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Research Article

Static and dynamic slope stability analyses based on finite elements method: The example of Birecik Slopes

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ABSTRACT

This study examines slope stability along a critical section of the Birecik coastal road in Şanlıurfa province, Turkey, known for its challenging terrain characterized by frequent segregations, low soil strength, and steep slopes near the Euphrates River. The research focused on assessing landslide risks and proposing mitigation measures to ensure safety for pedestrians and vehicles. Because the coastal road is heavily used and is stuck between the slopes and the Euphrates River. Initially, unmanned aerial vehicle (UAV) flights were used to create a three-dimensional model of the slope. On-site observations identified a critical section and a critical two-dimensional section obtained on the three-dimensional model using ArcGis10. Given the presence of nearby structures at the tip of the slope, ten adjacent structures were simulated using static and dynamic analyses to assess their impact on stability under potential future urban development scenarios. Stability analyses were conducted without structures initially and then with simulated structural loads applied as linear loads at the sloping tip and specific distances behind it. For dynamic analyses, Sivrice Earthquake (24.01.2020) parameters were used. For analysis, Plaxis two dimensional was used, and the strength reduction method was used based on the finite element method (FEM). This study revealed factors of safety, shear forces, and displacements, and the static and dynamic analysis results were compared. Results showed that horizontal displacements increased under earthquake conditions with minimal changes in safety factors. However, the slope is unsafe with a minimum factor of safety of 1.199 for static and 1.190 for dynamic analysis by affecting structural load at the tip of the slope. Also, results showed that for this model, the main reason that causes slope failure is structural load. For this study, the most remarkable result is that the dynamic shear stresses are lower than static shear stresses, while the dynamic displacements are higher than static displacements. The results show that plain strain or two-dimensional analyses are unreliable.

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INTRODUCTION

Slope stability is a subject that geotechnical engineering has been dealing with for a long time and is still an area that is approached with interest in both application and research by engineers and researchers interested in geotechnical engineering [1]. In addition, it is one of the most frequently encountered issues that force engineers working in geotechnical engineering to find solutions [2]. After the collapse events that occur due to the deterioration of the balance of the slopes, losses can be as significant as those caused by other natural disasters, especially earthquakes [3].

Slope stability is generally defined as the ratio of the forces that resist the effects that try to slip the layers to the forces that try to slip them. It is usually accepted as the weak part of the slope resting on a discontinuity [4]. The leading cause of slip on slopes is the forces of gravity. In addition, shear stresses of the slope may increase because of additional loads on the slopes, making the slope inclination steeper and causing the destruction of the toe, which prevents the slope from slipping, as a result of natural and artificial factors. Artificial and natural quakes (explosions, earthquakes, construction excavations, and other constructions, etc.) can reduce the friction (Ø) and cohesion (c) between the particles forming the soil. Also, the water pressure in the voids results from the partial or complete filling of the cavities in the soil layers with water. It increases the water content, especially in cohesive soils, causing a decrease in the shear strength of the soil. In slopes, the increases in shear forces and the water content, especially in cohesive soils, cause a reduction in the shear strength of the soil. In slopes, because of the increases of shear stresses in the soil layers forming the slope or the decreases of the shear strength of the soil, the balance of the slopes can be disturbed, and collapse occurs [5].

Earthquakes are the most significant and essential natural dynamic factor that threatens the long-term stability of slopes [6]. Although slopes maintain their stability under natural processes and external effects, it is unknown whether the slope has reached its shear strength. Slopes thought to be stable may lose their stability after sudden earthquakes that cause additional significant stresses on the soil [7]. Horizontal forces caused by earthquakes can cause instabilities such as rock falls and rotational and translational slope failures, especially on slopes with very steep inclinations. For this reason, considering the earthquake effect in the slope designs or analyses is vital for healthy slope designs and analyses and to prevent loss of lives and properties that may occur due to slope collapses [8].

There are many methods used within the scope of slope equilibrium analyses, finite element method (FEM), finite difference method, and probabilistic slope stability analyses. the most commonly used methods are limit equilibrium analyses and finite element method (FEM). In general, Limit Equilibrium Analyses Methods are used for static slope stability analyses, while dynamic slope stability analyses can be performed in addition to static slope stability analyses with finite element method (FEM).

In the limit equilibrium method, assumptions are made about the collapsing mass's motion behavior, the collapse surface's location and shape, and the forces acting on the collapsing mass [3]. In addition, in these methods, the stress-strain relationship is not considered, and the slope deformations cannot be obtained in Limit Equilibrium Analyses since it is assumed that the soil block on the possible failure surface moves as a whole [3,9]. Besides that, no failure surface is considered in Finite Element Method (FEM), and models with complex and irregular geometry can be analyzed accurately. In addition, values such as stresses, deformations, and pore pressures can be calculated in slope stability analyses made with the Finite Element Method (FEM) [10].

One of the methods used in dynamic slope stability analyses is pseudo-static analyses. In this method, dynamic slope stability analyses are performed by converting the horizontal and vertical accelerations of the earthquake into horizontal and vertical inertia forces and applying these forces to the center of collapsed mass on the possible slip surface [9]. In the analyses in question, the horizontal acceleration of the earthquake is assumed to be large enough to cause the slope to collapse, and this acceleration acts on the sliding mass as a horizontal static force[11]. This method is more accessible because the calculations continue after the earthquake accelerations are converted into inertial forces, similar to the static limit equilibrium analyses. However, representing the complex earthquake motion only with vertical and horizontal forces is the most significant disadvantage of this method. Therefore, it is not accepted as a healthy analysis method [9].

In pseudo-static analyses, the factor of safety of the slope against collapse is calculated, but the deformations in the slope cannot be obtained. However, due to earthquake forces, the displacements on the slope are considered when determining whether a slope is safe after an earthquake. Therefore, analyses that give displacements in seismic slope stability analyses are healthier and preferred [9]. That's why, in this study, dynamic analyses were performed on a numerical two-dimensional slope model by finite element method (FEM).

In recent years, many studies have been conducted on slope stability. For this purpose, factor of safety, displacement, and shear stresses occurring in slopes have been revealed by analyzing various conditions and models. In addition, various precautionary suggestions have been presented for slope safety as a result of the research. Static and dynamic analyses were carried out with plaxis 2D and 3D in wet and dry environments [12-14].

In the analysis performed on the three-dimensional dynamic slope model created within the scope of a project carried out in Three Gorges Reservoir, the slope was investigated in the rainless-earthquake, rainy-earthquake conditions. The results showed that porosity has a greater effect on the safety factor in rainfall conditions compared to the permeability coefficient and saturation. It was determined that the safety factor corresponding to the vertical downward seismic effect is smaller than the safety factor corresponding to the vertical upward seismic effect. [15].

Finite element and limit equilibrium analyzes were carried out under static and dynamic loading for dry and wet conditions on 3 critical slopes determined on the Gerese-Belta route in Southern Ethiopia. It was observed that the safety coefficients obtained from the Slide 2D program using the limit equilibrium analysis were higher than the safety coefficient values obtained from the finite element based Phase 2D program. As a result of this study, the Bench method used in limit equilibrium analysis was determined as an economical method that can be used to alleviate soil slopes and was recommended for use [16].

Micke Didit et al. [17] investigated the effect of the structural loads applied to the tip slope on slope stability using the finite difference method. For this purpose, a three-dimensional slope model was created, and analyses were performed. As a result of the analyses, it was revealed that the shear stresses on the slope increased as the structural load was applied closer to the slope tip. It was also understood that the safety factor value increased as the structural load was moved away from the sloping tip.

Dejian Li et al. [18] investigated the effect of large-diameter cast-in-situ piles on slope stability under impact load. Safety factors were calculated using the strength reduction method under the effect of static load and assuming the impact pile construction vibration at the toe of the slope as dynamic load. Here, the relationship between the reduction factor and the parameters of the slope shear strength and the displacements between two points at the toe of the slope was established. As a result, it was found that the safety factor obtained from the analysis under dynamic effect was lower than the safety factor obtained in static analysis.

Onyango et al. [19] conducted analyses to investigate the stability of a slope constructed on a specific section of the Qinglong-Xingyi Highway and to devise an appropriate stabilization method. For this purpose, a 2-dimensional slope model was created using the ANSYS program using the finite element method. After the analyses, it was understood that the slope was sensitive to external effects and that measures should be taken against slope failure. It was decided that piles placed in rock soil were the most appropriate measures to prevent slope failure. After the analyses by modeling the piles, it was understood that the slope failure surface disappeared, and the displacements decreased.

In this study, static and dynamic analyses were performed. Static analyses were used to examine the safety of the coastal road, which is heavily used, to understand the current situation of the slope. Understanding whether it is close to collapse is important without any dynamic effects because it can give important data before collapse so that there is enough time to take measures. The coastal road heavily used by vehicle and pedestrian traffic has to be investigated whether the slope in question would collapse after an earthquake that occurred suddenly and without any known time. Slides that are assumed to be safe in static conditions can fail after earthquakes, which causes additional forces and horizontal displacements. This reality makes it necessary to examine them under the dynamic effects of earthquakes. For that, dynamic analyses were performed to see the effects of earthquakes on slope stability. In this study, slope stability analyses were carried out in a pilot area of Birecik Coastal Road. To perform analyses, the slope model should first be generated. A Unmanned Aerial Vehicle drone was used to do that. By Unmanned Aerial Vehicle flights, point cloud of the field was genereated. Using the cloud point data of the field, the three dimensional model of the slopes was generated using ArcGis10.8. Then, the critical section of slopes was determined by observations made in the field. And again the critical section of slopes was generated using ArcGis10.8 for two dimensional stability analyses. It is converted to dxf format to upload to the Plaxis program. Then, the critical section of the slope was uploaded to Plaxis. Also, it was understood that a slope failure occurred in the area in 2019, and there were buildings at the tip of the slope when the failure occurred. The failure point that occurred in 2019 is near our examined point. For the possibility of construction of new buildings in the examined area in the future, ten adjacent buildings were modeled at the top of the slope, and their weight was calculated and implemented as a line load. The line load was affected at the top of the slope with different distances from the tip of the slope. In this scope, the static and dynamic analyses were performed, and Finite Element Method (FEM) was used. Sivrice earthquake data were used for dynamic analyses, which occurred in 2020. While performing static and dynamic stability analyses, the strength reduction (Phi-C reduction) technique was applied, the factors of safety were calculated for both cases, and the displacements and shear stresses were also revealed. Finally, the slope stability analyses were examined by comparing the dynamic and static analysis results. This study showed that dynamic shear stresses are lower than static shear stresses, while dynamic displacements are higher than static displacements. These results revealed that plain strain or two-dimensional analysis is inaccurate.

