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Engineering Geological Assessment of a Slope Instability: A Case Study in the Guzelyali Region (Canakkale, Turkey)

Bir Şev Duraysızlığının Mühendislik Jeolojisi Değerlendirmesi: Güzelyalı Bölgesinde Bir Vaka Çalışması (Çanakkale, Türkiye)

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ABSTRACT

Guzelyali village, 20 km southwest of Canakkale city, is located on the shore of the Canakkale Strait (Dardanelles). The residential area located at the entrance to Guzelyali village has experienced landslides at different times since November 2001. In February 2013, the Güzelyalı landslide was triggered again due to severe rainstorms. As a result of the landslide, deformations and cracks formed in buildings, garden walls and the Canakkale-Guzelyali road. In this study, the aim was to determine the most appropriate improvement method to prevent landslides by determining the depth of the slip surface that caused the Guzelyali landslide and the geotechnical properties of the units. For this purpose, field observations, drilling, obtaining appropriate samples from these works for index and mechanical tests and monitoring studies by using inclinometers were carried out in order to evaluate the instability. As a result of inclinometer measurements, the displacement speed of the landslide was generally determined as 2.5-63.5 cm/year, indicating the landslide moves very slowly. In addition, slope stability analyses were carried out using the limit equilibrium and the finite element methods. To determine the shear strength parameters along the failure surface at the time of the failure, back analyses were performed based on the Janbu model for non-circular failure models in the direction of the landslide movement. It was also proposed to establish drainage systems on slope's surface in the landslide area. However, considering the stability analysis and the land use in the landslide area, it is considered that remediation using micro piles will be a reliable and economical remediation method.

Keywords: Landslide, Non-circular failure, Back analysis, Slope stability, Guzelyali (Canakkale)

ÖZ

Güzelyalı köyü, Çanakkale şehirinin 20 km güneybatısında, Çanakkale Boğazı kıyında yer almaktadır. Güzelyalı köyünün girişinde yer alan yerleşim alanında Kasım 2001 tarihinden itibaren farklı zamanlarda *heyelanlar yaşanmıştır. Şubat 2013'te, Güzelyalı heyelanı şiddetli yağış nedeniyle tekrar tetiklenmiştir. Heyelan sonucu binalarda, bahçe duvarlarında ve Çanakkale-Güzelyalı yolunda deformasyonlar ve çatlaklar oluşmuştur. Bu çalışmada, Güzelyalı heyelanına neden olan kayma yüzeyinin derinliği ve birimlerin jeoteknik özellikleri belirlenerek heyelanların önlenmesi için en uygun iyileştirme yönteminin belirlenmesi amaçlanmıştır. Bu amaçla, duraysızlığın değerlendirilmesi amacıyla arazi gözlemleri, sondaj çalışmaları, sondaj çalışmaları ile indeks ve mekanik testler için örnek alma ve inklinometre kullanılarak izleme çalışmaları yapılmıştır. İnklinometre ölçümleri sonucunda heyelanın yer değiştirme hızı genel olarak 2,5-63,5 cm/yıl olarak belirlenmiş olup heyelanın çok yavaş hareket ettiğini göstermektedir. Ayrıca, limit denge yöntemi ve sonlu elemanlar yöntemi kullanılarak şev stabilitesi analizleri yapılmıştır. Yenilme anında yenilme yüzeyi boyunca makaslama dayanımı parametrelerini belirlemek için, heyelan hareketi yönünde dairesel olmayan yenilme modelleri için Janbu modeline dayalı olarak geriye dönük analizler yapılmıştır. Ayrıca, heyelan bölgesinde şev yüzeyinde drenaj sistemlerinin kurulması önerilmiştir. Ancak stabilite analizleri ve heyelan bölgesindeki arazi kullanımı dikkate alındığında mikro kazıklarla iyileştirmenin güvenilir ve ekonomik bir iyileştirme yöntemi olacağı düşünülmektedir.*

Anahtar Kelimeler: *Heyelan, Dairesel olmayan yenilme, Geriye dönük analiz, Şev stabilitesi, Güzelyalı (Çanakkale)*

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INTRODUCTION

Landslides are defined as one of the most destructive natural disasters following theearthquakes. In studies conducted in Turkey, landslides have first place among natural disasters regarding the number of occurrences (Ercanoglu and Gokceoglu, 2002; Gokceoglu et al., 2005). In many countries, economic losses and loss of life caused by landslides exceed the annual losses caused by earthquakes, floods and storms (Guzetti et al., 1999). In Turkey, which is among developing countries, in cities with rapid development, ands under threat of potential natural hazard may be permitted for the use without urban planning and without taking any precautions. Thus, the natural environment is disturbed. Canakkale, located in the northwest of Turkey, is one of the cities that has been rapidly developing in the last 15 years. Guzelyali village is situated on the shore of the Canakkale Strait (Dardanelles) . It is one of the most important holiday destinations in the province of Canakkale during the summer months. For this reason, the real estate values for houses in Guzelyali village are quite high compared to the Canakkale city center. Since the entrance of Guzelyali village is the closest place to Canakkale city center, it is the oldest settlement of summer houses. All these conditions have led to the construction of buildings very close to each other on a slope gently inclined toward the shore; hence, the slope is exposed to building loads. The landslides having different dimensions were commonly observed at the entrance to Guzelyali village during heavy rainy months. Two different landslide events happened in 2008 and 2011 in the military zone located just on the border of the study area. These landslide events were investigated by various researchers at different times. (Yigitbas et al. 2005; Yigitbas et al. 2008; Tunusluoglu et al. 2009; Tatar et al. 2011; Buyuksarac et al. 2015; Yigitbas et al. 2016; Tunusluoglu and Karaca, 2018). The studies showed that the main triggering factor in the Guzelyali landslide region is excessive precipitation. In addition, Yigitbas et al. (2005) stated that possible leaks from septic tanks may be sufficient to trigger the Guzelyali landslide. The sewerage system in the region did not exist until three years ago, so each building had a septic tank. This study aims to reveal the possible causes and mechanism of a landslide that occurred in Guzelyali village in Canakkale (Figure 1), and to determine the most appropriate improvement method to prevent further landslides.

Detailed information about the geology, geomorphology, and hydrogeological condition of the region and the geotechnical parameters of the units in the landslide area have vital importance for landslide stability analysis. For this reason, disturbed and undisturbed samples were taken during geotechnical drilling studies within the scope of field studies and the groundwater level was measured from boreholes. In addition, inclinometer measurements were carried out at certain drilling locations and the slip surface depth was determined. Within the scope of laboratory studies, the physical and mechanical properties of the units in the landslide area were determined. In order to determine the shear strength parameters at failure, back analyses were performed along cross-section lines. In addition, the limit equilibrium method (LEM) and shear strength reduction analysis (FEM-SSR) based on the finite element method were used for slope stability analysis. Finally, reliable remedial measures were proposed, such as carrying out micro pile works on the Canakkale-Izmir highway, the Canakkale-Guzelyali road and at the toe of the study area to ensure the stability of the landslide area. In addition, it is suggested to control the drainage from the Canakkale-Izmir highway, which played an important role in triggering the landslide in February 2013, and the surface drainage system in the landslide area.

