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Numerical investigation of the effect of slope angle and height on the stability of a slope composed of sandy soil

Kumlu zeminden oluşan bir şevin stabilitesine şev açısı ve yüksekliğinin etkisinin sayısal olarak incelenmesi

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Abstract
Slope stability issues are very frequently in civil engineering applications and are commonly encountered in huge and significant projects such as dams, highways and tunnels, etc. This study examines the impact of slope height (H) and slope angle (β) on the stability of loose granular soil slope underlined by dense granular soil layer. For this purpose, a number of finite element analyses were conducted on a full-scale soil slope. The computer program Plaxis 2D code was used which is based on the finite element method (FEM). The granular soils were described by non-linear hardening soil model, which is an advanced elastoplastic stress-strain constitutive soil model. Six different slope angles were investigated and for each angle, six different heights were chosen. In total, twelve series of numerical analyses were executed. In the first six series, it was assumed that there is no surcharge load on the top of the slope. In the second six series, the effect of surcharge load was also investigated. According to numerical analysis results, it was found that the slope height and slope angle have a considerable effect on the safety factor (FS) of the slope. It was also noticed that most of the failure surfaces of the slope were circular and classified as face slope failure. It was observed that by increasing slope height and the slope angle, the FS of the slope decreases and vice versa. In addition, curves and charts have been proposed to easily estimate the FS of loose granular soil slope.

Keywords: Loose granular soil, Safety factor, Plaxis 2D, Slope angle, Slope stability

Öz
İnşaat mühendisliği uygulamalarında şev stabilitesi sorunları çok yaygın olup özellikle baraj, otoyol, tünel vb. projelerin uygulamalarında sıklıkla karşılaşılmaktadır. Bu çalışmada, granüler (daneli) sıkı bir zemin tabakası üzerine oturan gevşek daneli bir zemin tabakasının olduğu bir zemin profili esas alınarak şev yüksekliği (H) ve şev açısı (β) değişiminin şev duraylılığı üzerindeki etkileri incelenmiştir. Bu amaçla tam ölçekli bir şevde çok sayıda sonlu elemanlar analizi yapılmıştır. Analizlerde sonlu elemanlar yöntemi (FEM) ile çalışan Plaxis 2D programı kullanılmıştır. İki granüler zemin, gelişmiş bir elastoplastic gerilme-şekil değiştirme modeli olan doğrusal olmayan bir pekleşen zemin modeli (hardening soil model) ile tanımlanmıştır. Altı farklı şev açısı incelenmiş olup her açı için altı farklı şev yüksekliği seçilmiştir. Toplamda on iki seri sayısal analiz yapılmıştır. İlk altı seride şevin tepesinde herhangi bir sürşarj yükü olmadığı varsayılmıştır. İkinci altı seride ise sürşarj yükünün etkisi de araştırılmıştır. Yapılan analizler sonucunda, şev yüksekliği ve eğim açısının şevin güvenlik katsayısı (FS) üzerinde önemli etkileri olduğu bulunmuştur. Analiz sonuçlarına göre, yenilme yüzeylerinin çoğunun dairesel olduğu ve yüzeysel (sığ) kayma olarak sınıflandırılabileceği görülmüştür. Şev yüksekliğinin ve şev açısının artması ile FS'nin azaldığı gözlemlenmiş olup bunun tersi durumda ise FS'nin arttığı görülmektedir. İlaveten, gevşek daneli zeminlerden oluşan şevlerin FS'sini kolayca tahmin etmek için eğriler ve çizelgeler önerilmiştir.

***Anahtar kelimeler**: Gevşek granüler zemin, Güvenlik katsayısı, Plaxis 2D, Şev açısı, Şev duraylılığı*

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1. Introduction

1. Giriş

Slope stability analysis is one of the significant research topics of geotechnical engineering. The reason for this is that slope instability can cause serious loss of life and property, similar to natural disasters such as earthquakes and floods. The stability of all-natural and artificial slopes against collapse under the influence of both their weight and applied loads are generally analysed by limit equilibrium methods based on elastic theory (Taşkıran et al., 2015). However, geotechnical engineers have utilized various methods and techniques for the analysis of earth slopes, some of these methods are Finite Element Method (FEM) based on cohesion (c) and soil internal friction angle (ϕ) reduction, Limit Equilibrium Method (LEM) or Limit Equilibrium Analysis (LEA), Finite Difference Method (FDM), Limit Analysis (LA), and combination of Finite Element Method and Finite Difference Method (Jha et al., 2018). Slope stability issues are extremely prevalent and ubiquitous. Large and significant projects such as dams, highways, and tunnels, are particularly prone to slope stability issues (Pourkhosravani & Kalantari, 2011). Slope stability issues can result in significant social and economic losses (Halder et al., 2020). In geotechnical projects such as Cuts, fills, dams and road embankments, it is necessary to do slope stability analysis because it does concern the safety of human life and properties. Therefore, sufficient inspections, remedies, and engineering solutions have to be supplied for slopes to prevent possibly devastating collapse (Shiferaw, 2021). Kanık (2019) used FEM for the slope stability of the abutments of Ayvali Dam (NE, Turkey) and determined how well the obtained results corresponded to the situations that emerged after the dam construction was completed. Kaya et al. (2016) used the LE method to study the stability assessment of high-steep cut slope debris on a landslide around the vicinity of Gümüşhane Imam-Hatip High School in NE Turkey. Slope stability analysis is one of the most important subjects in geotechnical engineering (Yang & Huang, 2009). Slope geometry, soil type, shear strength properties of soil, soil stratification, groundwater condition, and seepage have a considerable impact on slope failure, that's why it is important to consider all of these parameters while the analysis of slope stability (Halder et al., 2020).

