40th National geosciences
of Earth Sciences
چهلمین گردهمایی (همایش) ملی
علوم زمین
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Investigating the reactivation potential of an ancient landslide in the second lot of the Miyaneh-Ardabil railway

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Abstract— **In this study, a huge old landslide located at the chainage of 370 km of the second lot of the Miyaneh-Ardabil railway has been investigated. What makes this old landslide important is the presence of large bridge (# 12) on the railway route at the toe of this landslide. This landslide has occurred in geological units which consist of volcanic and pyroclastic rocks, mainly tuffs, andesitic tuffs, and andesites. In some parts of the study area, these geological units are geotechnically very weak and do not have favorable quality due to weathering of rock masses and occurrence of fault zones. The results of studies show that the main cause of landslides is the saturation of geotechnical materials due to long-term precipitations and the occurrence of medium to high magnitude earthquakes in the surrounding areas (according to high seismicity of the area). This study aims to investigate the engineering geological features of this large and old landslide and to provide solutions to reduce its risk. For this purpose, after evaluating the geotechnical parameters of materials, through laboratory and field tests, field surveys, experimental and analytical methods, engineering judgment and back analyses, the stability of the slope has been analyzed using limit equilibrium methods by considering appropriate failure criteria for the involved materials. The effect of the two main parameters of groundwater level fluctuations and seismic accelerations on the stability of the slope has been investigated. Based on the analyses results, the construction of drainage galleries for removing underground waters and surface drains for collecting surface waters, are suitable methods to increase the safety factor and reduce the risk of landslides.**

Keywords: landslide, limit equilibrium, reversal analysis, safety factor, stabilization

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1. Introduction

Landslides are among the most important natural hazards. An old landslide can be defined as a landslide that occurred many years ago and has been inactive for a considerable time after that. However, an old landslide can also be fully or partially reactivated by several new triggering factors, including heavy rainfalls, construction activities, and seismic vibrations. These landslides can cause severe damage to structures, roads, bridges, and even cause casualties if reactivated [1]. Therefore, studying these landslides from the perspective of engineering geology and determining their exact characteristics and the study of their possible long-term effects on the surrounding structures is essential and should not be ignored by contractors and clients.

Nowadays, high-precision computer software developed based on limit equilibrium methods is used to check the stability of slopes and landslides. The limit equilibrium methods include Fellenius [2], Taylor, Bishop [3], Morgenstern-Price [4], Spencer [5], Janbu [6], Sarma [7], methods proposed during the early decades of the 20th century. In these methods, which can be categorized as slice methods, the safety factor is calculated by satisfying the equilibrium of forces and momentums (or both) are active in slice boundaries. For instance, Spencer and Morgenstern-Price methods are based on satisfying both forces and momentums equilibrium, and the bishop method on the forces equilibrium only.

In this paper, after studying the geometric properties of the landslide, the engineering properties of the materials and possible triggering factors of landslide (including rainfall, groundwater, earthquakes), as well as the possibility of landslide reactivation are investigated and analyzed. Also, special attempt is made to examine the effect of rising water level and occurrence of seismic events on the stability of landslide using the limit equilibrium methods.

2. Description of landslide and its characteristics

Landslide 370 is an old landslide (Figure 1) that has occurred in a geologically dynamic region in the past. The exact age of the landslide is unknown, but due to morphological evidences a range of 100-200 years can be considered as an approximate age. As shown in Figure 1-b, due to the passage of the railway route (and a large bridge -No. 12- which is being constructed on nine concrete piers named P1 to P9) from the landslide toe, there are concerns about the possibility of reactivation of the landslides and the impact of the new movements on the stability of the bridge piers.

(a) (b)

Figure 1 - 370 km landslide a) Image is taken from Google Earth from the landslide area, the yellow part of the smaller and newer landslide that has occurred in the displaced mass. b) Picture of Bridge No. 12 to the northeast

Geological and morphological evidences show that this landslide has occurred many years ago, due to the unfavorable geotechnical quality of geological units and triggered by natural factors such as earthquakes, intense precipitations, and stream erosion. This very large landslide has gradually reached to relative equilibrium situation and been inactive for many years.

According to the existing classifications [8], the mode of movement in this massive landslide is mainly slide with components of flow in side areas. Sliding movement is more rotational and has taken place along the contact of the upper loose and weathered materials and bedrock with higher 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.

