Rainfall infiltration; Sensitivity analysis; Railway bridge

Introduction

Landslides are one of the most important natural hazards that cause significant economic losses annually and, in some cases, cause casualties (Camera et al., 2021; Piciullo et al., 2018; Tsaparas et al., 2002). In recent years, financial losses and casualties due to landslides with different mechanisms in Iran and the world have been significantly increasing. In the meantime, old and large landslides are more critical. Old landslides can be defined as landslides that happened years ago and have been stable and inactive for a considerable time since then (Ren et al., 2020). If natural or artificial changes occur in driving and resisting forces and consequently in the stability of an old landslide, its reactivation can have catastrophic consequences.

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Precipitation is one of the most important triggering factors for activating new landslides or re-activating old landslides. Studies have shown that long-term seasonal rainfalls have been main cause of many major landslides globally (Alsabhan et al., 2021; Chen et al., 2021; Fan et al., 2020; Jiao et al., 2021). Therefore, several studies have been devoted to rainfall-induced landslides from special perspectives (Liu et al., 2020). Researches have shown that the relationship between saturated soil permeability and rainfall pattern can significantly affect the seepage pattern on an unsaturated soil slope. Slope failure in unsaturated conditions is closely related to heavy precipitation and water infiltration into the soil. Due to precipitation infiltration into the soil, the negative pore water pressure is reduced, thus causing the loss of shear strength in the soil and eventually slope failure (Cai & Ugai, 2004; Kim et al., 2004; Tran et al., 2019; Tsaparas et al., 2002). Numerical methods and strength reduction methods have been used in many types of research to analyze landslide stability (Li et al., 2020; Lollino et al., 2011; Ren et al., 2020; Wang et al., 2020).

Also, in some cases, cutting trenches with precipitation can be the two leading causes of instability of rock and soil slopes. Trench excavation causes a rapid change of stress field in the natural slope and gradual yield and deformation of materials (rock and soil). These changes can lead to the expansion and development of existing cracks or new cracks in the material. Precipitation infiltration in these cracks significantly reduces the shear strength of weak soil and rock, which is very unfavorable for slope stability (Li et al., 2020).

Earthquakes can also cause enormous landslides to occur or reactivate. In many cases, inactive earthquake-induced landslides are retriggered by subsequent rainfall. Yang et al. (2017) investigated the hydro-mechanical behavior of partially saturated materials to predict the onset of rainfall-induced landslides after an earthquake. Fu et al. (2020) believe that a strong earthquake causes a lot of landslides. It also makes the slopes more vulnerable and prone to failure in subsequent rains, by releasing stress and creating cracks in rock and soil materials.

In this paper, the reactivation potential of a massive old landslide, located at km 370 of the Miyaneh-Ardabil railway (which is being constructed in northwestern Iran), has been investigated and analyzed. What makes this old landslide important and risky is the construction of a high and long bridge (# 12) at the toe of this giant landslide. On the other hand, Shahriar Dam is being built at the downstream side in a short distance from the landslide. Dam impoundment and rising water level in dam reservoir can be effective on the stability of landslide and bridge foundations at the toe area.

In addition to the ground disturbances created due to the construction of these two large projects, factors such as high seismicity of the region, long and intense precipitations, and vibrations due to passing trains during the operation phase, can be triggering factors for landslide reactivation.

In this study, after collecting the required geotechnical and engineering geological parameters, the stability of landslide in the dry and partially saturated state is analyzed using various slice methods including the simplified bishop method. An attempt was also made to investigate the effect of rising pore pressure, due to saturation of the landslide materials, on the stability of the slope. A sensitivity analysis was also performed to check the effect of each parameter on the stability of the landslide. In the next step, the pseudo-static method was employed to evaluate the effect of seismic loads on landslide stability. In another part of this study, the stability of slope was investigated concerning different characteristics of precipitations in terms of intensity and duration. Finally, according to the results of these studies, suggestions are made to prevent and reduce landslide reactivation risk.

Landslide #370 and its engineering geological characteristics

Landslide #370 is located in the second lot of the Miyaneh-Ardabil railway, at a distance of 30 km from Miyaneh city. Miyaneh-Ardabil Railway is a huge national project, approximately 175 km long, and is being implemented in seven separate lots in northwestern Iran, between two cities of Miyaneh and Ardabil. This project includes 62 tunnels (with a total length of 23,810 m), about 4 km of large valley bridges, 3 km of waterway bridges, and 10 galleries with a length of 4 km which are under construction. During the construction of this project, several instabilities occurred in the excavated trenches and natural slopes adjacent to the route. In addition, due to the limitations of the route, some parts of the selected route are located near or on old landslides. Landslide #370 is one of the most important ones which is located in the selected railway route. Bridge # 12, with a length of 400 m, supported by 9 tall concrete piers, passes through the toe of this old landslide (see Figs 1 and 2). Besides, the Ghezel-Ozan River, which is an important river in the region, flows in the valley adjacent to the landslide slope. Shahriar Dam has been constructed on this river, about 4 km downstream of the landslide slope. With the impounding of this dam, the dam lake's level reaches a level very close to the landslide toe. The access road to this dam is also constructed parallel to the railway track on this old landslide (Fig. 1).

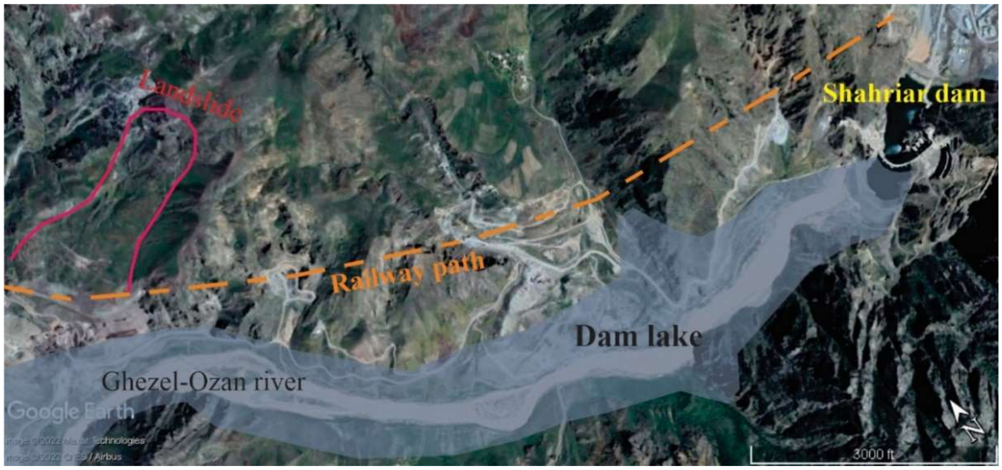
Figures 3 shows the engineering geological map and the cross section prepared along the length of the landslide. Landslide #370 has occurred in geological units that lithologically consist volcanic and pyroclastic rocks, including tuff, andesitic tuffs, and andesite. Due to occurrence of intense weathering and tectonic activities (jointing and faulting) in the region, these geological units are typically weak materials and have unfavorable conditions in most parts of the study area. According to field studies, the geological formation outcropped in the area around the landslide #370 can be subdivided into 4 engineering geological types (ET) as listed in Table 1 (See Fig 3).

Alluvial deposits (Q) mainly consist of weathering products of volcanic and pyroclastic rocks and are transported by rivers and located in the bottom of the main natural drains and seasonal rivers as well as along the Ghezel Ozan River. In addition, fill materials are widespread at the construction site due to massive earthworks (excavation of road trenches and bridge foundations). Although these two materials cover parts of the area, they have not been considered in stability analyses due to their limited thickness.

