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STABILITY ANALYSIS OF STONE COLUMN SLOPES UNDER DIFFERENT EARTHQUAKE LOADS

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Abstract: How a slope behaves under the action of a dynamic load such as an earthquake is of great importance in stability analyses of slopes. Improving the region where slope failure occurs or preventing potential slope failure can lead to reducing the factors that excite movement in a slope and/or increasing the sliding resistance of the soils. In this study, the stone column method was used as an improvement technique. In the analysis performed with Plaxis 2D, safety factors were defined for slopes with different slope angles, soil cohesion, and three different earthquake magnitudes. Later, the slopes with the same characteristics were improved using the stone column method. The slopes were improved with different s/D ratios and different internal friction angles of the stone column. The same earthquake forces were also applied to the improved slopes and the factors of safety were determined.

In the study, slope models with stone columns designed without the effect of earthquake force showed an increase in safety values in the range of 1.01to 1.34 times compared to slope models without stone columns. It was found that the safety values of the slope models with stone columns increased by 1.02-1.80 times compared to the slope models without stone columns under the effect of earthquake force.

Keywords: Acceleration, Earthquake forces, Slope stability, Stone columns, Finite Element Analysis

Farklı Deprem Kuvvetleri Altında Taş Kolonlu Şevlerin Stabilite Analizi

Öz: Bir şevin deprem gibi dinamik bir yükün etkisi altında nasıl tepki verdiği, şevlerin duraylılık analizlerinde çok önemlidir. Bir şev göçmenin meydana geldiği bölgeyi iyileştirmek veya olası bir şev göçmesini önlemek, bir şevde hareketi teşvik eden faktörlerin azalmasına ve/veya zeminlerin kayma direncinin artmasına sağlar. Bu çalışmada iyileştirme tekniği olarak Taş Kolon yöntemi kullanılmıştır. Plaxis 2D ile yapılan analizde, farklı şev açıları, zemin kohezyonu ve üç farklı deprem kuvveti ile modellenen şevlerin güvenlik faktörleri belirlenmiştir. Daha sonra aynı özelliklere sahip şevler taş kolon yöntemi ile iyileştirilmiştir. Eğimler, farklı s/D oranları ve farklı taş kolon iç sürtünme açıları kullanılarak iyileştirilmiştir. Aynı deprem kuvvetleri iyileştirilmiş şevlere de uygulanmış ve güvenlik faktörleri bulunmuştur.

Çalışmada, deprem kuvvetinin etkisi olmadan tasarlanan taş kolonlu şev modelleri, taş kolonsuz şev modellerine göre güvenlik değerlerinde 1.01-1.34 kat arasında bir artış göstermiştir. Taş kolonlu şev modellerinin güvenlik değerlerinin, deprem kuvvetinin etkisi altında taş kolonsuz şev modellerine göre 1,02-1,80 arttığı görülmüştür.

Anahtar Kelimeler: İvme, Deprem kuvvetleri, Şev stabilitesi, Taş kolonlar, Sonlu Elemanlar Analizi

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1. INTRODUCTION

A naturally or artificially formed slope, which is one of the most important topics in soil mechanics, is an inclined mass of soil that forms a certain angle with the horizontal surface. With the recent population growth, it has become a necessity for people to live on the hills and slopes that pose the risk of landslide. For similar reasons, there has been an increase in the number of embankments constructed on the slopes for specific reasons such as expanding residential areas and meeting water, irrigation, and electricity needs (Karikari and Agyei 2000). The ever-increasing number of embankments and dams poses serious risks. When embankments and dams are not properly designed and the necessary precautions are not taken to stabilize natural slopes, the soil mass that forms the slope slides downward, and the ground subsidence results in loss of life and property.

In recent years, with the development of computer programs, finite element programs have been used for slope stability analysis (Kohgo and Yamashita 1998). The advantages of finite element programs over other conventional limit equilibrium methods are as follows: Location and shape of the taper of the failure surface; no assumptions about strength and direction are required; and these programs are safer and more economical than other methods of numerical analysis at the design stage when the excavation and construction stages and other influences on the soil are considered. In addition, the finite element method can be applied to all types of collapse mechanisms in two or three dimensions under various soil, boundary, and loading conditions, as well as to complex slope geometries.

In this study, the Plaxis 2D program, one of the finite element programs, was used. In the Plaxis 2D program, the slope stability analysis is solved using the strength reduction approach (phi/c reduction method). In this approach, a solution is obtained by reducing the shear strength parameters (c and tanϕ) of the soil to the breakthrough level (Plaxis 2D Finite Elemet Program (1987)). A review of studies in the literature shows that the limit equilibrium methods (Spencer, Bishop, and Janbu) and the finite element method provide very similar values for the factor of safety in slope stability analysis (Griffiths, 1999).