Because there is no evidence of new movements, the main landslide can be classified as inactive and dormant [9]. A dormant landslide is an inactive landslide which can be reactivated by its original causes or other causes. In addition to the main landslide, there is a minor landslide (Figure 1a) in the main landslide due to the construction of the access road to the Shahriar Dam. During earthmoving operations for excavating road cuts, some new tensile cracks created in the accumulation zone of old landslide and new landslide formed in the toe area. This indicates that the road cuts with the designed slopes in loose and weathered materials have not been stable (Figure 2).

The dimensions of this landslide are so significant that according to the measurements made on satellite images, its length is about 900 meters, and its width is between 200 to 400 meters (average 300 meters). Therefore, according to the existing classifications, this landslide with an area of about 270,000 square meters is classified as a large landslide [9].

(a) (b)

Figure 2 - a) Cracks created near the slippery toe caused by local instabilities in the toe. b) Tensile cracks created in the coated materials forming the downstream slopes of the bridge

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 rupture surface of the slope. If reactivated in the future, it could be a retrogressive landslide. Due to two modes of movement in different parts of landslide, the style of activity of this landslide can be considered composite.

3. Geology of the landslide area

This landslide has occurred in geological units consisting of volcanic rocks and pyroclastic rocks, mainly tuff, andesitic tuff, and andesite. In some parts of the study area, these geological units are geotechnically weak/poor due to weathering and faulting phenomena and do not have favorable conditions. Table 1 lists the geological characteristics of the materials identified in the landslide area [10].

Table 1 - Geological units identified in the landslide area and their characteristics

unit	Engineering geology species	Description
Rock	VS	A set of tuffs (rock tuff, crystal tuff), Breccia tuff and volcanic Breccia with a combination of dacite and andesite
	V	Porphyry andesite lavas, pyroxene andesites with moderate weathering and alteration
Soil	USVS	Tuff and tuff breccia dacite and sometimes rhyolite and andesitic sections with advanced alteration. This unit has been severely crushed and turned into soil due to being involved in the earthflow
	Q	The result of weathering and alteration of permeable rocks (alluviums) that have settled in the valley and along the Ghezel Ozan River

4. Seismicity of the area

Due to the importance of seismicity and its effect on the occurrence or reactivation of landslides, it is necessary to conduct earthquake risk analysis studies with sufficient accuracy. According to the seismic hazard analysis studies performed for this area, the horizontal and vertical accelerations are 0.45g and 0.3g, respectively (assuming a 10% probability of occurrence in 50 years of the lifetime of the structures). In this study, based on engineering judgments, horizontal acceleration of 0.15-0.3 and vertical acceleration of 0.1-0.2, were used in the stability analyses.

5. Groundwater conditions

Various groundwater conditions are expected in the landslide area. Typically, the water table is lower than the slip surface and has no role in landslide movement. Obviously, during prolonged rainfalls, due to rising groundwater level and runoff, parts of the unsaturated materials are saturated. Consequently, the shear strength parameters of the materials drop sharply, which in critical situations can facilitate or trigger the sliding and flow motions in the landslide.

6. Climatic conditions of the region

According to the Amberg climatic classification model, the climatic situation of this region is of the "cold-dry" type. With about 43.2 mm of rainfall, April is the rainiest month, and August, with about 3.04 mm of precipitation, is the driest month of the year in this area. This area has relatively long rainy seasons, and snow cover is relatively high during the winter.

7. Engineering properties of materials

Table 2 lists the geotechnical properties of identified geological units, measured using different field and laboratory methods. Distribution of these materials in the landslide is also shown in geological cross-section prepared along the landslide length (Fig. 3). As shown, required input parameters of appropriate failure criteria (which selected according to nature of materials) are determined during geotechnical investigations.

8. Stability analyses

To study the stability conditions and investigate the effect of different parameters, especially groundwater level and seismic accelerations, on the stability of the old landslide materials, a geological cross-section was prepared along the landslide length (Figure 3). This geological cross-section passes through the positions of two piers of P8 and P9 (bridge number 12). Slide software (and Bishop's simplified method) were then employed for analyses. The assumptions used in these analyses are as follows:

Table 2 – Geotechnical parameters used in the analyses

Rock and soil layers	GSI	UCS (MPa)	s	a	$\gamma(t/m^2)$		$\varphi(degree)$	$C(KPa)$	
					dry	wet		dry	wet
V	50	45	0.0002	0.506	2.6	2.7			
VS	45	45	0.0001	0.508	2.55	2.65			
USVS					2.0	2.1	30	45	20-25
Q					2.0	2.05	30	5	5