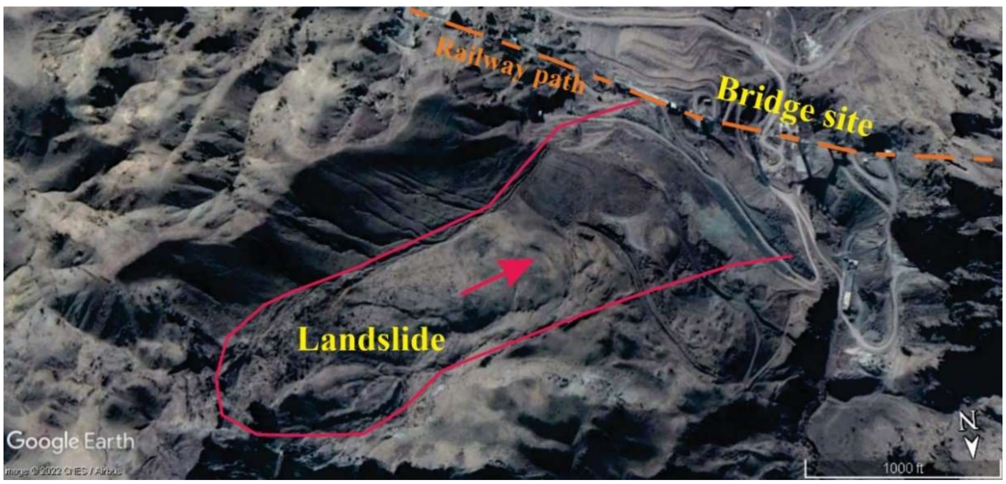
Among the 4 ETs identified in the area (Table 1), USVS and VS are the most important ones. As shown in Fig. 3 almost the entire failure surface is located at the USVS or at its contact with VS. Therefore, a more detailed study of their geotechnical properties is very important (see section 5).

Table 1. List of identified engineering geological types and their characteristics

No.	Engineering geological types (ET)	Lithology	Weathering / Alteration grade	Strength	Structure
1	Q	Alluvial deposits			Soil
2	USVS	tuff and tuff breccia, dacite and sometimes rhyolite	Very high	Very weak	Crushed, weathered, Earth like
3	VS	tuffs (rock tuff, crystal tuff), breccia tuff and volcanic breccia with a composition of dacite and andesite	Low	Moderate	Jointed, blocky rocks
4	V	porphyry andesite lavas, pyroxene andesites	Moderate	Weak-Mod.	Very blocky rocks



(a)



(b)

Figure 1. Two Satellite images (from Google Earth) show the landslide #370, Shahriar Dam site and Ghezel-Ozan River

Geological and morphological evidence shows that this landslide occurred many years ago due to the unfavorable geotechnical quality of geological units and with the help of natural phenomena such as earthquakes, precipitation, and toe erosion by surface waters. It seems that after a period of activity, this landslide has gradually reached a transient equilibrium. In fact, landslide #370 is an old landslide that occurred in a geologically dynamic region.

According to the existing classifications (Varnes, 1978), the mode of movement in this massive landslide is mainly sliding with components of flow movement. Sliding movement is more or less rotational type and has taken place along the contact of the upper loose and weathered materials and bedrock with better geotechnical quality. The flow component of the movement occurs especially during heavy rains and in the part of the material that becomes saturated with water. This landslide with an area of about 270,000 m^2 can be classified as a large landslide and according to the measurements made on satellite images, has a length and width of 900 m and 200-400 m (average 300 m), respectively.

Since there is no sign of a general movement, this landslide can be classified as an inactive and dormant landslide. However, due to the construction works at the slope in recent years, there is a possibility of reactivation of the old landslide. Recently, a small landslide at the toe area of the old landslide has occurred and a few tension cracks was observed in this area (See Fig. 1). In terms of distribution of activity in the landslide, the landslide materials have been moving downwards without a marked change in the position of the main failure surface of the slope. Due to two modes of movement in different parts of landslide, the style of activity of this landslide can be considered composite. So, according to (UNESCO Working Party On World Landslide Inventory, 1993) this landslide can be named as “Composite, Slow, Wet, Debris flow - Debris slide”.

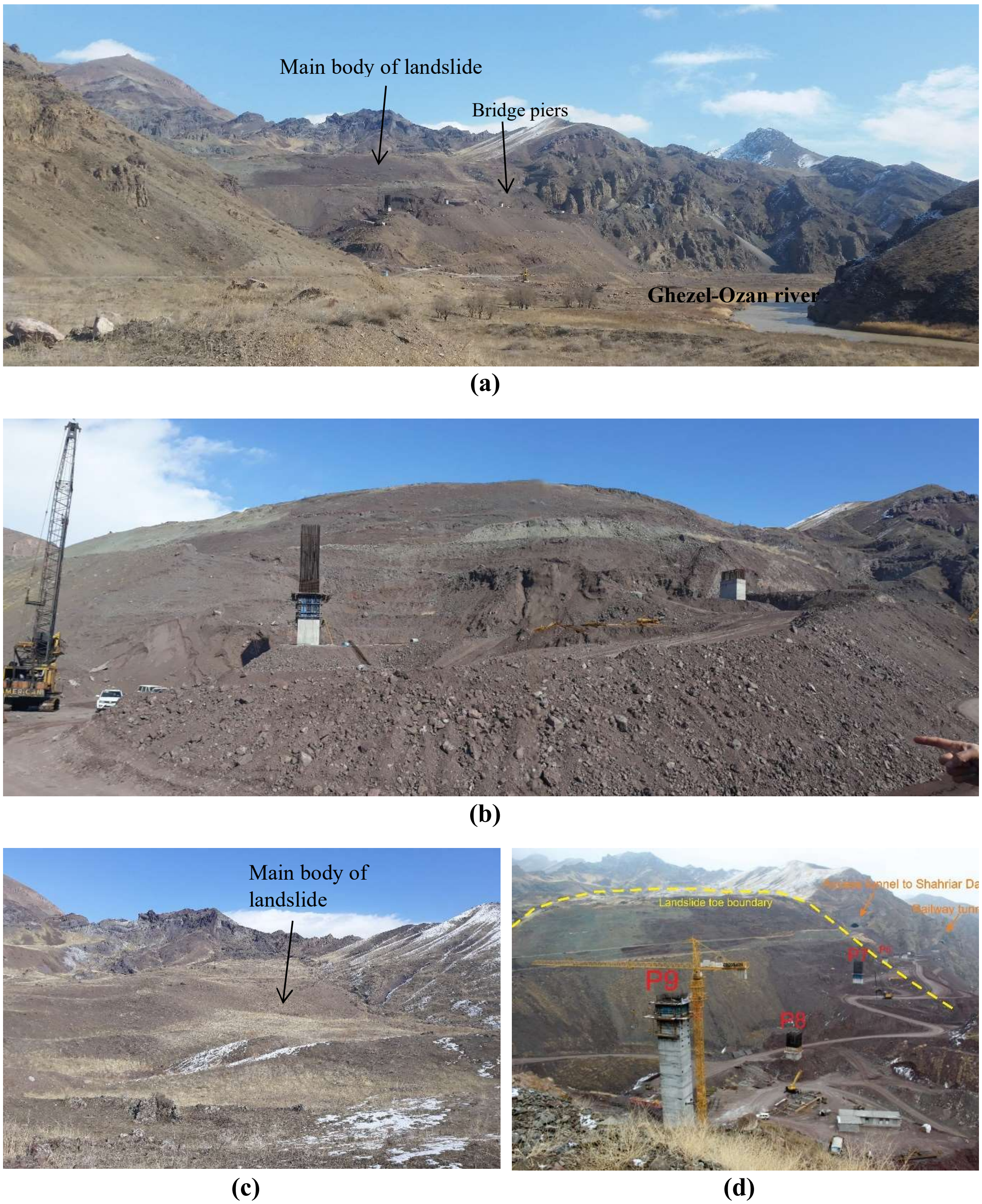


Figure 2. Views of the main body of the landslide and the bridge piers under construction in the toe area of the landslide

