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Stability Analyses of a Slope Reinforced with Piles Subjected to Static and Dynamic Loading Conditions

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Abstract: This paper focuses on a stability analysis related to a highway constructed on a slope with high shear potential reinforced with the piles. For this purpose, a series of two-dimensional simulations were carried out by employing the finite element method. In the study, in order to provide the current state of topography, a numerical model was created based on data obtained from field and laboratory tests. It is aimed to define the safety factor of a slope under both static and dynamic loads, and that value was calculated for the following three cases: (i) for the slope unreinforced with the piles subjected to static loading, (ii) for the slope reinforced with the piles subjected to static loading, (iii) for the slope reinforced with the piles subjected to both static and dynamic loading. The numerical results indicate that it is a good approach to be used the piles to enhance the stability of the slope even though dynamic loading brings about to decline in the slope safety factor. Plus, the relevant value was determined to be 1.446 in the second case explained above while the same value was calculated to be 1.104 in the third case. Therefore, it is understood that the dynamic loads caused by the vehicles should be considered in the design of these kinds of problems, and the improvement method should be evaluated in detail.

Keywords: dynamic load, finite element method, pile, safety factor, slope stability analysis

Statik ve Dinamik Yükleme Koşullarına Maruz Kazıklarla Güçlendirilen Bir Şevin Stabilite Analizleri

Öz: Bu makale, kazıklarla güçlendirilen yüksek kayma potansiyeline sahip bir şev üzerine inşa edilmiş karayolu inşaatının stabilite analizi üzerine odaklanmaktadır. Bu amaçla, sonlu elemanlar yöntemi kullanılarak bir dizi iki boyutlu sayısal analiz gerçekleştirilmiştir. Çalışmada, topoğrafyanın mevcut durumunu yansıtmak için saha ve laboratuvar testlerinden elde edilen verilerden faydalanılarak sayısal bir model oluşturulmuştur. Hem statik hem de dinamik yükler altında bir şevin güvenlik katsayısının tanımlanması amaçlanmış ve bu değer şu üç durum için hesaplanmıştır: (i) statik yüklemeye maruz kazıklarla güçlendirilmeyen şev için, (ii) statik yüklemeye maruz kazıklarla güçlendirilen şev için (iii) hem statik hem de dinamik yüklemeye maruz kazıklarla güçlendirilen şev için. Sayısal sonuçlar, şev stabilitesini artırmak için kazık kullanımının, dinamik yüklemenin şev güvenlik katsayısında düşüşe neden olsada, iyi bir yaklaşım olduğunu göstermektedir. Ayrıca, yukarıda açıklanan ikinci durumda güvenlik katsayısı 1.446 olarak belirlenirken, üçüncü durumda aynı değer 1.104 olarak hesaplanmıştır. Bu nedenle, bu tür problemlerin tasarımında taşıtların neden olduğu dinamik yüklerin dikkate alınması ve iyileştirme yönteminin detaylı bir şekilde değerlendirilmesi gerektiği anlaşılmaktadır.

Anahtar Kelimeler: dinamik yük, sonlu elemanlar yöntemi, kazık, güvenlik katsayısı, şev stabilite analizi

1. Introduction

Slope stability analysis has perpetually been a crucial interest in geotechnical engineering. It is often discussed which methods to reasonably consider in the applications and how to select the soil parameters in the analyses. Since the accuracy of slope stability analysis is closely interested in soil

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Bu makaleye atıf yapmak için
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behaviour, the soil parameters play a vital role for numerical analyses [1]. Therefore, it is required correctly to be determined soil parameters for an accurate slope stability analysis. For this purpose, the best method is to perform some site investigations. In addition to this, it is needed a method (i.e., limit equilibrium method, finite difference method, finite element method etc.) which has various material and soil models in which soil behaviour and loads (i.e., static, or dynamic) can be modelled realistically.

In recent years, the usage of the two-dimensional finite element simulation has become a tendency in the stability analysis of slopes, and therefore it has been widely employed by geotechnical researchers. Moreover, as computer performance is enhanced, the application of the finite element method in geotechnical analyses becomes increasingly common. This method has several advantages such as to model the slopes with high accuracy (i.e., complex geometry, different loading conditions, presence of material as reinforcement, the flow of water, usage of theories for complex behaviour of soil) and to better illustrate the deformations of soils. Another important advantage is that no assumption requires to be done in advance related to the location or shape of the failure surface. The failure appears naturally through the zones in the soil mass where the shear strength of soil is unable to maintain the applied shear stresses [2]. Yet, it is critical to comprehend the analysis outputs offered to the designers due to many numbers of variables [3]. Some studies, where the finite element method was employed, are presented in this section in order to indicate the success of the method.