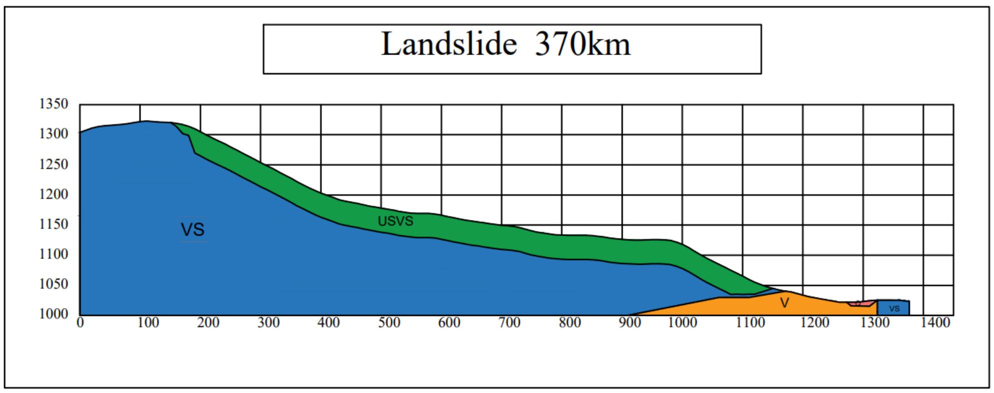

Figure 3 – Geological cross-section along the landslide length

In these analyses, the groundwater level was investigated in two different situations. In the first case, the average water level was considered in a level equal to the water level in Shahriar Dam (which its reservoir is located very close to the landslide toe). In the second case, the slope was considered wholly saturated. The slope was also analyzed using pseudo-static methods by considering different seismic accelerations. (Figure 4).

According to the results of the analyses (Table 3), the slope will be stable with considering the water level equal to maximum water level in Shahriar Dam reservoir. Consequently, there is no threat of reactivation of the landslide in this case. The obtained safety factors were in the range of 1.5-2. However, pseudo-static analyses show different results, and it is likely that if the slope is fully saturated and ample earthquakes occur close to the area simultaneously, the landslide will reactivate and destroy the bridge No. 12, which is located at the toe of the landslide.

Table 3 - Results obtained from the slope stability analyses

parameters	static		Pseudo-static					
			Low water level			High water level		
	Low water level	High water level	g=0.1	g=0.2	g=0.3	g=0.1	g=0.2	g=0.3
Safety factor	3.055	1.529	1.849	1.366	1.108	0.973	0.751	0.632
Toe safety factors	2.24	1.92	1.483	1.132	0.931	1.276	0.978	0.806

It should be emphasized that rising groundwater levels and slope saturation through heavy rains and earthquake shake have a significant impact on the safety factor and cause a sharp decline in slope stability.

9. Back analysis and determination of slide mass strength parameters

This study aimed to investigate the possibility of reactivation of the old landslide. To perform exact analyses, it was necessary to carefully examine the shear strength parameters of the materials involved in landslide and perform sensitivity analyses to find most effective parameters. To reach these goals, back analysis method, using the Monte Carlo technique and simplified bishop method in Slide software was employed (by employing probabilistic option). In this method, by considering a suitable statistical distribution for the shear strength parameters of the materials and sampling from these distributions as input parameters for each calculation, the probabilistic distribution of safety factor along the selected failure surface is obtained. Table 4 shows the statistical distribution considered for the landslide materials.

Table 4 - Statistical distribution for the old sliding materials

parameters	Type of statistical distribution	Mean	Standard deviation	Max relative	Min relative
Cohesion (kPa)	normal	20	5	15	15
Friction angle	normal	28	3	9	9

Figure 5-a shows the histogram diagram of the safety factor variations based on the simplified Bishop method which has separated safety factors less than (and equal to) one. This histogram is obtained for a fully saturated slope in static condition. As shown, 70% of the calculated safety factors are less than one, which means the occurrence probability of slope failure in this situation is 70%. In a fully saturated slope and under pseudo-static condition by assuming a horizontal acceleration of 0.1g (Figure 5-b), almost 100% of the calculated values of safety factors are less than one, and the slope will be completely unstable. Figure 5c shows these probabilities based on the s-curve for the fully saturated slope in static condition. Figure 5-d shows the changes in the shear strength parameters and the effect of these changes on the safety factor. As can be seen, the safety factor is very sensitive to the cohesion compared to the friction angle of the materials.

