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Numerical Investigation of the Behavior of Soil Improved with Rammed Aggregate Piers Under Seismic Loads

Darbeli Kırmataş Kolonlarla İyileştirilmiş Zeminlerin Sismik Yükler Altındaki Davranışının Sayısal Olarak İncelenmesi

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DARBELİ KIRMATAŞ KOLONLARLA İYİLEŞTİRİLMİŞ ZEMİNLERİN SİSMİK YÜKLER ALTINDAKİ DAVRANIŞININ SAYISAL OLARAK İNCELENMESİ

ÖZ

İnşaat mühendisliği uygulamalarında gevşek ve yumuşak zeminler üzerine temel inşa etmek için birçok zemin iyileştirme yöntemi geliştirilmiştir. Ancak mevcut zemin iyileştirme yöntemlerinin yüksek maliyetleri geoteknik mühendislerini geleneksel zemin iyileştirme yöntemlerine karşı alternatif yöntemler aramaya yöneltmiştir. Bu yöntemlerden biri de darbeli kırmataş kolonlardır. Bu çalışmada, mevcut yöntemlere göre zaman ve maliyet tasarrufu sağlayan darbeli kırmataş kolonların sismik yükler altında taşıma gücünün arttırılmasına ve oturmaların azaltılmasına nasıl katkı sağlayacağı araştırılmıştır. Bu amaçla, farklı kolon uzunlukları (4,5 m, 6,5 m, 8 m, 10 m) ve farklı kolon aralık/çap oranları (s/D=5, s/D=4, s/D=3 ve s/D=2) dikkate alınarak oluşturulan iki boyutlu modellere sismik yükler (yarı-statik katsayı) uygulanarak iyileştirme öncesi ve sonrası taşıma gücü ve oturma değerleri elde edilmiştir. Bu maksatla Plaxis 2D yazılımı kullanılarak bir dizi sonlu elemanlar analizi gerçekleştirilmiş ve analizlerde sismik yükler yarı-statik katsayılar kullanılarak uygulanmıştır. Çalışma sonucunda darbeli kırmataş kolonlar ile iyileştirilen zeminlerde taşıma gücü değerlerinin arttığı ve oturmaların azaldığı görülmüştür. Ayrıca, deprem ivmesindeki artışla birlikte taşıma gücü değerleri azalmakta ve oturmalar artmaktadır. Elde edilen sonuçlar tablo ve grafikler halinde sunulmuştur.

Anahtar Kelimeler: Darbeli Kırmataş Kolon, Zemin İyileştirme, Deprem, Taşıma Gücü, Oturma

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NUMERICAL INVESTIGATION OF THE BEHAVIOR OF SOIL IMPROVED WITH RAMMED AGGREGATE PIERS UNDER SEISMIC LOADS

ABSTRACT

Many soil improvement methods have been developed in civil engineering applications to build foundations on loose and soft soils. However, the high costs of existing soil improvement methods have led geotechnical engineers to search for alternative methods against traditional soil improvement methods. One of these methods is rammed aggregate piers. This study investigates how the rammed aggregate piers, which provide time and cost savings compared to the existing methods, will contribute to the bearing capacity increase and settlement reduction under seismic loads. For this purpose, by applying seismic loads as a pseudo-static coefficient to two-dimensional models, which are formed by taking different column lengths (4.5 m, 6.5 m, 8 m, 10 m) and different column spacing/diameter (s/D=5, s/D=4, s/D=3 and s/D=2) ratios into consideration, the bearing capacity and settlement values were obtained before and after the improvement. The seismic load was implemented using the pseudo-static coefficients. Plaxis 2D finite element software was used for these analyses. It is concluded that the values of bearing capacity increase, and settlements decrease in the soils improved with rammed aggregate piers. Besides, with the increase in earthquake acceleration, bearing capacities decrease, and settlements increase. The results are presented as tables and graphs.