This study conducted static and dynamic slope stability analyses in a pilot region of steep and high slopes on the Birecik Halfeti coastal road, consisting of fragmented, fractured, cracked, and low-strength sandy-clay limestone. First, a two-dimensional critical section was obtained from the three-dimensional terrain model created by the studies in the area under investigation. While choosing the critical section, the slope's height, the discontinuities' condition, and the slope's inclination were considered. In the geological survey report, in which the soil parameters are provided, it has been understood that there is no groundwater and no flowing surface water in the slopes that are the subject of the investigation. Also, observations made in the field show no flowing surface water. In light of these data, two-dimensional analyses were carried out, and the factors of slope safety, displacements, and shear stresses on the slope were calculated.

Usage of Plaxis Software

Plaxis software is a program based on FEM developed to perform stability analyses, stress deformation analyses, consolidation, structure-soil interaction, bearing capacity, and groundwater flow analyses within the scope of various applications in the field of geotechnical engineering [8]. While performing analyses with Plaxis software, analyses are performed in two-dimensional models under axisymmetric or plane strain and three-dimensional conditions. It uses triangular elements with 6 or 15 nodes to describe strains in two-dimensional analyses [20, 21]. The use of 15-node triangular elements provides a 4th-order interpolation for calculating numerical unions and displacements involving 12 stress points; the use of 6-node triangular elements gives a 2nd-order interpolation for calculating numerical unions and displacements involving 3 stress points (Fig. 1) [22].

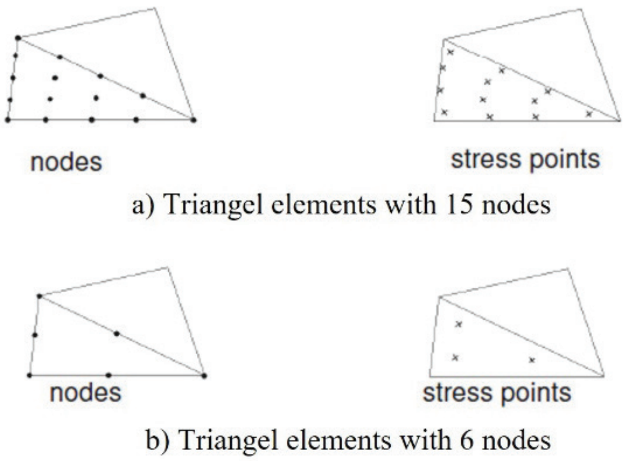


Figure 1. 15 and 6 nodes triangle elements [22] [created by author].

Mohr Coloumb and Hardening Soil Failure Criteria are used in slope stability analyses with Plaxis software. The Hardening Soil Failure Criteria is more suitable for excavation slopes, while the Mohr Coloumb failure criterion is more suitable for the analyses of existing slopes. In the analyses made according to the Mohr Coloumb Failure Criteria, it is generally accepted that the soil exhibits an elastic behavior until the failure occurs, and the soil behaves plastically after the collapse [23]. In addition, the most used methods in the calculation of the factor of safety in FEM are Strength Reduction Method and Gravity Increasing Method [24]. In the strength reduction method, the shear strength parameters (c and Ø) of the soil are gradually reduced until collapse occurs, and the factor of safety for slope is calculated with the help of stress-displacement analyses. It gives more effective results in the analyses of existing slopes [24]. In this study, the strength reduction (Phi-C) method was used to calculate the factor of safety within the scope of static and dynamic slope stability analyses.

MATERIALS AND METHODS

Generating of Slope Model

To perform slope stability analyses, a numerical model slope section is needed. For this reason, aerial photographs of the region were taken by unmanned aerial vehicle (UAV) flights over the study area. The study used an Octo V3 model UAV belonging to TurkUAV company and a Sony RX100 MII camera with a 20.2 Megapixel resolution CMOS sensor. The platform, which has a control distance of 1500 meters, has a flight time of 22 minutes (Fig. 2) [25].

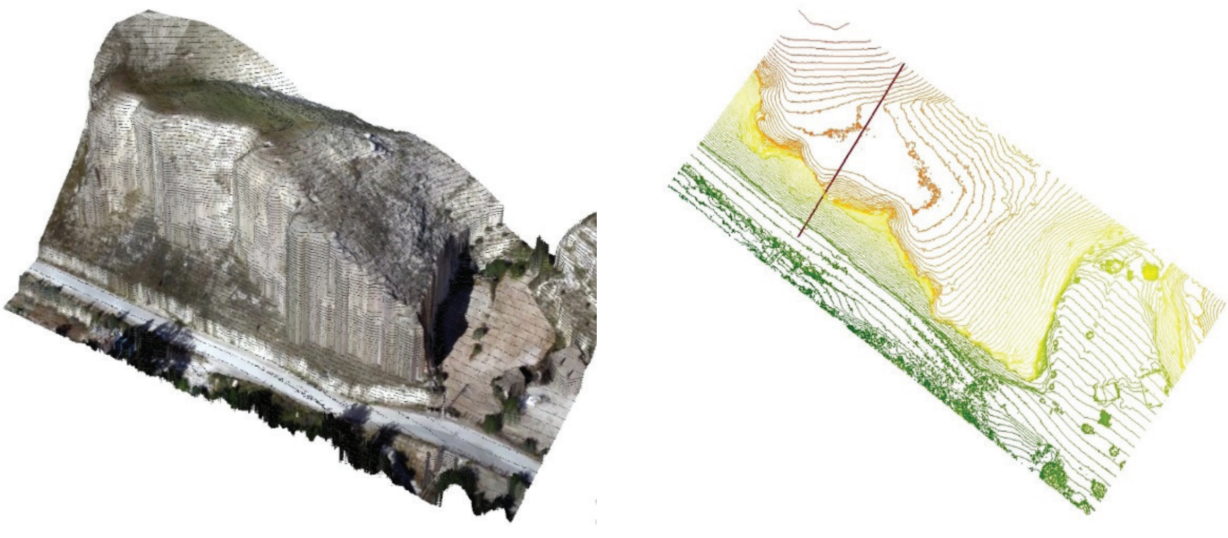
First of all, a flight plan was created. The flight plan was created with 4 transverse routes, longitudinal flights on these routes, and autonomous flights from a fixed height of 80 meters, such that aerial photographs were taken with 80% longitudinal and 70% transverse overlap. To ensure the spatial relationship of the images obtained from aerial photographs with the physical earth, 10 ground control points were marked

Figure 2. The digital camera system and UAV used in flight.

on the ground in the study area using the CORS-enabled GNSS system, and coordinate information was obtained.

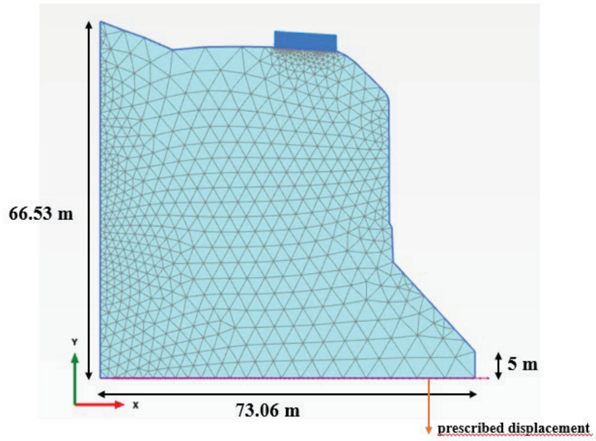
Aerial photographs of the area were taken along the route in the flight plan. Then, 222 aerial photographs suitable for model creation were evaluated. The software Pix4D, which is a part of Harran University and produces point clouds from aerial photographs, was used to evaluate the aerial photographs. As a result of the evaluation of the photographs, point cloud data consisting of 206767 points was obtained. Since the acquired point cloud data is in the WGS84 system, it was converted to the UTM 3-degree projection defined in the ITRF-96 coordinate system using ground control points (Fig. 3). The three-dimensional numerical model of the area is also obtained in this coordinate system [24]. The position accuracy of the model created for the study area is ±1.27 cm, and this accuracy has been tested with ground control points. The three-dimensional model of the study area with contours, the digital elevation model with contour curves, and the critical section were created using the ArcGis10.8 version and are shown in Figure 4. Finally, after the observations made in the field, the essential section line of the slope, considered

Figure 3. UAV flight in the field to create the slope model.

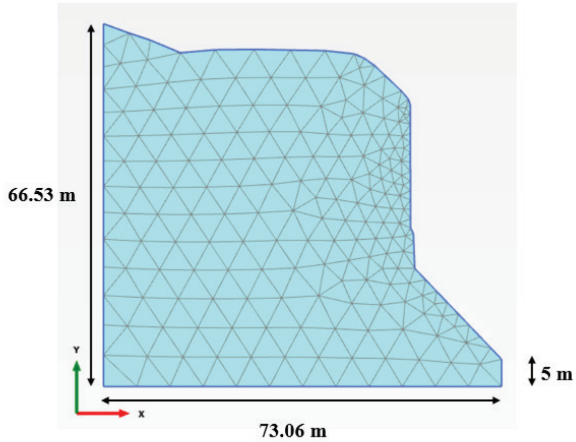


(a) (b)

Figure 4. Slope models obtained by field study, a) contoured three-dimensional model of the study area, b) contoured digital elevation model and critical section line of the study area



(a)



(b)

Figure 5. (a) 2d critical slope model inserted into plaxis software, (b) for dynamic and static analyses with the initial location of the line load.

risky according to the slope height, inclination, and current discontinuities, as shown in Figure 4-b, was produced using the ArcGis10.8 program. The critical section obtained was transferred to Plaxis software, as shown in Figure 5.

The Building Properties Used in Analyses

For two-dimensional analyses, it is thought that there are 10 adjacent buildings with 4-story concrete structures, and all building's properties are the same. The Building was modeled as 4 floors, 3 m floor height, 12 m width, and 12 m length. The foundation is modeled as 12 m in width, 120 m in length, and 0.5 m in thickness. The building and the foundation weights are calculated. While calculating the floor weight, the mass of the building participating in the earthquake was taken as a basis, and the live load and dead load values given in Turkish Code 498 (TS498) [26] and the mass participation ratio presented in Turkish Seismic Code 2018 (TSC2018) were used. Finally, using these parameters, a line load was calculated as 766.17 kN/m/m, which was applied to the top of the slope through 12 m.