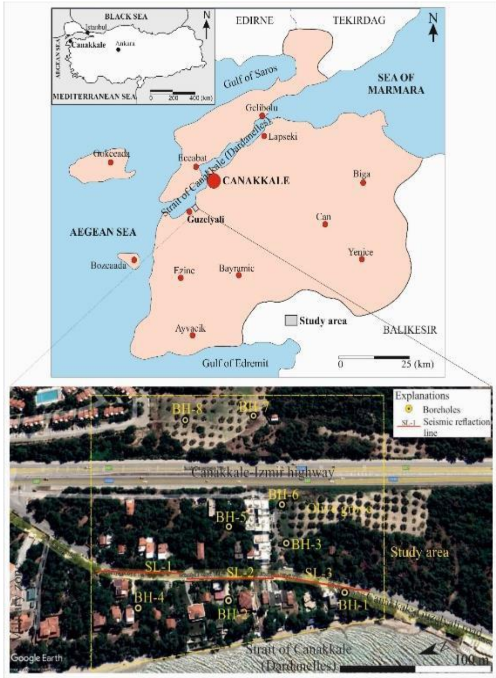


Figure 1. Location map of the study area.

Şekil 1. *Çalışma alanının yerbulduru haritası.*

MORPHOLOGY AND CLIMATE

One of the important parameters for landslide analysis is topographic data. The general topographic and morphological features of the Guzelyali landslide area were evaluated using a digital elevation model created from the 1/1000 scale topographic map of the region. The toe area of the Guzelyali landslide is located on the shore of the Canakkale Strait (Dardanelles), and the distance between the crown area of the landslide and the toe area is approximately 250 meters. The topographic elevation of the landslide area ranges from 0 to 35 m. The slope of the study area generally varies up to 15°. However, perpendicular to the coast, the slope increases to about 25° and 36° (Figure 2).

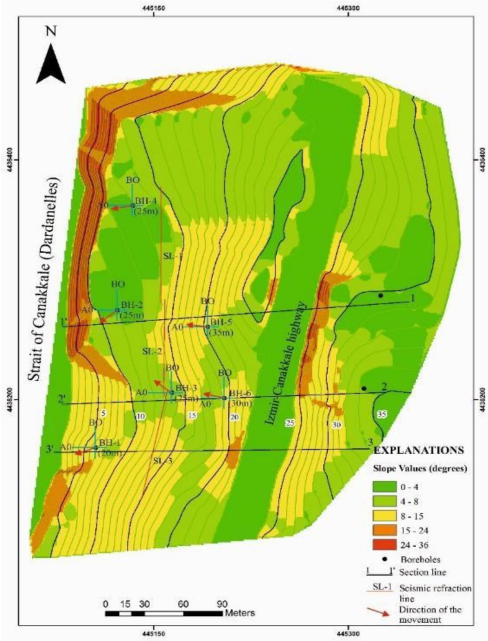


Figure 2. Slope map of the study area with movement direction of the landslide based on the inclinometer data.

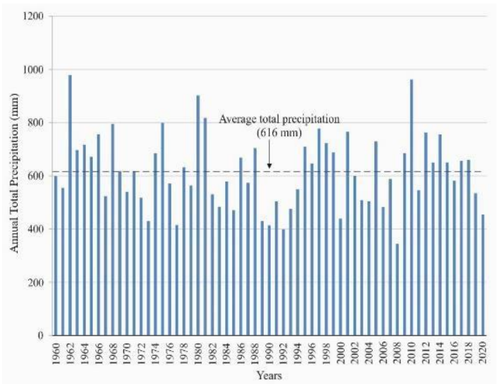
Şekil 2. *Çalışma alanının eğim haritası ile inklinometre verilerine dayalı heyelanın hareket yönü.*

The Guzelyali landslide region has undulating topography. Due to the inability to drain the surface waters, especially on concave slopes, the surface waters infiltrating into the Kirazli Formation cause an increase in the pore water pressure of the soil and become an encouraging factor in the loss of stability of the soil material. Considering the studies conducted in the region, the main cause of landslides is excessive precipitation. Also, landslides after severe rainstorms on different dates caused serious damage in the region. For this reason, precipitation data for the region were examined in detail. In order to evaluate precipitation, data were obtained from the Canakkale Meteorology Station, the closest to the Guzelyali landslide area. Long-term (years 1960-2020) average annual precipitation and average total precipitation data obtained from Canakkale Meteorology Station were approximately 55 mm and 616 mm, respectively (Figure 3a). When the precipitation data recorded by Canakkale Meteorology Station is examined, the amount of precipitation falling in December 2012 and January and February 2013 was approximately twice as much as the average precipitation amount for the same months between 1960 and 2020. In other words, the total monthly precipitation values recorded by the Canakkale Meteorology Station were 222.7 mm, 167.4 mm and 141.6 mm for December 2012 and January and February 2013, respectively (Figure 3b). However, the long-term (years of 1960-2020) precipitation values for December, January and February obtained from Canakkale Meteorology Station were recorded as 110.8 mm, 88 mm and 71 mm, respectively.

GEOLOGICAL SETTING AND SEISMOTECTONICS

The study area, Guzelyali village in Canakkale and its surroundings, consists of Middle Miocene-Pliocene sedimentary units. These sedimentary units are defined as the "Canakkale Group" (Siyako, 2006). The formations namely the Canakkale Group are composed of 4 litho-stratigraphic units from bottom to top, namely the Gazhanedere Formation, the Kirazli Formation, the Camrakdere Formation, and the Alcitepe Formation (Siyako, 2006). As a result of the field and drilling studies in the study area, the landslide area consists of the Gazhanedere Formation and Kirazli Formation. At the bottom, there is the Gazhanedere Formation consisting of conglomerate, sandstone, reddish-gray colored claystone and marl intercalations, and overlying this is the Kirazli Formation, which is yellowish colored, uncemented sandstone, pebbly sandstone and siltstone lithology. Also, intercalations of siltstone and claystone with conglomerates in the form of channel fillings are sparsely observed in the sandstones (Figure 4).

(a)



(b)

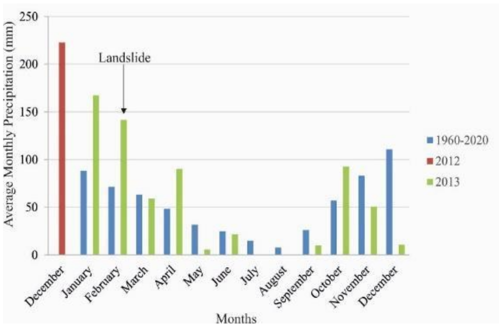


Figure 3. a) Variation of annual precipitation values recorded in Canakkale meteorology station, b) histograms showing long-term (1960–2020 and 2013) monthly precipitation values for Canakkale.

Şekil 3. *a) Çanakkale meteoroloji istasyonunda kaydedilen yıllık yağış değerlerinin değişimi b) Çanakkale için uzun dönem (1960–2020 ve 2013) aylık yağış değerlerini gösteren histogramlar.*

The North Anatolian Fault Zone (NAFZ) is one of the most important fault systems in the world in terms of earthquake productivity. The central segment of the NAFZ affects the province of Canakkale. The central segment extends in a wide zone between Biga, Can, Yenice, Bayramic, Ezine and Kestanbol as active faults that produce many earthquakes and continue into the Aegean Sea (Gurbuz et al. 2000). According to the Interactive Web Application for the Turkey Earthquake Hazard Map prepared by AFAD (Republic of Turkey Prime Ministry Disaster and Emergency Management Presidency) in 2018, the peak horizontal ground acceleration value for Guzelyali village, Canakkale province, was determined as 0.296 g (repetition period 475 years).