From the past until today, many authors have worked on slope stability problems and they have developed various methods for estimating the FS of the slope involving computer-based finite element analysis methods. However, among all of these methods, none is recommended above the others, that's why most of the time engineers use their experience and engineering judgment for the reliability of any solution (Albataineh, 2006). In slope stability analysis, the common problem of engineers is to locate the critical slip surface of the slope while using hand calculations. There are some approaches suggested by various researchers to locate the critical failure slip of the slope (Boutrup & Lovell, 1980; Siegel, 1975; Goh, 1999; Zolfaghari et al., 2005; Bolton et al., 2003; Cheng, 2003). Nonetheless, many engineers would rather have to utilize their expertise to discover the most critical failure surface of the slope, and then use trial and error processes to estimate the FS. Currently, there are many commercial software packages, so with the help of such software, the analysis of slope stability is done more easily by mathematical modelling. Nowadays, mathematical models are used in a variety of disciplines, including civil engineering also, to predict certain natural behaviours (Akbaş, 2015; Alemdag et al., 2015; Awlla et al., 2020; Keskin et al., 2022; Awla & Karaton, 2021). When finite element method analysis is used for determining the FS of the slope, it does not need to make a previous assumption about the critical failure surface. In numerical analysis, the strength reduction method is used for calculating FS, in this technique, the shear strength parameters of the soil are decreased in stages until soil failure happens. After that, the FS of the slope is determined as the proportion of the actual properties of the shear strength of the soil and the reduced (critical) shear strength parameters of the soil. In the strength reduction method, the FS is defined as in equation (1) (Griffiths & Lane, 1999);

$$FS = \frac{\tan \phi_{input}}{\tan \phi_{reduced}} = \frac{c_{input}}{c_{reduced}} \quad (1)$$

Taşkıran et al., (2015) investigated the applicability of the Strength reduction method by using Plaxis 2D and 3D program code which is based on the Finite Element Method for analysis of slope stability problems. In addition, slope stability analyses were also carried out using the Limit Equilibrium Method (LEM) and the FS obtained from both methods were compared. It was found that the FS values obtained with the three-dimensional slope model were greater than the value obtained in the two-dimensional case, and the FS values obtained by the strength reduction technique were in harmony with the FS values obtained by the limit equilibrium methods. Many researchers have used this method for slope stability analysis and it has been incorporated into various commercial program codes (Dawson et al., 1999). Generally, the Mohr-Coulomb failure criterion is used in the phi-c reduction method, and the definition of FS in this method is in good agreement with the equilibrium method. The researchers state that the results of the two methods are approximately the same, however, the limit equilibrium results are somewhat conservative (Djilali et al., 2017; Azadmanesh & Arafati, 2012; Khabbaz et al., 2012). When analysing slope stability, engineering properties of the soil, slope geometry, and groundwater situations are usually taken into account. This points up that the significance of the slope geometry in estimating the FS (Shepheard et al., 2017).

There are various techniques that can be used for slope stabilization, Broms and Wong, (1985) classified slope stabilization as structural and geometric. Geometric methods include reducing the angle and height of the slope, as the angle of the slope (β) is reduced from a steep slope to a gentler slope, thereby obtaining the higher FS of the slope. By decreasing the slope height (H), the FS is also increased because the driving force of gravity is reduced, causing the slope to collapse. Many researchers have used soil improvement to study the behaviour of the reinforced slope stability soil using different types of materials (Anvari et al., 2017; Li et al., 2020; Aksoy et al., 2021a; Aksoy et al., 2021b). A number of researchers have studied a few case studies of slope failure and performed static and dynamic analysis using numerical analysis and compared to analytical methods to better understand the slope failure mechanism (Huvaj & Oğuz, 2018; Tien Bui et al., 2019; Moayedi et al., 2019; Awlla et al., 2020; Gör, 2021; Gör et al., 2022).

There are many methods and techniques to improve the stability of slopes, and modifying the geometry of the slope is one of the options. This article aims to investigate the influence of the geometry of the slope (slope angle and height of the slope) on the stability of the slope of a loose granular soil resting on dense soil. Parametric studies are slope angle (H:V), slope height (H) and surcharge load on the top of the slope.

