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Research Article

Slope Stability Analysis in Road Cuts

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ABSTRACT

The stability problems observed in the cut section during the highway construction works in Aktaş Village of Siirt Province (eastern Turkey) were analysed by the limit equilibrium and finite element methods, and factor of safety and collapse surfaces were determined. This section is of critical importance since similar high cut sections are frewuently encountered in the study area. In the light of field investigations, laboratory and literature shear strength parameters for analyses were obtained. In stability problems, it is difficult to determine the location and shape of the sliding surface. On the model reflecting the current situation, collapse surfaces were detected and calculations for safety analysis were made by using Plaxis V24 2D, which is based on the finite element method, and Slide2, which is based on the limit equilibrium method. Although the two methods seem compatible in terms of factor of safety, factor of safety obtained with the finite element method are lower. In addition, it has been determined that the finite element method gives more positive and reliable results in terms of determining the locations of failure zones in the soil and obtaining stress deformation curves.

1. INTRODUCTION

Slopes become unstable when the shear stresses required to establish equilibrium on a given potential sliding surface reach or exceed the available shear resistance [1]. Although slope stability is an interdisciplinary subject, it has become one of the main problems of geotechnical engineering, differing from others in terms of the causes, effects and numerical explanation of the phenomenon. In the event that adequate drainage is not provided, *i)* the increase in pore water pressures caused by surface and rainwater, *ii)* disruption of natural drainage as a result of heavy rainfall, *iii)* careless excavations during road widening, *iv)* accumulation of load-forming material on sloping land, and *v)* earthquakes and volcanic events are the most important factors that cause stability problems that distrupt the structure of sloping lands. In Turkey and elsewhere in the world, landslides have occurred in the past and continue to in the present time both because they are natural events that shape the world and because appropriate measures have not been taken, and they subsequently have caused serious loss of life and property and agricultural damages. The first reliable record of a historical landslide is on the one that occurred in the Romance river valley in 1219, during which a landslide mass formed a dam on the river, which subsequently collapsed, killing thousands of people [2]. In 1960, 116 students at a school in Wales, England, were killed when piles of slag slid into residential areas following a mining excavation [3]. According to 2018 Natural Disaster Statistics Report of Disaster Management in Turkey, landslides ranked second to earthquakes among natural disasters between 1980-2017[4].

When we look at the causes of landslides occurring along the highways in our country, the main reasons can be listed as morphological structure including mountainous areas and crossing points, being located in active earthquake zones, having high slope gradients and unfavorable geological conditions. When landslides are considered as a soil mechanics problem, attention should be paid to surface and groundwater as well as the shear strength parameters of the soil. Knowledge on these parameters plays an important role in determining the collapse mechanism. Analyses performed in regard to shear strength parameters of the soil are defined as the slope stability analyses [5]. Slope stability analyses first appeared in 1773 when Coulomb focused on parameters such as shear strength angle and cohesion. At the same time, Coulomb's development of the equilibrium state of the forces in the shear wedge in the soil mass was examined in detail [6]. When the stability of a slope failed, the factor of safety of the slope is considered to be one (1.0). Among many methods used by researchers, the two most widely used ones are the finite element and the limit equilibrium methods. In limit equilibrium method, a potential shear surface is defined as an inclined surface and the soil shear strength is calculated by considering the equilibrium state of the forces and moments acting on the soil mass on the shear surface according to the "Coulomb" collapse criterion [1]. The finite element method, on the other hand, is a method in which the stress and strain behavior of the soil is taken into account. This method, considering the soil geometry and boundary conditions, provides the closest results to the reality. A review of the literature also shows that the finite element and the limit equilibrium are the most widely used analysis methods in slope stability problems.