Another focus of this study is how a geometric slope behaves under the action of an earthquake force. In general, soils have different physical properties, resistivities, and loading characteristics. Accordingly, the soil may generally behave differently under the influence of a dynamic load, such as an earthquake. In one study, it was reported that the deformation increases, the stiffness decreases, and the soil softens after the internal structure of clays with low plasticity is broken due to the increased pore water pressure under the influence of cyclic loading (Oezay and Erken 2003). The behaviour of clays with low plasticity under repeated loading. Similarly, it has been observed in various studies that the strength properties of soil masses deteriorate under the influence of an earthquake, a dynamic loading, depending on the magnitude of the loading and the duration of the exposure (Seed and Chan 1966; Thiers and Seed 1969; Ogawa et al. 1977; Ansal and Erken 1986; Hack et al. 2007). Numerous studies have been conducted to investigate how slopes behave during earthquakes and what precautions should be taken. In a study conducted in 2008, the authors of the study focused on the strengthening of slopes affected by seismic stability and tried to explain the methods and techniques to improve the slopes that are unsuitable in terms of safety, with a seismic stability analysis using the pseudostatic approach (Malhotra and Lee 2008). In a study conducted in 2012, the safety factors and horizontal earthquake acceleration coefficient (kh) of the embankments model on which two channels is located were investigated by performing an earthquake analysis in different earthquake zones (Chatterjee and Choudhury 2012). In a study conducted in 2014, a dynamic analysis of the foundations adjacent to the sand embankments, which are generally prone to earthquakes, was performed using the finite element method (Azzam 2014). Most of the studies investigated the behavior of unconsolidated slopes under the action of earthquake forces (Kumar 2008; Malhotra and Lee 2008; Chatterjee and Choudhury 2012; Azzam 2014; Bray and Travasarou 2011; hosh 2014; Kontoe et al. 2013; Melo and

Sharma 2014; Nadı et al. 2014; Presti et al. 2014; Yang et al. 2014; Karray et al. 2017; Jia 2017; Qin and Chiaa 2018). The main point that distinguishes this study from the other studies mentioned in the literature is the evaluation of how the stability condition changes under earthquake load action by using a pseudostatic method (in the 2D finite element program Plaxis) in an improved (over stone column) clay slope.

If the analyzes reveal a slope stability problem, slope stability can be achieved by numerous improvement methods (surface drainage, relief, stabilization with the wall, equipment of the slope, excavation, underpinning, soil compaction, stone columns, planting, etc.). The stone column technique, which is also used in the study as a healing method, is one of these methods. (Numerous studies have been conducted on the stability of slopes and split slopes, and stone columns have been used to improve them (Connor and Gorski 2000; White et al. 2002; Kirscha and Sondermann 2003; Plomteux and Porhaba, 2004; Deb et al. 2008; Vekli et al. 2012; Zhang et al. 2014; Fathi and Mohtasham 2016; Çadır et al. 2021). In addition to the use of stone columns for slope stability, numerous studies have also been conducted on their usability under the action of earthquake loads. In these studies, it was shown that stone columns can also be used under the action of earthquake loads. (Adalier and Elgamal 2004; Al-Homoud and Degen 2006; Kim et al. 2012; Ryu and Kim 2013; Raju et al. 2013; Zhan et al. 2014; Salahi et al. 2015; Tang et al. 2015; Pal and Deb 2018; Lu et al. 2018; Hasheminezad and Bahdori, 2019; Çadır et al. 2021). Reviewing the studies, it can be seen that recently the behavior of slopes under the influence of earthquake forces has been investigated in addition to static forces. Many countries, including Turkey, are located in earthquake zones. Therefore, it is of utmost importance how stone columns behave under a dynamic force such as an earthquake, taking into account the improvement measures taken. The research and studies conducted show that stone columns used for soil improvement reduce soil deformation during severe seismic actions (Kim et al. 2012; Ryu and Kim 2013). In addition, it has been shown that stone columns can withstand greater shear stress than the surrounding soil under the influence of seismic actions, which can be used in calculating the reduction of shear stress applied to the soil by seismic waves (Kim et al. 2012; Ryu and Kim 2013). Improvement methods such as stone columns and gravel-filled trenches can increase the average friction by placing them on the sliding surface and at the base of the slope (Baez 1995). This maintains the stability of the slope. At the same time, a drainage unit for the slope is created in this case (Baez 1995; Bromhead 1986). From this perspective, the effectiveness of stone columns can be manifested by reducing seismic loading on the soil and achieving drainage and soil compaction effects during movement (Ryu and Kim 2013; Baez 1995; Bromhead 1986; Abramson 1996).

In the earlier studies described above, many investigations were conducted to determine how soils improved with stone columns will behave under the influence of earthquakes. However, it was found that the study of the stability (safety situation) of a slope reinforced with stone columns under the action of earthquake force is incomplete considering various parameters. From this point of view, in this study, unlike the other studies mentioned above, slopes of soft soils reinforced with stone columns were improved from the slope surface and their stability under the action of various earthquake forces was investigated. In the study, factors of safety were obtained by analyzing the slopes without and with In the study, factors of safety were obtained by analysing the slopes without and with stone columns with different earthquake forces (a=1.795 m/s^2, a=2,928 m/s^2, a=3.810 m/s^2) cohesion (c:10 kN/m^2, 15 kN/m^2) and the angle of slope (β:20°, 25°) using Plaxis 2D program. Later, the factor of safety was determined at the same slope angle under the influence of earthquake forces. Then, after improving the slope with stone columns, slope analyses were performed at different internal friction angles (ϕs:35°,40°), different s/D intervals (s/D: 2, 3), and at the same cohesion ratio (c:10 kN/m2, 15 kN/m2) and slope angle, and the safety factor was calculated. Finally, the factor of safety of the slope improved with the stone columns was calculated under the influence of the earthquake forces at the same parameters. As a result of the study, the behaviour of slopes with and without stone columns under the influence of different earthquake forces was compared using the Plaxis 2D program.