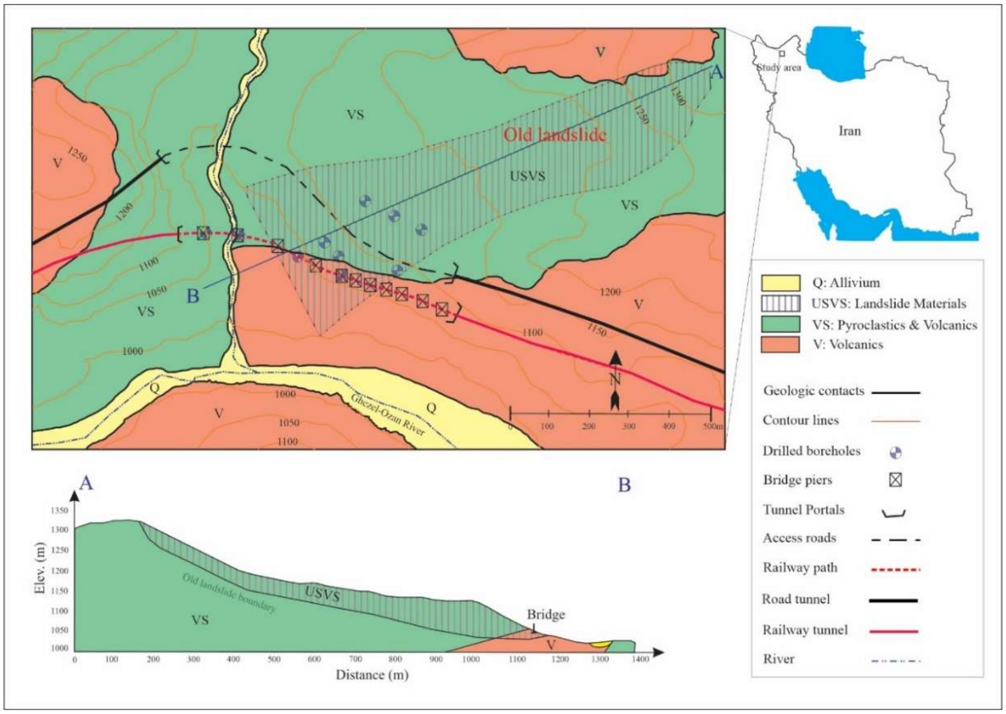


Figure 3. Engineering geological map and section of the landslide area

Groundwater conditions

Various groundwater conditions are expected in the landslide area. During dry seasons, the groundwater level is lower than the identified old failure surface and has no role in landslide movement or reactivation. Obviously, in the wet seasons, during prolonged precipitations, due to rising groundwater level and runoff, parts of the unsaturated landslide materials are saturated. Consequently, pore pressure increases and the shear strength parameters of the materials drop sharply, which in critical situations can facilitate or trigger the sliding and flow movements in the landslide.

Geotechnical properties of the materials

As shown in Fig. 3, ten boreholes have been drilled for geotechnical studies in the landslide area. Although these boreholes have been drilled with the aim of collecting required data for designing bridge foundations, but they are also useful for determination of geotechnical properties of landslide materials. List of drilled boreholes and their characteristics is presented in Table 2. Core Recovery (CR) and Rock Quality Designation (RQD) have been determined in these boreholes in rock units. Also, in these studies, by taking samples from different depths of boreholes, physical, mechanical and rock strength parameters have been determined using laboratory tests. The information obtained from the drilled boreholes, laboratory tests and the results of the field studies were used to determine the variation ranges of the geomechanical properties of different identified engineering geological types. In the field laboratory studies, the characteristics of the engineering geological types (rock units) were estimated using rock mass classification systems (Hassanpour et al., 2019, 2022) and suggested ISRM methods (Ulusay, 2014). The summary results of these investigations are presented in Table 3.

Since all three identified rock units are isotropic and exhibit "non-structural controlled" behavior, the Hoek-Brown (H-B) failure criterion (Hoek et al., 2002) can be considered a suitable failure criterion for determining their shear strength characteristics.

Table 2. List of drilled boreholes and their characteristics

No	Borehole	Depth (m)	Groundwater depth (m)	Eng. Geol. Types	Length along the borehole (m)	Average RQD (%)	Samples	In-situ tests
1	BH1	21.3	---	USVS	11	0	6, 8, 10	SPT
				VS	10	55	-	-
2	BH2	20	---	USVS	7	0	2, 4, 6	SPT
				VS	13	60	-	
3	BH3	20	---	USVS	20	0	-	-
				VS	-	-	-	-
4	BH4	50	---	USVS	15	0	-	-
				VS	35	60	-	
5	BH5	58	---	USVS	41	0	-	-
				VS	17	50	-	
6	BH6	51	34	USVS	51	0	-	-
				VS	-	55	-	-
7	BH7	25	---	Q	18	-	2, 4, 8, 10, 16, 18	SPT
				VS	7	30	-	-
8	BH8	30	---	USVS	18	-	6, 8, 16,18	SPT
				VS	12	10-35	-	-
9	BH9	30	---	Q	8	-	4, 6,8	SPT
				VS	22	35-10	-	-
10	BH10	18	---	USVS	10	0	2, 4, 6, 8	SPT
				VS	8	35	-	-

Table 3. Geotechnical characteristics of identified engineering geological types (rock units)

						Discontinuity surface conditions						
Eng. Geol. Types (rocks)	Rock Strength or UCS (MPa)	Joint count numbet or Jv	RQD (%)	No of joint sets	Spacing of critical discontinuity (m)	weathering	roughness	Aperture (mm)	Filling materials	Persistence (m)	Basic RMR	Geological strength index or GSI
USVS	10-15	40-45	0	> 4	0.05-0.10	Very High	Smooth	> 5	Soft clay	Very low	15-25	10-20
VS	40-50	18-22	55-65	3 + Random	0.10-0.20	Mod.	Slightly rough	1-5	Soft clay	1-3	50-60	45-55
V	50-60	15-17	65-75	3 + Random	0.20-0.25	Mod.	Slightly rough	1-5	Soft clay	1-3	55-65	50-60

In this criterion, peak strength (s_1) for an isotropic rock mass in a given confining stress (s_3) can be obtained by Eq. (1):

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}} + s\right)^a \quad (1)$$

Where, s_{ci} is uniaxial compressive strength (*UCS*) of intact rock, and three parameters of m_b, s and a are factors related to rock mass characteristics and are obtained by the following Eqs. (2)-(4):

$$m_b = m_i\, e^{\left(\frac{GSI-100}{28-14D}\right)} \quad (2)$$

$$s = e^{\left(\frac{GSI-100}{9-3D}\right)} \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right) \quad (4)$$

Where m_i is intact rock constant, *GSI* is geological strength index and *D* is disturbance factor. The variation ranges of above-mentioned parameters for identified rock units are calculated using above equations and presented in Table 4.