Keywords: Rammed Aggregate Piers, Soil İmprovement, Earthquake, Bearing Capacity, Settlement

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Highlights

- Soil improvement with rammed aggregate piers
- Increasing the bearing capacity
- Reduction of settlements

1. INTRODUCTION

Insufficient soil bearing capacity is commonly encountered in civil engineering applications. In such cases, the soil needs to be improved to increase its bearing capacity and reduce the inevitable settlement as required. The rapidly increasing population and the expansion of residential areas often necessitate the use of soils that carry risks in terms of geotechnical such as settlement, bearing capacity, and liquefaction for construction. In this case, bypassing the problematic soils by using deep foundations or improving them is necessary. In this case, the most preferred solution is the deep foundation, but soil improvement methods at intermediate foundation depths (<40 ft) are preferable thanks to their economy and shorter time [10,33]. Deep dynamic compaction, vibro compaction, compaction piles, traditional stone columns, and explosive compaction can be examples of traditional soil improvement methods that contribute to increasing the bearing capacity by compacting loose soils [41]. However, the insufficiency of traditional methods has led researchers to search for new alternative approaches. These are Rapid Impact Compaction (RIC), Horizontal Soil-Cement Mixed Beams (HSM), Low Mobility Grout (LMG), Resin Injection (RES), Soil-Cement Rafts (SCR), Reinforced Gravel Rafts (RGR) and Rammed Aggregate Piers (RAPs). These methods not only increase the density of soils but also contribute to the increase of bearing capacity and consequently reduction of settlements by increasing soil shear strength, drainage, and stiffness. In addition, it improves against liquefaction [2,4,5,12,30,34].

Improvement with RAPs is a method used to reinforce loose and soft soils based on the compaction of crushed rock with vertical impact energy by replacing the soil. This method, which has been developed in the recent past, is aimed at increasing the bearing capacity and shear strength of the insufficient soil under shallow foundations and reducing the settlements to the appropriate levels [3,11,17,20,21 ,22,24,46,23,25,43,47]. Moreover, the process of soil improvement with RAPs has been investigated by many researchers both experimentally and numerically in the past [7,8,13,14,15,16,18,29,35,39,40,43]. RAPs have been widely used in problematic soil types to increase bearing capacity, decrease settlements, and accelerate the rate of consolidation of soft clay by the enhanced drainage effect of the RAP body [27]. Besides enhancing bearing capacity and ensuring restricted and uniform settlements throughout shallow foundations, RAPs are also considered effective measures against liquefaction [9,32,41,45]. During the pier construction, the stones are forced to move laterally at the bottom while compressing the aggregates placed in the borehole by impacting from above. Thus, the soil is compacted to attain an increase in the stiffness of the ground, and a solid foundation is formed [28,44].

Excessive settlements and low bearing capacities are the most critical problems in loose and soft soils. Therefore, estimating settlement and bearing capacity of shallow foundations in geotechnical engineering is a significant effort. Accordingly, in recent years, various methods have been proposed to estimate the settlement and bearing capacity for limit analysis, slip tendency, limit equilibrium, and numerical analysis methods (e.g., finite element (FE) method) [36]. The bearing capacity of soil was widely investigated by Terzaghi [37], Meyerhoff [26], Vesic [42] and other researchers ending up with the classification of bearing capacity factors in three as N_c, N_q, and N_γ [1,6]. These factors vary according to the internal friction angle of the soil, while the bearing capacity depends on the soil's cohesion and unit weight and the extent of the load applied. The probability of devastating results of a natural disaster (earthquake) and the effects of such a disaster on the loss of bearing capacity has been a research topic for many authors based on the rapid increase in construction in recent years, e.g., Richards et al. [31].

In this study, firstly, FE models were created using Plaxis 2D FE software to determine the bearing capacity and settlement without RAPs. Thereafter, the FE models were improved by applying RAPs at different spacing/diameter (s/D) ratios (s/D:5, s/D:4, s/D:3, and s/D:2); at different RAP depths depending on the foundation width B (2.25B, 3.25B, 4B, and 5B) and the effects of these varying parameters on the settlements and bearing capacities were examined in detail. In the sequel, the earthquake coefficient (pseudo-static coefficient) proposed by Terzaghi

[38] according to earthquake destructiveness was applied to these models with and without RAPs. Following the analyses carried out for different column lengths and s/D ratios, the extent of variation in the bearing capacities and settlements under static and seismic loads were presented in tables and graphs.