2. METHODOLOGY AND FINITE ELEMENTS ANALYSES

2.1. Safety Factor without Earthquake Load

Primarily, the slopes without and with stone columns were modelled via Plaxis 2D finite elements programme without earthquake force. In the programme, a one-layer soil mass with a slope angle of (β) 20°- 25°, slope width of 25 m, slope heights of 5 and 10 m and total slope height of 18 m was modelled. Then in the slopes with the same properties were modelled at different s/D intervals (2, 3) and after being improved with stone columns (Figure 1).

The boundary conditions of the model are fixed at the side walls in x-direction, free in y-direction, free at the top of the slope in x- and y-direction and free at the bottom of the slope in x- and y-direction. All models with and without stone columns are modeled as triangular elements with 15 nodes, considering the model type "plain strain". The element distribution was chosen as medium and the average element size was 1 m. While the average number of elements is 1300 and the average number of nodes is 1500 for models without stone columns, the average number of elements is 1500 and the average number of nodes is 1800 for models with stone columns.

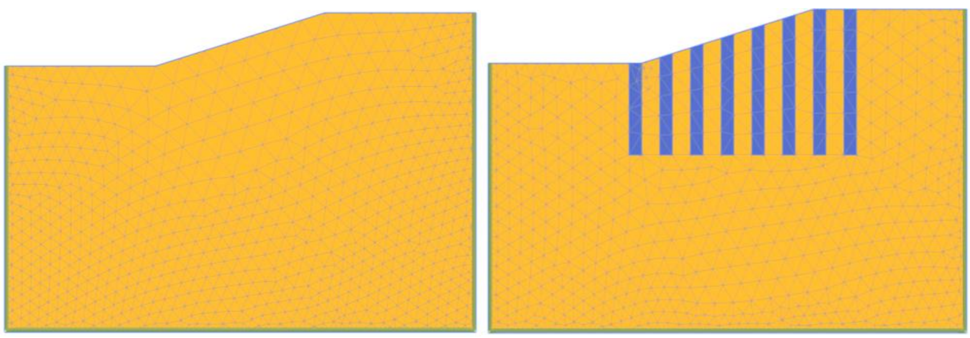


Figure 1:

Creating the mesh in geometric models of slope supported and not supported with stone columns.

The properties of the materials used in the model are listed in Table 1. The Mohr-Coulomb material model was used to model soil behaviour in the programme. The Mohr-Coulomb material model is widely used in geotechnical engineering. This material model was preferred because it requires a total of 5 parameters that are widely used and can be determined by simple laboratory experiments on soil samples (Table 1).

After all the works were completed, the models of the slope without and with stone columns were analysed, and at the end of the analysis, the values of the safety factors were determined (Table 2). In addition, the effect of the stone column on the improvement of the slope was determined by relating the value of the safety factor of the slope with stone columns and the value of the safety factor of the slope without stone columns. The Safety Improved Factor (SIF) values are given in (Table 2).

Table 1. Model Parameters

Metarial	**Clay**	**Gravel**
Drainage Status	Undrained	Drained
Dry weight per unit of volume, γ_k (kN/m^3)	18	19
Saturated weight per unit of volume, γ_d (kN/m^3)	21	22
Permeability, k_x,k_y (m/day)	1x10^{-8}	100
Elasticity Module, E (kN/m^2)	3000	75000
Poisson Rate, ν	0.33	0.3
Effective Cohesion, c (kN/m^2)	10/15	1x10^{-9}
Effective Internal Angle of Friction, ϕ_s (°)	10°	35°/40°
Stagnant Soil Pressure Coefficient, K_0	0.93	0.344
Diameter of the Stone Column, D (mm)	-	80

Table 2. Safety factor and SIF values supported and not supported with SCs without earthquake force

Internal Friction Angle of The Stone Columns (ϕ_s)	**Slope Angle (β)**	**(c/φ)**	**c/(γH) Values**	**The factor of safety slope without SC**	**Safety Improvement Factor without Earthquake Force (SIF)**	
				Without SC	**s/D=2**	**s/D=3**
φs=35°	**β=20°**	**c=10 φ=10°**	**c/(γH) =0.11**	1.524	1.22	1.16
			c/(γH) =0.06	1.092	1.26	1.20
				Without SC	**s/D=2**	**s/D=3**
		c=20 φ=10°	**c/(γH) =0.22**	2.299	1.03	1.02
			c/(γH) =0.11	1.524	1.18	1.13
				Without SC	**s/D=2**	**s/D=3**
φs=40°	**β=20°**	**c=10 φ=10°**	**c/(γH) =0.11**	1.524	1.34	1.23
			c/(γH) =0.06	1.092	1.32	1.25
				Without SC	**s/D=2**	**s/D=3**
		c=20 φ=10°	**c/(γH) =0.22**	2.299	1.14	1.10
			c/(γH) =0.11	1.524	1.22	1.19
				Without SC	**s/D=2**	**s/D=3**
φs=35°	**β=25°**	**c=10 φ=10°**	**c/(γH) =0.11**	1.361	1.16	1.15
			c/(γH) =0.06	0.9471	1.26	1.20
				Without SC	**s/D=2**	**s/D=3**
		c=20 φ=10°	**c/(γH) =0.22**	2.105	1.06	1.01
			c/(γH) =0.11	1.362	1.14	1.11
				Without SC	**s/D=2**	**s/D=3**
φs=40°	**β=25°**	**c=10 φ=10°**	**c/(γH) =0.11**	1.361	1.29	1.22
			c/(γH) =0.06	0.947	1.31	1.25
				Without SC	**s/D=2**	**s/D=3**
		c=20 φ=10°	**c/(γH) =0.22**	2.105	1.08	1.06
			c/(γH) =0.11	1.362	1.24	1.17