Keskin and Laman (2007) determined that displacement and stress states can be obtained by using the finite element method in slope stability problems and pointed out the advantages of this method over the limit equilibrium method [7]. Moudabel (2013) analyzed a slope case using the finite element and limit equilibrium methods and concluded that the factor of safety obtained was higher in the finite element method than the limit equilibrium method [8]. Bol et al. (2017) used the limit equilibrium and finite element methods to ensure the safety of a highway slope that lost its stability due to excessive rainfall and developed appropriate solutions [9]. Huvaj and Oğuz (2018) compared the safety and collapse surface factors with deterministic and probabilistic approaches using the limit equilibrium and finite element methods for a landslide in Norway [10]. Büyükağnıcı and Işık (2019) studied stability analysis in three slope cases and compared the success of TS 8853, Eurocode 7 and BS 8006 standards. In another study, the finite element and limit equilibrium methods were used in the analyses and it was determined as a result of the study that the TS 8853 and limit equilibrium methods were more reliable than the Eurocode 7 for stability analysis [11]. Gör (2021) addressed a slope stability problem observed on a highway in Van province with the limit equilibrium method and developed appropriate solution proposals with static and earthquake analysis [12]. Mburu et al. (2022) studied two cases of landslides due to rainfall infiltration and obtained different results in terms of margins of error by using the slip surface search method utilizing a software that included the finite element and limit equilibrium methods for the stability of unsaturated slopes [13]. Ullah et al. (2020) investigated slope stability analysis using five methods: finite element method, limit equilibrium method, artificial neural network method, limit analysis and vector method. The study showed that the finite element method gave the most realistic result [14].

In this study, during the highway construction works carried out by the 9th Regional Directorate of Highways in Aktaş Village of Siirt Province, the stability problems observed in the cut section were analyzed by the finite element and limit equilibrium method in static and earthquake conditions and were compared in terms of collapse surfaces and factor of safety.

2. MATERIAL AND METHOD

2.1 Study Area and Its Geological Framework

In 2019 during the highway construction work in Aktaş Village, Kurtalan District, Siirt Province a movement was observed on the cut and fill slope and the work was stopped. It was anticipated that weakness of the geological units, weather conditions and precipitation triggered the landslide and in 2021 the movement repeated itself at Km:13+600-14+600 of the Siirt-Kurtalan Road. The study area falls within the borders of Siirt province and is included in the span of authority of the 9th Regional Directorate of Highways as shown in Fig. 1.

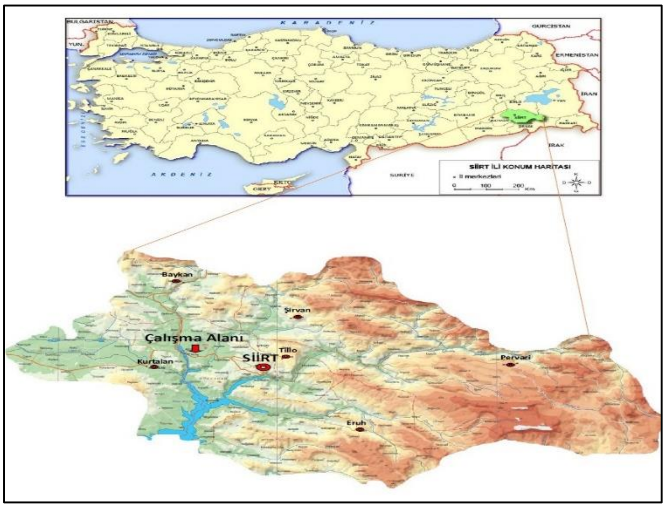

Figure 1 Location map of the study area [15]

As seen on a 1/500.000 scale geological map (Fig. 2) the study area and its immediate vicinity is covered by Late Eocene-Oligocene Germik Formation. The residual soil observed at the higher elevations of the area where the slope instability is observed consists of a clayey gravel - silty clay unit which can be defined as light brown - brown, grayish - grayish green, beige in color and very firm to hard, solid to very solid, with medium to high plasticity, and moist. The rock units in the area are consisted of shale, anhydrite and gypsum. These rocks are mostly light brown - brown, grayish green, grayish white colored, and are generally moderately to very but sometimes completely weathered. They are weak, very weak, but sometimes extremely weak in strength. In some places these rocks are strong to moderately strong, generally very fractured - fractured, and fragmented. Fractures are filled by clay, joint surfaces are generally slippery, sometimes rough, sometimes friable to dispersible. Cracks along the joint planes are filled by clay and gypsum.