Griffiths and Lane [2] presented some instances of finite element stability analysis of slope with comparison against limit equilibrium methods. It was stated that the finite element method with an elastic-perfectly plastic (Mohr-Coulomb) model was a reliable and powerful method for evaluating the safety factor of slopes. It was also suggested that the widespread use of the method should be seriously taken into consideration by geotechnical engineers as a more robust choice to traditional limit equilibrium methods.

A comparison study was carried out by Rabie [4] in order to estimate the safety factor of slopes subjected to the effect of rainfall by using limit equilibrium methods and finite element method. It was reported that the limit equilibrium methods are quite conservative compared to the finite element method, and when the latter method was used for estimating the safety factor of slopes, there was no need any assumptions to be made in advance related the location and shape of the failure surface. Additionally, the finite element method found high safety factor values for both unsaturated and saturated slopes, unlike the limit equilibrium methods.

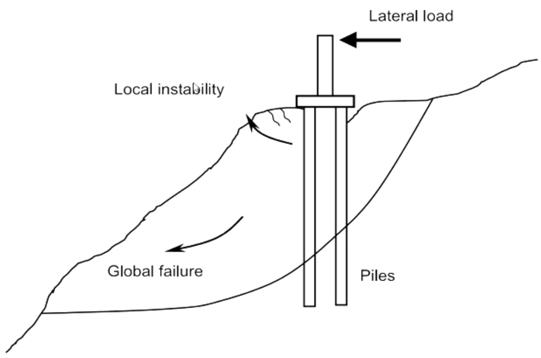


Figure 1. Slope instability due to laterally loaded piles [5]

Many high-rise structures, transmission towers and bridges constructed on slopes subjected to high lateral loading such as earthquakes and high-speed vehicles are reinforced with the piles with large diameter in order to improve the resistance of slopes [5]. However, these kinds of loads bring about to decrease in the safety factor against global failure and local instability of slopes because of the stresses transmitted from the piles to the slope while mobilizing lateral resistance (see Figure 1). Therefore, the pile length, pile diameter, and pile position or location are significant variables for increasing the resistance of the slope, and several previous studies about the slopes reinforced with the piles are presented to clearly understand the effect of piles in the improvement of slopes.

Kelesoglu [6] investigated the effect of each variables contributing the slope stability such as supporting with piles, slope curvature, and local loading of the slope by the structures by using the strength reduction method. It was stated that the stability of concave slopes is greater than that of straight slopes. The safety factor values were increased up to 5 to 10% for smooth concave curvatures and 15 to 25% for slopes that had sharp concave curvatures compared to a straight slope. Plus, piles that have radial, circular and rectangular cross-sections produced close results from the point of the safety factor. There was quite a good agreement on the optimum position of the pile row such that the location was generally between the middle of the slope and the middle of the critical shear surface, yet mostly close to the middle of the slope with no surcharge. Nevertheless, when there was local loading on the top of slope, because of the mobilized shear strains under surcharge, the pile row had to move uphill towards the load to provide the global and local stability of the slope.

Li et al. [7] performed a series of numerical analyses not only to study the most suitable position of the piles in slope improvement but also to assess the influences of pile location and spacing on the improvement of slope reinforced with a single row of piles. It was indicated that the slope stability was significantly affected by the interaction of soil and pile, and therefore the failure mechanism of the piled slope was different when the piles were located in the upper, centre, and lower parts of the slope. It was also indicated that the piles should be located in the middle-slightly upper part of the slope to achieve the maximum safety factor.

Ho [8] carried out some numerical analyses so as to determine the failure mechanism of a slope and to investigate the performance of the piles. The results indicated that the free-head pile performed less efficiently in order to enhance the stability compared to the fixed-head pile, and therefore, it was expressed that the pile head conditions changed the failure surface of the whole system.