Table 4. Geotechnical characteristics of identified engineering geological types (rock units)

Eng. Geol. Types (rocks)	GSI	UCS (MPa)	Hoek-Brown constant parameters				Av. Shear strength parameters		Hydraulic conductivity (k)		Unit weight or g (gr/cm^3)	
			m_i	m_b	a	s	Cohesion or C (MPa)	Friction angle or f	Value (m/s)	Isotropy	dry	Saturated
USVS	10-20	10-15	7	0.122	0.561	1.196e-5	0.06	20	1e-5	Yes	2	2.1
VS	45-55	40-50	13	2.179	0.505	3.8e-3	2.4	33	1e-7	Yes	2.55	2.65
V	50-60	50-60	13	2.606	0.508	6.7e-3	3.2	335	1e-8	Yes	2.6	2.7

The variations of peak strength and shear strength of USVS and VS engineering geological types for different stress levels have been estimated using H-B criterion and presented in the graphs a to d of Fig. 4. Three strength curves of “Min.”, “Mean” and “Max.”, in each graph are related to the minimum, average and maximum values of input parameters, respectively. Hence, these graphs show all possible ranges of strength values for each engineering geological type (ET).

Stability analysis of landslide #370

Deterministic method

Limit equilibrium methods are simple methods that provide a relatively good estimate of the safety factor if the input parameters are selected correctly (Duncan, 1996; Li et al., 2009; Loukidis et al., 2003). Over the past decades, various limit equilibrium methods have been introduced by researchers, such as (Bishop, 1955; Janbu, 1973; Morgenstern and Price, 1965; Spencer, 1967). All of these methods divide the slope into different slices and calculate the safety factor for the entire slope by analyzing forces and momentums applied in each slice. To employ these methods in the slope stability analyses, the following steps must be performed:

Building an engineering geological model for the landslide area and identification of materials involved in the landslide phenomenon;

Selecting suitable failure criteria for involved materials according to their geological properties;

Defining variation ranges of geotechnical input parameters for the involved materials

Recognizing groundwater fluctuations based on borehole information and hydrogeological investigations

Evaluation of seismic loads according to seismic hazard analyses for the landslide site

Determining the approximate position of the potential failure surface according to the field evidences

Building the model in the appropriate software, selecting the analysis method and calculating factor of safety of the slope for different scenarios.

In this study, as the first step, a suitable engineering geological section was prepared along the landslide length (Fig 3). According to this model the USVS type which comprises very weak old landslide materials and VS type as the strong bedrock are the main types which potentially involve in the reactivation process of the landslide.

As mentioned in the previous section, the Hoek-Brown (HB) failure criterion was used to evaluate the shear strength properties of the USVS and VS engineering geological types. The required input geotechnical parameters are presented in Tables 2 and 3.

The “Slope stability” mode of "Slide" software was employed to build the model. Also, the simplified Bishop method (Bishop, 1955), which is the most common method of limit equilibrium, is used in the first stage of stability analyses.

Due to the prominent role of pore pressure in slope stability, it is necessary to examine its fluctuations during the construction and operation periods (Morsali et al., 2017). In this study, "steady state groundwater" mode in the "Slide" software was used to determine the spatial variations of pore pressure in the slope. Using this software and knowing the hydraulic characteristics of engineering geological types (Table 4) and also considering some simple assumptions about the water head, the groundwater flow net can be drawn using the finite element method, and the total head and pore pressure at each point of the slope can be determined. By drawing the flow net, the results of slope stability analyses will be more accurate.

In addition, in another part of this study, the effect of different rainfall scenarios on rising water table and increasing saturated parts of the slope will be evaluated using numerical methods trough Flac2D (Itasca Consulting Group Inc. 2018) software (see section 4).

According to the results of the analyses (Table 5), landslide 370 in static conditions and in a situation where the groundwater level is equal to the maximum level of Shahriar Dam Lake (dry slope) is stable. The results also show that if the groundwater level rises, this landslide is still stable in static conditions and possesses a safety factor between 1.5 and 2. However, studies show that small landslides are more likely to occur in the upper parts and near the landslide crown in the saturated state. Two examples of slope stability analysis using Slide software is shown in Fig. 5.

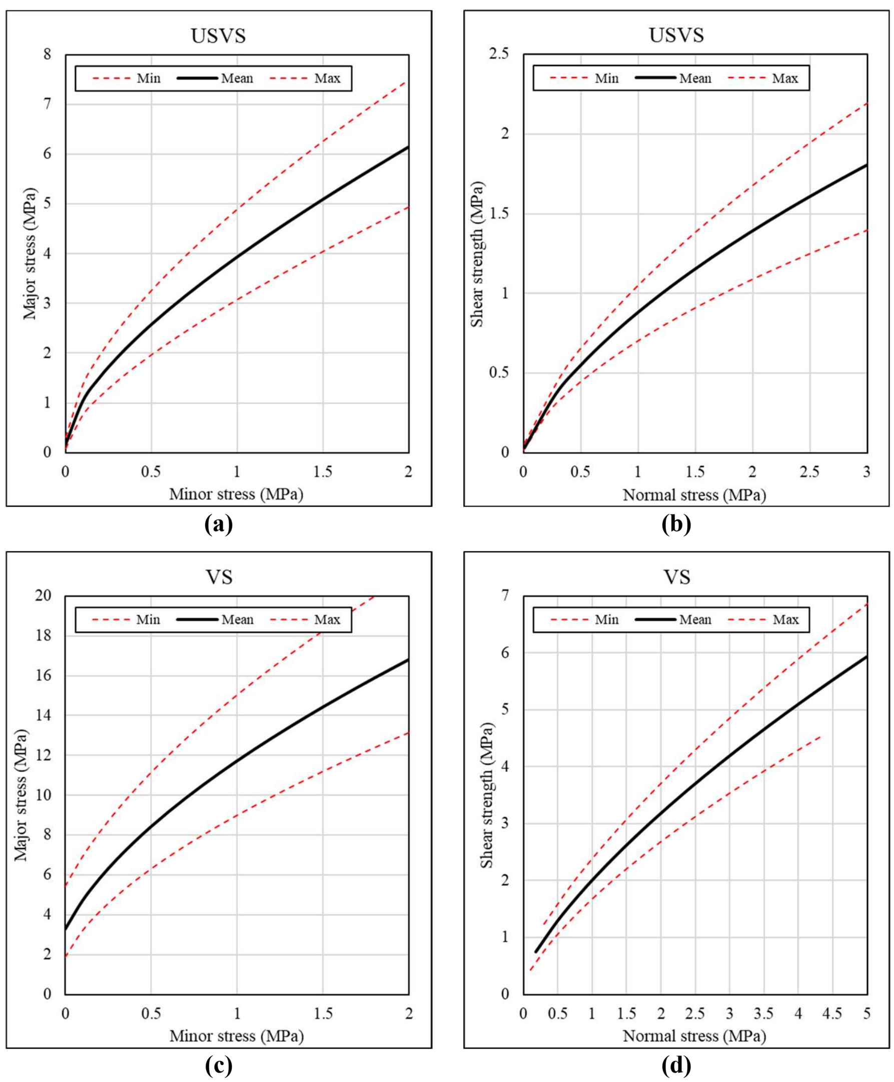
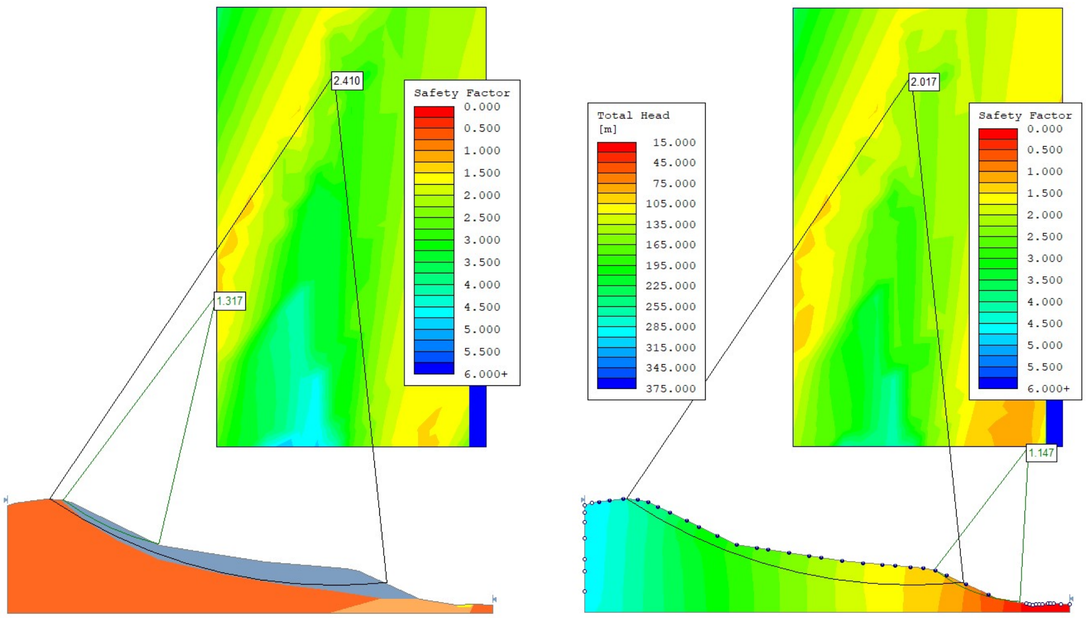