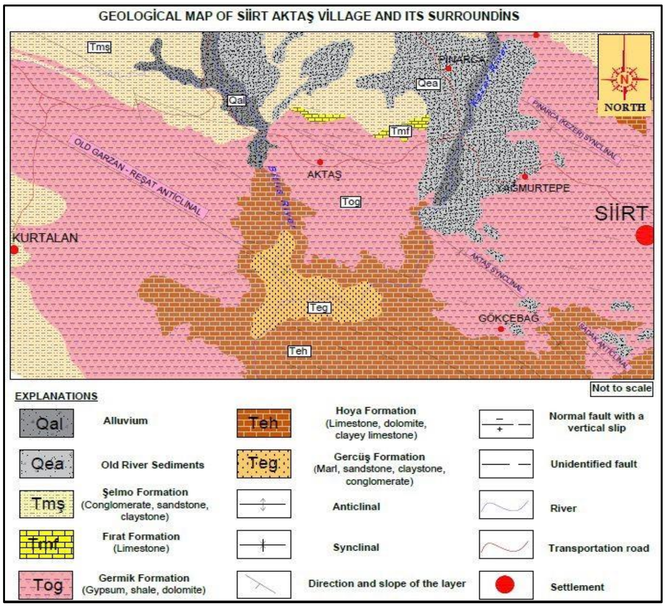

Figure 2 General geology map of the study area [16]

2.2 Field and Laboratory Studies

In order to detail the geological-geotechnical aspects of the geological units in the study area, to determine the groundwater level, to determine the engineering properties of the units observed in the study area and to examine the existing and potential geotechnical problems, exploratory boreholes (267.00 m in total) were drilled in ten locations, and in four of the boreholes inclinometers were used (Fig. 3), and observations were made at different locations in the study area (Fig. 4). During the drilling of the boreholes, parallel to the progress, SPT in-situ tests were carried out, and core samples (RC) and undisturbed samples (UD) were collected. During the drilling works groundwater was encountered at different levels in different locations (Table 1) because groundwater changes the shear strength of the soil and therefore may adversely affect the slope stability. Soil and rock samples were collected according to the methods recommended in the relevant standards, namely TS 1900-2/T1 [17], ISRM [18], TS EN ISO 17892-1 [19], TS EN ISO 17892-2 [20], TS EN ISO 17892- 8 [21], ASTM D2487 [22], AASHTO T88 [23], AASHTO T89 [24], AASHTO T90 [25].

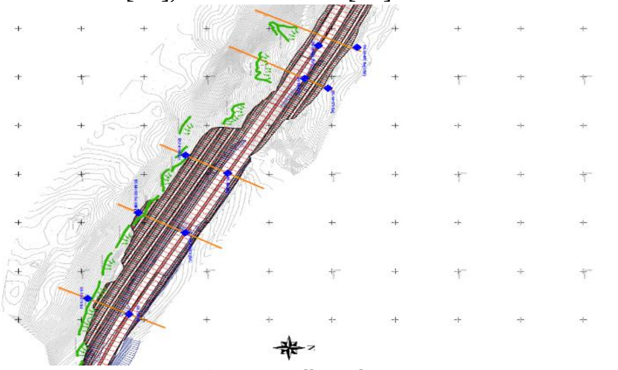

Figure 3 Drilling plan

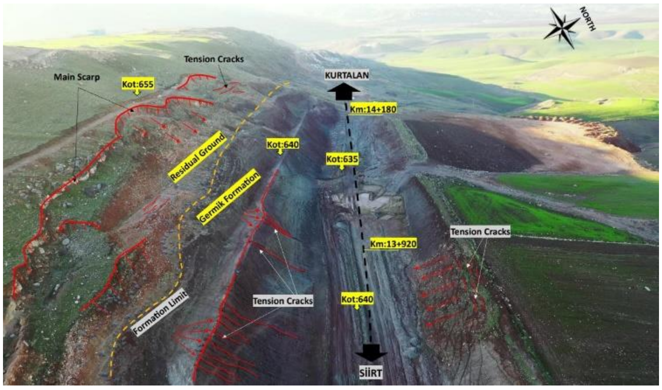

Figure 4 Bird's-eye view of the landslide area

TABLE 1
SHOWING GROUNDWATER LEVEL AT DRILLING LOCATIONS

Drilling Number		Location of Drilling	Depth (m)	Ground water Level (m)	Coordinates (Ed50 3°) North	East	Elevation (m)
1	SK-13+810	Cut/Landslide	21,00	2,00	4202876,39	483688,34	631,17
2	SK-13+810 Sol		35,00	-	4202810,5	483656,16	659,57
3	SK-14+000 (INK)		21,00	1,90	4202966,05	483520,85	626,79
4	SK-14+000 Sol (INK)		39,00	-	4202891,28	483479,49	659,90
5	SK-14+140		18,00	1,70	4203033,63	483398,25	620,26
6	SK-14+140 Sol		35,00	2,00	4202966,34	483361,17	649,00

Groundwater status of the ground and the existing soil layers in the study area were evaluated as a result of the studies. Critical embankment section was determined to solve the stability problem in the cut section along the road. According to Technical Specifications of K.G.M Research Engineering, slope stability analyses should be performed to determine the slope ratios safely when the cut height is h≥15 m [26]. In this case, the cut section with a height of 39 m was determined as the critical section. For the Km:14+000 cut section, drilling data from SK-14+000 (INK) and SK-14+000 Sol (INK) were utilized as indicated in Figs. 5 and 6.