2. Numerical modelling and analysis

2. Sayısal modelleme ve analiz

In this study, Plaxis 2D program code was used which is based on finite element method program. Because it is not easy to do the experimental test for the large-scale slope in the field and in the laboratory as well, which is why FEM was used in this study. Plaxis is one of the powerful programs which can help users in characterizing geotechnical problems in a realistic manner. The stability of a structure during and after construction may be assessed using staged construction analysis (Sharma et al., 2019). This study investigates the effect of height and slope angle on the stability of loose granular soil slope underlain by dense granular soil. For this purpose, a series of finite element analyses were done. The two-dimensional finite element method was used with 15-node plane strain model using the Plaxis 2D computer program. Each series was carried out to discover the influence of one parameter while the other parameters were kept unchanged. The varied parameters include the slope angle, height of the slope, and surcharge load on the top of the slope. All of the numerical analysis programs with various parameters are summarized in Figure 1 and Table 1.

In this study, the hardening soil model was used to model the nonlinear behavior of the soil. This constitutive model is one of the advanced soil models and is used to simulate various types of soil. The material properties of the loose and dense granular soils were taken from Plaxis 2D material model manual and are summarized in Table 2. The sufficiently fine mesh was used to reduce the effect of mesh dependence on numerical analysis results. Figure 2 displays the typical generated mesh for full-scale slope geometry and boundary conditions. The vertical boundaries of the model were supposed to be deformable vertically and fixed laterally, whereas the bottom boundary was assumed to be definitely fixed. In this study, it is assumed that the water table is located below the dense soil layer and this has no effect on the results of the analysis. Since the surface of the slope is not completely horizontal, therefore the first stress state of the slope was produced by employing the force of gravity and after that, the safety analysis was applied to determine the FS of the slope in each series. To decrease the percentage of error in the numerical analysis, in all the phases of calculation, the tolerated error was set equal to 0.001.
In Plaxis, the FS for the slope is calculated using phi-c reduction calculation type, which decreases the shear strength parameters of the soil, cohesion (c) and angle of internal friction (ø) in steps until the failure takes place in the soil body, as in the following equation 2:

$$\sum Msf = \frac{\tan \phi_{input}}{\tan \phi_{reduced}} = \frac{c_{input}}{c_{reduced}} \quad (2)$$

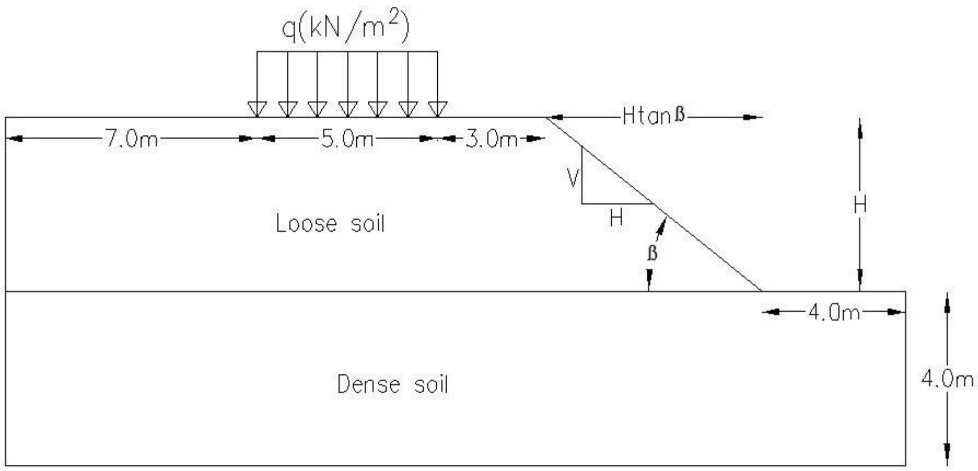

Figure 1. Geometric parameters studied in numerical analyses
Şekil 1. *Sayısal analizlerde çalışılan geometrik parametreler*

Table 1. Numerical analysis parameters
Tablo 1. *Sayısal analiz parametreleri*

Series	Constant parameters	Variable parameters
1	Slope (1.25H:1V) q = 0 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
2	Slope (1.50H:1V) q = 0 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
3	Slope (2.0H:1V) q = 0 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
4	Slope (2.5H:1V) q = 0 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
5	Slope (3.0H:1V) q = 0 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
6	Slope (3.5H:1V) q = 0 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
7	Slope (1.25H:1V) q = 10 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
8	Slope (1.50H:1V) q = 10 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
9	Slope (2.0H:1V) q = 10 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
10	Slope (2.5H:1V) q = 10 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
11	Slope (3.0H:1V) q = 10 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)
12	Slope (3.5H:1V) q = 10 kN/m^2	H = 1, 2, 4, 6, 8, 10 (m)

Table 2. Parameters of the sand used in FEM analyses (Brinkgreve et al., 2016)
Tablo 2. *FEM analizlerinde kullanılan kumun parametreleri (Brinkgreve et al., 2016)*