2. MATERIALS AND METHODS

The principal purpose of this study is to investigate the settlements and the losses of bearing capacity in soils unimproved and improved with RAPs, both under static and seismic loads. For this purpose, it was evaluating the difference in performance between unimproved soils and the soils that improved with RAPs and observed how the depth of RAPs and column spacing could affect the settlement and bearing capacity. It turns out that models with 36 m width and 12 m height would be favorable due to considering the effect area of RAPs and load. It was decided that these dimensions were sufficient to obtain the correct result because the increase in these dimensions did not cause a significant change in the results (Fig. 1).

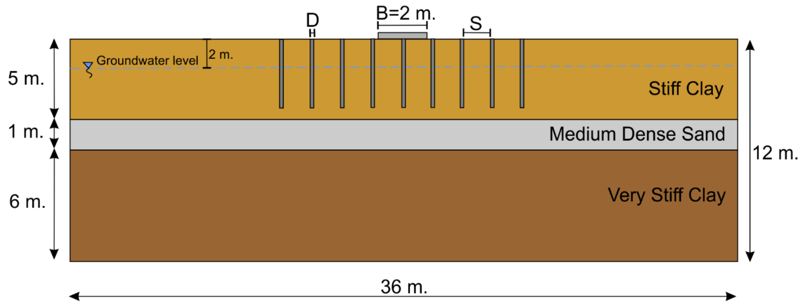


Figure 1: Schematic illustration of the model used in the analyses

The foundation width (B) is selected as 2 m. The foundation is placed in the middle of the area at an equal distance from the right and left. 18 tons of load and 1 m displacement are applied to the foundation. The main reason for choosing a 1-meter displacement load used here is to quickly achieve the maximum load that soil can bear. Settlements and bearing capacities were obtained arising from these loads. Strength reduction method was used to calculate the bearing capacity. The M_{stage} parameter is used in the analysis, which controls the staged construction process. This multiplier starts from zero and reaches the ultimate level of 1,0 at the end of the analysis phase. The plane deformation (plane strain) modeling is used as the type of analysis. The analyses are performed with 15-node triangular elements, and the Mohr-Coulomb material model is used for soils and RAPs. The material properties used were taken from a similar study in the literature by Kurt [19] (Table 1).

Table 1: Material properties

	Stiff Clay	Medium Dense Sand	Very Stiff Clay	RAPs
Drainage Condition	**Undrained**	**Drained**	**Undrained**	**Drained**
$_{k}$ (kN/m^3)	17	19	19	21
$_{d}$ (kN/m^3)	19	20	20	22
e	1	0.5	1	0.3
E (kN/m^2)	10,000	20,000	25,000	150,000
	0.4	0.25	0.4	0.25
c_u (kN/m^2)	50	0.01	120	0.01
	-	35	-	45
	-	5	-	12
k_x(m/day)	0.0001	10	0.0001	100
k_y(m/day)	0.0001	10	0.0001	100

2.1. Static settlement and bearing capacity analyses with and without RAPs

In this context, firstly, static settlements and bearing capacities were calculated without using the coefficient of earthquake acceleration. Static settlements were calculated with 18 tons of load applied along the foundation's width. At the same time, the bearing capacities were calculated from the applied 1 m displacement along the whole width of the foundation (Fig. 1). Since the value of bearing capacity will be kN/m^2, the value of vertical load has to be divided into foundation width, i.e., 2 m.

2D models with and without RAPs were created by introducing the material properties of soil and RAPs into the Plaxis software (Fig. 2). As shown in Fig. 1, soil layers consist of 6 m of very stiff clay lying on an impermeable rock, 1 m of medium-dense sand lying in the middle, and 5 m of stiff clay extending to the surface. The groundwater level is 2 m below the ground surface. For the models with RAPs, soil improvement was made with RAPs, each 50 cm in diameter (Fig. 2(a)). Model geometries with or without RAPs were formed, and the mesh was created using 15-node triangular elements for both soil layers and RAPs.