Figure 4. Variations of peak strength (a and c) and shear strength (b and d) of USVS and VS engineering geological types for different stress levels calculated using H-B criterion

Table 5. Results obtained from the slope stability analyses using limit equilibrium method and deterministic approach

parameters	static		Pseudo-static					
			Dry			Saturated		
	Dry	Saturated	k_h=0.1g k_v=0.07g	k_h=0.2g k_v=0.14g	k_h=0.3g k_v=0.21g	k_h=0.1g k_v=0.07g	k_h=0.2g k_v=0.14g	k_h=0.3g k_v=0.21g
Min. safety factor (Main slide)	2.410	2.017	1.616	1.107	0.988	1.221	0.929	0.832
Min. safety factor (Minor slides)	1.317 In the crown area	1.147 In the toe area	1.046 In the crown area	0.872 In the crown area	0.751 In the crown area	0.893 In the toe area	0.737 In the toe area	0.633 In the toe area



(a) **(b)**

Figure 5. An example of slope stability analyses performed by Slide software for static, dry (a) and saturated (b) conditions

Due to the high seismicity of the region and the high impact of earthquake vibrations on landslide stability conditions, seismic hazard analyses were performed for the landslide area and bridge project site. According to the results of these studies, the horizontal and vertical peak ground accelerations were estimated as 0.45g and 0.3g, respectively for this site (assuming a 10% probability of occurrence in 50 years of the structure's lifetime). These values were considered the upper limit, and the effect of lower horizontal and vertical ground accelerations was also evaluated in the stability analyses.

The stability of the landslide 370 in the pseudo-static conditions was investigated in both dry and partially saturated modes, assuming different values for horizontal and vertical ground accelerations. The results of these analyses (Table 5) show that if the slope is partially saturated and large earthquakes occur in the close areas, landslide 370 will be reactivated, and the stability of Bridge No. 12 will be threatened.

probabilistic method

The values considered for the input parameters used in the stability analysis (especially the values of the shear strength parameters of the landslide materials) always have uncertainties. These uncertainties cause the output results to be questioned. One of the appropriate methods to consider these uncertainties is using probabilistic methods in stability analysis methods. In the probabilistic method, input parameters are considered random variables. Assuming that the values of these random variables are distributed around their mean so that they can be defined by one of the continuous distribution functions, such as the normal distribution, these distribution functions can be used as input for probabilistic analyses instead of a single value. The question is how to use this input information to determine the output parameter distribution function (here, the stability safety factor). One solution is to use random sampling methods such as the Monte-Carlo method. This method uses random or pseudo-random numbers to sample probabilistic distribution functions. If a sufficient number of random samples are selected and used to calculate the safety factor, a distribution of values will be generated for this final parameter, which will be its probability distribution function. In this study, the capabilities of slide software have been used to perform such probabilistic analyses.

In addition, using probabilistic methods in stability analysis makes it possible to analyze the sensitivity of safety factor to the variations of different input parameters. Using this technique, the most critical parameters that affect the stability of slope can be identified. It is also possible to estimate the variation ranges of input parameters, especially shear strength parameters, by performing back analyses. Usually, a better understanding of the variation ranges of the input parameters can be achieved using this useful method.

In these analyses, the three parameters of mi, GSI and UCS of the USVS engineering geological type, as the main unit which comprises almost the whole length of the failure surface of the landslide, are considered as random variables. The normal distribution function as a suitable distribution, with characteristics listed in Table 6, was selected to define variation ranges of these random variables.

The summary results of the probabilistic analyses performed in this study are presented in Fig. 6. The histograms and S-shaped graphs presented in Fig. 6a-d shows the variations of safety factor and its probability for two different conditions: 1) static and dry condition and 2) pseudo-static (K_h = 0.2g and K_v = 0.14g) and partially saturated conditions. As shown, mean safety factor for two conditions is 2.4 and 0.93, respectively. Besides, Probability of failure (PF=percent of FS<1) in two cases are 0% and 61%, respectively.

These results show that the simultaneous effect of slope saturation (due to an intense, long-time rainfall) and earthquake occurrence can be very significant, reactivate the landslide and cause a likely catastrophic tragedy by destroying railway bridge during project operation.

Figure 7 shows the sensitivity of the safety factor to changes in two parameters, mb and UCS, of the USVS engineering geology type. As shown, both the properties of intact rock or UCS and the rock mass characteristics of the materials involved in slope failure have a great influence on slope stability. Therefore, in this study, choosing the right method to determine the properties of materials is very important.

Evaluating effect of rainfalls on the stability of landslide

In this study, a numerical simulation was performed to evaluate the stability of the landslide and investigate the effect of different rainfall durations and intensities on the landslide.

Table 6. Statistical distributions considered for the materials involved in the slope failure

Engineering geological type	Parameters	Distribution function	Mean	Standard deviation	Max. relative	Min. relative
USVS	UCS (MPa)	normal	15	3	9	9
	mb		0.12	0.03	0.09	0.09
	s		4.5e-6	1e-6	3e-6	3e-6

The FLAC software was used to perform numerical simulations according to its capabilities. Using FLAC software, a two-phase flow (i.e., air and water flow) was employed in the performed analyses.