2.2. The Safety Factor with Earthquake Load

In this part of the study, the factors of safety of the slopes without and with stone columns under the earthquake force were determined. In the Plaxis programme used in the study, a pseudostatic approach was used to determine the safety condition of a geometric slope under the influence of an earthquake force. In this approach, the earthquake load is assumed to be kh (seismic coefficient) in terms of an earthquake force. The first pseudostatic approach was developed by Terzaghi (1950). In this approach, neglecting the dynamic properties of the earthquake, it is assumed that an additional static force acts on the slope. In the pseudostatic method, a lateral force is assumed to act through the centre of mass and to slide outward from the inside of the slope. The pseudo-static lateral force (Fh) is calculated as follows (Figure 2);

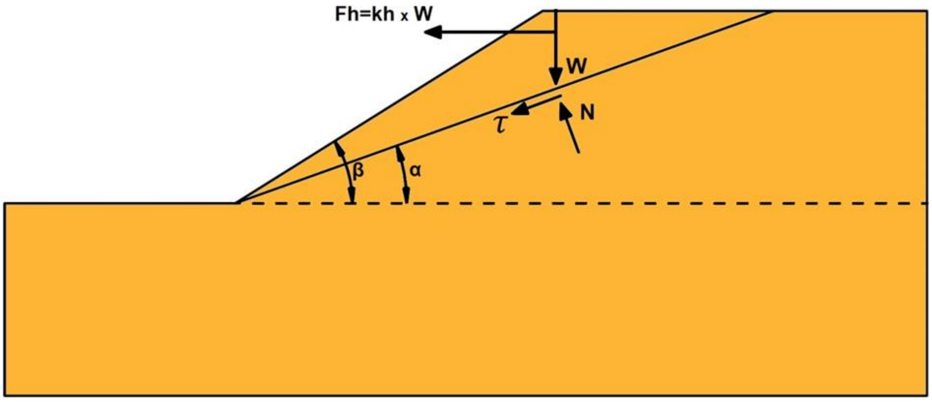


Figure 2:
Fh force acting on the center of gravity on the slope

$$Fh = m.a = W*amax/g = W*kh \quad (1)$$

Here,

m : the total mass of the sliding material (kg) is equal to W/g.

a : acceleration. (horizontal acceleration on the soil) (m/sn2)

W : total weight of the sliding material (kN)

g: gravitational acceleration (m/s2)

amax : maximum horizontal acceleration created by the earthquake on the soil (m/sn2).

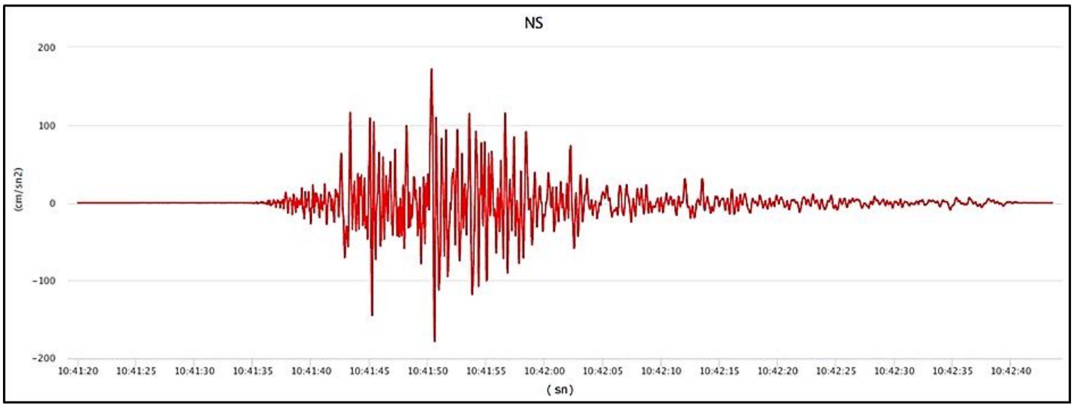
Therefore seismic coefficient here kh, can be found as

$$kh=amax/g \quad (2)$$

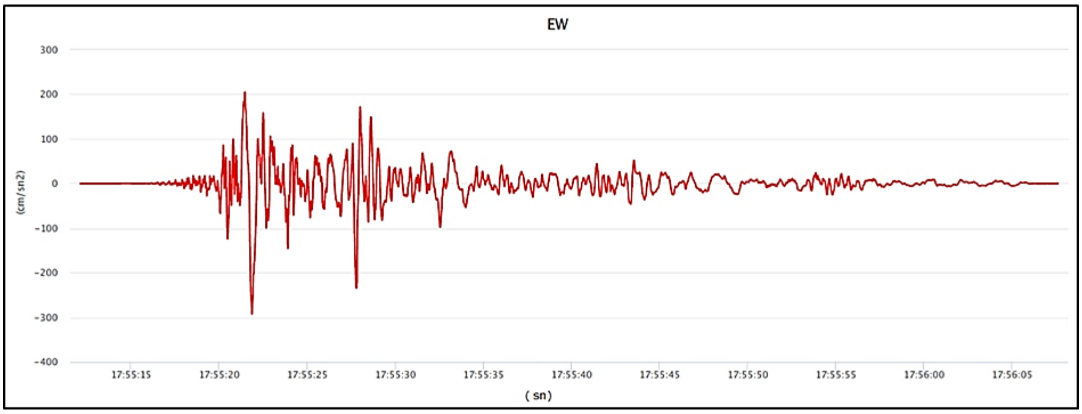
Besides, seismic coefficient is also known as pseudo -static coefficient (non-dimensional).