Stability Analyses

The soil structure of the slope consists of a single layer, and the highest point of the slope is 66.53 m, and its width is 73.06 m. Two-dimensional slope stability analyses were performed in Plain Strain conditions and using triangular elements with 15 nodes. Soil material was modeled according to Mohr-Coulomb, and long-term drained analyses were performed for static and dynamic analyses. First, analyses were carried out to determine the absence of structure loads on the slope. Then, the analyses were carried out by placing a line load through 12 m on top of the slope. The soil parameters used in the analyses are given in Table 1. Since there is no groundwater and surface water, the groundwater level wasn't specified in the model.

Static Slope Stability Analyses

Static analyses were first performed without the line load on the slope. It was carried out in two stages: Deformations and factor of safety (FS). Then, the line load was applied on the top of the slope as 766,17 kN/m/m (very high for a four-story structure) through 12 m at the tip of the slope, 5 m, 10 m, and 15 m backward from the tip of the slope, and analyses were carried out. Analyses were carried out in two stages, if the load is on the slope: Loading and FS. In the Loading phase, the loads were activated, and plastic analysis was performed. In the FS phase, the factor of safety was calculated, and Phi-C reduction (safety) analysis was performed. Since the slope was not completely horizontal, the Gravity Loading calculation was made in the initial phase. In addition, in the static stability analyses, the slope model was meshed with medium coarseness, passed to the calculation stages, and the analyses were completed.

Table 1. Soil parameters used in analyses [27] [created by author]

Natural Per Unit Weight (γ_n) (kN/m^3)	Modulus of Elasticity (Mpa)	Poisson Ratio	Cohesion (c) kN/m^2	Internal Friction Angle (Ø)
18.10	78.56	0.30	275	32.5

Dynamic Slope Stability Analyses

Rayleigh damping is needed both to resist Rayleigh waves and to obtain more realistic results in the analyses made with plain strain models in which the earthquake situation is examined. For soils, damping usually occurs due to improved plasticity, viscous properties, and friction (Lanzo and Vucetic, 1999). In Plaxis software, damping is expressed in terms of Rayleigh damping, which is proportional to the stiffness and mass of the model [28].

$$C = \alpha M + \beta K \quad (1)$$

In this equation, C is the damping, K is the stiffness, M is the mass, and α (alpha) and β (beta) are the Rayleigh coefficients. The coefficient α (alpha) expresses the contribution of the mass during damping. Lower frequencies are damped as the value of α (alpha) increases. The coefficient β (beta) expresses the contribution of stiffness during damping. As the β (beta) increases, it dampens more significant frequencies.

At the point of calculating the periods of the soil, if the soil layer consists of a single layer, the soil's natural period can be calculated using equation 2 [29]. In equation 2, H represents the thickness of the soil layer, and V is shear wave velocity. For the calculation of α and β, firstly, two frequencies were calculated for soil, and equation 2 was used. Then frequencies were converted to frequency of vibrations, and for calculation of α and β, % 5 damping ratio was used, and they are calculated as Rayleigh α (alpha)= 0.62874, Rayleigh β (beta)= 0.00347. These coefficient values were used in analyses.

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$$T_g = \frac{4H}{V} \quad (2)$$

$$\alpha + \beta * \omega_i^2 = 2 * \omega_i * \xi_i \quad (3)$$

Dynamic analyses were first carried out to assess the slope's absence of line load. Then, as in the static analyses, the line load was applied 766,17 kN/m/m through 12 m at the tip of the slope, 5 m, 10 m, and 15 m backward from the tip, and analyses were carried out. Dynamic analysis was carried out in three stages: Earthquake, Deformations, and FS (factor of safety) for the absence of structure load. In the Earthquake phase, the Sivrice earthquake was affected, and dynamic analysis was performed. In the Deformations phase, the limits of deformations were determined, and plastic analysis was performed, and in the FS phase, the Phi-C reduction (Safety) analysis was performed.

In case the Line Load is applied on top of the slope, dynamic analyses were solved in four stages. In the first loading phase, loads were activated, and plastic analysis was carried out. In the second phase, the Earthquake phase, the Sivrice earthquake was applied, and dynamic analysis was carried out. The third stage was made as Deformations and plastic analysis were carried out, the fourth stage was the FS stage, the factor of safety calculation was made, and Phi-C reduction (Safety) analysis was performed.

In the dynamic analyses, Line Displacement was defined at the bottom of the slope, and Ux=0.01m was entered, Displacement X: prescribed, Displacement Y: Fixed was set, and in this stage, acceleration time parameters of Sivrice earthquake were loaded into the program as the table. The highest ground acceleration value of the Sivrice earthquake transferred to the program is 292.8 cm/s2, and the earthquake's time interval was 30 seconds (Fig. 6).

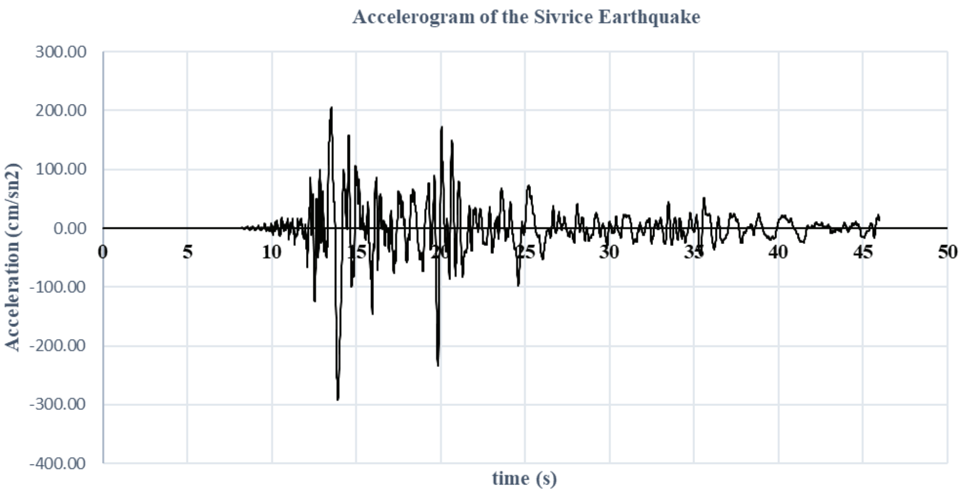


Figure 6. The accelogram of the Sivrice earthquake [30] [open access by AFAD].

Xmin: Viscous, Xmax: None, Ymin: Viscous, Ymax: None were determined to absorb the stress increases caused by the dynamic earthquake effect. If this is not done, the stress increases will be reflected in the soil body [30]. In addition, medium mesh coarseness was used for the slope model in dynamic stability analyses, the calculation phases were started, and the analyses were completed.

RESULTS AND DISCUSSION

Static Analyses Results

According to the results of the static analyses, the safety factor was found to be the highest for the absence of line load on top of the slope, and the safety factor was calculated as 1.695. In addition, the case with the lowest factor of safety in static analyses, that is, the riskiest case, is that the line load is at the tip of the slope. If the line load is applied at the tip of the slope, the slope's safety factor against collapse was calculated as 1.199, as it is seen in Table 2 that the factors of safety increase as the line load moves away from the tip of the slope.

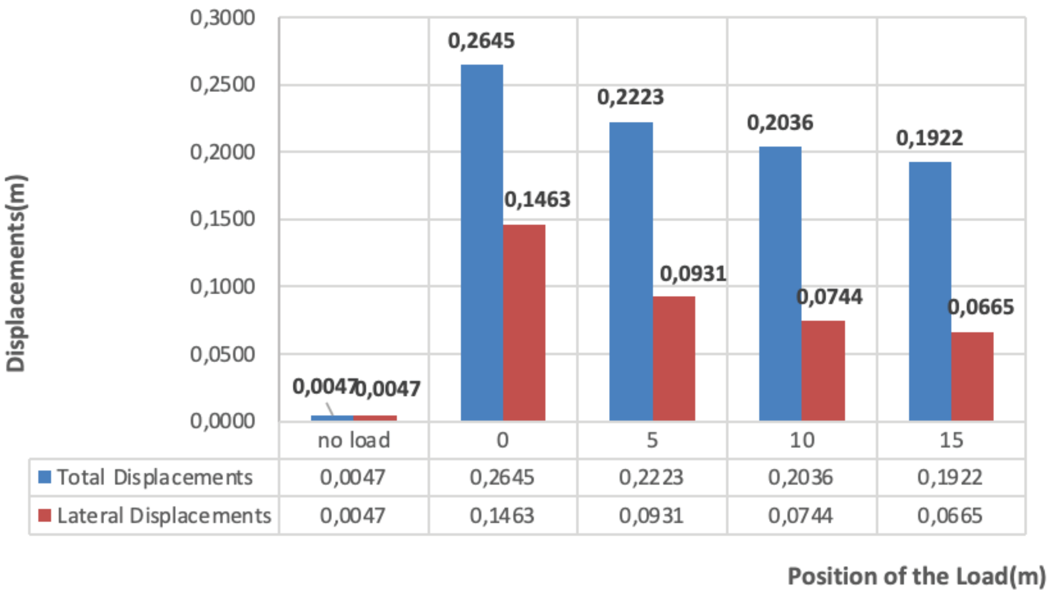
In static analyses, the largest horizontal displacement value occurs when the line load is applied at the tip of the slope, and the total displacement value is calculated as 0.2645 m. Also, according to the results of the static analyses, it is seen in Figure 7 that the displacements increase significantly when the line load is placed at the tip of the slope compared to the case in which no load on a slope, and the displacements decrease with the line load moving away from the tip of the slope. In the absence of the load, the displacements occur as 0.0047 m and in a small area of the vertical surface of the slope.

The largest horizontal displacements occur on the vertical surface of the slope and around the load. It is also seen in Figure 8 that the horizontal displacements on the vertical surface of the slope decrease as the load moves away from the tip of the slope by changing its color from red to yellow.

According to the results of static analyses, there is an increase in the maximum shear stress values when the line load is applied to the slope. It is seen in Figure 9 that as the line load moves away from the tip of the slope, there is a slight decrease in the maximum shear stress values compared to the situation when the load is at the tip of the slope. As the load moves away from the tip of the slope, maximum shear stresses decrease.