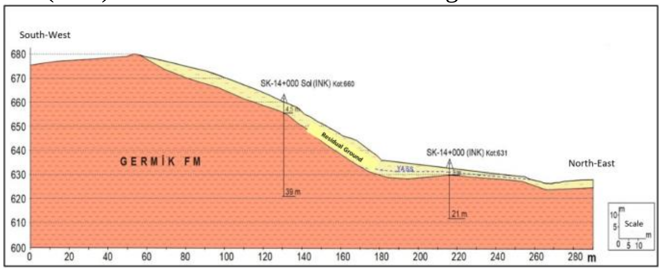

Figure 5 Critical geological cut section Km:14+000

Figure 6 Core samples collected during the study

Parameters were calculated for the soil and rock mass to be used in the analysis by using literature, field and laboratory data. These parameters are summarized in Table 2.

TABLE 2
ENGINEERING PARAMETERS OF SOIL AND ROCK MATERIALS TO BE USED IN THE ANALYSIS

Material	Material Model	Material Behavior	c' kPa	ϕ' °	E kN/m^2	ν	Ψ °	γ_{dry} kN/m^3	γ_{sat} kN/m^3
Clay-Silt	Mohr Coulomb	Drained	7	30	49600	0.35	-	17	20
Gypsum-Shale-Anhydrite			187	37	207010	0.25	7	20	22

2.3 Numerical Modeling

In this part of the study, slope stability analyses were investigated by deterministic methods, finite element and limit equilibrium methods, in order to provide the closest solution to the stability problem. The purpose of the limit equilibrium method is to determine the static or seismic equilibrium conditions at the assumed critical sliding surface with a factor of safety. The limit equilibrium method is a frequently used method in slope stability analyses because it is applicable to soils and weathered rocks that acquired soil properties, and shear stresses can be determined along the sliding surfaces assuming that a slope is collapsing. In the analyses carried out with the limit equilibrium method, the Simplified Bishop Method, which deals with the equilibrium of a circular sliding surface, where a sliding mass can be divided into slices and equilibrium equations can be written for each of slice is used. This method, first developed in its general form by Bishop [27], which is based on the assumption that the shear stresses between the circular shear slices are assumed to be zero and the normal stress and weight exerted on the center of the slice. When the forces in the vertical direction of a slice in Fig. 7 are split into their components, they contribute to determination of a factor of safety and the relation (1) in Fig. 7 is obtained in terms of total stresses. The factor of safety provides information about whether or not a slope is stable, or to what extent it is stable.

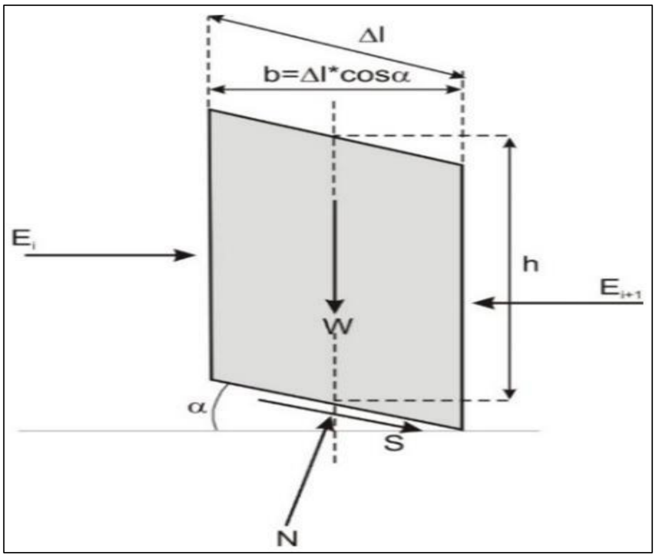

Figure 7 Forces acting on the slice according to the Simplified Bishop Method

$$F = \frac{\Sigma\left[\frac{c*\Delta l*\cos\alpha + W*\tan\Phi}{\cos\alpha + (\sin\alpha*\tan\Phi)/F}\right]}{\Sigma W*\sin\alpha} \qquad (1)$$