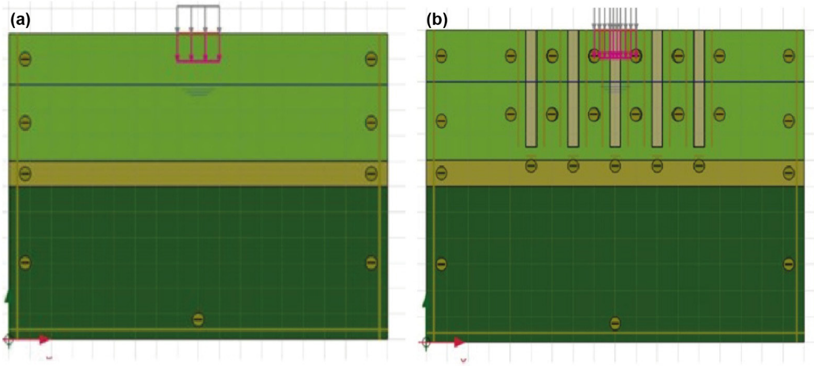


Figure 2: Models without and with RAPs

2.2. Seismic settlement and bearing capacity analyses with and without RAPs

The value suggested by Terzaghi [38] according to earthquake destructiveness was used to determine the earthquake coefficient (pseudo-static coefficient) considered in the analyses. Earthquake load was applied as a seismic coefficient (k_h). Then, the settlement and bearing capacity for the cases with and without RAPs were calculated.

The use of the value originally suggested by Terzaghi [38] is shown below.

- “Severe” earthquakes (Rossi-Forrel IX) $k_h = 0.1$
- “Violent, destructive” earthquakes (Rossi-Forrel IX) k_h =0.2
- “Catastrophic” earthquakes k_h =0.5

First of all, the modeling was carried out by following the steps in the static analysis. Then, in the analysis phase, the pseudo-static coefficient is activated. The acceleration value in the horizontal direction (acceleration-x) was entered using the suggested value (k_h=0.2) for a destructive earthquake. Then, the settlement and bearing capacity after an earthquake were calculated. Likewise, for a catastrophic earthquake (k_h=0.5), the settlement and bearing capacity were recalculated for the cases with and without improvement with RAPs. The same procedure was followed for a severe earthquake (k_h=0.1).

3. RESULTS AND DISCUSSION

Analysis results using the k_h=0,1 earthquake acceleration will not be mentioned because the results obtained from this earthquake analysis are not significantly higher than those obtained from the analysis made under static conditions. The results for the two other cases are given below.

3.1. The results of the static analyses with and without RAPs

The settlement values obtained from the analyses of models under static loads with and without RAPs in which the foundation is exposed to 90 kN/m^2 of uniformly distributed load, varying according to the depth of RAPs and the distance between RAPs, are given in Table 2. The deformed shapes of the models due to the analyses to calculate settlement are shown in Fig. 3. The values of settlement varying according to the distance between RAPs with a constant RAP length of 6.5 m and the length of RAPs with a constant spacing of 1.5 m are given in Fig. 4.

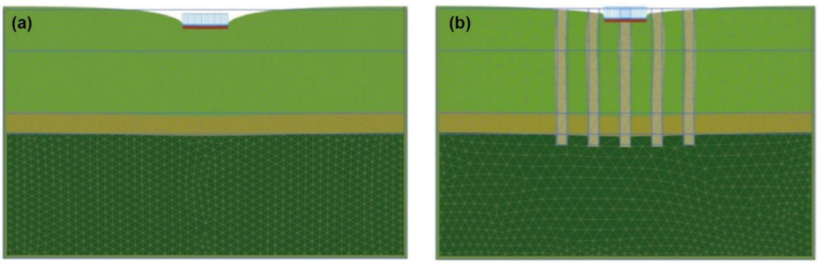


Figure 3: Deformed shapes of the models due to settlement analyses with and without RAPS both without earthquake effect

Table 2: Settlement values with and without RAPs, both without earthquake effect

Settlement Without RAPs (mm)	Settlement With RAPs (mm)					
	RAPs Diameter (cm)	RAPs Length (m)	Distance Between RAPs (m)			
			s=2.5	s=2	s=1.5	s=1
17	50	L= 4.5	14.00	13.85	12.09	8.70
		L= 6.5	13.28	13.06	11.36	8.50
		L= 8.0	13.26	11.09	11.09	7.50
		L= 10.0	13.00	10.27	9.00	7.60

In the analyses without earthquake effect, it was seen that the settlement value of the soil improved with RAPs decreased compared to soil without RAPs. It was also seen that the settlements increased as column spacing increased (Fig. 4).