From the foregoing literature review, it can be understood that there are many factors that affect the safety factor of a slope reinforced with the piles. To lessen the burden on this study, the performance of the slope stability in terms of safety factors was investigated under different loading conditions by considering the pile diameter and pile length planned to be performed in practice. It was aimed to define the safety factor of a slope under both static and dynamic loads, and that value was calculated for the following three cases.

i. for the slope unreinforced with the piles subjected to static loading
ii. for the slope reinforced with the piles subjected to static loading
iii. for the slope reinforced with the piles subjected to both static and dynamic loading

Considering that both since slope stability problems were generally studied under the effect of static loading and modelling this sort of problem in a computer environment is quite difficult because of the complexity of applying the dynamic load, the foregoing third case employing in this study especially gives a novel identity to the study.

The highway on the slope was subjected to a prespecified static load of f_s, afterwards, a repeated load with the amplitude of f_d was superimposed to the static load, and a sinusoidal periodic harmonic load with 1 Hz frequency was continued until the desired cycle. The amplitude of repeated load (f_d) was selected to be 50% because this value is assumed appropriate for expressing the stresses likely to be experienced, or especially for representing an extreme occurrence [9].

When it is necessary to state with a general expression, the safety factor of the slope attributes to the ratio of the shear strength of soil to the shear stress of a possible failure surface in the slope as given below [10].

$$F_S = \frac{\tau_f}{\tau} \geq 1 \quad (1)$$

In addition to this, when the foregoing expression is expanded with parameters expressing the engineering properties of soils, as the conventional definition of the safety factor for any point within a soil mass, it is the ratio between the shear strength and stress at that point.

$$F_S = \frac{\tau_f}{\tau} = \frac{(c + \sigma \cdot \tan\phi)}{\tau} \geq 1 \quad (2)$$

Since the finite element method offers the safety factor of a slope for the different circumstances with no assumption requires to be done in advance related to the location or shape of the failure surface, in this study several results obtained from the two-dimensional finite element method are presented in order to prevent the cracks observed during the highway construction on a slope as shown in Figure 2. For this purpose, an application of two rows of bored piles in the length of 30 m and a diameter of 1.5 m was designed to increase the slope safety factor. As a result of this, a series of numerical analyses (i.e., safety analysis) were employed for the three cases given above, and the obtained results are shown in detail.

Figure 2. Cracks on the current highway due to landslide and settlement

2. Materials and Methods

2.1. Description of Numerical Model

Numerical investigations throughout the study for the assessment of safety factor of slope under a combination of static and dynamic loads were performed with a two-dimensional finite element method. Since the use of an accurate soil model is essential for the prediction of soil responses, the numerical analyses in this study were carried out employing the Hardening Soil model to reflect the behaviour of soils more realistically [11]. Hardening Soil model is a model which was developed for simulating soil behaviour, and due to this second-order model (i.e., more complex soil model), sand and gravel behaviours as well as softer soil types such as clay and silt can be simulated realistically [12]. Furthermore, the numerical model of the slope was studied with the plane strain condition in two-dimensional analyses owing to the necessity of the problem. The finite element modelling of the near field in this study was constructed within the vertical and horizontal lengths of 60 m and 195 m, respectively. While the numerical model was generated, the obtained field and laboratory tests results were taken into consideration.

In situations involving dynamic loading, the finite element model boundary conditions were established with a relatively reliable artificial boundary called viscous or dashpot boundary where the stress waves hitting the model boundaries because of the dynamic load are damped without reflecting back due to damping. Therefore, the viscous boundaries were defined at the vertical boundaries of the model and the base horizontal boundary of the model, but the top horizontal boundary was free by the nature of the problem. The viscous boundary provides satisfactory responses for body waves because they absorb reflected energy with the advantage of using frequency independence to applied stresses [13].

In the finite element method, mesh density is a critical issue which closely relates to the accuracy of the finite element models while it directly determines their complexity level. Due to its importance, in generating finite element models, the foremost problem is to choose appropriate elements size so that the created models yield accurate finite element analysis results while saving as much computing time as possible [14]. Because of those reasons, a series of numerical analyses, where different mesh densities were considered, were performed in order to determine optimum mesh density. In the numerical analyses, five different mesh densities which were presented by the software from very coarse to very fine sizes were tested. Subsequently, the meshes of the finite elements were chosen as medium sizes, since there was no major change in the results when the mesh density was increased from medium to very fine. Due to using medium mesh density, it was provided to minimize the calculating time and computer memory [15]. Hence, the generated mesh as medium for the finite element model consists of 3255 elements and 26836 nodes, and the created model for the numerical analyses is presented in Figure 3. Moreover, the enhanced mesh refinements were made in areas where structural elements (i.e., pile elements).