The pseudostatic method provides a quick solution by simplifying the earthquake effect in cases that require a quick solution. Another advantage of the method is that it gives the safety of a slope under the action of an earthquake. However, the most obvious shortcoming of the method is that it simplifies the solution of the above-mentioned earthquake. Moreover, the method is a rough calculation method that does not provide direct information about deformations. Considering all this, this method was preferred in this study for the analysis of slope stability under the action of an earthquake, which requires a quick solution and presupposes previous knowledge (Kramer 1996).

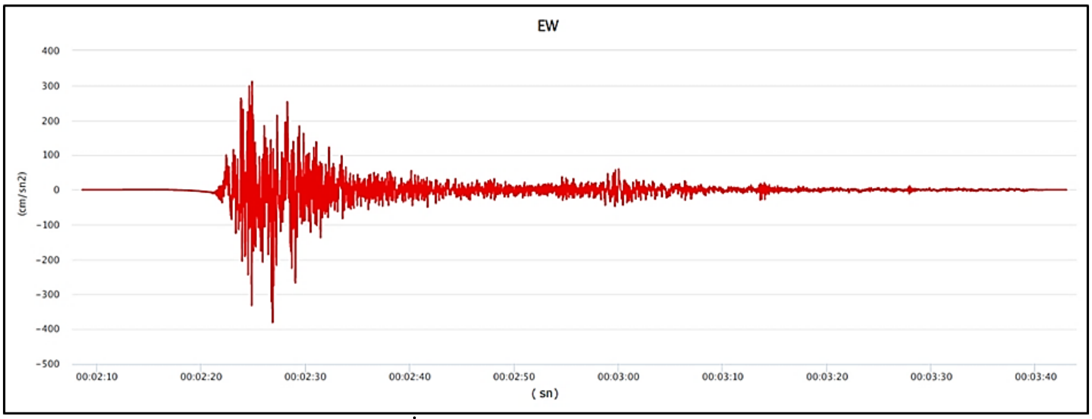
In this study, the maximum acceleration (a_{max}) was used to determine the seismic coefficient used. The Van Muradiye earthquake (2011), the Elazığ Sivrice (2020), and the İzmit Gölcük (1999) earthquake were used as maximum acceleration values (Figure 3).



Van-Muradiye Earthquake



Elazığ-Sivrice Earthquake



İzmit-Gölcük Earthquake

Figure 3:

Acceleration-time graph of the earthquakes

The characteristics of the Van Muradiye earthquake (2011), Elazığ Sivrice (2020) and İzmit Gölcük (1999) earthquakes are presented in Table 3.

Table 3. Characteristics of earthquakes (AFAD 2021)

Characteristics of earthquakes	Location		
	Van	**Elazığ**	**İzmit**
Station Code/Name	6503/Muradiye	2308/Sivrice	5401/Gölcük
Peak Ground Acc. (gal)	178.35 (NS)	292.80 (EW)	381.07 (EW)
Epicentral Distance (km)	42.24	23.81	35.96
Mechanism	Reserve Fault	Strike-Slip Fault	Strike-Slip Fault
Magnitude (M_W)	7.0	6.8	7.6
Effective Time (s)	23.04	23.77	31.90
Predominant Period (s)	0.542	1.487	1.715

Considering the maximum acceleration values of the Van Muradiye (2011), Elazığ Sivrice (2020), and İzmit Gölcük (1999) earthquakes, the seismic coefficients (equations (1) and (2)) were calculated as follows: (kh):0.182g (1.785 m/sn^2), 0.298g (2.928 m/sn^2), and 0.388g (3.806 m/sn^2), respectively.

In this section of the study different from without earthquake case, seismic coefficient (kh) value was entered and safety factor were obtained for the slopes without and with Stone Column under earthquake force by conducting the analyses (Table 4.-5.-6.). In addition, the values of the safety factors of the slopes with and without stone columns were determined proportionally to each other as in the without an earthquake, and the values of the safety improvement factor (SIFEF) under the action of earthquakes were obtained. (Table 4.-5.-6.).

Table 4. Safety factor not supported with SCs and SIFEF values for Van Earthquake

Internal Friction Angle of The Stone Columns (ϕs)	Slope Angle (β)	(c/ϕ)	c/(γH)	The factor of safety slope without SC	Safety Improvement Factor with Earthquake Force (SIFEF)	
				Without SC	**s/D=2**	**s/D=3**
ϕs=35°	**β=20°**	**c=10 ϕ=10°**	**c/(γH) =0.11**	0.954	1.08	1.07
			c/(γH) =0.06	0.667	1.16	1.13
				Without SC	**s/D=2**	**s/D=3**
		c=20 ϕ=10°	**c/(γH) =0.22**	1.348	1.05	1.03
			c/(γH) =0.11	0.963	1.09	1.06
				Without SC	**s/D=2**	**s/D=3**
ϕs=40°	**β=20°**	**c=10 ϕ=10°**	**c/(γH) =0.11**	0.954	1.09	1.07
			c/(γH) =0.06	0.667	1.17	1.15
				Without SC	**s/D=2**	**s/D=3**
		c=20 ϕ=10°	**c/(γH) =0.22**	1.348	1.05	1.04
			c/(γH) =0.11	0.963	1.10	1.08
				Without SC	**s/D=2**	**s/D=3**
ϕs=35°	**β=25°**	**c=10 ϕ=10°**	**c/(γH) =0.11**	0.935	1.09	1.08
			c/(γH) =0.06	0.613	1.21	1.13
				Without SC	**s/D=2**	**s/D=3**
		c=20 ϕ=10°	**c/(γH) =0.22**	1.325	1.05	1.03
			c/(γH) =0.11	0.931	1.11	1.02