One of the methods developed to investigate the behavior of soils is the finite element method. In addition to the factor of safety, information such as displacement, change in pore water pressure and determination of the location of failure zones in the soil are also needed. In such cases, stress-deformation analysis of the soil is also required. In the slope and slope environment, these calculations can be performed numerically by the finite element method under the assumption of a continuous medium in two or three dimensions. The most important feature of the finite element method is that the stress-strain properties of the soil can be represented by models such as linear-elastic, hyperbolic-elastic and elasto-plastic models based on the results of laboratory tests [2]. This method was described by Zeinkiweicz (1977) as a method to mathematically model and analyse a continuous system [28]. Since the total stress is divided into pore water pressure and effective stress in soil mechanics problems, the material behavior is expressed as effective stress. By finite element analysis, vertical and lateral movements, stresses, pore water pressure and water flow status can be determined. Although many software programs have been developed for the limit equilibrium method and finite element methods, in this study, Slide2 software was used for the limit equilibrium method and Plaxis V24 2D software was used for the finite element method and stability analyses were performed for both static and seismic conditions. Stability analysis in case of earthquakes can be performed as pseudo-static analysis. This approach was first applied to seismic slope stability by Terzaghi (1950). Pseudo-static accelerations produce inertial forces and the magnitude of acceleration is related to the magnitude of ground motion. Terzaghi (1950) suggested that these coefficients can be taken as in Table 3 [29].

TABLE 3
SEISMIC COEFFICIENTS OF EARTHQUAKES (TERZAGHI,1950).

Explanation	Seismic coefficient
In severe earthquakes (Rossi-Forrel IX)	$k_h = 0.10$
In destructive earthquakes (Rossi-Forrel IX)	$k_h = 0.20$
In catastrophic earthquakes	$k_h = 0.50$

The ground acceleration coefficient for Siirt - Kurtalan Divided Road (Aktaş Variant) Km: 13+700 - 14+600 was determined as 0.237 g by using the “Earthquake Hazard Map of Turkey” which was prepared by AFAD (2018) to indicate the earthquake zones in the country (Fig. 8). However, the value for ground acceleration is taken as 0.1185 g, half of the maximum ground acceleration value (0.237 g) to include the increasing or decreasing effects of the quasi-static coefficient [30].

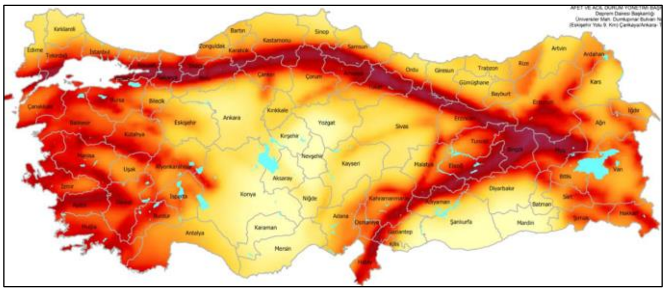

Figure 8 Earthquake hazard map of the study area [31]

Local Soil Class and Earthquake Ground Motion Level were determined as ZD and DD-2, respectively. The model of the slope for the Km:14+000 section, which was determined as the critical section, is shown in Figs. 9 and 10.

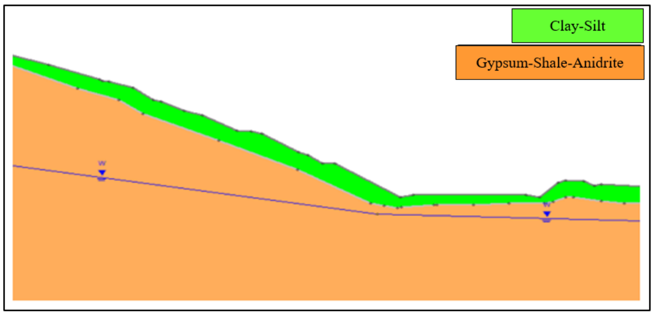

Figure 9 Slope model of Km:14+000 cut section used in the analysis (Slide2) [32]