Table 2. Factors of safety obtained by static slope stability analyses

The position of the line load and factors of safety					
Position of the load	**No load**	**At the tip of slope**	**5 m back from tip of slope**	**10 m back from tip of slope.**	**15 m back from tip of slope**
Factor of safety (FS)	1.695	1.199	1.280	1.355	1.437

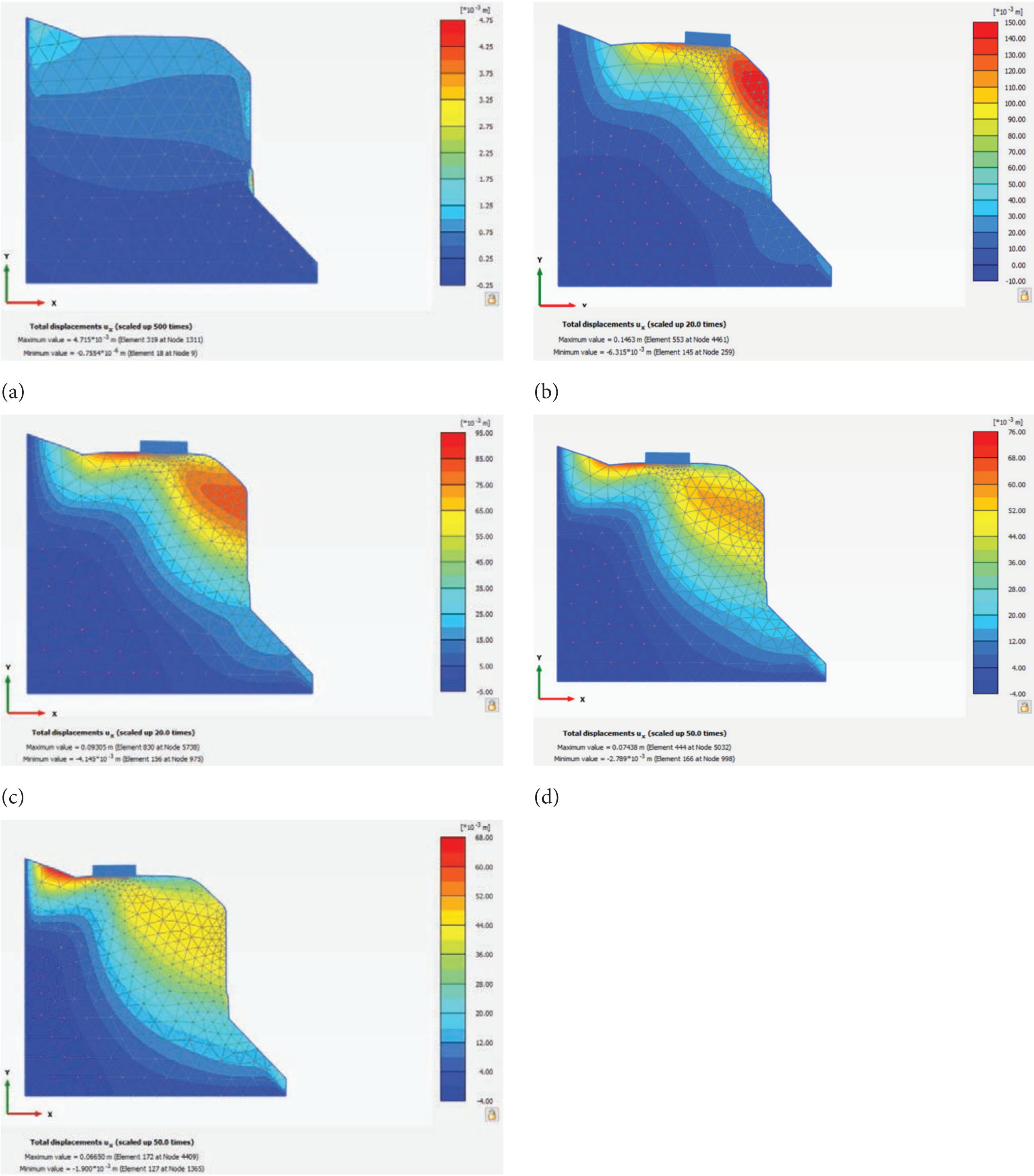


	no load	0	5	10	15
Total Displacements	0,0047	0,2645	0,2223	0,2036	0,1922
Lateral Displacements	0,0047	0,1463	0,0931	0,0744	0,0665

Figure 7. Total and horizontal displacements (m).

It is seen in Figure 10 that the most significant shear stresses occur at the base of the slope and at the intersection of the vertical surface of the slope and the inclined surface.

It can be seen in Figure 11 that a potential slip surface occurs surface when no load is on the slope. However, the fractures occur in the intersections of vertical and inclined



(a) (b) (c) (d) (e)

Figure 8. The locations of largest horizontal displacements occurred as a result of static analyses: a) no load on the slope, b) line load at the tip of the slope, c) line load 5 m behind the tip of the slope, d) line load 10 m behind the tip of the slope, e) line load 15 m behind the tip of the slope.

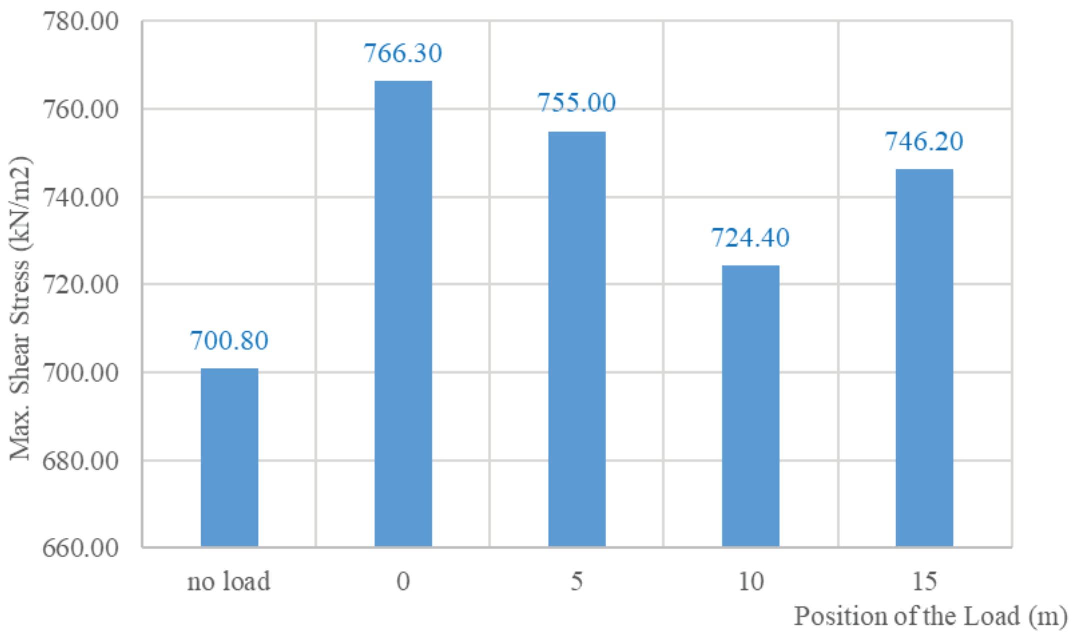


Figure 9. The maximum shear stresses occurred in the slope due to static analyses.

surfaces. Also, the possible slip surface becomes very evident when the load is placed at the sloping tip, and the potential slip surface almost disappears when the load is 5 m away from the sloping tip. The potential slip surface is formed again when the load is 10 m away from the tip of the slope but not as prominent as when the load is at the tip of the slope. And if the load is 15 m away from the tip of the slope, the potential slip surface almost completely disappears.

In high-load situations, the safety factor increases as the excavation length increases. This is most likely due to model-specific reasons. The reason why larger models (16 – 32 m) provide a slightly higher safety factor is probably a result of element distribution [31]. PLAXIS automatically creates a finer mesh around the surface charge area and may have made more minor elements on this region in the large model than in the small model. A thinner mesh will reduce the safety factor. More extended excavation will not reduce the safety factor when the surface load is high enough.

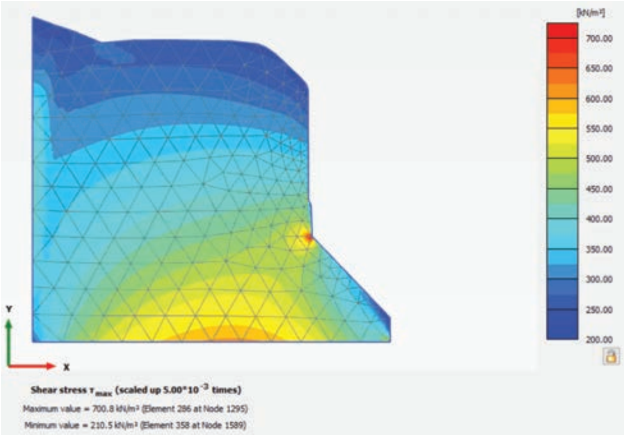
Dynamic Analyses Results

The factors of safety (FS) obtained from dynamic analyses are given in Table 3. As shown in Table 3, there is a severe decrease in safety factors with the effect of the load on the tip of the slope. It is also seen that the factors of safety increase as the load moves away from the tip of the slope. According to the results of the dynamic analyses, as expected, the safest case with the highest safety factor of the slope occurs when there is no load on top of the slope. Also, the most negative situation with the most minor safety factor in dynamic analyses is that the load was placed on the tip of the slope.

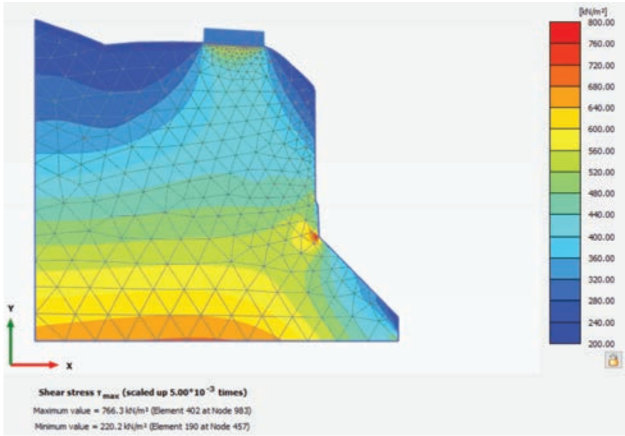
The displacements obtained in dynamic analyses are given in Figure 12. It can be seen that the total displacements in the slope decrease when the load is applied at the tip of the slope, and when the load is moved away from the tip of the slope, the displacements increase. Also, it can be seen that horizontal displacements have constantly increased. Horizontal displacements under dynamic loading were found to be 0.203, 0.246, 0.257, 0.289, and 0.418 for unloaded and 0.5, 10, and 15 m loading conditions, respectively. Total displacements under dynamic loading were found to be 0.333, 0.253, 0.266, 0.323, and 0.419 for unloaded and 0.5, 10, and 15 m loading conditions, respectively (Fig. 12).