Parameters	Dense sand	Loose sand
Dry Unit Weight (γ_d) (kN/m^3)	17.50	17.00
E_{50}^{ref} (P_{ref} = 100 kPa) (kN/m^2)	37000	20000
E_{ur}^{ref} (P_{ref} = 100 kPa) (kN/m^2)	90000	60000
E_{oed}^{ref} (P_{ref} = 100 kPa) (kN/m^2)	29600	16000
Cohesion, (c) (kN/m^2)	5.00	2.50
Friction angle, (ϕ) (^{0})	41.0	34.0
Dialatancy angle (ψ) (^{0})	14.00	0.00
Poisson's ratio (ν_{ur})	0.20	0.20
K_0^{nc}	0.34	0.44
m, Power	0.50	0.65

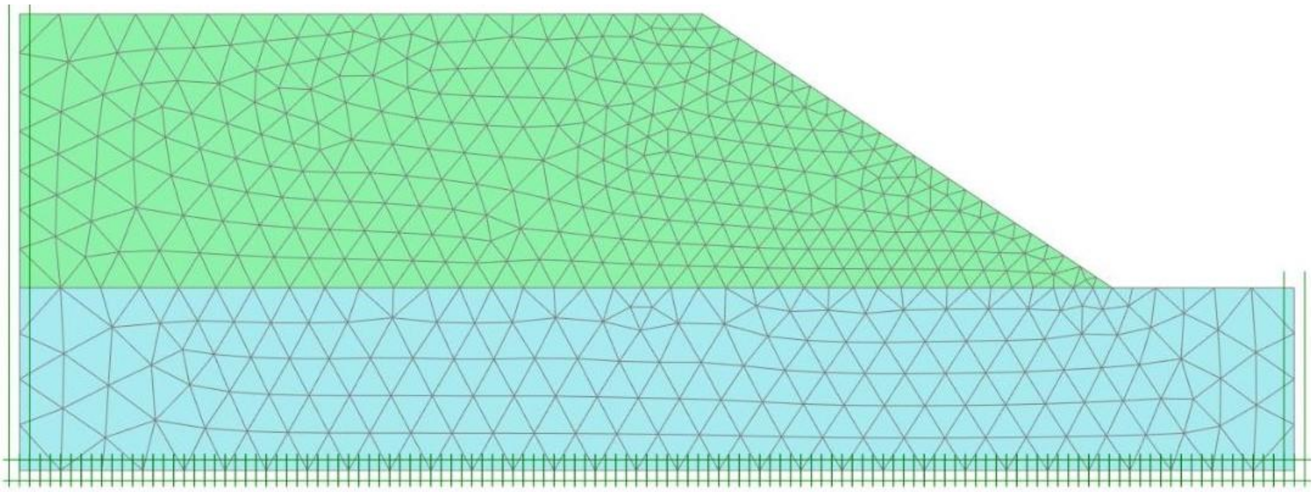

Figure 2. Typical generated mesh for prototype slope geometry
Şekil 2. *Prototip şev geometrisi için tipik olarak oluşturulan ağ*

3. Results and discussion
3. Bulgular ve tartışma

A total of seventy-two numerical analysis tests were conducted on the effect of slope angle and the height of the slope on the stability of loose granular soil slope underlying dense soil. The influence of slope height and angle was achieved and discussed.

3.1. Effect of slope angle and height (with no surcharge load - q = 0 kN/m^2)
3.1. Şev açısı ve yüksekliğinin etkisi (sürşarj yükü olmadan - q = 0 kN/m^2)

In order to determine the effect of slope angle and height on slope stability with zero surcharge load at the top of the slope, thirty-six numerical analysis tests were performed. Six slope angle geometries were studied and for each slope angle geometry, six different slope heights were also investigated. Figure 3 shows the change of FS of the slope with slope angle and height. It can be seen that with the steepest slope and the highest height, the FS is the minimum. Also, with the gentlest slope angle and the minimum height, the FS is the maximum. This considerable influence of slope geometry on slope stability was also found in (Shiferaw, 2021). Since it can be said that the geometry of the slope has a considerable effect on the stability of the slope, therefore to avoid any slope failure, the geometry of the slope must be built in such a way that it can have a high safety factor. For a better understanding of how the angle and height of the slope affect the FS of the slope, a graphical representation using a histogram has been made, as shown in Figure 4. Figure 5 displays the percent increase in FS between the steepest and gentlest slopes for different heights. It can be seen that the FS increases greatly when the slope angle is changed from steepest (1.25H:1V) to the most gentle one (3.5:1V). It can be noticed that as the height of the slope increases, the percentage increase in FS also increases. According to the numerical analysis obtained in this study, most of the failure surface was circular and a little bit above the toe of the slope and classified as face slope failure, as shown in Figure 6. This is because the soil used in this study is loose granular soil and it easily collapses at the face of the slope.