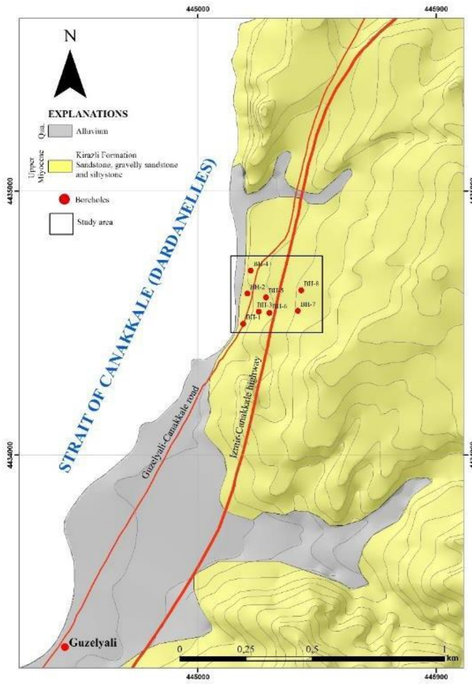


Figure 4. Geological map of the study area.

Şekil 4. *Çalışma alanının jeoloji haritası.*

LANDSLIDE AND GEOTECHNICAL INVESTIGATIONS

Guzelyali Landslide

There are approximately 45 summer houses at the entrance of Guzelyali village. About two-thirds of these houses were directly affected by the landslide. The first landslide event at the entrance to Guzelyali village occurred in November 2001, and the landslide recurred in January 2004. As a result of the investigations carried out in the spring of 2005, and autumn of 2008, the landslides in the region were found to coincide with precipitation periods. The landslides caused separations in adjacent buildings and vertical displacements between 60 and 80 cm from the road level of garage entrances (Figure 5a,b). In addition, some structures in the toe region of the mass movement were tilted backwards close to 7°, and there was settling (15-20 cm) of the building foundations (Figure 5c,d). In February 2013, the Guzelyali landslide reactivated as a result of severe rainstorms and incorrect infrastructure works carried out during the Canakkale-Izmir highway construction (Figure 5a). The drainage of the highway was directed to the landslide area through a culvert in an uncontrolled manner. As a result of the landslide, the Canakkale-Guzelyali road was closed due to settlement and cracks, the drinking water pipeline burst, and deformations occurred in structures and garden walls (Figure 5e, f, g, h).

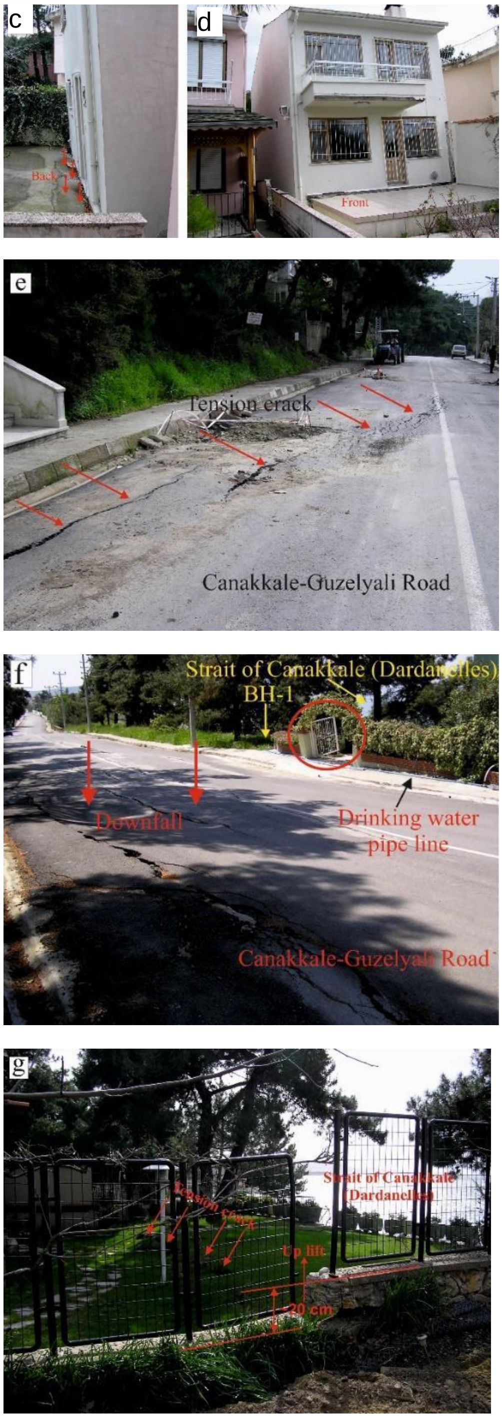


Figure 5. a) Separations in adjacent buildings and incorrect infrastructure, b) vertical displacement of garage entrance from the road level, c-d) building tilted backward by landslide, e-h) deformations of the road, garden walls and structures.

***Şekil 5.** a) Bitişik binalardaki ayrılmalar ve yanlış altyapı yapıları, b) garaj girişinin yol seviyesinden dikey olarak yer değiştirmesi, c-d) heyelan nedeniyle geriye doğru yatan bina, e-h) yol, bahçe duvarları ve yapılardaki deformasyonlar.*

Site Investigations and Sampling

The fact that there is a landslide that could trigger at any time in the Guzelyali region revealed the need to examine this region in detail. In February 2015, a research was initiated by Canakkale Municipality to determine the causes of the landslide. Within the scope of these studies, eight geotechnical borehole studies with a depth of 20-36 m and a total length of 231 m were carried out to determine the failure mechanism, the depth of the slip surface and the geotechnical properties of the failure materials for the landslide in the Guzelyali region (Figure 2) (Table 1). In order to determine the physical and mechanical properties of soils in the landslide zone, disturbed and undisturbed samples were taken using an SPT sampler and Shelby tube during drilling studies, and laboratory experiments were carried out. In addition, static groundwater level measurements were made 48 hours after the drilling process was completed (Table 1).

Inclinometer Measurements

Unlike the studies carried out in the region, the inclinometer study was carried out for the first time in this study and the slip surface was determined precisely. Inclinometer pipes parallel to the movement direction of the landslide were placed in 6 boreholes (Figure 2), and inclinometer measurements were recorded at every 0.5 m interval in these boreholes. Also, inclinometer measurements were taken from March to June 2015. As a result of the inclinometer measurements, the depth of the slip zone was determined to be between 6.5 and 25 meters. The high movements were measured in boreholes 1 and 2, and the cumulative displacements were recorded as 36.5 mm and 40 mm, respectively, at the end of the 4th week. In the 5th week, the inclinometer could not be lowered into these boreholes. The velocity of sliding motion in boreholes 1 and 2 was determined as 1.58 mm/day (576.7 mm/year) and 1.74 mm/day (635.1 mm/year), respectively.

Inclinometer measurements were taken at regular intervals in all boreholes and graphs of depth versus cumulative displacement and graphs of depth versus incremental displacement were plotted. The cumulative and incremental displacement data for BH-1 are given in Figure 6. The results of the inclinometer measurements are given in Table 2. From the inclinometer measurements, the landslide progressed slowly (0.16-0.08 mm/day) in the upper sections of the Canakkale-Guzelyali road, but accelerated (1.58-1.74 mm/day) in the lower sections of the Canakkale-Guzelyali road. In addition, the slip surface for the landslide passed through the contact between the Kirazli Formation and Gazhanedere Formation, which is thought to

be the path followed by groundwater. As a result of the evaluation of inclinometer measurements, the landslide had a non-circular slip surface.

Table 1. Data from geotechnical boreholes in the study area.

Çizelge 1. *Çalışma alanındaki jeoteknik sondajların verileri.*

Borehole no.	Coordinates (WGS1984 3^0)			Depth (m)	Groundwater depth (m)
	X (East)	Y (North)	Z (Elevation)		
BH-1	445107.82	4436083.89	7	20	14.5
BH-2	445124.42	4436198.50	11	25	15
BH-3	445166.45	4436129.85	14	25	10
BH-4	445136.33	4436285.66	13	25	9
BH-5	445194.18	4436184.60	20	35	20
BH-6	445207.0	4436125.23	19	30	7
BH-7	445314.60	4436133.15	34	36	9
BH-8	445327.41	4436210.64	30	35	4.5

Table 2. Summary of inclinometer results.