In dynamic analyses, in every case, it can be seen that the largest displacements occur at the toe of the slope and in a small area of the vertical surface where the vertical surface intersects with the inclined surface, which starts with the toe of the slope. Also, it can be seen in Figure 13 that while the load is moving away from the tip of the slope, the displacement effect is decreased by changing the color red to turquoise.

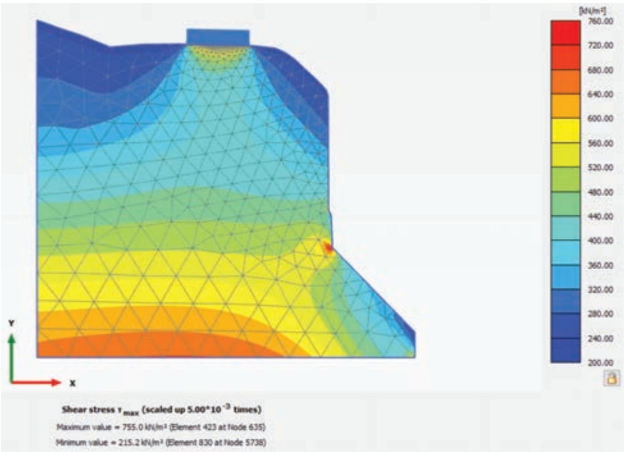
As is seen in Figure 14, as a result of dynamic analysis, there is an increase in the maximum shear stress values by applying the load on top of the slope. A slight decrease in the maximum shear stress values occurs as the load is 10 m away from the tip of the slope. Shear stress takes its maximum value when the load is 15 m away from the tip of the slope, as shown in Figure 14. Under dynamic loads, the maximum shear stress was calculated as 671.70 kN/m2, 686.70 kN/m2, 700.20 kN/m2, 683 kN/m2, 1022 kN/m2 for unloaded and 0, 5, 10 and 15 m loaded cases (Fig. 14). Also, it can be seen in



(a)



(b)



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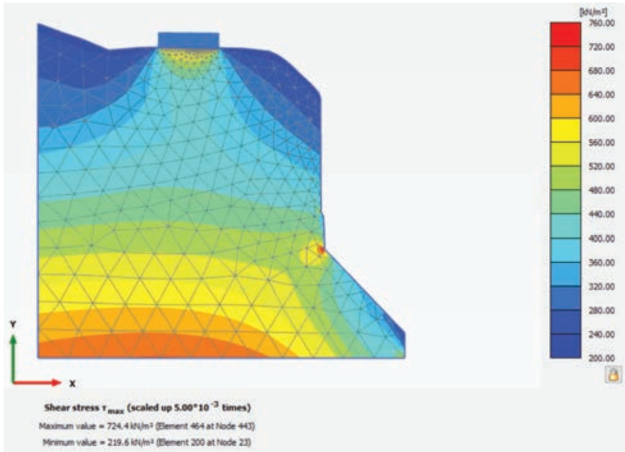
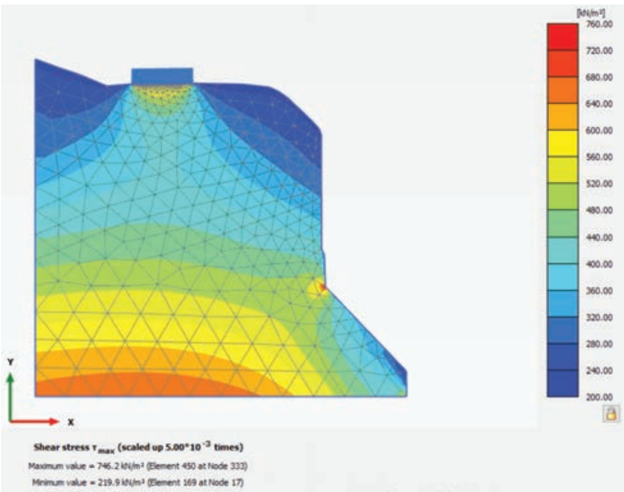


(d)



(e)

Figure 10. The locations of max. Shear stresses occurred in the slope as a result of static analyses: a) no load on the slope, b) line load at the tip of the slope, c) line load 5 m behind the tip of the slope, d) line load 10 m behind the tip of the slope, e) line load 15 m behind the tip of the slope.

Figure 15 that maximum shear occurs at the bottom of the slope and the intersection of the vertical surface and inclined surface. It is seen in Figure 10 that the most significant shear stresses occur at the base of the slope and at the intersection of the vertical surface of the slope and the inclined surface.

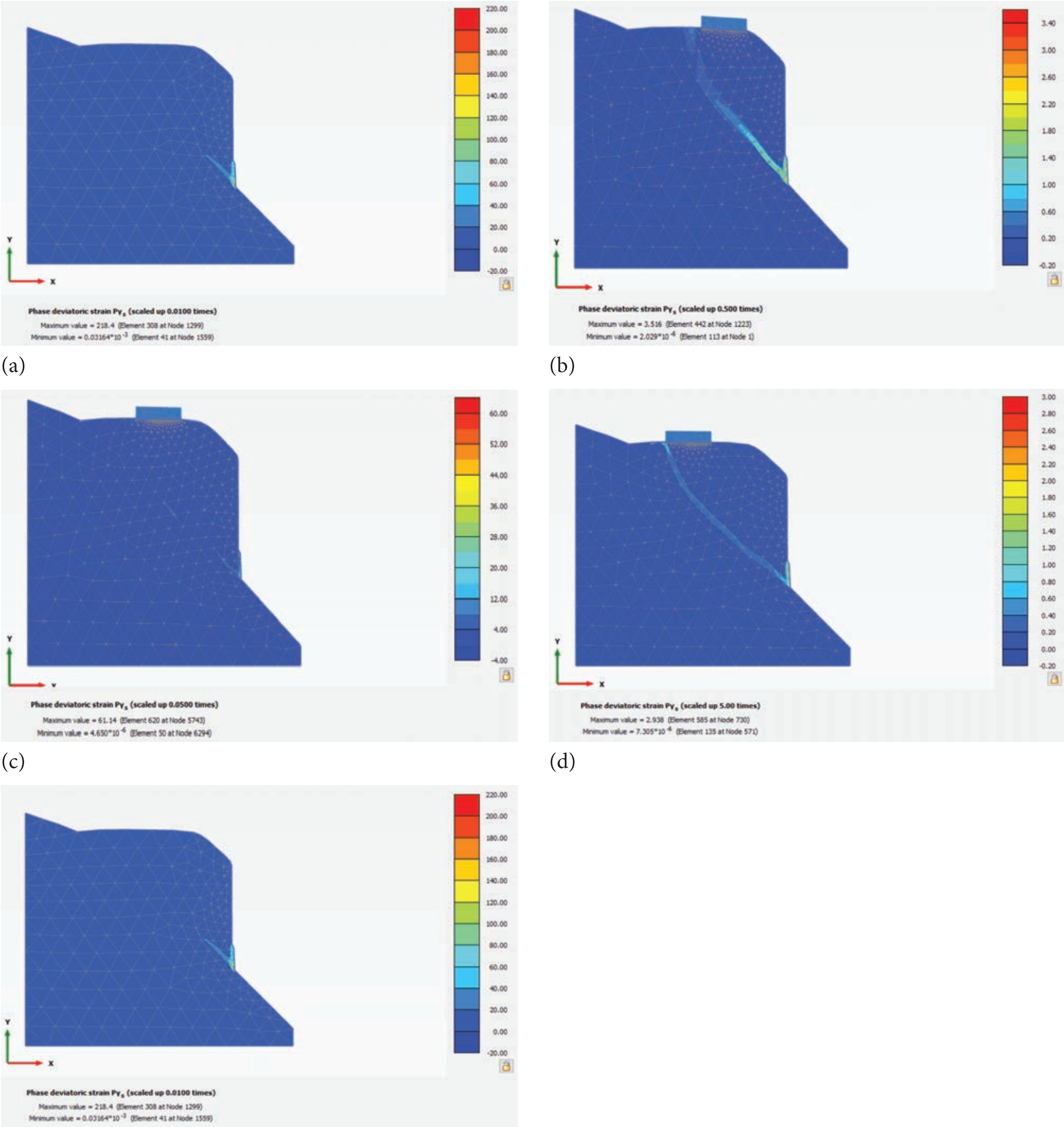


Figure 11. Fracture mechanism that occurred in the slope as a result of static analyses; a) no load on the slope, b) line load at tip of the slope, c) line load 5 m behind the tip of the slope, d) line load 10 m behind the tip of the slope, e) line load 15 m behind the tip of the slope.

Table 3. Results of dynamic analyses

The position of the line load and factors of safety					
Position of the load	**No load**	**At the tip of the slope**	**5 m back from the tip of the slope**	**10 m back from the tip of the slope**	**15 m back from the tip of the slope**
Factor of safety (FS)	1.664	1.190	1.296	1.351	1.442

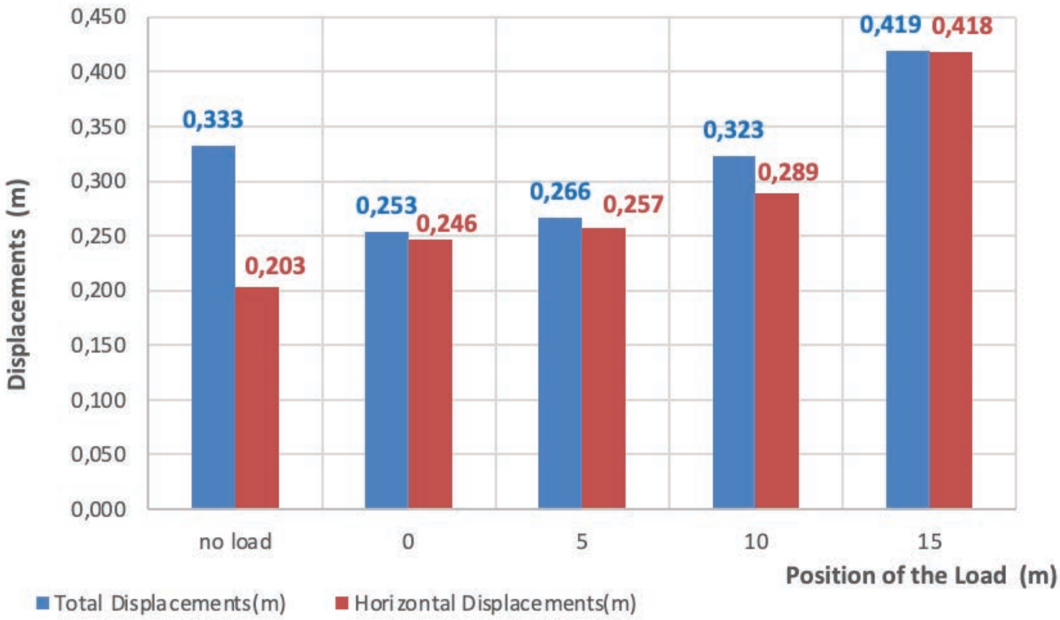


Figure 12. Displacements occurred in the slope due to dynamic analyses.