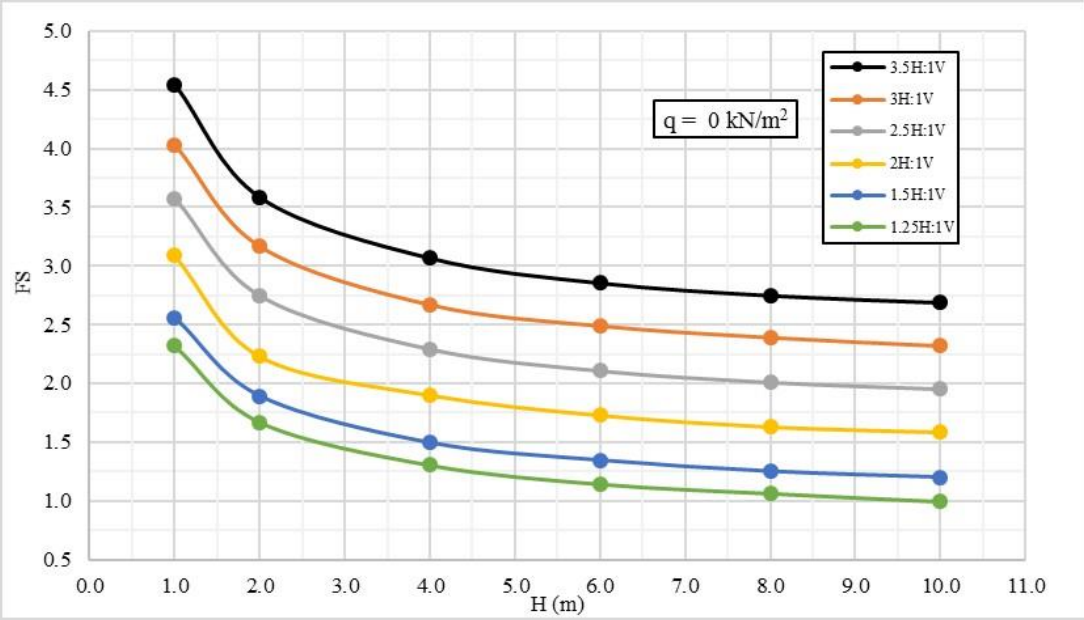

Figure 3. Variation of FS of the slope with various slope angles and heights for q = 0 kN/m^2
Şekil 3. *q = 0 kN/m^2 için FS'nin çeşitli şev açıları ve yükseklikleri ile değişimi*

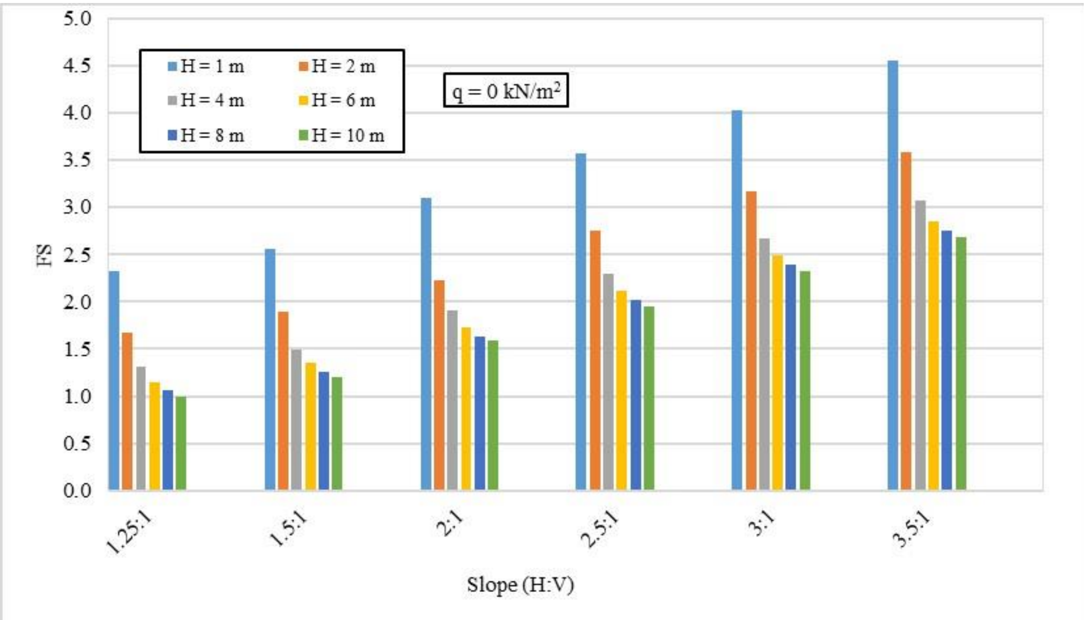

Figure 4. Graphical representation of the change in FS of the slope with the different angles and heights of the slope for q = 0 kN/m^2
Şekil 4. *q = 0 kN/m^2 için farklı şev açıları ve yükseklikleri ile FS değişiminin grafiksel gösterimi*