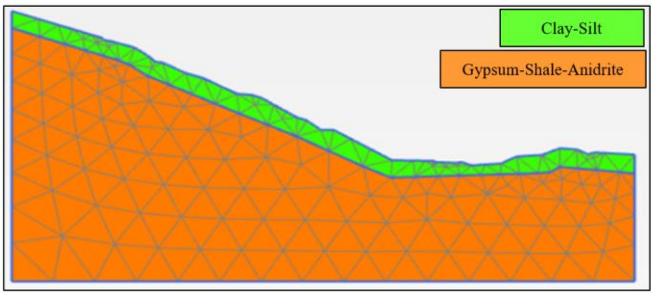

Figure 10 Geometric model and finite element mesh of Km:14+000 cut section (Plaxis V24 2D) [33]

In the design calculations, the Mohr-Coulomb Model was used for the silty-clay unit specified as residual soil whereas the Generalized Hoek Brown soil behavior model was used for the gypsum-shale-anhydrite unit. Standard boundary conditions were assumed in both Plaxis and Slide programs. Default boundary conditions, all displacements are limited at the bottom of the soil section. Lateral displacements are limited on the left and right boundaries. The most suitable mesh structure was investigated in the finite element network and analyzed by selecting the medium (mesh).

3. RESEARCH FINDINGS

Since the slope height is 39 m, Km:14+000 cut section is of critical importance and for this cut section the analysis was carried out in two stages. Accordingly, slope stability analysis was performed according to the limit equilibrium and finite element methods, and the factor of safety obtained is given in Table 3. In the factor of safety analyzes made with Plaxis, calculations were made using the strength reduction method. In this method, the shear strength parameters, cohesion and friction angle are gradually reduced until the slope collapses and factor of safety at the moment of collapse is determined. Since the model geometry is not horizontal, the “weight loading” calculation was made in Plaxis at the first stage before starting the analysis.

TABLE 4
RESULTS OF FACTOR OF SAFETY ANALYSIS FOR KM:14+000 CUT SECTION

Method	Conditions	Initial Status	Design Status	Specification Criteria
Finite Element Method (Plaxis V24)	Static	1,444	2,01	1,5
	Earthquake	1,068	1,921	1,1
Limit Equilibrium Method (Slide2)	Static	1,431	1,706	1,5
	Earthquake	1,126	1,436	1,1

As shown in Fig. 11, first of all, it is seen that the slope is stable but does not meet the specification criteria in the analyses performed using the finite element and limit equilibrium methods under static loads in sloping terrain conditions. When earthquake loads are applied, it is seen that the slope is in equilibrium but again does not meet the specification criteria.

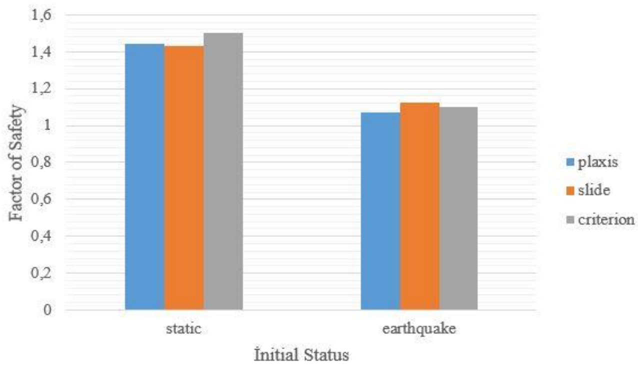

Figure 11 Km: 14+000 section in the initial state factor of safety analysis

When the safety coefficient was evaluated in terms of the method used, the calculation results of the two methods are oberved to be similar. However, the finite element method (Plaxis) concludes the slip circle at a single point giving the smallest safety coefficient. Although this may seem useful to stay on the safe side, it should be taken into account that slip circles may occur in other parts of the section. In the limit equilibrium method (Slide2), the slip circle can be determined anywhere in the ground. The slip plane determined by the finite element and limit equilibrium methods in the slope stability analysis under static and earthquake loading for Km:14+000 section is shown in Figs.12 and 13.