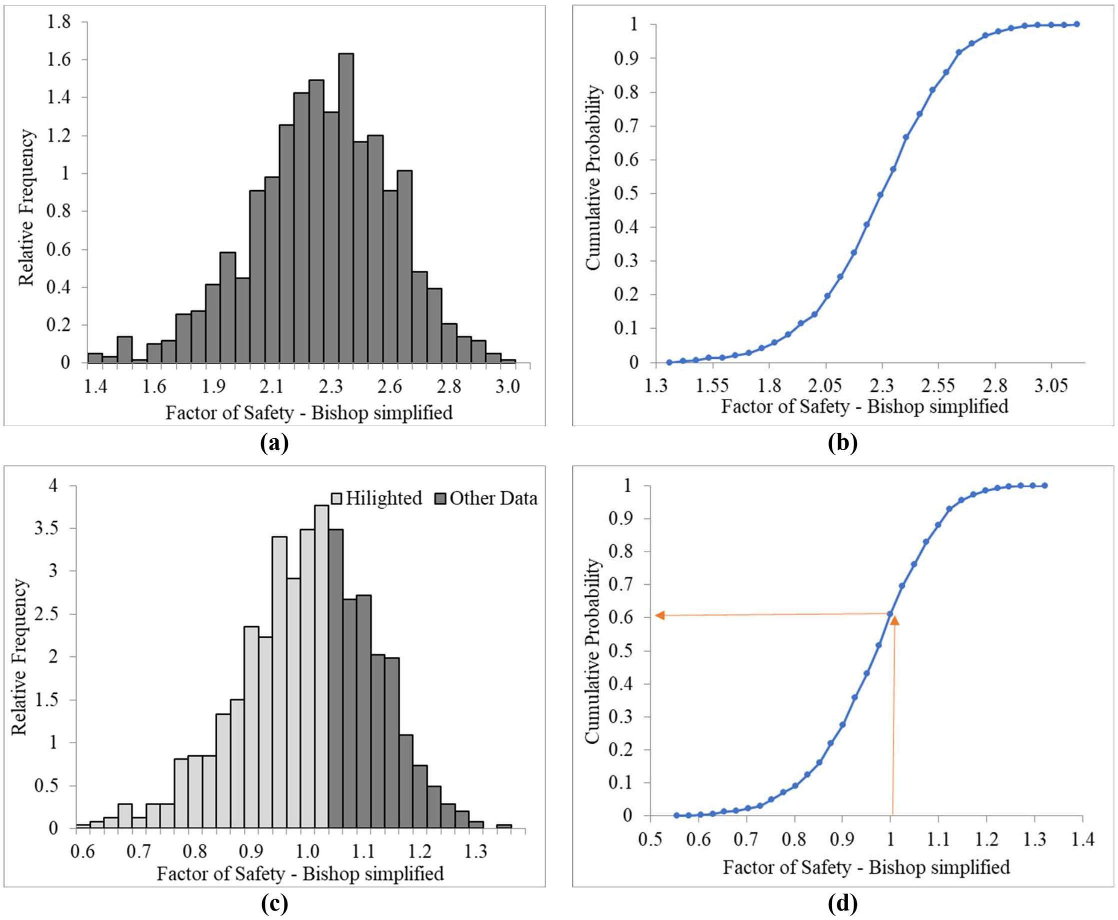


Figure 6. Results of stability analyses of the landslide using probabilistic approach; a, b) static and dry condition and c, d) pseudo-static ($K_h = 0.2g$ and $K_v = 0.14g$) and partially saturated conditions

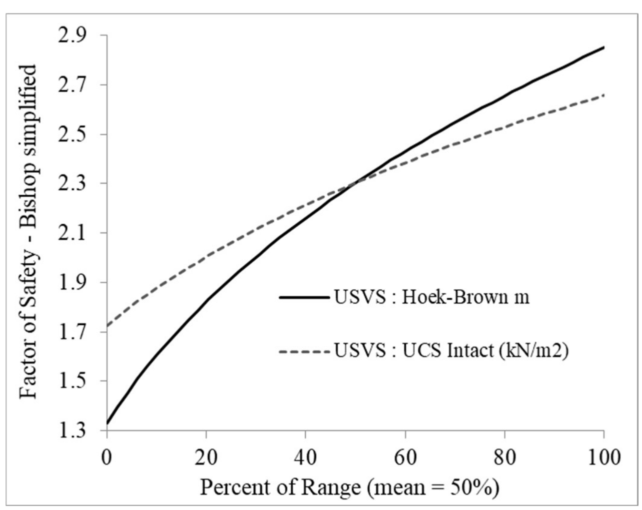


Figure 7. Influence of variations of rock mass properties on the factor of safety of slope (the graph has been prepared for dry and static conditions)

Precipitation records in the area

The climatic situation of this area is "cold-dry" according to the climatic classification systems. According to recorded climatic data in the nearest stations, the average annual precipitation in the area is 250mm. Recorded data show that with an average precipitation of about 43.00 mm, April is the rainiest month, and August, with an average precipitation of about 3.00 mm, is the driest month of the year. The area has a relatively long rainy season and relatively long snow cover in winter. Also, based on precipitation records, there is a possibility of heavy but short-term precipitation in this area. The events of April and May 2012 and March and April 2019 are examples of such events. Figure 8 shows the monthly and cumulative monthly rainfalls in 2012. According to detailed data, in this year about 40 mm of rainfall occurred in a few hours (May 4th) which is a record for the area. Studies show that if such rains continue for a few consecutive days, they can be very effective in saturating the landslide materials. It is predicted that similar events will be frequent in the region in the coming years due to the climate change and changing rainfall patterns.

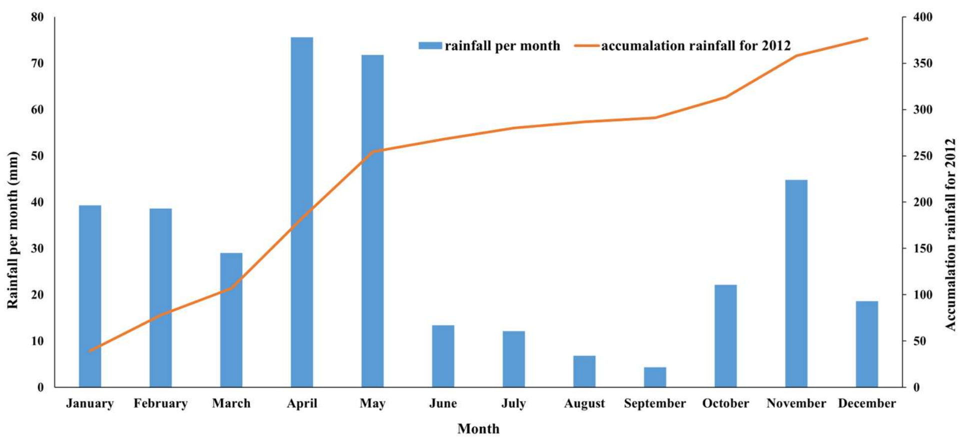


Figure 8. Monthly and cumulative monthly rainfalls in 2012

In this study, landslide stability was analyzed for two different rainfall scenarios in terms of intensity and duration. In the first scenario, according to the climatic characteristics of the region, it was assumed that the amount of rainfall for a long period (seven months) would be 150 mm (on average 20 mm per month). In the second scenario, a different amount of rainfall was assumed to occur in a short period of four days. The purpose of these analyzes is to determine the effect of the intensity and duration of rainfall on the stability of the studied landslide and to investigate the possibility of its reactivation due to these rainfalls.