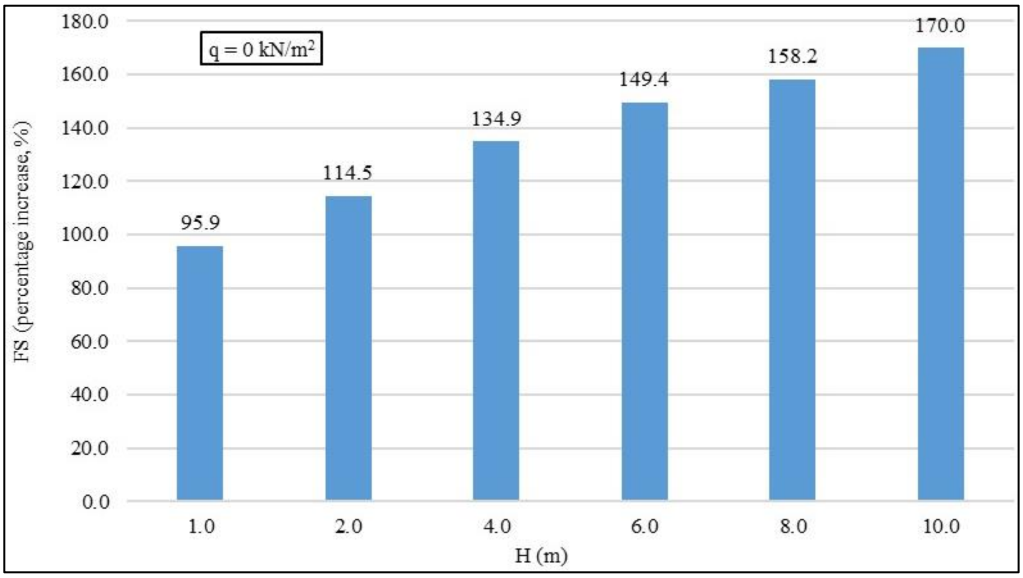

Figure 5. Percentage of increase in FS between the steepest (1.25H:1V) and gentlest (3.5H:1V) slopes for q = 0 kN/m^2

Şekil 5. *q = 0 kN/m^2 için en dik (1.25H:1V) ve en az eğimli (3.5H:1V) şevler arasında FS'deki artış yüzdesi*

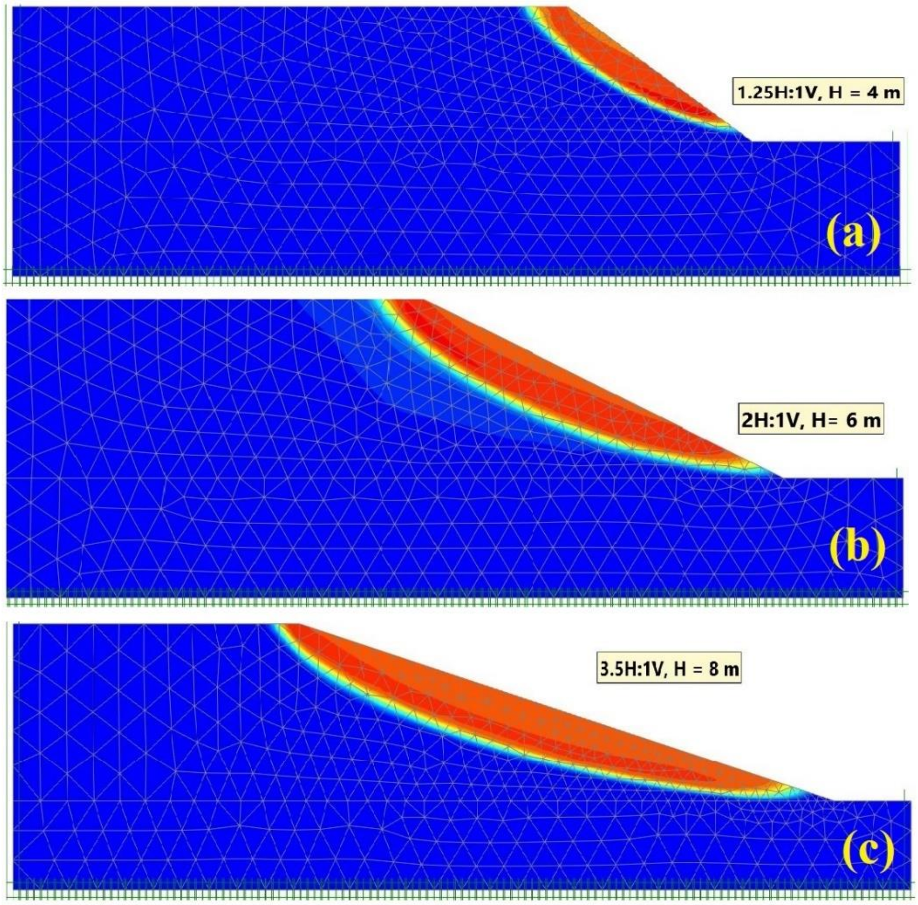

Figure 6. Typical failure of the slope surfaces obtained from a numerical analysis based on the strength reduction method

Şekil 6. *Mukavemet azaltma yöntemine dayalı sayısal bir analizden elde edilen şev yüzeylerinin tipik yenilmesi*

3.2. Effect of slope angle and height (with surcharge load - q = 10 kN/m^2)

3.2. Şev açısı ve yüksekliğinin etkisi (sürşarj yükü olduğunda - q = 10 kN/m^2)