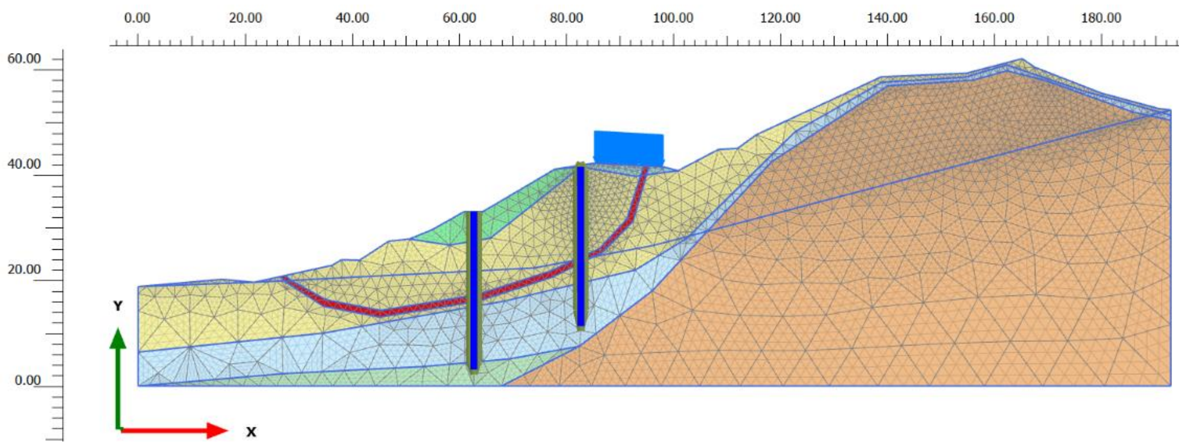
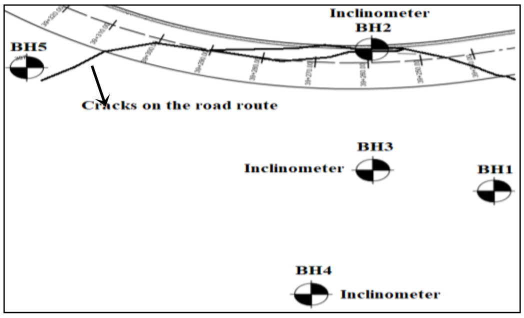


Figure 3. Finite element model with medium mesh density

2.2. Description of Materials in the Slope Problem

The working area is in Adana city and Kozan district, and the area is rich in terms of underground and surface waters. Some field (i.e., standard penetration test, inclinometer, and phreatic level) and laboratory tests (i.e., particle-size analysis, atterberg limits test, soil compaction test, and triaxial shear test) were conducted by the privately held company so as to determine soil profile and the properties of various soils that comprise the slope, and the numerical model was created by considering those test results. Within the scope of field studies, observational investigations were made, boreholes were drilled, in-situ experiments such as standard penetration test were conducted, distributed and undistributed soil samples were taken for the laboratory tests, landslide monitoring studies were carried out as seen in Figure 4(a). For the field investigation, five boreholes (i.e., BH1=30 m, BH2=33 m, BH3=30 m, BH4=21 m, and BH5=30 m) with a total depth of 144 m were drilled within the scope of slope sliding work as presented in Figure 4(b). Furthermore, to observe the movement of the slope, three inclinometer instruments were placed inside the boreholes of 2, 3, and 4.

(a)



(b)

Figure 4. (**a**) Boreholes application and in-situ experiments; (**b**) Boreholes' layout and the cracks on the highway route

According to the results obtained from field and laboratory tests, soil profile has a quite complex variable surface, and there is also a variable phreatic level. Plus, soil profile generally consists of gravel (42%), sand (42%), and silt-clay (16%), and clay content can also increase in some regions. The numerical model created in the light of these investigations are presented in Figure 5 in detail.