Çizelge 2. *İnklinometre sonuçlarının özeti.*

Borehole no.	Depth (m)	Inclinometer casing (m)	Slip surface depth (m)	Measurement duration (days)	Displacement amount (mm)	Rate (mm/day)
BH-1	20	20	11	23	36.5	1.58
BH-2	25	25	17.5	23	40	1.74
BH-3	25	25	16.5	113	18.5	0.16
BH-4	25	25	6.5	112	39	0.35
BH-5	35	35	25	112	9	0.08
BH-6	30	30	19	111	10	0.09

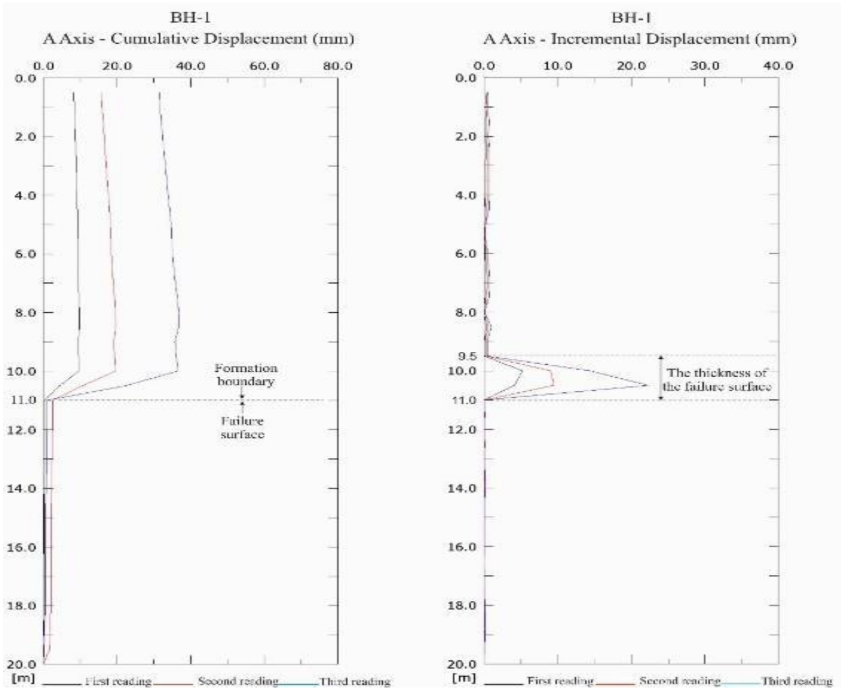


Figure 6. Cumulative and incremental displacement graphic in BH-1.

Şekil 6. *BH-1 için kümülatif ve kademeli artışı gösteren yer değiştirme grafiği*

Laboratory Studies

Laboratory experiments were carried out on disturbed samples taken with the SPT sampler and undisturbed samples taken with Shelby tube within the scope of drilling studies to determine the physical and mechanical properties of the landslide material. In this study, moisture content, particle size distribution, Atterberg limits, unconfined compressive strength tests and direct shear tests were carried out. The study area generally consists of low-strength clayey units belonging to the group of low plasticity inorganic clays (CL) from the Kirazlı Formation and high plasticity inorganic clays (CH) from the Gazhanedere Formation (Table 3). In order to determine the shear strength parameters of the undisturbed samples taken from the Kirazlı Formation, consolidated-drained (CD) type direct shear tests were performed. As a result of the experiment, the mean peak and residual shear strength parameters were determined as c_p=27.2 kPa and ϕ_p=26.7° and c_r=15.3 kPa,

ϕ_r=17.3°, respectively. Also, the natural unit weight (γ_n) was 18.5 kN/m^3. The mean unconfined compressive strength values for the undisturbed samples taken from the Gazhanedere Formation were determined as 196.5 kPa, and the natural unit weight (γ_n) was 18.5 kN/m^3 (Table 4).

SLOPE STABILITY ASSESSMENTS

The main aim of this study was to use both the classical limit equilibrium method (LEM) and the finite element method-shear strength reduction (FEM-SSR) method to investigate the slope stability of the Guzelyali landslide area. For this purpose, three different cross-section lines were drawn to define the landslide area. On the cross-sections, the position of the slip surface determined from inclinometer measurements, formation transitions and groundwater level were shown (Figure 7a-c). In addition, due to the presence of two-story buildings in the landslide area, the building load was defined as 25 kN/m^2 for limit equilibrium analysis. As a result of the evaluation of the inclinometer measurements, the slip surface continues along the contact of the Gazhanedere Formation and Kirazlı Formation, which is located below the groundwater level.

Table 3. Test results.

Çizelge 3. *Deney sonuçları.*

Borehole No.	Sample No.	Depth (m)	Atterberg Limits			Soil Classification	Moisture Content (%)
			LL (%)	PL (%)	PI (%)	USCS	-
BH-1	UD-1	2,50-3,00	41,8	21,6	20,2	CL	15,2
	UD-2	5,50-6,00	39,1	29,2	9,9	CL	28,7
	UD-3	8,50-9,00	42,7	22,5	20,2	CL	41,3
	CORE	10,50-14,00	47,3	22,6	24,7	CL	17,7
	SPT-8	12,00-12,45	38,7	21,2	17,5	CL	26,6
	SPT-9	15,00-15,45	36,7	15,3	21,4	CL	33,0
	CORE	15,20-20,00	46,2	22,5	23,7	CL	20,2

BACK ANALYSIS OF THE SLOPE FAILURE

For determining the shear strength parameters of landslide material at the time of failure by back analyses, LEM is the most widely used method (Chandler 1977; Hoek and Bray, 1981; Sonmez et al., 1998; Ulusay et al., 2001; Isık et al., 2004; Wyllie and Mah, 2004; Topal and Akin, 2009; Kayabasi and Gokceoglu, 2012; Topsakal and Topal, 2014; Ulusay et al., 2014; Topal and Hatipoglu, 2015; Kaya, 2017). In this method, to determine the c-ϕ pairs at the time of failure, one of the c-ϕ pairs is kept constant and the calculation is made. Thus, the c-ϕ pairs that ensure the limit equilibrium condition (Factor of Safety, F=1) are determined. In order to determine the shear strength parameters along the failure surface at the time of the failure, back analyses were performed using three parallel slope sections in the direction of the landslide movement (Figure 2). The position of the slip surface in the sections was determined from the inclinometer measurements. The Janbu method was used for back analysis. The c-ϕ pair (c=17 kN/m^2, ϕ=4.7^0) obtained as a result of back analysis (Figure 8) and the peak and residual c-ϕ pairs obtained as a result of the direct shear strength test in the laboratory (Table 4) were compared.

The cohesion value, one of the shear strength parameters calculated by back analysis, was compatible with the cohesion values for the residual shear strength parameters, but the internal friction angle value was different. This is explained by the fact that the undrained friction angle (ϕ) value of the clayey soil, which cannot be drained due to excessive precipitation and where pore water pressure increases, is smaller than the effective internal friction angle value (Craig 1992; Parry 1995; Bowles 1996; Teoman et al. 2004). Consequently, the Kirazlı Formation in static conditions had a safety coefficient of 1.0 as a result of the limit equilibrium analysis using the shear strength parameters (c=17 kN/m^2, $\phi=4.7^0$) determined by back analysis (Figure 9).