To also study the effect of the surcharge load, it was also assumed that there is a surcharge load of 10 kN/m^2 at the top of the slope and 3.0 m away from the crest of the slope. For this purpose, again six slope angle geometries were studied and for each slope angle geometry, six different slope heights were also investigated. Figure 7 shows the change of FS of the slope with various slope angles and heights. It can be seen that with an existing surcharge load at the top of the slope, the FS is decreased relative to the slope with zero surcharge load at the top. Just as for the slope condition with no surcharge load, the steepest slope with the highest height, the FS is the minimum and the gentlest slope with the minimum height, the FS is the maximum. This indicates that the slope geometry has a great influence on slope stabilization in both situations with existing surcharge load and also with no surcharge load. Figure 8 illustrates the graphical chart which shows the change in FS of the slope with different slope geometry and with existing surcharge load. Figure 9 presents the percentage increase in FS between the steepest and gentlest slopes for different heights with existing surcharge load on the top of the slope. As in the case with no surcharge load, the FS increases greatly when the slope angle is changed from steepest (1.25H:1V) to gentlest (3.5:1V).

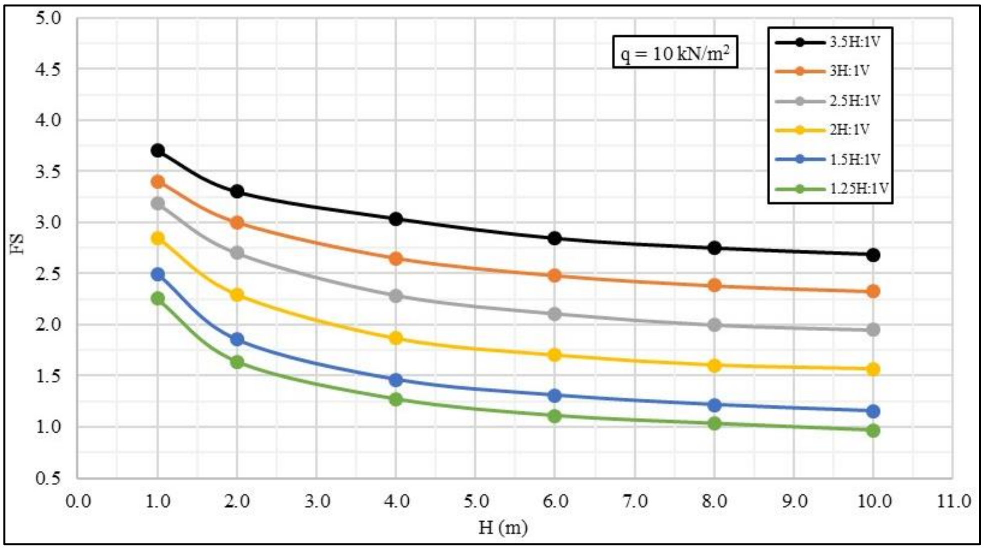

Figure 7. Variation of FS of the slope with various slope angles and heights for q = 10 kN/m^2
Şekil 7. *q =10 kN/m^2 için FS'nin çeşitli şev açıları ve yükseklikleri ile değişimi*

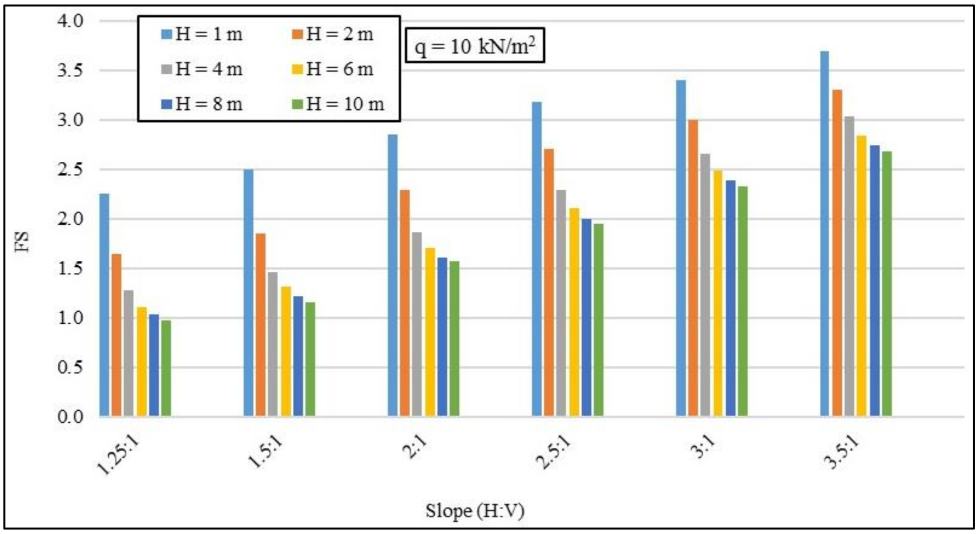

Figure 8. Graphical representation of the change in FS of the slope with the different angles and heights of the slope for q = 10 kN/m^2
Şekil 8. *q = 10 kN/m^2 için farklı şev açıları ve yükseklikleri ile FS değişiminin grafiksel gösterimi*

Huang (1983) recommended minimum FS for slopes under different conditions. Many design FS in slope stability analysis cannot be identified with precision. As a result, in a chosen design, a level of risk should be determined. The factor of safety fulfills this requirement. The factor should take into account not only the uncertainties in design parameters but also the results of failure. A higher risk of failure or a lower factor of safety may be acceptable if the consequences of failure are minor.