Evaluations of Results

Factor of safety (FS)

There is a maximum difference of 29.262 % between the safety factor calculated in static analyses, and this difference is at most 28.571% in dynamic analyses. In the static and dynamic analyses, Table 4 shows that applying the load on top of the slope affects the safety of the slope. Safety factors increase when the load moves away from the tip of the slope. Also, the position of the load 5 m and more away from the tip of the slope does not have any impact on the factor of safety for static and dynamic analysis in terms of destabilizing the slope. FS>1 indicates a stable slope [32, 33]. According to Christian, if FS is greater than 1, the slope is stable, but if FS is less than 1, the slope is unstable. According to the study conducted by Le Ta Meko et al. (2023), the factor of safety is gradually decreasing [34]. A significant strain has occurred here, and this strain's contours define the sliding surface. According to the study by Shah et al. (2021), as the slope decreases, the factor of safety decreases [35]. In this study, the slope is stable under all conditions. In their study conducted in 2023 by Kassa and Meten [36], FS values decrease under static and dynamic loading conditions, and the slope is not stable. According to the modeling results, the factor safety increases for the slope angle decreases (Kale et al. [37]). According to the results of the analysis, a decrease in slope height tends to increase the safety factor [38-40]. In this study, the factor of safety gradually increases under static and dynamic loads. In this respect, this study is compatible with the studies done by Kassa et al., Kale et al., Anbalagan, Raghuvanshi et al. (2014), and Shiferaw [36-40].

Theoretically, all slopes with a factor of safety greater than one are safe. However, many design standards recommend using a FoS greater than one. This is because, over time, the slope becomes unstable due to rain, earthquakes, or erosion. In this case, the slope's safety factor decreases temporarily or permanently. Over time, the factor of safety becomes less than one, and the slope collapses or landslides may occur. It is seen in Table 4 that the safety factors obtained in dynamic analyses are less than for cases where there is no load and the load is at the tip of the slope compared to the static analyses. In the other cases, it can be seen that the safety factors are nearly equal to or higher than those obtained in static analyses. As a result of the static analysis, the factor of safety was calculated as 1.695, 1.199, 1.280, 1.355, 1.437 for no-load and 0.5, 10.15 m loading conditions, respectively. Under dynamic loading conditions, it was found to be 1.664, 1.190, 1.296, 1.351, 1.442 in unloaded and 0, 5, 10, 15 m loading conditions, respectively.

If the static analysis is taken as a reference, which is the case that there is no load on the slope, the factor of safety obtained from the most critical case, which is the load on the slope tip in dynamic analysis, decreases by 29.794 %.

If no structure is on top of the slope for long-term stability, the minimum safety factor must be 1.20 based on effective stress according to Turkish Code 8853. And if there is a structure on the slope, the factor of safety should be at least 1.20 in case of earthquake and 1.80 based on total stress according to TS8853 [41]. It is understood that the slope under investigation is unsafe in cases where the load is on top of the slope for static and dynamic analysis. For the other four cases, it is safe against collapse, according to TS8853 [41].

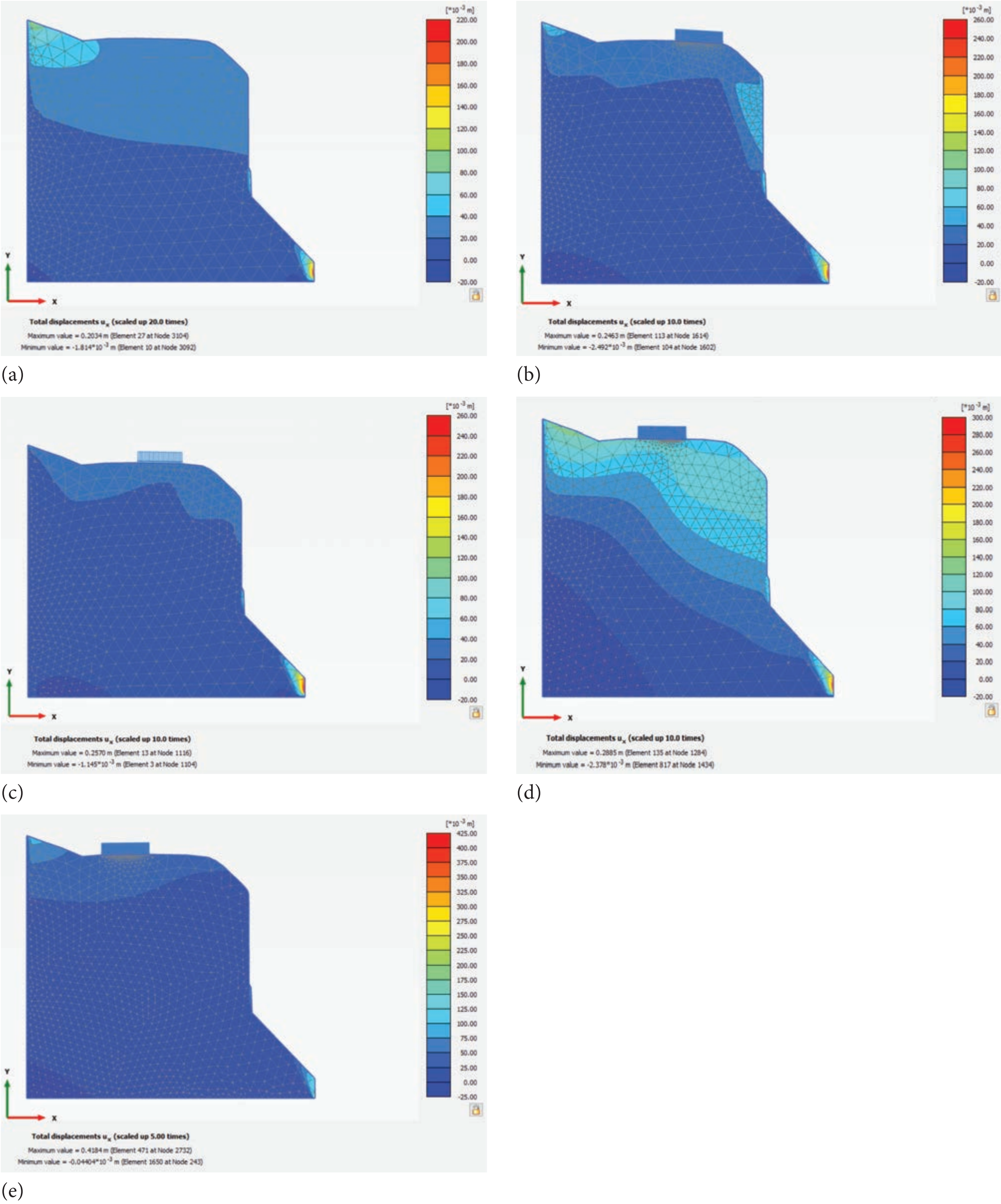


Figure 13. The locations of horizontal displacements that occured in the slope as a result of the dynamic analyses: a) no load on the slope, b) the load is at the tip of the slope, c) the load is 5m behind the tip of the slope, d) the load is 10m behind the tip of the slope, e) the load is 15m behind the tip of the slope.

Also, the minimum factor of safety for slope stability is accepted to be at least 1.0 for Eurocode7 and BS. That's why it can be stated that the slope under investigation is safe, according to Eurocode7 and BS [42]. Also, it can be understood from dynamic analyses that in terms of displacements, the slope under investigation is unsafe against

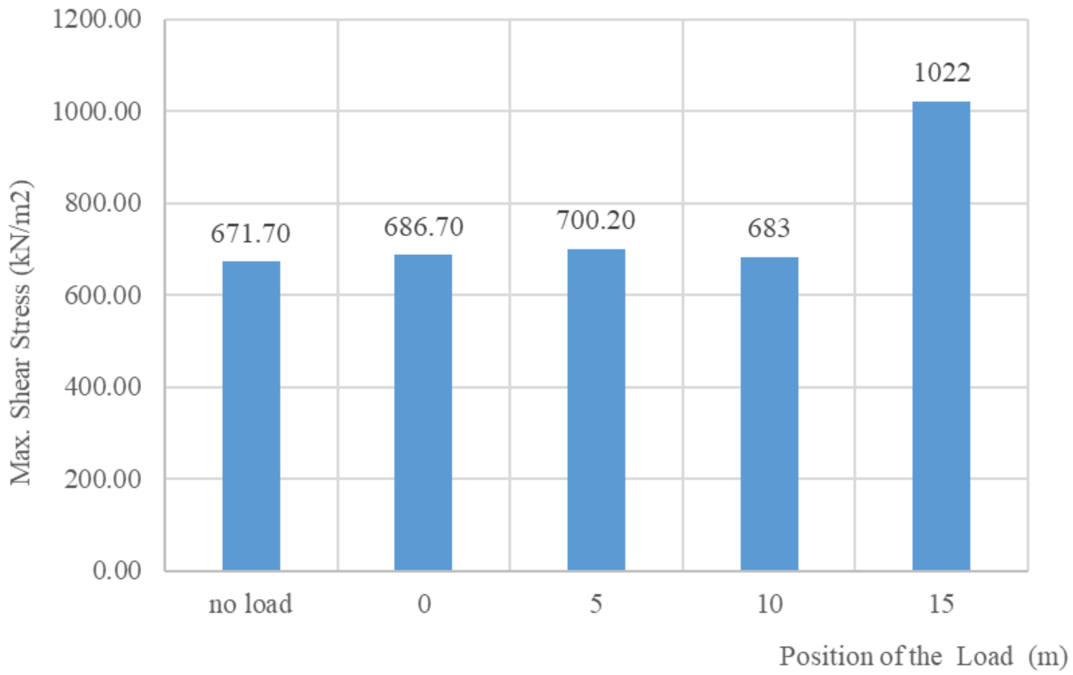


Figure 14. The maximum shear stresses occurred in the slope due to dynamic analyses.

collapse. Although the calculated factors of safety generally indicate that the slope is safe according to Eurocode7, BS, and TC8853, the soil strength forming the slope is very low, the soil layer is very cracked and fractured, the discontinuities are many, and their directions are variable and since these features cannot be fully modeled in Plaxis software the slopes can be evaluated as risky.