Although the FEM-SSR method has some limitations, it is widely used in current geotechnical applications. The biggest factor in this technique being a strong alternative to the traditional limit equilibrium method (LEM) is the hardware and software development of computer technology. In the last decades, FEM-SSR is used together with LEM in many studies (Isik et al. 2004; Teoman et al. 2004; Cheng et al. 2007; Topal Akin 2009; Topsakal and Topal 2015; Topal and Hatipoglu 2015; Alemdag et al. 2015; Tschuchnigg et al. 2015; Kaya et al. 2016; Kaya 2017). As a result of the comparison of the factors of safety (FOS) obtained from FEM-SSR and LEM in these studies, the factors of safety were generally similar (Chen et al., 2007). In the FEM-SSR method, unlike the LEM method, the elastic parameters of the soil, in-situ stresses and material weight are also taken into account. PHASE 8.0 (Rocscience Inc., 2011) package program was used for FEM-SSR analysis to investigate the stability of the landslide in the study area. In addition, in the FEM-SSR method, the definition of strength factor reduction (SRF) is used instead of the factor of safety (FOS).

The dynamic elastic parameters (E_{dyn} and u_{dyn}), input parameters for the FEM-SSR method, were determined by using the seismic refraction method from the geophysical studies conducted by Buyuksarac et al. (2015) in the landslide area. Part of the report prepared by Buyuksarac et al. (2015) was published in a study called Canakkale Landslides, prepared by Yigitbas et al. (2016). Data for three seismic profiles with a total length of 330 m in the landslide area were taken from the Canakkale Landslides study. The locations of the seismic profiles are shown in Figs. 1 and 2. When the data obtained as a result of seismic refraction studies were examined, three different layers were determined with the help of three seismic profiles. The mean primary-wave (V_p) and secondary wave (V_s) velocities for the Kirazli Formation, Kirazli Formation (saturated) and Gazhanedere Formation in these layers in the study area were found to be 450, 750, and 1150, and 175, 270, and 360 m/s, respectively (Table 5).

Table 3. Test results (continued)

Çizelge 3. *Deney sonuçları (devam ediyor).*

Borehole No.	Sample No.	Depth (m)	Atterberg Limits			Soil Classification	Moisture Content (%)
			LL (%)	PL (%)	PI (%)	USCS	
BH-1	SPT-10	19,50-19,95	33,0	17,5	15,5	SC	33,5
	UD-1	2,50-3,00	43,9	20,2	23,7	CL	20,8
	UD-2	5,75-6,50	73,9	28,4	45,5	CH	21,8
	UD-3	8,50-9,00	61,8	27,8	34,0	CH	19,3
	SPT-7	10,50-10,95	33,5	17,6	15,9	CL	22,9
BH-2	CORE	12,50-13,50	45,8	20,6	25,2	CL	21,3
	UD-4	14,50-15,00	46,6	21,5	25,1	CL	39,6
	SPT-10	15,00-15,45	47,6	24,5	23,1	CL	43,2
	SPT-11	16,50-16,95	33,5	19,7	13,8	CL	38,3
	SPT-12	18,00-18,45	57,3	18,3	39,0	CH	25,3
	UD-1	2,50-3,00	69,8	28,5	41,3	CH	20,7
	SPT-2	3,00-3,45	61,3	25,5	35,8	CH	24,2
	UD-2	5,50-6,00	56,3	25,6	30,7	CH	25,5
	UD-3	8,50-9,00	62,6	27,4	35,2	CH	23,8
BH-3	SPT-7	10,50-10,95	41,1	22,6	18,5	CL	24,9
	UD-4	11,50-12,00	47,1	25,5	21,6	CL	22,7
	SPT-10	15,00-15,45	37,1	18,4	18,7	CL	23,3
	CORE	16,50-19,00	48,5	23,5	25,0	CL	19,5
	SPT-11	19,50-19,95	45,2	25,2	20,0	CL	24,5
	UD-1	2,50-3,00	42,0	28,5	13,5	ML	13,6
	UD-2	5,50-6,00	35,4	18,5	16,9	CL	30,7
BH-4	UD-3	8,50-9,00	29,3	17,6	11,7	SC	16,1
	UD-4	11,50-12,00	33,2	28,5	4,7	SM	21,6
	SPT-10	15,00-15,45	36,6	19,5	17,1	CL	34,6

Table 3. Test results (continued)

Çizelge 3. *Deney sonuçları (devam ediyor).*

Borehole No.	Sample No.	Depth (m)	Atterberg Limits			Soil Classification	Moisture Content (%)
			LL (%)	PL (%)	PI (%)	USCS	-
BH-4	SPT-12	18,00-18,45	35,9	19,4	16,5	CL	33,6
	SPT-14	24,00-24,45	34,9	17,7	17,2	CL	31,7
BH-5	SPT-5	7,50-7,95	42,6	21,3	21,3	CL	14,8
	UD-4	11,50-11,80	40,0	20,5	19,5	CL	25,6
	SPT-9	13,50-13,95	46,1	20,5	25,6	CL	33,1
	SPT-10	15,00-15,45	37,0	18,5	18,5	CL	35,8
BH-6	UD-1	2,50-3,00	65,7	28,6	37,1	CH	17,7
	UD-2	5,50-6,00	63,9	27,5	36,4	CH	21,4
	SPT-4	6,00-6,45	64,1	27,4	36,7	CH	23,7
	UD-3	8,50-9,00	71,4	30,7	40,7	CH	20,1
	SPT-7	10,50-10,95	57,3	25,7	31,6	CH	24,4
	SPT-8	12,00-12,45	57,5	24,7	32,8	CH	21,7
	CORE	18,00-19,50	63,8	26,3	37,5	CH	22,7
	CORE	19,50-21,00	48,3	25,3	23,0	CL	13,9
	CORE	23,00-24,00	62,2	25,4	36,8	CH	20,9
	CORE	25,00-27,00	59,2	30,3	28,9	CH	30,1
	CORE	27,00-28,50	67,8	28,1	39,7	CH	24,5
BH-7	UD-1	2,50-3,00	59,9	25,5	34,4	CH	30,3
	SPT-4	6,00-6,45	36,1	18,7	17,4	CL	13,7
	UD-2	8,50-9,00	72,8	27,6	45,2	CH	21,7
	SPT-7	10,50-10,95	58,9	28,6	30,3	CH	22,1
	SPT-9	13,50-13,70	64,2	27,7	36,5	CH	24,1
	SPT-10	15,00-15,25	47,9	24,6	23,3	CL	22,4
	CORE	16,00-16,50	48,2	25,4	22,8	CL	22,0

Table 3. Test results (continued)