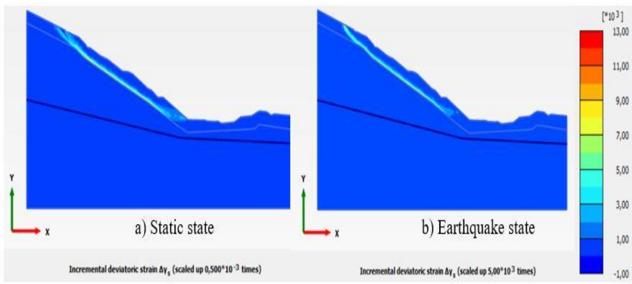

Figure 12 The slip plane determined by the finite element method in the initial state of Km:14+000 section (Plaxis V24 2D)

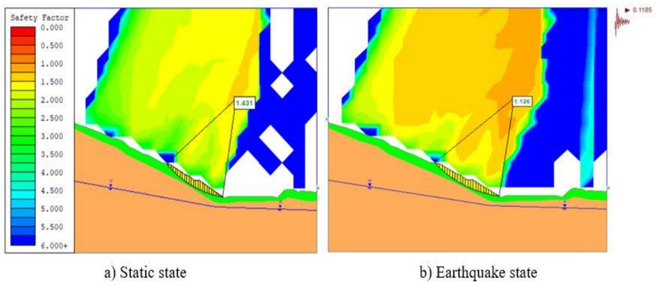

Figure 13 Slip plane determined by the limit equilibrium method in the initial state at Km:14+000 section (Slide2)

In the initial condition, the slope was found to be unsafe according to the specifications, so the cut slope was tilted at a slope ratio of 3/2 (horizontal/vertical) and supported with a shoring wall. As shown in Fig. 14, the safety coefficient of the slope supported by the shoring wall shows values above the specification criteria. Thus, the slope has been made safe.

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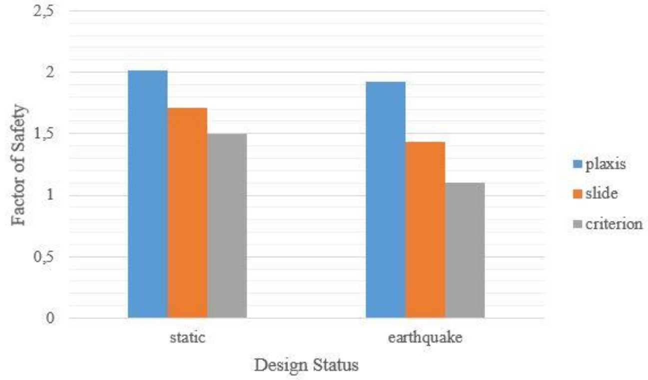

Figure 14 Km: 14+000 section factor of safety analysis in design condition

With the shoring wall design, the problem on the left slope has been eliminated and the new slip circle is seen on the right cut slope but it is safe. Figs. 15 and 16 show the slip plane in the design case.

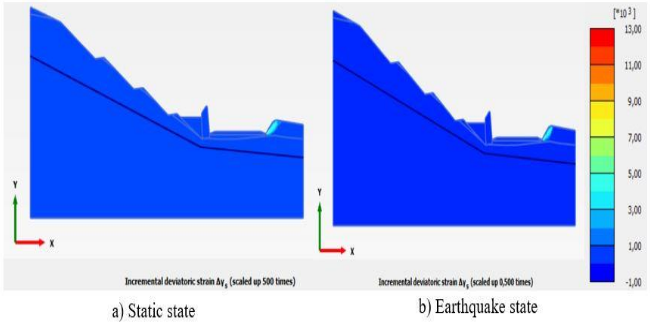

Figure 15 Slip plane determined by the finite element method in the design condition of Km:14+000 section (Plaxis V24 2D)

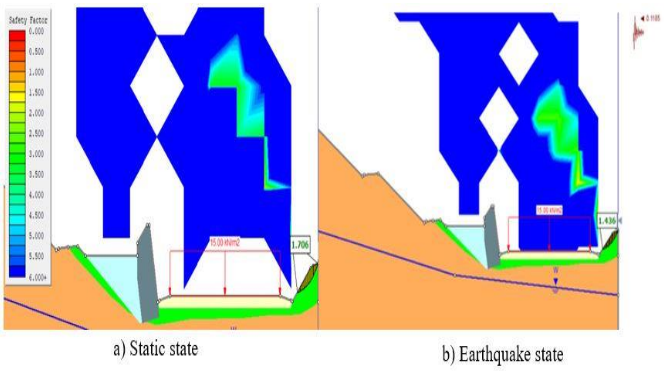

Figure 16 Km: 14+000 section design case slip plane determined by the limit equilibrium method (Slide2)

Vertical and horizontal displacements may occur in the ground during a mass movement. In order to determine the displacement of the slope section at Km:14+000, deformation analysis was performed by the finite element method. These analyses were performed using Plaxis V24 2D software. Fig. 17 show the total displacement values at initial and design state for static and seismic conditions.