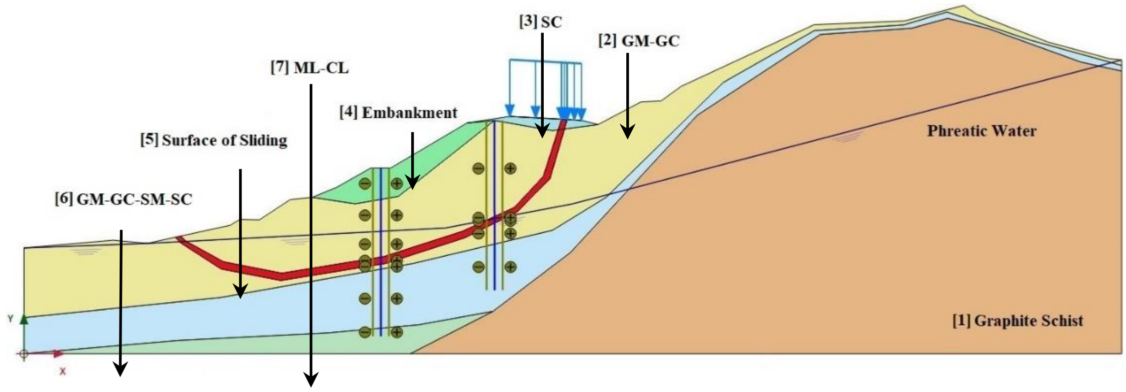


Figure 5. Detailed representation of slope: soil profile, load, and two rows of bored piles

Table 1. The properties of soils regarding for Hardening Soil model

Parameter	Unit	[1]	[2]	[3]	[4]	[5]	[6]	[7]
Unsaturated unit weight, γ_{unsat}	kN/m^3	19	18	18	18	19	18	18
Saturated unit weight, γ_{sat}	kN/m^3	20	19	19	19	20	19	19
Secant stiffness, E_{50}	MPa	150	54	9.6	9.6	5	9.6	150
Tangent stiffness, E_{eod}	MPa	150	54	9.6	9.6	5	9.6	150
Unloading/Reloading stiffness, E_{ur}	MPa	450	162	25	20	15	25	450
Internal friction angle, ϕ	(°)	15	33	30	30	17	30	10
Dilatancy angle, ψ	(°)	0	3	0	0	0	5	0
Cohesion, c	kPa	100	2	5	5	5	0	100
Damping ratio, ξ	(%)	5	5	5	5	5	5	5
Poisson's ratio, ν	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2

It can be seen in that figure the soil profile, a highway subjected to the loads constructed on a slope, two rows of bored piles, and the interface elements representing the interaction between the ground and the pile. Furthermore, the properties of various soils taken into consideration in the numerical analyses are presented in detail in Table 1. Another important effort that needs to be defined in the numerical analyses is to input the pile properties. For this purpose, the plate elements in the length of 30 m and a diameter of 1.5 were created including the material characteristics as given in Table 2. As shown in the table, the properties of the concrete material were assigned for the pile element, and the pile mechanically behaves as a linear elastic material with the damping ratios of 5% generally proposed in concrete applications [16].

Table 2. The material properties of the pile

Parameter	**Unit**	**Value**
Material model	-	Linear elastic
Unit weight of concrete, γ	kN/m^3	24.0
Young's modulus, E	kPa	3×10^7
Damping ratio, ξ (%)	(%)	5.0
Poisson's ratio, v	-	0.2

In order to model of the piles in two-dimensional finite element simulation with plane strain condition, PLAXIS 2D offers a special structural element (i.e., plate element). Finally, to provide the interaction between piles and soils, an average interface coefficient (R_{inter}=0.8 for the interaction between the concrete pile and sand soil according to the structural elements in PLAXIS 2D) value was accepted due to the fact that there were various soil layers along the piles and more than one interface coefficient cannot be entered as an input parameter.

2.3.Pattern of Applied Loads

The pattern of applied loads employed in the study is presented in Figure 6. According to the figure, the highway on the slope was first subjected to a prespecified static load of f_s, afterwards, a repeated load derived in a certain proportion of the applied static load is superimposed to the static load.