Çizelge 3. *Deney sonuçları (devam ediyor).*

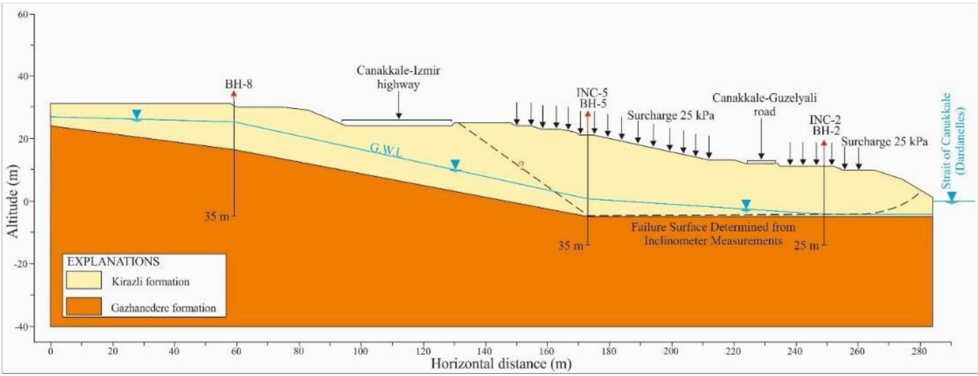
Borehole No.	Sample No.	Depth (m)	Atterberg Limits			Soil Classification	Moisture Content (%)
			LL (%)	PL (%)	PI (%)	USCS	
BH-7	CORE	18,00-19,50	72,9	28,5	44,4	CH	16,4
	CORE	28,50-30,00	68,7	27,5	41,2	CH	15,9
BH-8	UD-1	2,50-3,00	55,6	20,7	34,9	CH	17,5
	SPT-3	4,50-4,95	62,3	27,0	35,3	CH	32,0
	UD-2	5,50-6,00	72,3	27,3	45,0	CH	27,4
	SPT-5	7,50-7,95	41,1	27,0	14,1	ML	19,0
	CORE	8,70-9,00	68,7	27,4	41,3	CH	21,6
	UD-3	12,00-12,50	69,3	28,4	40,9	CH	31,8
	CORE	17,00-17,50	69,7	31,4	38,3	CH	18,2
	CORE	23,00-24,00	57,5	26,6	30,9	CH	27,1
	CORE	28,00-28,50	43,3	24,6	18,7	CL	24,9
	CORE	33,00-33,50	73,0	28,0	45,0	CH	29,8

Table 4. Geotechnical properties of the formations.

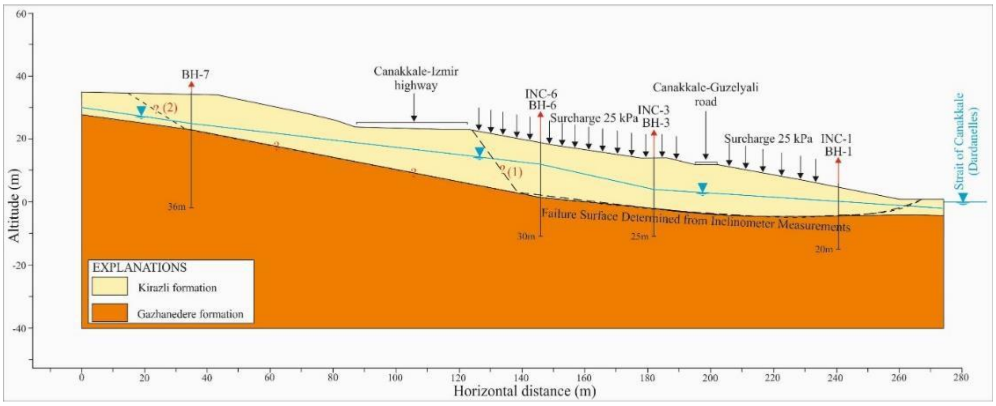
Çizelge 4. *Formasyonların jeoteknik özellikleri.*

Formation Name	γ_n (kN/m^3)	γ_s (kN/m^3)	Direct Shear Strength				q_u (kN/m^2)
			Peak Strength		Residual Strength		
			c (average) (kN/m^2)	ϕ (average) (^{0})	c (average) (kN/m^2)	ϕ (average) (^{0})	
Kirazli formation	18.5	19	36.9 – 15.4 (27.2)	30 – 23.6 (26.7)	19.6 – 7.6 (15.3)	21 – 13.9 (17.3)	-
Gazhanedere formation	18.5	19	-	-	-	-	221.5 – 176.4 (196.5)

(a)



(b)



(c)

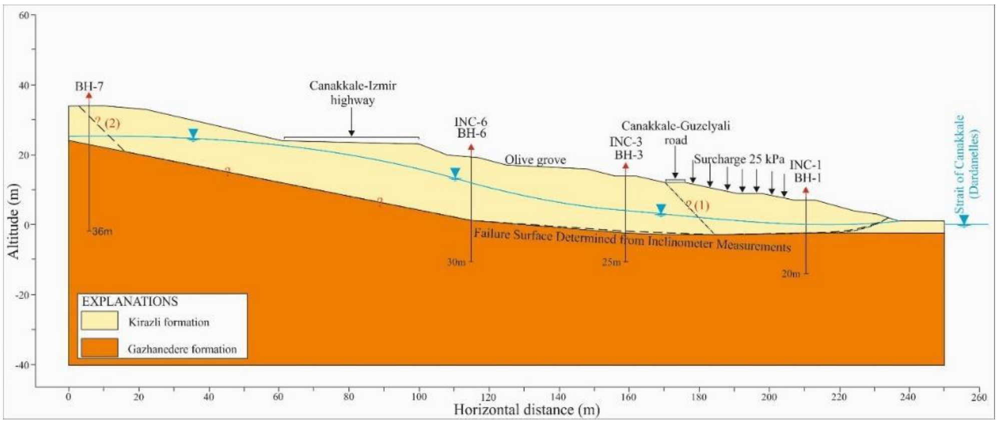


Figure 7. Cross-sections of landslide along section lines a) 1-1′, b) 2-2′, c) 3-3′.

Şekil 7. *Kesit hatları boyunca heyelanın enine kesitleri a) 1-1′, b) 2-2′, c) 3-3′*

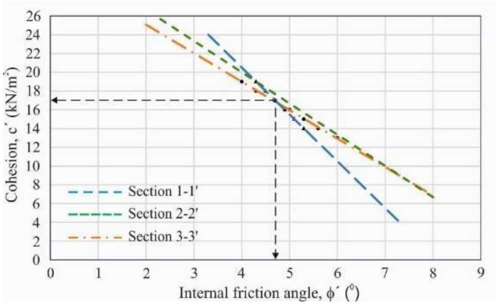


Figure 8. c′-ϕ′ pairs at the time of failure with back analysis.

Şekil 8. *Geriye dönük analizlerle yenilme anındaki c′-ϕ′ çifti.*

The obtained velocities (V_p and V_s) were used as input parameters in the following equation suggested by Bowles (1996), and the dynamic elastic parameters (E_{dyn} and ν_{dyn}) of the landslide zone were calculated. E_{dyn} and ν_{dyn} are given by Equation 1 and Equation 2.

$$E_{dyn} = G\left[\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2}\right] \quad (1)$$

$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)} \quad (2)$$

where V_p: primary-wave velocity (m/s), V_s: secondary-wave velocity (m/s), and G: shear modulus (kN/m^2).

In this study, it is assumed that the material in the landslide area will have elasto-plastic strength and will fail in accordance with the Mohr-Coulomb failure criterion. In the analyses made using the FEM-SSR method, the SRF value was found to be 1.01-1.05 (Figure 9).

Table 5. Material parameters used in finite element method analysis.