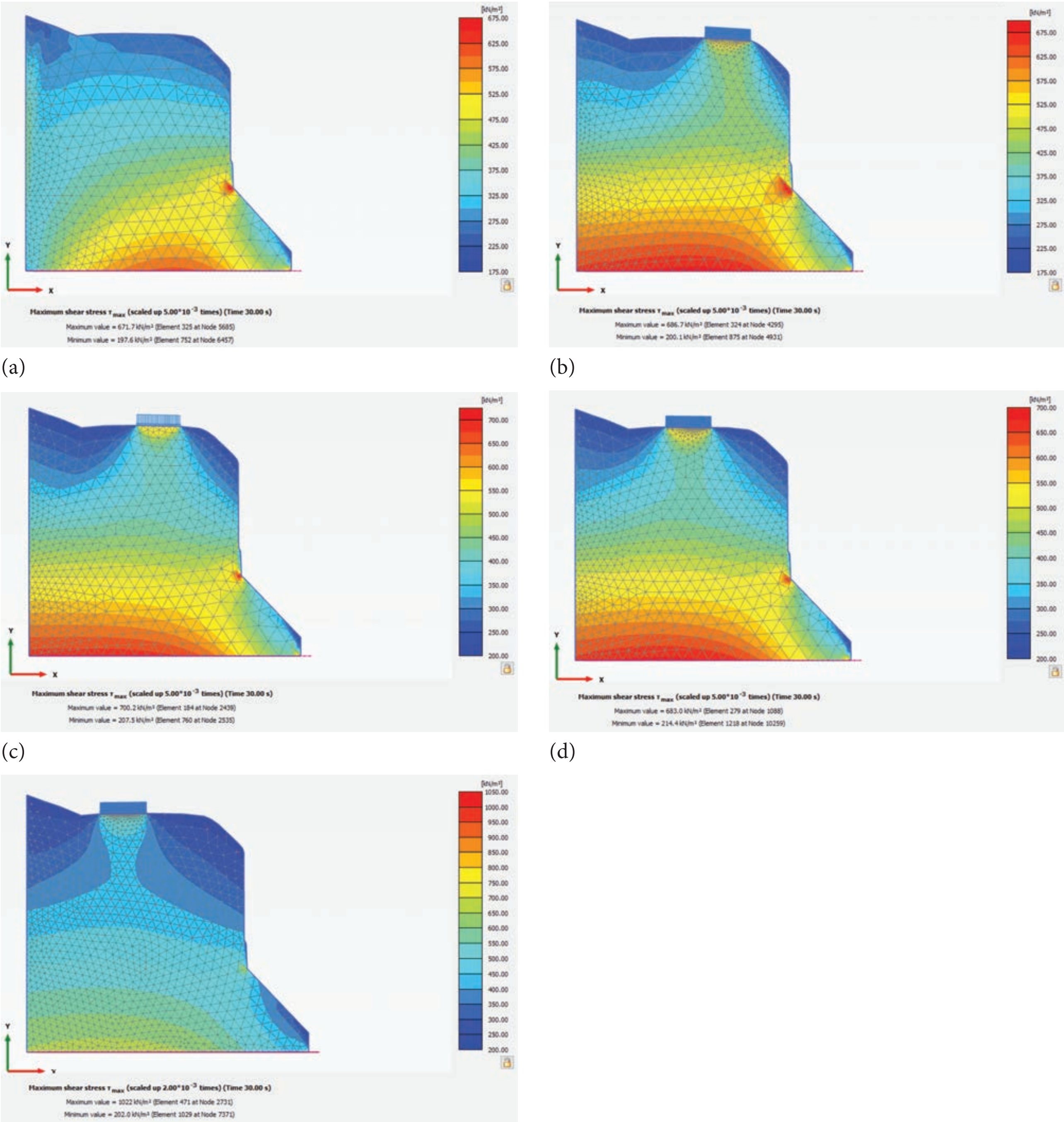
As seen in Figures 7 and 9, when shear stresses are increased by placing the load on top of the slope, the horizontal displacements increase, and when shear stresses decrease, the horizontal displacements decrease. The horizontal displacement is reduced while shear stress is raised only for the caseload 15 m away from the tip of the slope. This is because the slope soil's backward becomes more rigid compared to the tip of the slope, and shear stress can be absorbed. Figures 11 and 14 show horizontal displacements increase by applying earthquake effects in dynamic analysis.

Largest Horizontal Displacements (Ux)

Permanent damage from earthquakes causes permanent deformations. A moderate input to the base displacement causes large deformations in the changes. Calculations are made with undrained effects and zero dilatation angles. Suction develops in water during earthquakes, and large values can work for fine-grained, homogeneous soils. However, cavitation occurs in cracks in clay and coarse soils. A FEM-based software, PLAXIS (2D), is used in the numerical analysis. The slope is divided into small elements, and a stress-strain relationship is defined for each case. Mesh refinement and some elements strongly affect the calculated FoS (Fig. 13, 15). As seen in Figure 13, the maximum total displacement in the unloaded condition was calculated as 0.2034 m. When the loading condition was examined for 0, 5, 10, and 15 m, it was seen that the total displacements increased, and the maximum movements were concentrated in the region where the loading condition was present (Figs. 13a-13e).

In static analyses, minimal horizontal displacements occur when no load is on the slope. The largest horizontal displacements are increased significantly by placing the load at the tip of the slope. The largest horizontal displacements decrease as the structure moves away from the tip of the slope. The fact that the largest horizontal displacements in the static analyses occur when the load is at the tip of the slope is due to the increases in stresses in the slope soil by the line load. It is also seen in Figure 16 that as the load moves away from the tip of the slope, the largest horizontal displacements decrease regularly in static analyses. As a result of the static analysis (Fig. 16), horizontal displacements were calculated as 0.0047 m, 0.1463 m, 0.0931 m, 0.0744 m, and 0.0665 m for unloaded and 0, 5, 10, and 15 m loading conditions, respectively. As a result of dynamic analysis, horizontal displacements were calculated as 0.203 m, 0.246 m, 0.257 m, 0.289 m, and 0.418 m for unloaded and 0, 5, 10, and 15 m loading conditions, respectively (Fig. 16).

When the earthquake is applied to the slope, the largest horizontal displacements increase significantly compared to the static analysis results. It is seen in Figure 16 that as



(a) (b) (c) (d) (e)

Figure 15. The locations of max. Shear stresses occurred in the slope result of dynamic analyses: a) no load on the slope, b) line load at the tip of the slope, c) line load 5 m behind the tip of the slope, d) line load 10 m behind the tip of the slope, e) line load 15 m behind the tip of the slope.

the load moves away from the tip of the slope, the largest horizontal displacements continually increase. In the literature, it is accepted that the limit of displacements for slope should be between 50 and 100 mm [7]. Because of that, it can be concluded that according to the analysis results regarding displacements, the slope under investigation is unsafe. The Nguyen et al. study determined that horizontal displacements decreased under dynamic loads [41]. According to the survey by Shiferaw et al., total displacements increase under static and dynamic load conditions [14]. This is attributed to the fact that actual measurements do not confirm the calculated results. Horizontal displacement results were supported by the study by Shiferaw et al. [14]. In addition, the increase in displacement (Fig. 13) will

Table 4. Factors of safety obtained from the result of static analyses and dynamic analyses and the differences between them (%)

	Static analyses		Dynamic analyses			
Position of the load (m)	**Factor of safety (FS)**	**Difference (%)**	**Factor of safety (FS)**	**Difference (%)**	**Differences between the factors of safety (%)**	**Decrease in the most critical case(%)**
no load	**1.695**		**1.664**		1.830	**29.794**
0	**1.199**	**29.262**	**1.190**	28.486	0.751	
5	1.280	24.484	1.296	22.120	-1.250	
10	1.355	20.060	1.351	18.810	0.295	
15	1.437	15.221	1.442	13.341	-0.348	

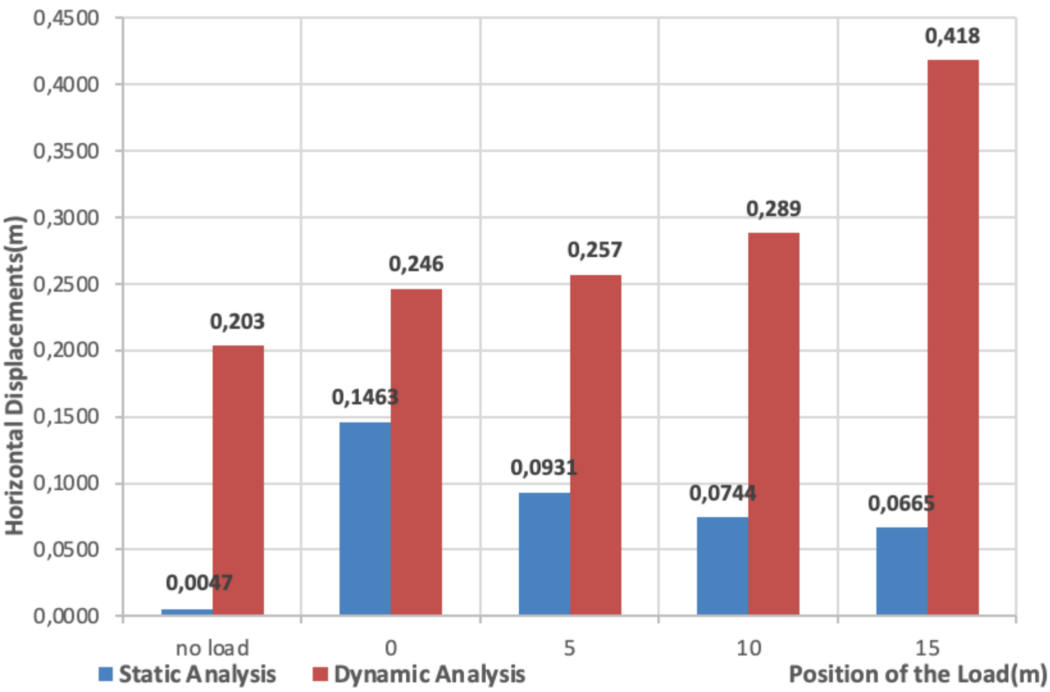


Figure 16. Horizontal Displacements obtained by dynamic and static analyses

cause damage to wastewater and drinking water infrastructure systems, and water leaks to the sloping ground due to these damages. In this case, it will cause sliding surfaces to become more apparent or new sliding surfaces to form, and as a result, collapses will occur.