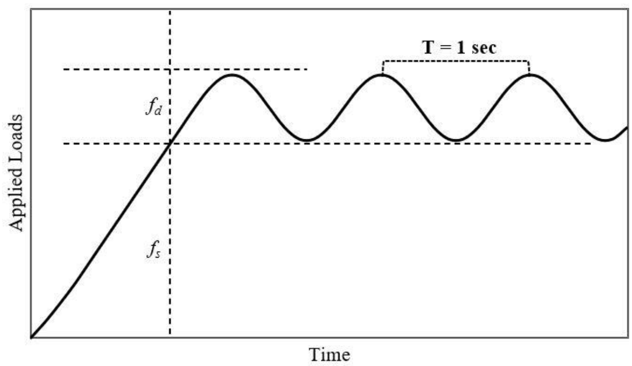


Figure 6. Typical time history of initial static and dynamic loads

The proportion of the repeated load (f_d) was selected as 50% of the prespecified static load. The reason why that proportion was chosen can be explained as relevant proportion represents a significant situation. For example, the proportion values of the repeated load such as 20% and 30% are assumed appropriate for expressing the stresses likely to be experienced or due to the loading of vibrating machines resting on foundations, whereas the value of 50% represents an extreme occurrence [9, 17, 18]. Therefore, such a dynamic load proportion was employed because it was thought that it represented the worst condition.

In road embankment design, the designers encounter some difficulties in determining repeated loads applicable for practical geotechnical analysis. This situation is especially obvious for designing complex geotechnical problems which are pertaining to the structures constructed on weak soils. Plus, since repeated loads have a complex nature, it is difficult to model. However, some examples considering a variety of load values were adopted in different countries such as at least 10 kPa in Finland, 12 kPa in the USA, 15 kPa in the Netherlands, 20 kPa in China, 20 kPa in Australia, and 25 kPa in Poland [19]. Therefore, in the scope of this study, a total load of 30 kPa, which is 10 kPa (f_d) dynamic and 20 kPa (f_s) static, was applied on the slope. It is thought that the static load stems from a structure's own weight (i.e., the weight of the embankment) whereas the dynamic load emerges from the activities over the highway.

3. Findings and Discussion

A series of finite element simulations were performed so as to examine the effect of the improvement method on the slope stability. In the planned improvement method, an application of two rows of bored piles in the length of 30 m and a diameter of 1.5 m was preferred to enhance the safety of the slope. It was aimed to determine the stability safety factor of the slope under a combination of static and dynamic loads, and that value was calculated for the following three cases: (i) for the slope unreinforced with the piles subjected to static loading, (ii) for the slope reinforced with the piles subjected to static loading, (iii) for the slope reinforced with the piles subjected to both static and dynamic loading. The created model in finite element method for this purpose was presented in Figure 3.

The first step in the analyses is to define the calculation type of the initial phase. The available options are "Gravity loading" and "K_0 procedure" to create the initial stress of the soil for the initial phase. In geotechnical engineering, most analysis problems need the specification of initial stresses, and the initial stresses in a soil body are affected by the material weight and its formation history. The stress state is usually determined by an initial vertical effective stress. The initial stresses may be created by employing the "Gravity loading" or "K_0 procedure" in PLAXIS 2D that is the numerical simulation software preferred for this study [20]. However, it is suggested that the "K_0 procedure" should preferably be used in situations with a horizontal soil surface layers and horizontal phreatic levels to the surface. As seen in Figure 7 for all other situations, "Gravity loading" should be used. Therefore, in the numerical analysis performed within the scope of this study for the initial stresses, the option of "Gravity loading" was selected.

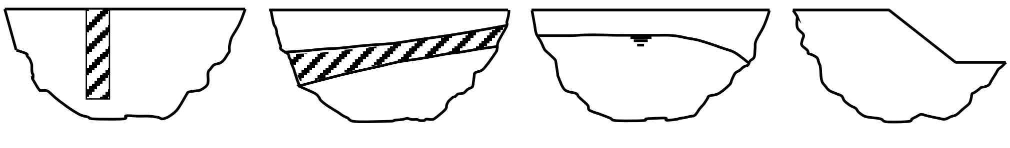


Figure 7. Instances of non-horizontal weight stratifications and surfaces [20]

Following the initial phase, several plastic calculations were performed in order to define the structural elements such as piles, interface elements between pile and soil, and static load. After these phases were completed, there was a safety reduction analysis so as to determine stability safety factor of a slope subjected to static loading. Together with the determination of the safety factor for the static load, the plastic calculation was completed, and the most difficult part of the numerical analysis appeared which was the dynamic analysis part.