10. Slope stabilization measures

To reduce the risk of unstable slopes, there are various solutions depending on the material types and movement modes, etc. In the soft rock slopes or in the sediments, reducing the angle of slope, constructing retaining walls to prevent severe erosion of the slope, and installing drainage systems are routine solutions. In the hard rock slopes, methods such as reducing the height and angle of the slope, installing anchors and bolts, mesh and shotcrete, are very common [11]. These methods can be preventive or corrective. In the studied landslide, all the proposed solutions have a preventive aspect to prevent reactivation of the landslide.

In addition, the methods selected for stabilizing the unstable slopes should be chosen according to the triggering mechanism and also taking into account the possible costs. Due to the mentioned characteristics of this landslide, mainly due to its huge dimensions, it is not possible to control the movements of the main body of landslide using mechanical methods. On the other hand, avoiding landslide area is impossible due to the need to change the route's geometry, the level of water in Shahriar Dam reservoir, and related costs. Since the infiltration of surface waters after long-period precipitations plays a key role in reactivating of the landslide, surface drainage methods (collecting ditches) must be the first priority. It is also emphasized that a network of underground drains should be designed and constructed as drainage galleries to drain groundwater and prevent complete saturation of the slope.

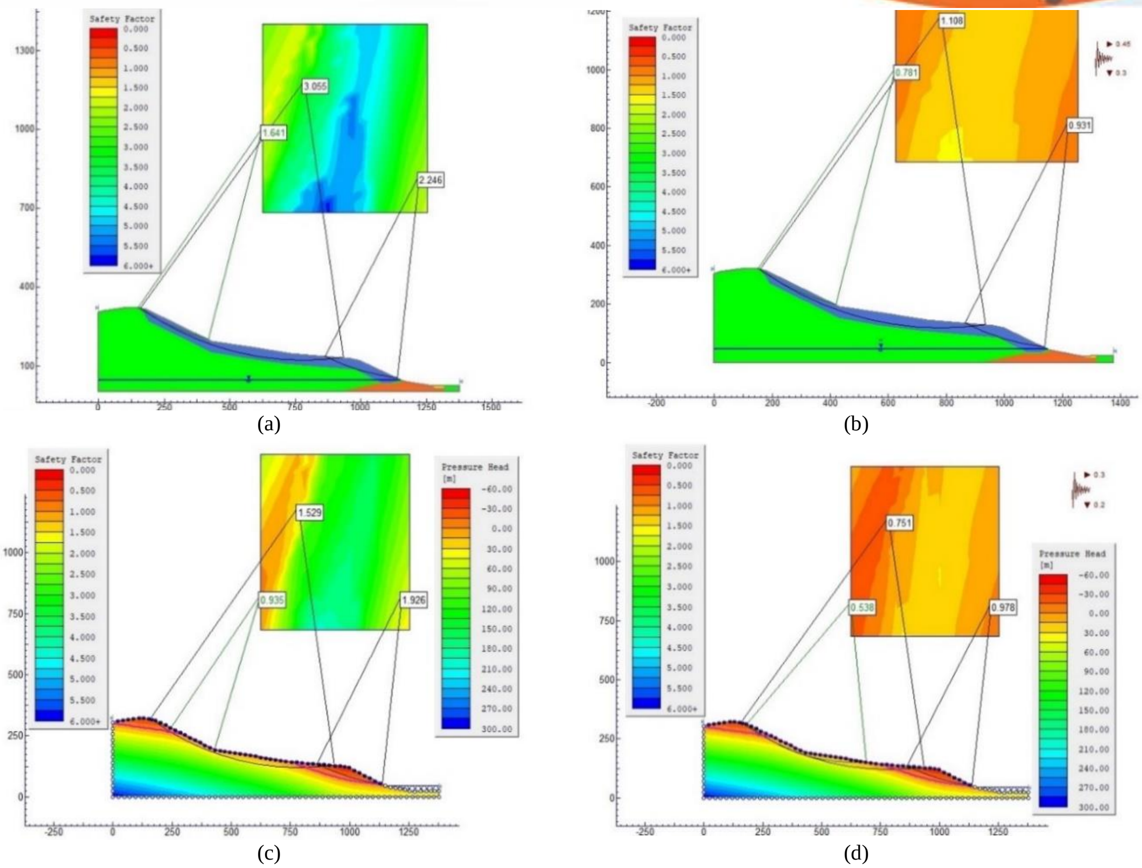

Figure 4 - Example of the results of slope stability analysis a) Static state with the low water level. b) pseudo-static state with 0.3 g and low water level. c) Static mode with a high water level. d) pseudo-static state with 0.2 g and high-water level