Maximum Shear Stresses (τ max)

Figure 9 shows that a higher maximum shear stress is generally obtained in static analyses. The maximum shear stresses occured in dynamic analyses are higher only when the load is 15 m away from the tip of the slope. This is because the slope height increases from the tip of the slope to the backward, that is, towards the infinite part of the slope. In addition, the maximum shear stresses in dynamic analyses are smaller than the maximum shear stresses obtained in static analyses because the shear stresses are damped with the increase in displacements due to the dynamic earthquake effect. It is observed that the maximum shear stress increases compared to the unloaded case due to the increase in total displacements. The stresses are concentrated from the load region to the lower part of the soil (Fig. 14,15).

In static and dynamic analyses, it is seen that the maximum shear stresses occur at the base of the slope and the intersection of the vertical surface and the inclined surface of the slope. In the field, it has been observed that there are

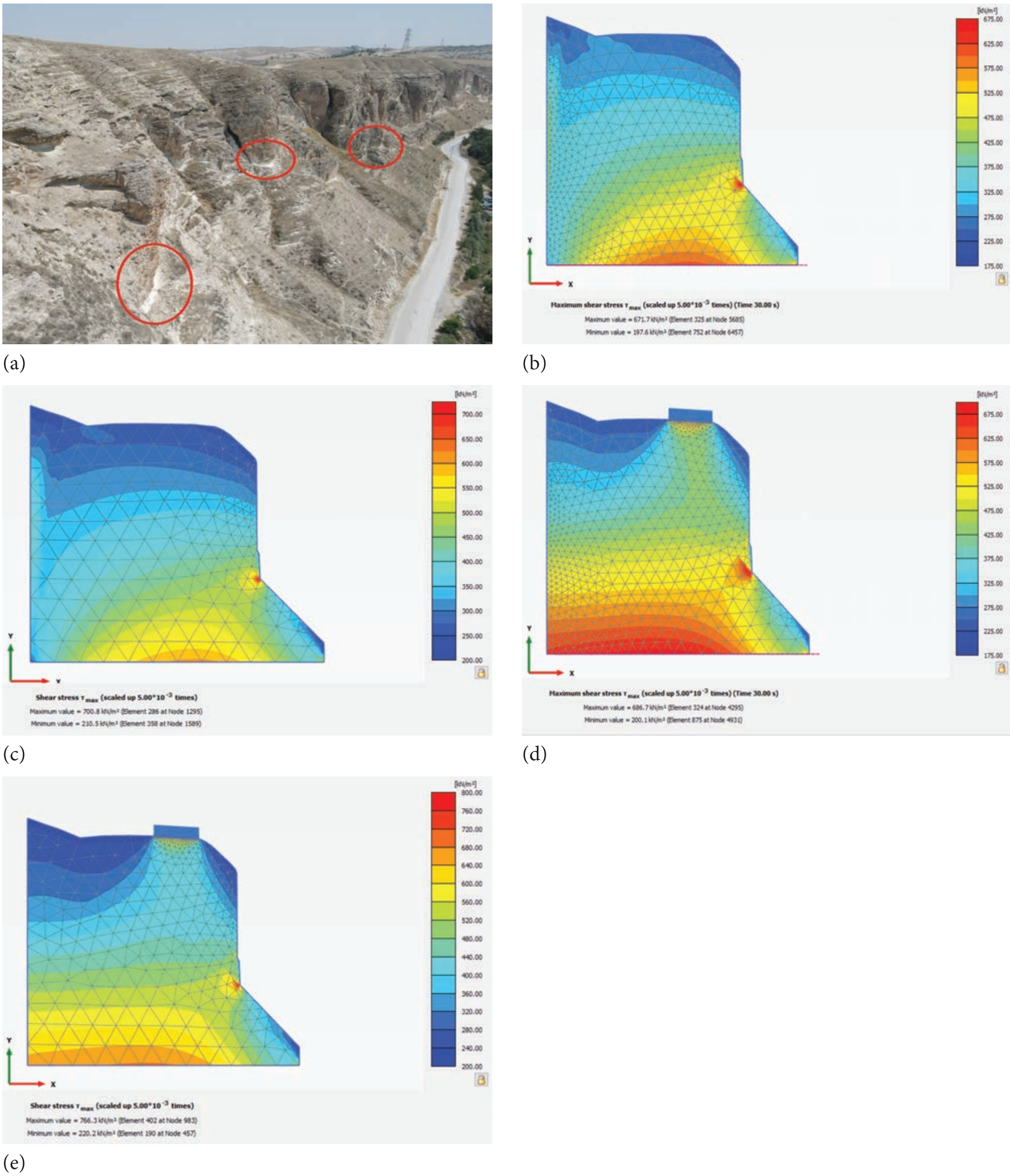


Figure 17. As result of the analyses, the locations of the maximum shear stresses occurred in the slope and the crushing-cover slips observed in the field; a) crushing-cover slips observed in the field, b) static analyses: the structure is not on the slope, c) dynamic analyses: the structure is not on the slope, d) static analyses: the structure is at the tip of the slope, e) dynamic analyses: the structure is at the tip of the slope.

crushes and cover throws at the point where the inclined surface starts with the toe of the slope and the starting of the vertical surface of the slope. In this sense, it is understood that the results of the analyses are consistent with the observations made in the field. The maximum shear stress places that occur in the slope are shown in Figure 17. The geometry of the slope is one of the significant essential parameters which affect its stability [44]. The slope geometry can be altered by decreasing the slope angle and height and removing material from the landslide point in the study area [38-40]. Slope angle and height affect slope stability, as adding these parameters increases shear stress while reducing shear strength on the implicit failure surface [43]. According to the study conducted by Rawat and Mohanty (2021), it was observed that shear stresses increased towards the ends of the slope [46]. Hamouma et al. (2020) reported that shear stresses increase when moving from a smooth surface to a rough surface [47]. Shear stress results are consistent with the study by Rawat and Mohanty and Hamouma [46,47].

CONCLUSION

This study investigates the slope stability in a pilot area along the Birecik Halfeti coastal road. Both static and dynamic analyses were conducted using Finite Element Method (FEM) and Plaxis V20 software. The analyses considered various scenarios with and without external loads applied to different distances on the slope. The findings revealed that plain strain (two-dimensional) analysis is accurate, and they are summarized below.

1. It is understood that the main factor that reduces safety for static and dynamic analyses is the load to be applied at the top of the slope. A dynamic earthquake has a minimal effect on safety.
2. The factor of safety decreases by dynamic effect 1.695 to 1.664 (%1.830) with no load, which is consistent with the result of the study conducted by Dejian Li et al. (2023).
3. As a result of the static and dynamic analyses, the most significant shear stresses occurred in the intersection of the vertical surface and inclined surface, starting with the toe and bottom of the slope. These results are consistent with the crushing and capping in the intersection of the vertical surface and inclined surface observed in the field.
4. It is expected that higher shear stresses will occur for dynamic analyses than static analyses. However, shear stresses obtained from dynamic analyses are lower than those obtained from static analyses, while the displacements in dynamic analyses are higher than those in static analyses. It can be stated that this is a fault of plain strain or two-dimensional analyses.
5. According to the factor of safety obtained in dynamic and static analyses, it is understood that the slope is unsafe just in case the load is at the tip of the slope. The other four cases are safe, according to TS8853. However, according to Eurocode7 and BS, the slope is safe for all cases.
6. According to the study conducted by Micke Didit et al. (2022), the displacement in static analysis decreases when the load moves away from the tip of the slope, and the results are consistent with our study.
7. The increases in displacements due to dynamic effects will also affect the safety of the polygon points of the region's high and medium voltage lines and close to the slope tips. In this case, these lines and polygon points must be moved further away to a safer distance.
8. Additionally, more reliable results will be obtained by supporting 2D analyses with 3D analyses and investigating slope safety by modeling the discontinuities and separations in 2D and 3D models.
9. The most suitable stabilization methods for this slope are considered to ensure the safety of the coastal road by laying it on a slope with 45 degrees and beveling, removing the parts where segregations are intense, and then covering it with a steel wire mesh.
10. In the scenario of opening the region to possible construction in the future and constructing structures at the tip of the slope, it was understood that the slope was unsafe when the structure load was applied at the tip of the slope. In this case, as an alternative suggestion for risk mitigation, it is recommended as a priority measure not to allow constructions at a safe distance from the tip of the slope in the long term. However, if construction cannot be prevented, it will eliminate the possibility of reducing the slope's inclination and beveling it. Under this condition, building pile retaining walls that will stop the movement in the slope becomes necessary. However, the slope height is too high, and in some places, it restricts the construction of retaining walls; in this case, it becomes necessary to prevent the leakage of surface water or water from construction and infrastructure systems to the sloping ground. Also, it becomes necessary to establish a slope monitoring mechanism that will allow constant monitoring of the slope movements and formation of new possible sliding surfaces in the slope and to take instant measures according to the data to be obtained
11. The region in question receives the most precipitation during winter, while summers are dry and hot. This situation contributes to the continuous and repeated occurrence of dissociations in the limestone that forms the slope. With global climate change, the sudden and sometimes excessive occurrence of precipitation contrary to the characteristics of the region and the increase of summer temperatures above the regional average and their duration will contribute to the intensification of the expansion-contraction cycle, further increase of existing discontinuities and separations in the slope and the occurrence of slope failures on a larger scale in this region. Considering this fact, taking more extensive measures to prevent partial ruptures on the slope surface and total failures will be necessary. For this purpose, it would be healthy to build pile retaining walls to prevent displacements and possibly sliding surfaces. As a result, existing separations can be removed using machinery or special explosives, and the surface should be covered with wire mesh to prevent small pieces from separating and falling from the surface due to seasonal effects.

This study was carried out to investigate the safety of the heavily used road sandwiched between the coastal road and the slopes. An actual application was included using an unmanned aerial vehicle. Slides that are assumed to be safe in static conditions can fail after earthquakes, which causes additional forces and horizontal displacements. This reality makes it necessary to examine them under the dynamic effects of earthquakes. For that, dynamic analyses were performed to see the impact of earthquakes on slope stability.

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AUTHORSHIP CONTRIBUTIONS

"Taylan" Study conception and design, Acquisition of data, Analysis and interpretation of data, Drafting of manuscript, Critical revision

"Ulukavak" Acquisition of data, Critical revision, Drafting of manuscript

"Sarıışık" Critical revision, Drafting of the manuscript

"Can" Critical revision, Drafting of manuscript, Analysis, and interpretation of data.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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