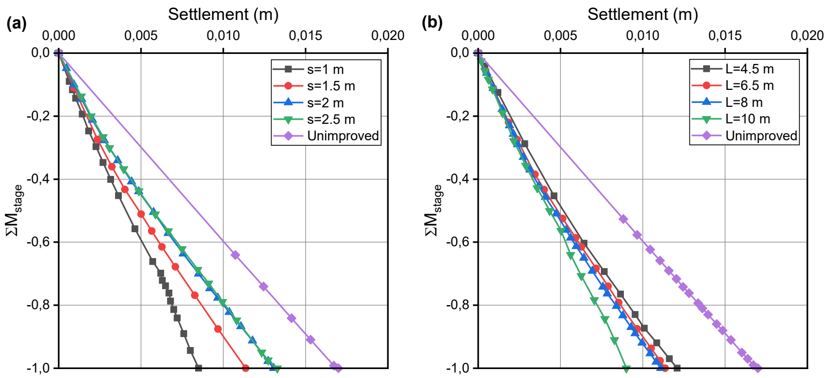


Figure 4: Settlement of soil without earthquake effect: (a) without RAPs and depending on the distance between RAPs of 6.5 m in length, (b) without RAPs and depending on the length of RAPs with 1.5 m spacing

The deformed shapes of the models following the analyses in order to calculate the bearing capacities of the soil with and without RAPs were obtained, as can be seen in Fig. 5. These analyses were performed applying a vertical displacement of 1 m. The values of bearing capacity varying according to the length of RAPs and the distance between RAPs are given in Table 3. The bearing capacity values varying according to the distance between RAPs with a constant RAP length of 6.5 m and the length of RAPs with a constant spacing of 1.5 m are given in Fig. 6.

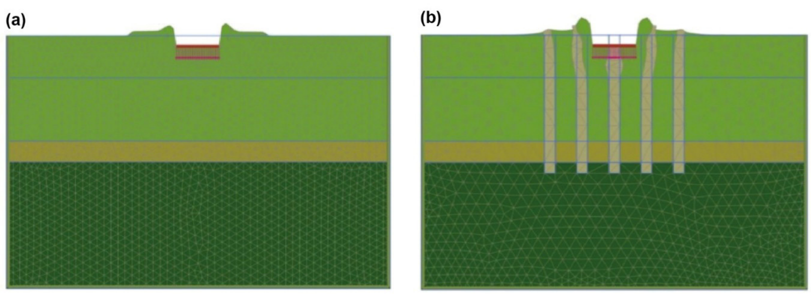


Figure 5: Deformed shapes of the models following the analyses to calculate the bearing capacities without earthquake effect

Table 3: Bearing capacities with and without RAPs, both without earthquake effect

Bearing Capacity Without RAPs (kN/m²)	Bearing Capacities With RAPs (kN/m²)					
	RAPs Diameter (cm)	RAPs Length (m)	Distance Between RAPs (m)			
			s=2.5	s=2	s=1.5	s=1
259.20	50	L= 4.5	435.15	435.65	483.10	595.00
		L= 6.5	435.85	436.90	455.45	630.00
		L= 8.0	437.95	437.20	457.45	634.00
		L= 10.0	483.00	439.20	477.65	636.50

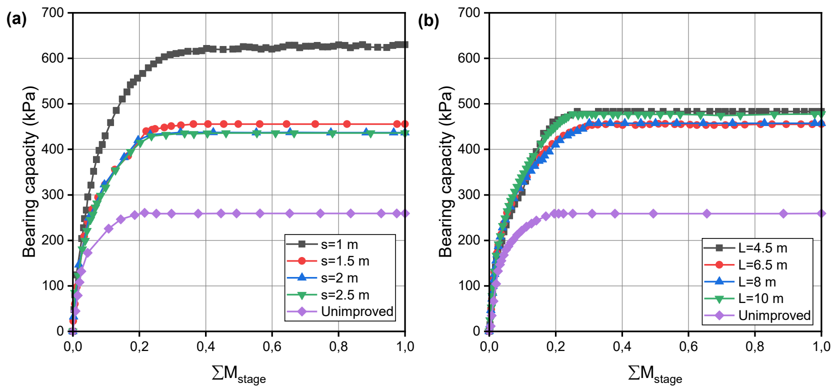


Figure 6: Bearing capacities of soil without earthquake effect: (a) without RAPs and depending on the distance between RAPs of 6.5 m in length, (b) without RAPs and depending on the length of RAPs with 1.5 m spacing

According to the results of analyses performed without considering an earthquake, it was concluded that the values of bearing capacity of the soil improved with RAPs increased compared to the soil without RAPs. Besides, the analysis carried out with different s/D ratios in the soil model with RAPs found that the bearing capacity values decreased as s/D ratios increased. Moreover, the values of bearing capacity increased as the depth of RAPs increased.