Rainfall Infiltration effect

During precipitation, depending on the permeability of the soil, in addition to the runoff, part of the rain water infiltrates into the ground, which increases the degree of saturation of the material and reduces the capillary pressure in the soil. Capillary pressure in unsaturated soils can significantly affect the stability of a slope. Capillary forces create more cohesion in the soil by holding fine-grained particles together. Usually, as the soil saturation increases, the apparent cohesion created by the capillary forces decreases (Kim et al., 2004; Tran et al., 2019; Tsaparas et al., 2002). While low-intensity and long-term precipitation may be helpful for slope stability under certain conditions, high-intensity, short-term precipitation may cause soil saturation and slope failure (Itasca, 2018). So far, many studies have been conducted in this field, and various experimental equations have been developed to define the relationship between volumetric water content and soil suction in unsaturated soils (Brooks and Corey, 1964; Fredlund and Xing, 1994; McKee and Bumb, 1987; Van Genuchten, 1980). Among these methods, Van Genuchten empirical relationship has been used by many researchers and is considered as an accepted method (Tran et al., 2019). Two-phase flow logic uses the extended form of Darcy law for fluid conduction. The pore pressure is negative and is related to saturation by an empirical law in the unsaturated part. In the study of fluid flow in unconfined aquifers, it is assumed that water is the only fluid in the formulation and air is at constant atmospheric pressure in the void space. In the FLAC standard fluid-flow logic, capillary effects are not considered (Itasca Consulting Group Inc. 2018). In this study, Van Genuchten's empirical equation (Eq. 5-6) (Van Genuchten, 1980), which is based on equations proposed by (Mualem, 1976), and is available in FLAC, has been used in the numerical analyses for considering effect of capillary forces in unsaturated soils.

$$P_c = P_0 \left[S_e^{-1/a} - 1\right]^{1-a} \tag{5}$$

$$S_e = \frac{S_w - S_r}{1 - S_r} \tag{6}$$

where, S_e, S_w and S_r are effective, water and residual saturation degrees, respectively. P_0 and a are the Van Genuchten parameters are obtained experimentally. Parameter P_0 measures soil capillary strength. Parameter a also indicates the slope of the capillary curve. P_c is also capillary pressure (Itasca, 2018).

Safety factor

In numerical softwares such as FLAC, the shear strength reduction technique is used to obtain the safety factor. To calculate the safety factor of the slope using the shear strength reduction technique, a set of simulations is performed with the shear strength parameters C^{trial} and □^{trial} defined as follows **Eqs. 7** and **8**:

$$C^{trial} = \frac{1}{F^{trial}} C \tag{7}$$

$$\phi^{trial} = arctan\left(\frac{1}{F^{trial}} tan\phi\right) \tag{8}$$

where F^{trial} is the trial factor of safety. The initial shear strength parameters are set to be sufficiently large to ensure the stability of the slope. These parameters are then reduced incrementally until a failure occurs. Corresponding safety factor, F^{trial}, is considered to be the factor of safety of the slope.

Numerical modeling of the landslides #370

Flowchart presented in Fig. 9 shows the steps of the modeling process of the landslide stability. As shown, modeling of two-phase flow was performed in parallel with the mechanical modeling using the FLAC-2D software. In the modelling process, the prepared geological cross section of the landslide slope (Fig. 3) was used as the main input of the model. The lateral boundaries of the model in the vertical direction and the lower boundary in both the horizontal and vertical directions were considered fixed. Also, according to complexity and huge dimensions of the slope, a standard mesh has been used. The Mohr-Coulomb failure criterion was assigned to all geological materials of the model. The equivalent Mohr-Coulomb parameters were estimated based on Hoek-Brown parameters. In addition, the pore air pressure was assumed to be equal to the atmospheric pressure. The other parameters used in the two-phase flow analyses are listed in Table 7.

Table 7. Geotechnical and hydraulic properties of landslide materials used in the two-phase flow analyses

Soil	Bulk modulus (Pa)	Shear modulus (Pa)	Porosity	P0 (van Genuchten parameter) (pa)	Residual saturation
USVS	3.333E8	1.538E8	0.15	2875	0.01
VS	4.333E9	2.6E9	0.1	2347	0.05

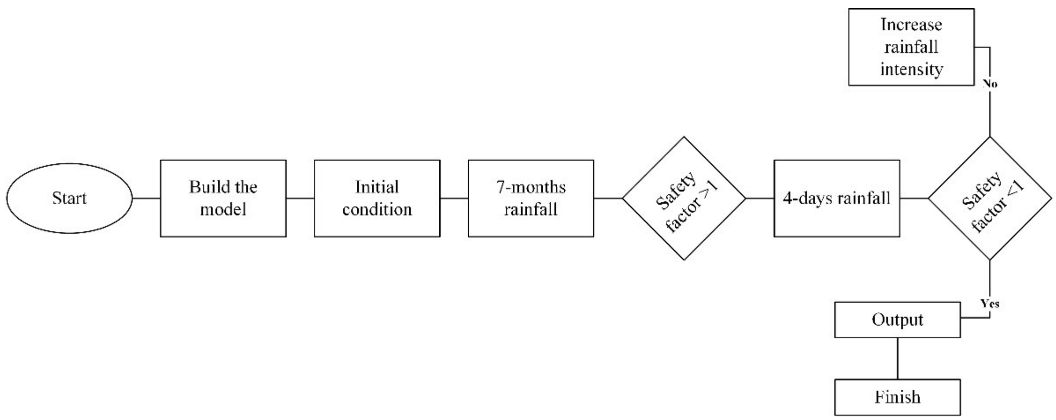


Figure 9. Flowchart of the modeling process

As mentioned, in the performed analyses, initially, a long (7 months) but low intensity rainfall (with a monthly average of 20 mm) was applied to the model. The results of numerical analyses showed that the initial soil saturation, which was assumed to be 0.19, has reached to about 0.22 by applying low intensity, long background rainfall (Fig. 10a). As shown in the graphs presented in Figs 10b, c by applying short-term rainfalls, this parameter increased further and reached to maximum 0.69 when the most critical rainfall scenario was applied in the model. It is clear that pore pressure also increases simultaneously.

By increasing the pore pressure and degree of saturation in the slope, the safety factor of the slope decreases. The results of the numerical analyses show that although the old landslide is still stable with increasing rainfall intensity, there is a possibility of local instabilities in some parts of the slope, especially in the upper parts of landslide. The graphs presented in Fig. 11 show the safety factor contours and velocity vectors in the slope for a short period, 200mm rainfall scenario. As shown, the overall slope is stable, but safety factor of the most critical surface, in the upper part of the slope is equal to 1.16 which is very close to unstable conditions. These results agree with the analyses performed based on the limit equilibrium method.

Risk reduction methods

One of the goals of this study was to propose ways to reduce the risk in case of reactivation of the landslide. The solutions to reduce the risk of this phenomenon can be divided into three categories:

A) Avoiding landslide

It is clear that when designing the route of roads and railways, in order to avoid unstable slopes, it is necessary to identify the exact location of old and inactive landslides in addition to the new and active landslides that have occurred on the route.