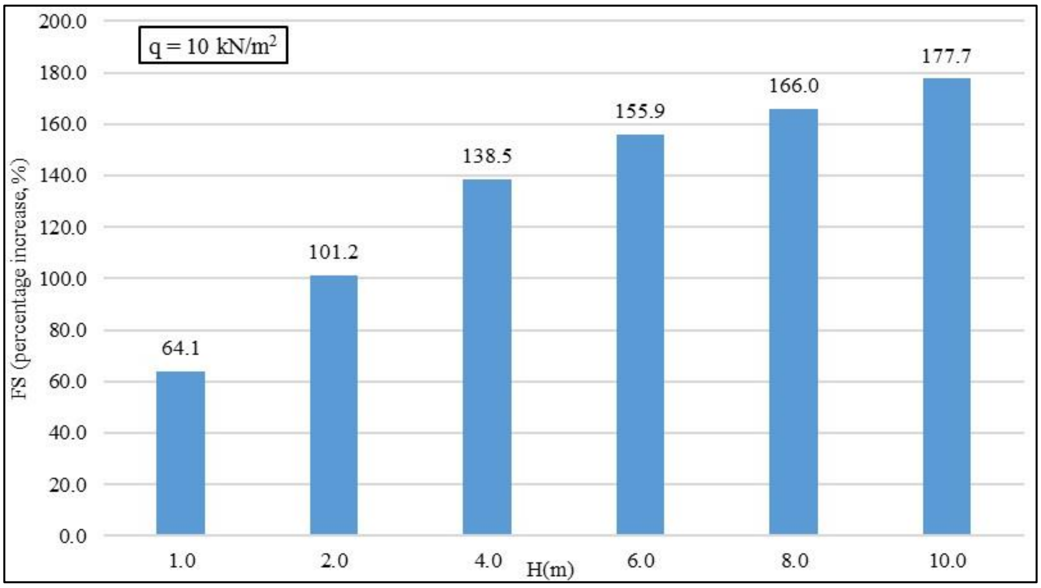

Figure 9. Percentage of increase in FS between the steepest (1.25H:1V) and gentlest (3.5H:1V) slopes for q = 10 kN/m^2

Şekil 9. *q = 10 kN/m^2 için en dik (1.25H:1V) ve en az eğimli (3.5H:1V) şevler arasında FS'deki artış yüzdesi*

4. Conclusion and recommendations

4. Sonuçlar ve öneriler

In this study, the influence of slope angle (β) and slope height (H) on the stability of loose granular soil slope resting on dense soil layer was studied. The studied parameters were slope angle, the height of the slope, and the existing surcharge load on the top of the slope. According to the numerical analysis results, the following conclusion can be drawn.

- According to the numerical analysis results, it was found that the slope angle (β), the height of the slope (H), and existing the surcharge load (q) on the top of the slope have a great influence on the stability of the slope.
- As the height of the slope and slope angle increase, the FS of the slope decrease in both cases; slopes with and without surcharge load and vice versa.
- When the surcharge load exists at the top of the slope, the FS decreases for the same slope geometry compared to the same slope without surcharge load at the top of the slope.
- As the geometry of the slope changes from a steep slope to a gentler slope, the FS increases dramatically. for example, in the case without surcharge load, when the slope changes from (1.25H: 1V) with H = 10m to the slope (3.5H: 1V) with H = 10m, the percentage increase of FS is equal to 170.0%.
- The proposed curves and graphs in this study can be used to easily estimate the FS of loose granular soil.
- Based on the strength reduction methods, it was found that all slip failure surfaces were classified as face slope failure for loose granular soil slope.
- In this study, it was found that the minimum FS is one. However, when the FS is one, the slope is safe under certain conditions, but in some cases, it is not safe when the slope is subject to rainfall or an earthquake and especially when there is a danger to people's lives.

This study examines the effect of slope geometry on slope stabilization of loose granular soil underlying dense granular soil. Due to the importance of the study, the authors recommend studying the influence of the slope geometry on the stabilization of the slope for the different types of soil and slope with stratified soils and with the existing water table.

Author contribution
Yazar katkısı

Nichirvan Ramadhan TAHER and Mesut GÖR: Methodology, Software, Data collection and/or processing, Data analysis and interpretation, Writing - original draft.
Hüseyin Suha AKSOY and Halmat Ahmed AWLLA: Literature search, Critical revision of manuscript, Writing - review & editing.

Declaration of ethical code
Etik beyanı

The authors of this article declare that the materials and methods used in this study do not require ethical committee approval and/or legal-specific permission.

Conflicts of interest
Çıkar çatışması beyanı

The authors declare that there is no conflict of interest.

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