3.2. The results of the analyses considering destructive earthquakes (kh = 0.2)

The analyses were performed using the suggested earthquake effect coefficient (k_h=0.2). The deformed shapes of the models following the analyses to calculate the settlements and the values of bearing capacity are given in Fig. 7 and Fig. 9, respectively. The settlement values obtained from the analyses varying according to the depth of RAPs and the distance between RAPs, are given in Table 4. The values of bearing capacity varying according to the depth of RAPs and the distance between RAPs are given in Table 5. The values of settlement varying according to the length of RAPs with a constant spacing of 1.5 m and to the distance between RAPs with a constant RAP length of 6.5 m are given in Fig. 8. The values of bearing capacity varying according to the length of RAPs with a constant spacing of 1.5 m and to the distance between RAPs with a constant RAP length of 6.5 m are given in Fig. 10.

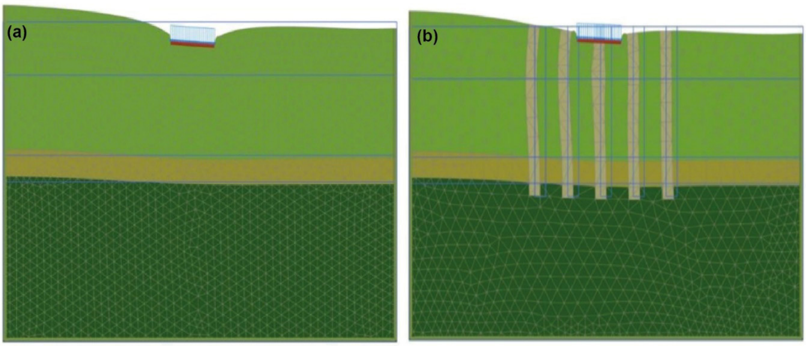


Figure 7: Deformed shapes of the models due to settlement analyses with and without RAPs (k_h=0.2)

Table 4: Settlement values with and without RAPs both under earthquake effect (k_h=0.2)

Settlement Without RAPs (mm)	Settlement with RAPs (mm)					
	RAPs Diameter (cm)	RAPs Length (m)	Distance Between RAPs (m)			
			s=2.5	s=2	s=1.5	s=1
18	50	L= 4.5	14.82	14.50	12.09	12.4
		L= 6.5	13.86	13.44	12.00	11.68
		L= 8.0	13.86	13.00	11.09	10.19
		L= 10.0	13.84	12.10	10.81	10.05

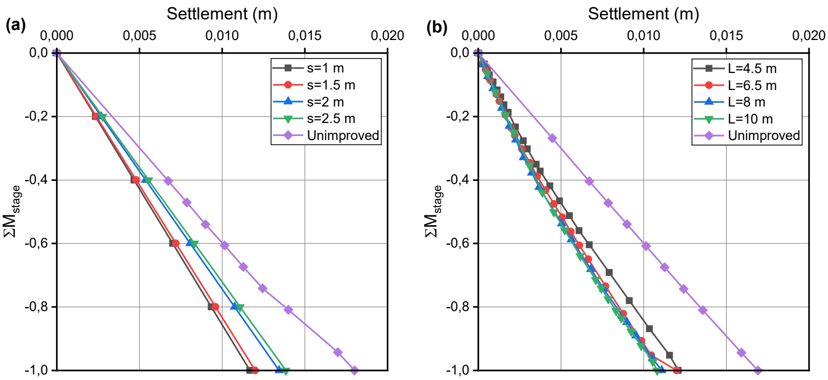


Figure 8: Settlement of soil with earthquake effect (k_h=0.2): (a) without RAPs and depending on the distance between RAPs of 6.5 m in length, (b) without RAPs and depending on the length of RAPs with 1.5 m spacing