In the dynamic analysis phase, the repeated load (i.e., sinusoidal load cycles with the frequency of 1 Hz were continued until the 100 cycles) was become activated. When the previous studies were considered, it was indicated that the largest portion of the settlements occurred after the first ten cycles [17, 18]. Therefore, it was thought that it is more effective to model the 100 cycles in the numerical analyses instead of modelling prolonged load cycles because of some limitations like much time consuming and computational effort. Moreover, modeling this sort of problem subjected to the dynamic load in a computer environment is quite difficult because the dynamic analysis time is highly longer than static analysis time. Following the completion of the implementation of the dynamic load, the last phase was reached where there was another safety reduction analysis so as to determine the stability safety factor of a slope subjected to both static and dynamic loading.

According to the numerical analysis results, the highway constructed on the slope without applying any reinforcement is in danger since the safety factor of the slope was determined to be 1.062 as seen in Figure 8. It was understood that the obtained safety factor value is quite low despite of being greater than 1, and also from the observational investigations, this conclusion was indeed expected to occur since there were encountered some cracks on the highway (see Figure 2), and therefore, an urgent improvement was required to apply to the slope.

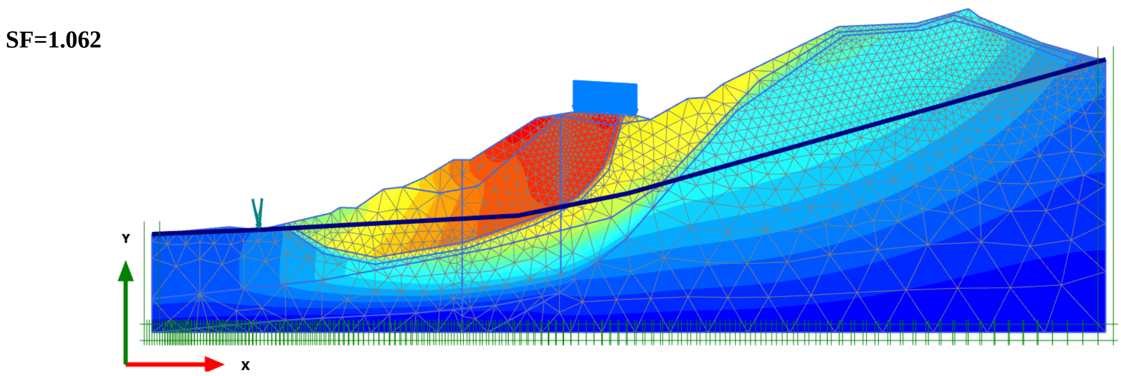


Figure 8. Failure mechanism of the slope with no reinforcement (case i)

Because of the foregoing reason, an application of two rows of bored piles in the length of 30 m and a diameter of 1.5 m was planned to enhance the safety of the slope. After the improvement method was applied, the safety factor of slope under static loading was determined to be 1.446, and accordingly, the slope was become more stable compared to the previous case as seen in Figure 9.

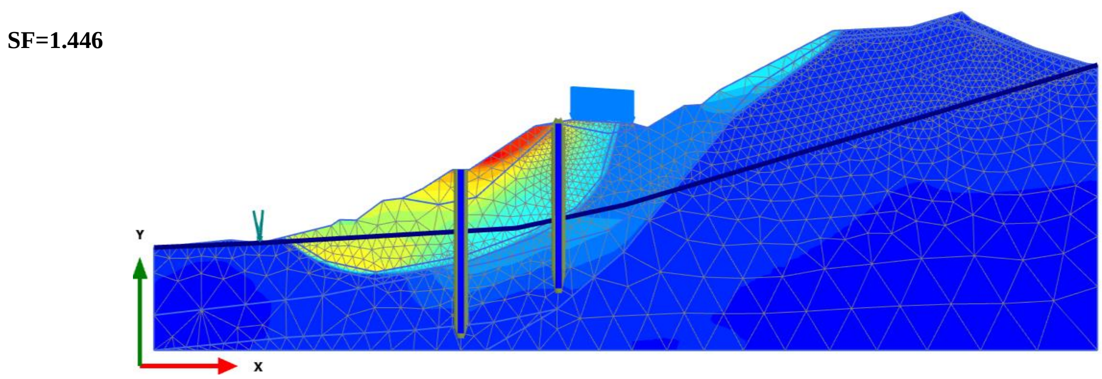


Figure 9. Failure mechanism of the slope reinforced with piles subjected to static loading (case ii)