				Without SC	s/D=2	s/D=3
ϕs=40°	β=25°	c=10 ϕ=10°	c/(γH) =0.11	0.935	1.10	1.08
			c/(γH) =0.06	0.613	1.22	1.15
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	1.325	1.06	1.05
			c/(γH) =0.11	0.931	1.08	1.05

Table 5. Safety factor not supported with SCs and SIFEF values for Elazığ Earthquake

Internal Friction Angle of The Stone Columns (ϕs)	Slope Angle (β)	(c/ϕ)	c/(γH)	The factor of safety slope without SC	Safety Improvement Factor with Earthquake Force (SIFEF)	
					s/D=2	s/D=3
ϕs=35°	β=20°	c=10 ϕ=10°	c/(γH) =0.11	0.698	1.16	1.13
			c/(γH) =0.06	0.563	1.20	1.11
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	1.002	1.15	1.13
			c/(γH) =0.11	0.754	1.19	1.10
				Without SC	s/D=2	s/D=3
ϕs=40°	β=20°	c=10 ϕ=10°	c/(γH) =0.11	0.698	1.27	1.16
			c/(γH) =0.06	0.563	1.23	1.15
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	1.002	1.22	1.12
			c/(γH) =0.11	0.754	1.21	1.13
				Without SC	s/D=2	s/D=3
ϕs=35°	β=25°	c=10 ϕ=10°	c/(γH) =0.11	0.583	1.33	1.24
			c/(γH) =0.06	0.487	1.30	1.20
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	0.889	1.29	1.20
			c/(γH) =0.11	0.676	1.25	1.18
				Without SC	s/D=2	s/D=3
ϕs=40°	β=25°	c=10 ϕ=10°	c/(γH) =0.11	0.583	1.41	1.33
			c/(γH) =0.06	0.487	1.31	1.23
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	0.889	1.32	1.23
			c/(γH) =0.11	0.676	1.31	1.22

Table 6. Safety factor not supported with SCs and SIFEF values for Gölcük Earthquake

Internal Friction Angle of The Stone Columns (ϕs)	Slope Angle (β)	c/ϕ	c/(γH)	The factor of safety slope without SC	Safety Improvement Factor with Earthquake Force (SIFEF)	
					s/D=2	s/D=3
ϕs=35°	β=20°	c=10 ϕ=10°	c/(γH) =0.11	0.463	1.41	1.24
			c/(γH) =0.06	0.332	1.36	1.25
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	0.761	1.30	1.15
			c/(γH) =0.11	0.522	1.45	1.25
				Without SC	s/D=2	s/D=3
ϕs=40°	β=20°	c=10 ϕ=10°	c/(γH) =0.11	0.463	1.60	1.37
			c/(γH) =0.06	0.344	1.58	1.49
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	0.761	1.46	1.34
			c/(γH) =0.11	0.522	1.55	1.46
				Without SC	s/D=2	s/D=3
ϕs=35°	β=25°	c=10 ϕ=10°	c/(γH) =0.11	0.407	1.52	1.30
			c/(γH) =0.06	0.298	1.40	1.30
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	0.713	1.37	1.20
			c/(γH) =0.11	0.489	1.48	1.26
				Without SC	s/D=2	s/D=3
ϕs=40°	β=25°	c=10 ϕ=10°	c/(γH) =0.11	0.407	1.74	1.47
			c/(γH) =0.06	0.298	1.80	1.61
				Without SC	s/D=2	s/D=3
		c=20 ϕ=10°	c/(γH) =0.22	0.713	1.41	1.27
			c/(γH) =0.11	0.489	1.77	1.59

3. RESULTS OF THE ANALYSES

Many researchers use (dimensionless) c/(γ.H) ratios to reduce the number of variables in parametric studies conducted on stability maps. The c/(γ.H) ratio was also used for the analysis in this study. In addition, the changes of stone column material and slope angle are important variables in the analysis of slope stability. Considering this situation, it is considered important to report the improvement factor under the effect of three different earthquake accelerations for different s/D ratios in the analyses. Studies such as Vekli et al. (2012) and Naderi et al. (2020) have shown that the stability of slopes with stone columns increases. Moreover, Çadır et al. (2021) found in their study that the slope improved with a stone column increases the safety factor under the influence of earthquake force. In the study, the behaviour of stone columns under the influence of different earthquake forces was investigated. Figure 4 shows the influence of stone column spacing under the influence of different earthquake forces on SIFEF.