Çizelge 5. *Sonlu elemanlar yöntemiyle yapılan analizlerde kullanılan malzeme parametreleri.*

Formation Name	Strength type	Material type	Elastic type	V_p (m/s)	V_s (m/s)	Young's modulus (MPa)	Poisson's ratio
Kirazli formation	Mohr-Coulomb	Plastic	Isotropic	350-550 (450)	150-195 (175)	162.09	0.41
Kirazli formation (saturated)	Mohr-Coulomb	Plastic	Isotropic	650-900 (750)	264-274 (270)	402.55	0.43
Gazhanedere formation	Mohr-Coulomb	Plastic	Isotropic	1045-1200 (1150)	345-382 (360)	702.84	0.45

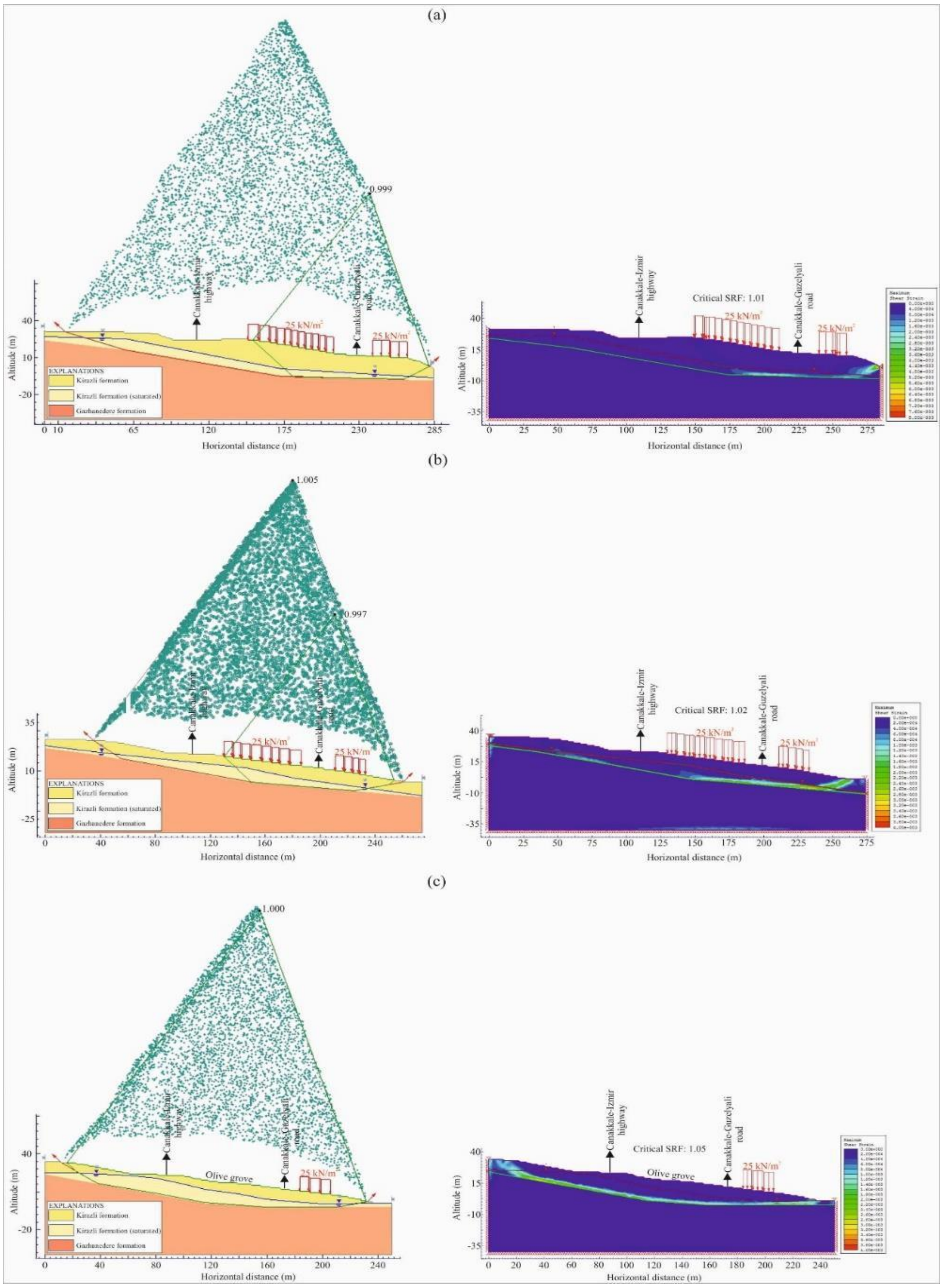


Figure 9. Back analysis results for a) 1-1′, b) 2-2′ and c) 3-3′ cross-sections using LEM and FEM-SSR methods.

Şekil 9. *LEM ve FEM-SSR yöntemleri kullanılarak a) 1-1′, b) 2-2′ and c) 3-3′ kesitleri için geriye dönük analizler.*

REMEDIATION OF THE GUZELYALI LANDSLIDE

In the literature, there are different applications for the solution of landslide problems, with the aim of reducing driving forces and increasing resisting forces (Turner and Schuster 1996; Topal and Akin 2009; Chowdhury 2010; Fahimifar et al. 2014; Tunusluoglu 2014). Suggestions for slowing down and preventing the Guzelyali landslide can be listed below.

The surface waters collected through the surface drainage system and surface drainage canals built on the Canakkale-Izmir highway and surroundings and the Canakkale-Guzelyali road should be directed towards the Canakkale Strait (Dardanelles). Thus, the surface waters that infiltrate the landslide area will be reduced and the speed of the landslide will be slowed down. However, to prevent the landslide completely, additional reinforcement work should be done in the region.

Due to the intense construction in the landslide area, land use is extremely limited. In addition, the slip surface passes an average of 18 meters below the surface. For these reasons, it was decided that strengthening with micro piles would be a more reliable and economical reinforcement method in order to stabilize the landslide area. Limit equilibrium (LEM) analyses were used to ensure the stability of the region by safely countering the lateral active forces with micro piles.

The Turkish General Directorate of Highways, in the stability analysis of road slopes, accepts the factor of safety value of 1.5 and higher values as safe for static situations, while the values of 1.1 and higher are considered safe for dynamic situations (General Directorate of Highways 2012). In order to stay on the safe side in this study, values of 1.2 and higher were accepted as safe. Marcuson and Franklin (1983) suggested taking 1/3-1/2 of the peak horizontal ground acceleration (PHGA) value measured in the region to determine the horizontal ground acceleration value used in stability analysis. Isik et al. (2004) used 1/3 of the PHGA value. However, Topal and Akin (2009) used 1/2 of the PHGA value, staying on the conservative side in long-term slope stability analyses. The PHGA value determined for the study area in the Turkey Earthquake Hazard Map prepared by AFAD (2018) is 0.296 g. In this study, 0.15 g, half of the PHGA value, was used for the long-term slope stability analysis by staying on the conservative side. Although the PHGA value determined by AFAD was used in this study, sensitivity analyses were also performed using different PGHA values for each cross-section line. According to the sensitivity analysis results given in Figure 10, if the values of 0.175 g for cross-section-1 and cross-section-2 and 0.173 g for cross-section-3 are exceeded, the shear strength capacities of the micro piles will be exceeded and failure will be possible.

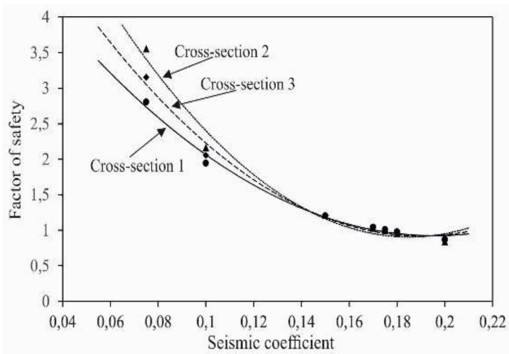


Figure 10. Sensitivity analysis results for the three slope cross-sections stabilized in dynamic conditions by micro-piles.

Şekil 10. *Mikro kazıklarla dinamik koşullarda stabilize edilmiş üç şevin enine kesitleri için duyarlılık analizi sonuçları.*

In order to ensure the stability of the landslide zone, the LEM analysis method was performed under dynamic conditions by using three cross-section lines. As a result of the LEM analyses for cross-section 1-1′, the shear strength capacities of the micro piles designed for the Canakkale- Guzelyali road and the toe region of the landslide should be at least 3450 kN and 4000 kN, respectively. As a result of the LEM analyses for cross-section 2-2′ and cross-section 3-3′, the region will be stable if the shear strength capacities of micro piles designed for the Canakkale-Izmir highway, the Canakkale-Guzelyali road and the toe region of the landslide are at least 1900 kN, 3450 kN, 4000 kN and 1500 kN, 3450 kN, 4000 kN, respectively (Figure 11).