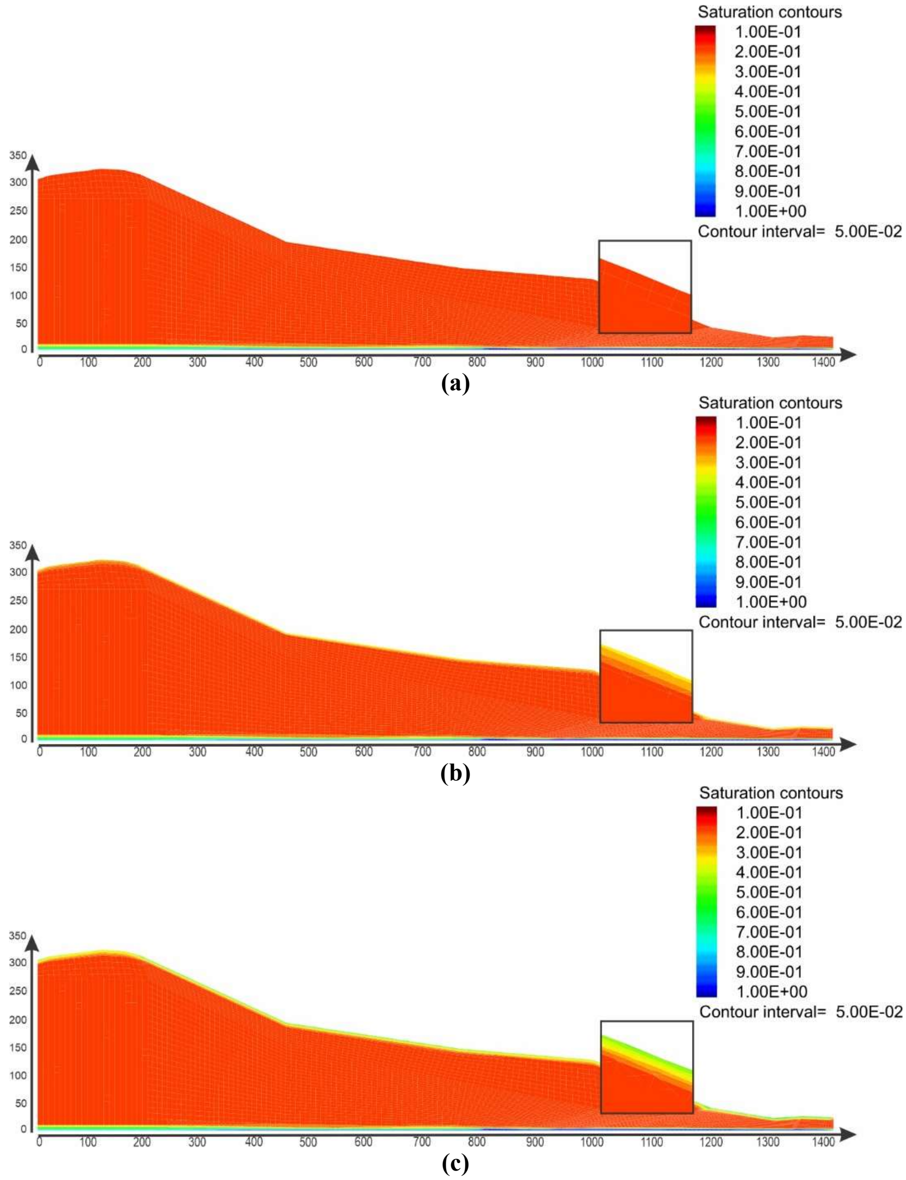


Figure 10. Distribution of saturation degree in the slope after: a) seven months background precipitation; b) occurrence of a 100mm rainfall in four days and c) occurrence of a 200mm rainfall in four days

In the case of old landslides, it is sometimes difficult to identify them due to the disappearance of their movement traces due to erosional processes, and this issue can create a serious problem for the route, especially in railway lines that are less flexible to change the route.

In the studied project, after the detection of landslide #370, it was not possible to change the route due to the fixed structures (two long tunnels) before and after bridge #12. In fact, it was not economically viable to change a big section of the route and avoid the landslide.

B) Stabilizing the landslide

Considering the large dimensions of the landslide, it is not possible to build protective engineering structures such as retaining walls, concrete piles, etc. in reasonable volumes to stabilize the old landslide.

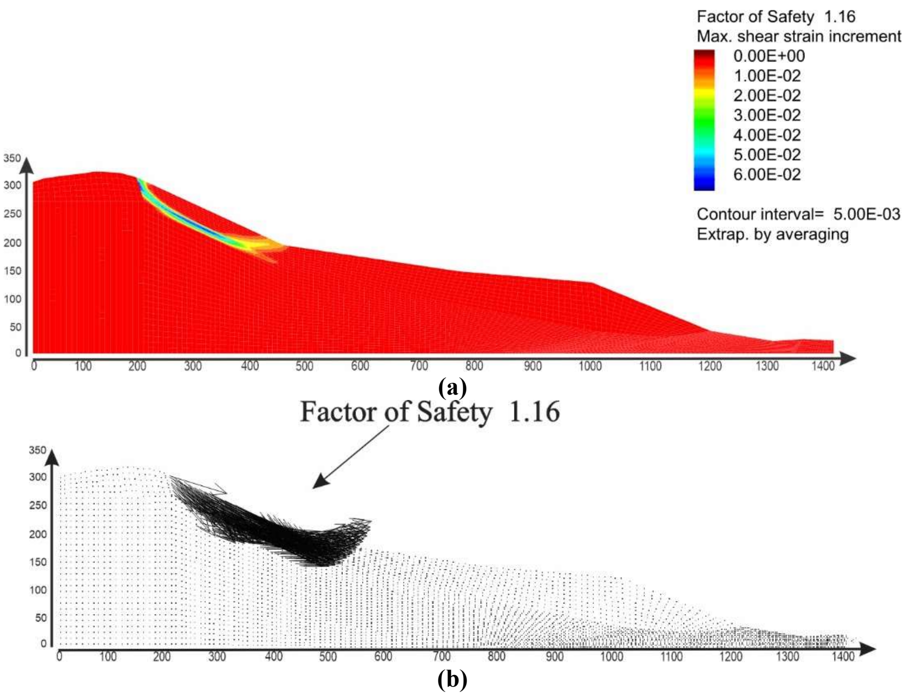


Figure 11. Safety factor in the slope after applying 200mm rainfall in four days: a) factor of safety vs max.shear strain; b) factor of safety vs velocity vector

A simple solution to increase the safety factor can be the implementation of surface and deep drainage systems. Implementing a surface water collection system and drilling galleries can be useful to reduce the groundwater level. Although these solutions have little effect, they are economically feasible.

C) Designing warning systems

Another effective solution is to use warning systems based on permanent monitoring of slope movements. Installation, reading and timely and fast interpretation of a consistent network of inclinometers, piezometers and benchmarks can be very effective in announcing the landslide activity in time and preventing a possible disaster.

Conclusion

In this study, an attempt was made to study the characteristics of an old dormant landslide located near an important structure, and to investigate the possibility of its reactivation under the influence of factors such as rainfalls and earthquakes. The results of these studies showed that under normal conditions this landslide is stable, but in the case of the occurrence of phenomena such as intense rainfalls and large earthquakes, the probability of landslide reactivation is very high. Since the pattern of rainfall in the region is changing due to climate change, intense rainfalls are expected to be a frequent phenomenon in the region in the coming years. On the other hand, the studied area is located in an active area, and the return period of large earthquakes in this area that can cause landslide reactivation is less than the lifetime of the structure. These conditions significantly increase the need to pay attention to the stability of this geological phenomenon. Unfortunately, there is no effective solution for the complete stabilization of the slope due to its large dimensions. Therefore, the development of effective monitoring and warning systems is the main solution to reduce and manage the risk of this phenomenon and prevent a probable tragic disaster.

Conflict-of-interest statement

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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