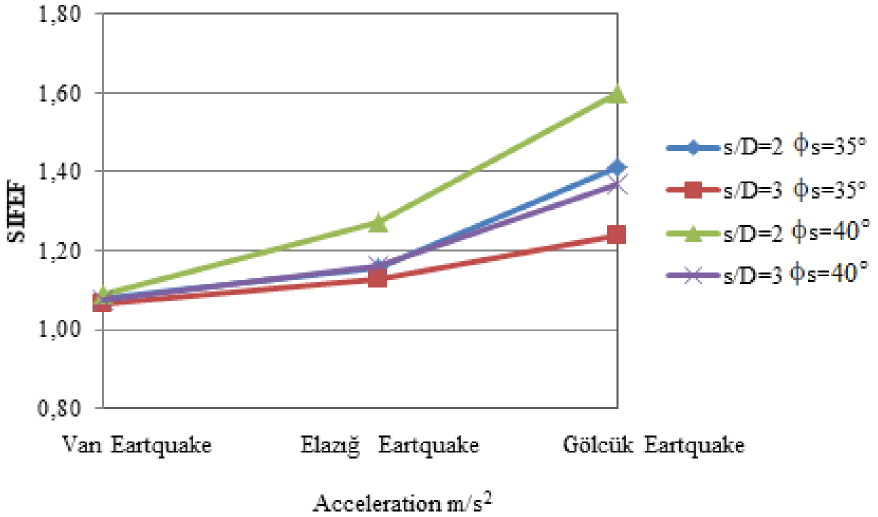


Figure 4:
Different accelerations - SIFEF value (β=20°)

As can be seen in Figure 4, as the earthquake acceleration increases for the same c/γ.H and slope angle values, the improvement factor of the stone column also increases. It was observed that the SIFEF values increased as the internal friction angle of the stone column increased. Increasing the ϕs value of the stone column from 350 to 400 brings the SIFEF values s/D=2 and s/D=3 to almost the same value. Therefore, choosing the best possible stone column material leads to a reduction in the number of stone columns. This is important because it reduces the cost and the manufacturing time.

In Figure 5, all variables are the same as Figure 4 and only β have changed. As can be seen in Figure 5, the increase in SIFEF values became more pronounced with the increase to 250. Therefore, it can be concluded that the effect of stone columns under earthquake loading increases with the increase of the slope angle.

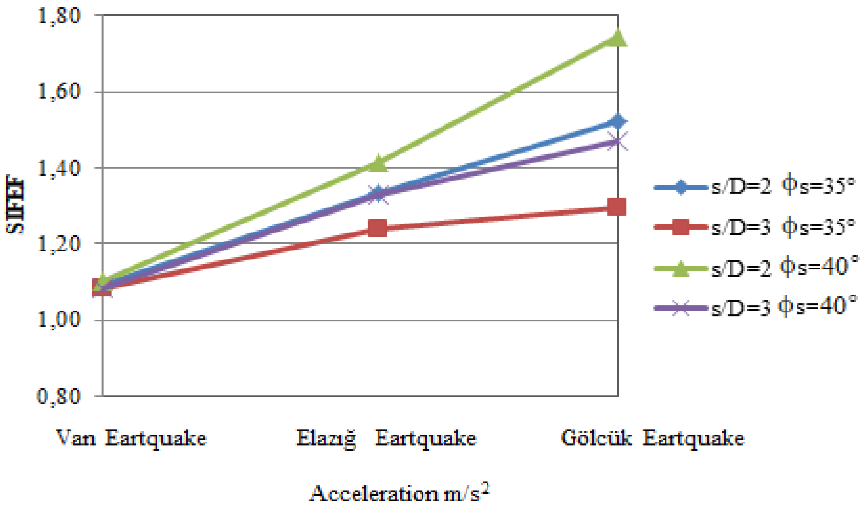


Figure 5:
Different accelerations - SIFEF value (β=25°)

In Figure 6, examines the effects of stone columns for earthquake and non-earthquake situations. It is obvious that stone columns have a positive effect on slope stability. It was investigated whether this situation changes when the earthquake force acts or not, and if so, how strong the effect is. Figure 7 show that the stone column has almost the same effect under seismic and non-seismic conditions. The increase in the horizontal earthquake force acting on the stone column has significantly increased the effect of the stone column, especially at high accelerations, compared to the non-earthquake situation.

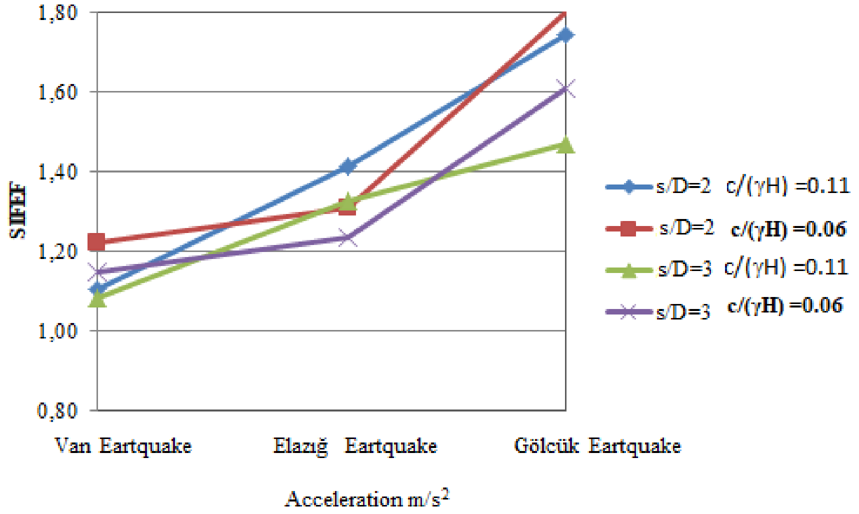


Figure 6:
Different c/(γH) - SIFEF value (β=20°)

In Figure 7, examines the effects of stone columns for earthquake and non-earthquake situations. It is obvious that stone columns have a positive effect on slope stability. It was investigated whether this situation changes when the earthquake force acts or not, and if so, how strong the effect is. Figure 7 show that the stone column has almost the same effect under seismic and non-seismic conditions. The increase in the horizontal earthquake force acting on the stone column has significantly increased the effect of the stone column, especially at high accelerations, compared to the non-earthquake situation.