DISCUSSION

It was concluded that the main triggering factor for landslides around Guzelyali village from past to present is excessive precipitation, and other triggering factors are anthropological mistakes and excessive construction. The gentle slope of the study area is between 0-15° and the dominant slope shape changes from convex to concave. A rugged landslide topography has developed in the region. Due to the inability to drain surface waters, especially on concave slopes, the surface waters infiltrating the Kirazli Formation cause pore water pressure to increase, which leads to a decrease in the shear strength of the soil material. Since the study area is located in a coniferous pine forest, drying cracks occur on the ground as a result of tree roots absorbing ground water, especially in summer. In addition, tree roots increase the soil's permeability and the infiltration capacity of surface waters (Greenway, 1987). As a result of heavy rains, the surface waters infiltrate towards the claystone and white-colored marl forming the upper layer of the Gazhanedere Formation from the sandstone and silty units of the Kirazli Formation that forms the study area and the cracks seen on the surface. It is thought that the Kirazli Formation started to move in the direction of slope along the plane formed by the contact of the two formations and caused a landslide. This is also consistent with the inclinometer results.

The classical limit equilibrium method (LEM) and the finite element method (FEM-SSR) were used together to investigate the slope stability of the Guzelyali landslide area. In the back analysis for cross-section 2-2′ using the FEM-SSR method, an intense decrease was observed in the shear strength of the soil in the region between BH-6 and BH-1. It was also observed that the shear strength of the soil in the BH-7 drilling site decreased. This showed that there are two different weakness planes. However, in the LEM analysis, movement will occur along a single weakness plane with a factor of safety 0.997. Considering two different slip surfaces obtained as a result of the FEM-SSR method, detailed the LEM analysis was made and the other slip surface (FOS=1.005) was found.

The landslide movement velocities obtained by inclinometer measurements were compared with the landslide velocity classification prepared by Cruden and Varnes (1996) and it was determined that the Guzelyali landslide was in the very slow velocity class. In addition, in the landslide velocity classification, it is stated that people living in regions where landslides are very slow will continue to live in their existing structures by maintaining their homes. This is exactly the case in the Guzelyali landslide region, and people living in the region continue to live in the landslide area by having their houses and gardens repaired every year.

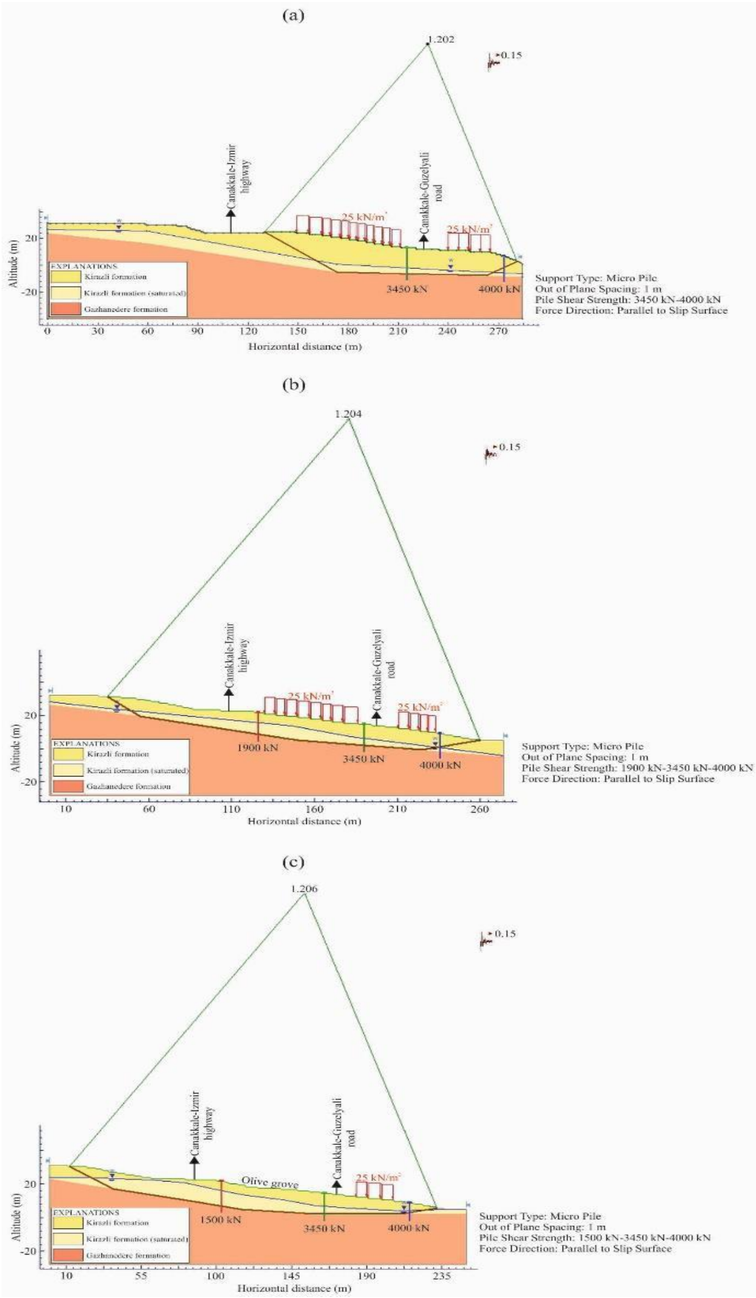


Figure 11. Remediation of the landslide area with micro piles by performing LEM analysis under pseudo-static condition a) 1-1′, b) 2-2′ and c) 3-3′ cross sections.

Şekil 11. Pseudostatik koşullar altında LEM analizi yapılarak heyelan bölgesinin mikro kazıklarla iyileştirilmesi a) 1-1′, b) 2-2′ ve c) 3-3′ kesitler.

CONCLUSIONS

In this study, the failure mechanism of the landslide affecting part of Guzelyali village in Canakkale province was investigated by the limit equilibrium method and the finite element method. Detailed field and laboratory studies were carried out in the region after the landslide. The results obtained from these studies and analyses can be summarized as follows;

(a) The landslides in the region until the present day were generally triggered by excessive precipitation. The precipitation amounts falling in December 2012 and January and February 2013 were approximately twice the average for the same months between 1960 and 2020. This situation increases the possibility that the groundwater level in the landslide area rose compared to its current position. For this reason, it is recommended to install systems to ensure surface water drainage in the landslide area.

(b) To evaluate the instability, field observations, drilling studies, index and mechanical tests and inclinometer measurements were carried out. With the inclinometer studies, the depth of the slip zone was determined to be between 6.5 and 25 meters. According to the inclinometer measurement data, the landslide progresses very slowly (0.16-0.08 mm/day) in BH-6, BH-5 and BH-3 drilling regions, and accelerates (1.58-1.74 mm/day) in BH-1 and BH-2 drilling regions.

(c) Within the scope of remedial studies, the stability of the landslide area can be ensured with micro-pile designs.

(d) This study revealed that using the FEM-SSR method, in addition to LEM analyses, is a useful method for determining possible weakness planes and, thus, reliable and realistic precautions in slope stability studies.

(e) It is recommended that there should not be any construction in the landslide area in the coming years. Every structure built in the landslide area will increase the driving forces and decrease the factor of safety. This may cause the Guzelyali landslide to reactivate.

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