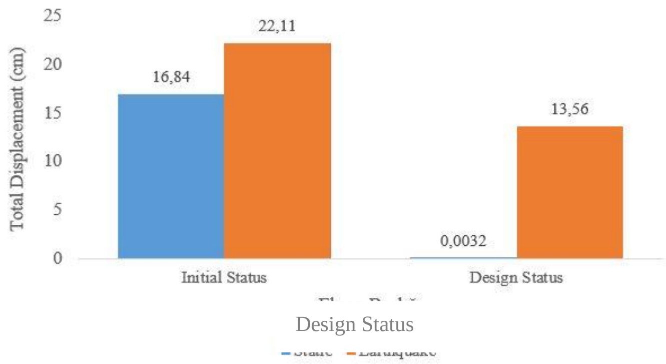

Figure 17 Total displacements at Km:14+000 slope section

In Fig.17, it is observed that the displacement value in the ground decreases with the wall design when both static and earthquake loads are applied. The deformations in the shear plane in the initial state are shown in Fig.18.

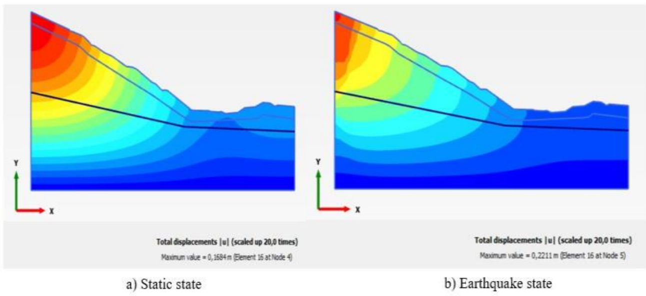

Figure 18 View of total displacements in the initial state by the finite element method (PLAXİS V24 2D)

The deformations in the shear plane after wall design are shown in Fig.19.

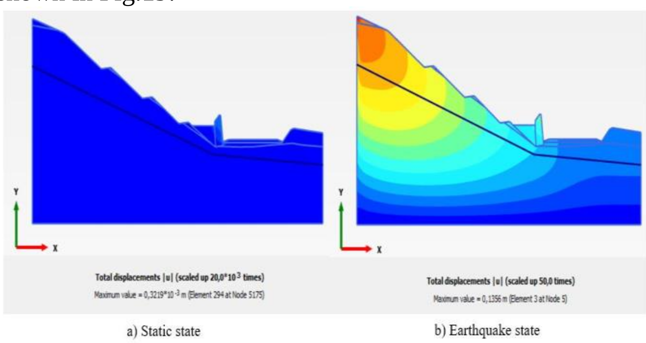

Figure 19 View of the total displacements in the design state by the finite element method (PLAXIS V24 2D).

In Fig. 19, no slippage or deformation of the slope is observed with the wall design in the static case. In the case of earthquake, the deformations decreased significantly. It can be said that the stability problem on the slope has been solved significantly with the wall design.

4. CONCLUSION AND RECOMMENDATIONS

In this study, by applying the limit equilibrium analysis and the finite element methods, static and earthquake analysis of a mass movement occurred during excavation works on the highway were performed and were compared in terms of factor of safety and collapse surfaces. In the initial condition, it is observed that the Km:14+000 cut section is stable under static and earthquake load but does not meet the limit of the Specification for Highways Research Engineering Works. For this reason, the cut slope was tilted at a slope ratio of 3/2 horizontal/vertical) and supported with a shoring wall. Stability analysis of the design condition shows that the slope is safe and meets the specification criteria. When the coefficient of safety was evaluated in terms of the method used, the calculation results of the two methods were similar. However, the finite element method (Plaxis) concluded that the slip circle at a single point giving the smallest coefficient of safety. Although this seems useful to stay on the safe side, it should be taken into consideration that the slip circles may occur in other parts of the section. In the limit equilibrium method (Slide2), the slip circle can be determined anywhere in the soil. Plaxis stays on the safer side in terms of the safety factor and helps to take precautions in advance to avoid any problems in the future. It can be said that the slip plane in the slope passes through the same region in the analyses performed by both methods. In addition, it is possible to determine the lateral and vertical displacements in the slope and to obtain the stress-deformation graph with the finite element method. It helps to understand the slope stability problem in a better way. It can be said that the finite element method, which depends on the unit deformation affecting the safety coefficient of the slope, is superior to the limit equilibrium method.

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