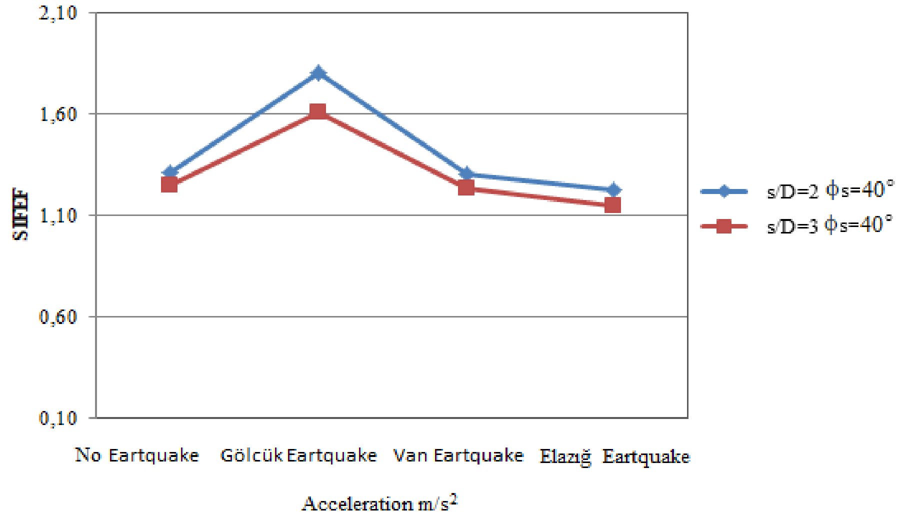


Figure 7:
No Earthquake effect and different accelerations - SIFEF value

As can be seen in Figure 8, the change in the cohesion of the soil material under the same geometric conditions (γ.H) changes the SIFEF values. As the cohesion of the soil material increases, the safety factor increases. However, when considering the safety improvement factor, it has been shown that the value of c=10 kN/m^2 is higher than c=20 kN/m^2 for all earthquake conditions. This situation shows that the spacing of the stone columns is more effective than the cohesion of the soil in case of improvement.

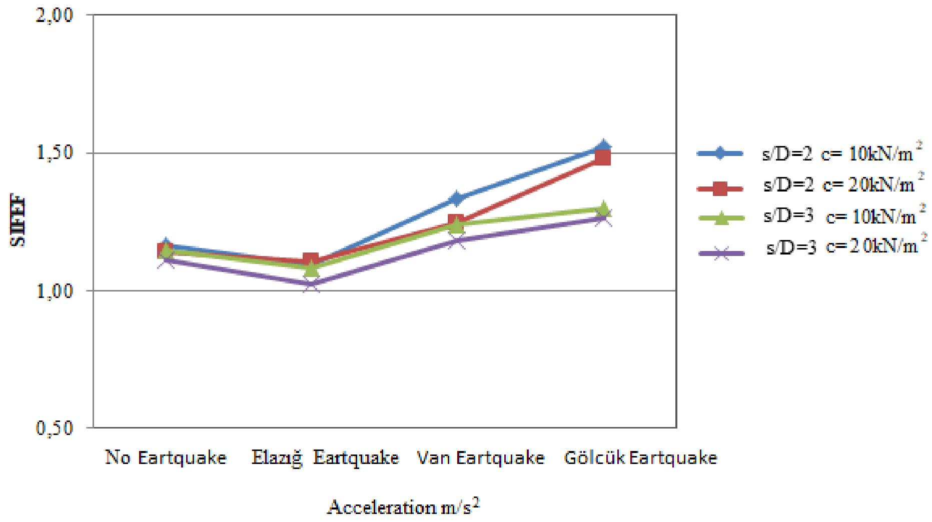


Figure 8:
Different soil cohesion and different accelerations - SIFEF value

4. CONCLUSIONS AND DISCUSSIONS

This study focuses on the safety improvement factors of the slopes, not the safety factors under earthquake action. The pseudo-static method, which is the subject of this study, offers the possibility to quickly and easily determine the safety number of a slope under earthquake action. Therefore, this study will be a guide in improving slopes with stone columns, especially in earthquake areas. In this study, three different earthquakes (Gölcük, Van and Elazığ earthquakes) were used to demonstrate the effectiveness of stone columns under the effect of earthquakes with SIFEF values. To effectively apply this method to slopes to be improved with stone columns, it is recommended to follow a specific path. First, the maximum acceleration that can occur in the area to be rehabilitated is determined. Then, the geometric properties of the slope to be created or the existing slope are determined. After determining the physical properties and strength parameters of the soil slope, the safety factor of the slope is determined. The ϕs value of the stone column material to be used for the slope is determined. In order for the slope to achieve the safety factor according to the relevant regulations, the s/D range is selected according to the current c/γ.H ratio. The safety factor of the improved slope is obtained by multiplying the safety factor by the SIFEF. The s/D ratio or ϕs can be increased or decreased depending on the number of safety found.

CONFLICT OF INTEREST

Authors confirm that there is no known conflict of interest or common interest with any institution/organization or person.

AUTHOR CONTRIBUTION

Mustafa Vekli contributed to the determination and management of the conceptual and/or design processes of the study, data analysis and interpretation, drafting the article, examining the intellectual content and final approval of the paper. Cenk Cuma Çadır contributed to the determination and management of the conceptual and/or design processes of the study, data collection, data analysis and interpretation, drafting the paper, and examining the intellectual content.

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