In the last part of the study, the slope was subjected to both static and dynamic loading, and as a result of this, the safety factor was determined to be 1.104. It was understood that dynamic loading brings about the decrease of the safety factor of slope even though the slope was reinforced with the large-diameter piles. That result indeed is an expected conclusion owing to applying the dynamic load in addition to static load (a total load of 30 kPa, which is 10 kPa (f_d) dynamic and 20 kPa (f_s) static). What is more, by the nature of the dynamic load, this kind of load causes the vibration in the system applied, and this vibration gives rise to more deformation to the contrary of the case in the static loading as seen in Figure 10. When figures related to the failure mechanisms are investigated, the red colour refers to the most affected areas of the slope whereas the blue colour presents the least affected areas of the slope (Figures 8, 9, and 10).

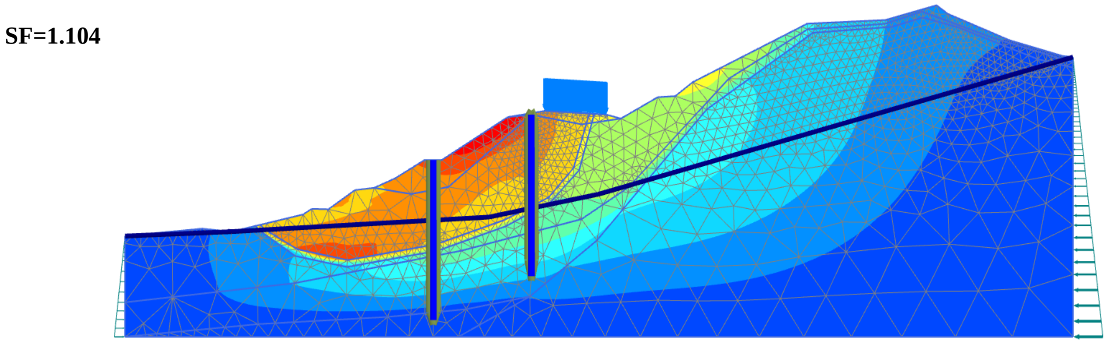


Figure 10. Failure mechanism of the slope reinforced with piles subjected to both static and dynamic loading (case iii)

As understood from the figures, the slope reinforced with the piles under the effect of dynamic loading has more areas in the red shades than the slope under the effect of static loading. Therefore, the dynamic loads (i.e., repeated, or cyclic loads) occurring by the vehicles should be considered in the design of these kinds of problems, and the improvement method should be evaluated in detail so as to enhance the safety factor of a slope. Consequently, the suggested design in this study shows its reliability both static and dynamic loading conditions.

4. Conclusions

Numerical investigations throughout the study for the assessment of safety factor of the slope subjected to the combination of static and dynamic loads are presented in the paper. A series of two-dimensional analyses are conducted by using the finite element method. Viscous (dashpot) boundaries are defined at the model boundaries, and Hardening Soil model is adopted for the proposed methodology with a Rayleigh damping model.

The beneficial findings can be concluded as follows:

- The finite element method is a useful alternative for carrying out slope stability analysis.
- Due to the finite element method, it is possible to clearly illustrate the failure mechanism of a slope under different loading conditions.
- Although it is quite a time-consuming analysis, the sinusoidal dynamic load is effectively modelled in the finite element method.
- The status of the slope unreinforced with the piles subjected to static loading is quite critical since the safety factor is slightly larger than 1.
- Reinforcing the slope with piles subjected to static loading is contributed significantly to the value of the safety factor.
- Superimposing dynamic load to the static load brings about to decrease in the stability safety factor of the slope even though the slope was reinforced with the large-diameter piles.

- The safety factor of the slope reinforced with piles for static loading is determined to be 1.446 whereas the same value for the slope reinforced with piles for static and dynamic loading is calculated to be 1.104. Therefore, dynamic loading caused by the vehicles should be considered in the design of these sorts of problems.

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Authors' Contributions

MT and BE designed the structure of the paper. BU provided the data required for the study. MT, BU, and BE played a significant role in the creating of the numerical model. AY investigated the results obtained from the numerical analyses, and also AY is the overall supervisor of the study.

All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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