11. Conclusion

Due to the reactivation potential of a large ancient landslide in the area and the crossing of bridge No. 12 of the Miyaneh-Ardabil Railway through its toe, it is necessary to implement long-term stabilization plans to reduce the risk. Therefore, engineering geological studies were conducted in the area, and the impact of factors such as infiltration of surface water due to long precipitations and seismicity of the area was analyzed using limit equilibrium methods. The high reactivation potential of the landslide in the fully saturated materials and under pseudo-static condition was approved. Also, stabilization of the slope by constructing drainage galleries to extract groundwater and surface drains to collect runoffs was recognized as a necessity.

Since the reactivation of this landslide can be very dangerous for the bridge No 12, following activities are very necessary to provide required data for preventing a big tragedy:

- Performing sufficient geotechnical investigations for providing required data from deeper parts of the landslide body.
- Employing radar interferometry (InSAR) method (to determine the probable slope movements in the past).
- Installing piezometers and investigating groundwater level fluctuations in the slope;
- Completing stability analyses based on exact deep geotechnical data;
- Designing appropriate monitoring and warning systems based on results of analyses;

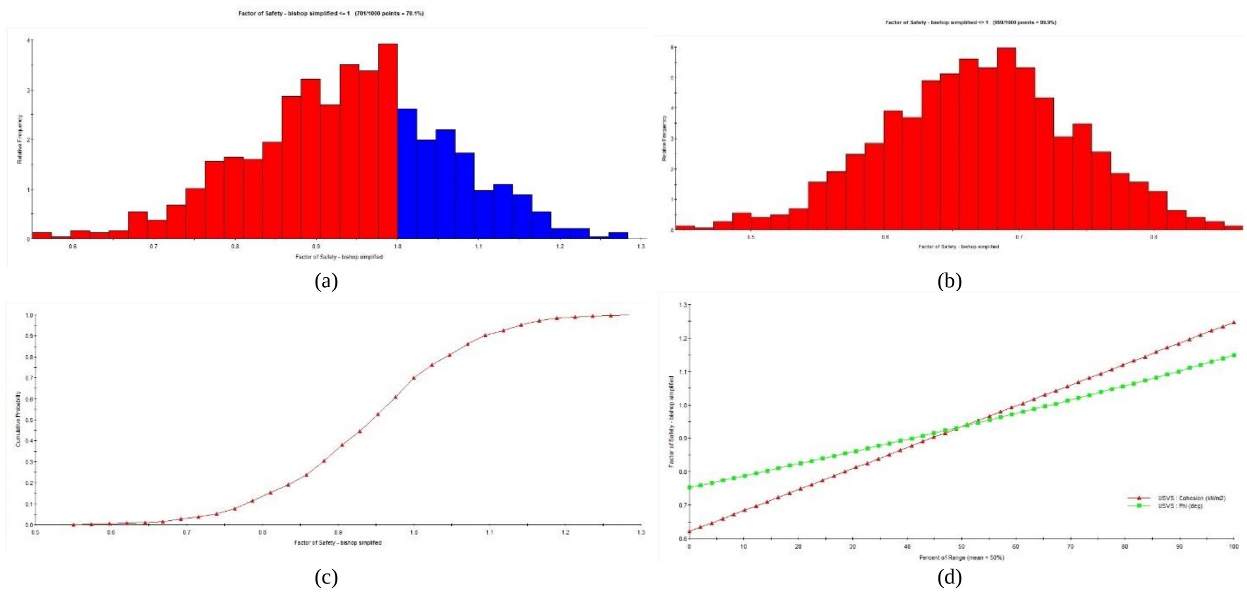

Figure 5- Results of Reverse analysis a) Histogram of safety factor changes based on Bishop method in a saturated static state. b) Histogram of safety factor changes based on pseudo-static bishop method with a saturation of 0.1 g. c) Graph s shape of the saturated static state. d) Spider diagram Sensitivity analysis of static saturation state.

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