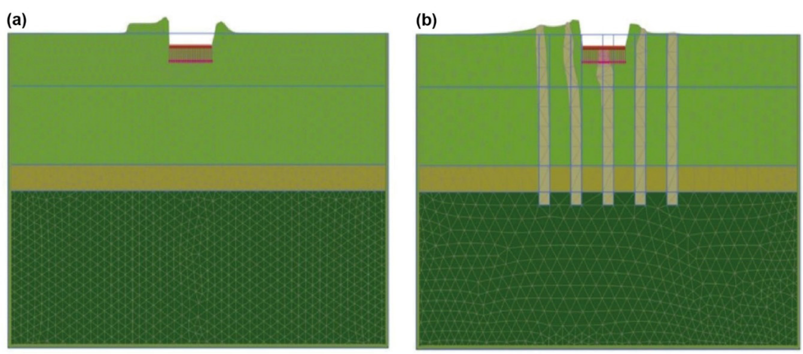
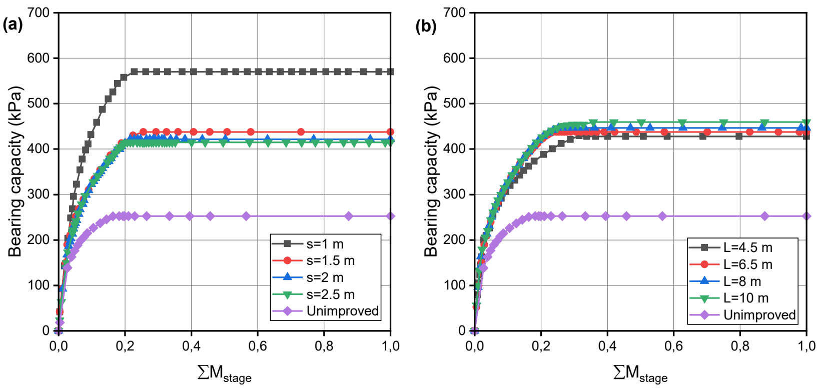


Figure 9: Deformed shapes of the models following the analyses to calculate the bearing capacities with and without RAPs (k_h=0.2)

Table 5: Bearing capacities with and without RAPs both under earthquake effect (k_h=0.2)

Bearing Capacity Without RAPs (kN/m²)	Bearing Capacity With RAPs (kN/m²)					
	RAPs Diameter (cm)	RAPs Length (m)	Distance Between RAPs (m)			
			s=2.5	s=2	s=1.5	s=1
252.40	50	L= 4.5	412.00	410.70	427.90	550.00
		L= 6.5	415.00	421.70	437.70	570.00
		L= 8.0	414.00	424.85	446.70	590.00
		L= 10.0	416.25	432.25	459.70	598.00



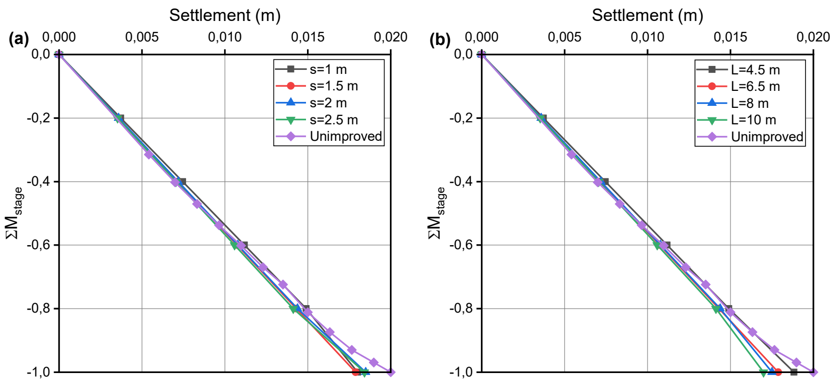
Figue 10 Bearing capacity of soil with earthquake effect (k_h=0.2): (a) without RAPs and depending on distance between RAPs of 6.5 m in length, (b) without RAPs and depending on the length of RAPs with 1.5 m spacing

3.3 The results of the analyses considering catastrophic earthquakes (k_h=0.5)

The analyses were performed using the suggested earthquake effect coefficient (k_h=0.5). The settlement values obtained from the analyses varying according to the depth of RAPs and the distance between RAPs, are given in Table 6. The values of bearing capacity varying according to the depth of RAPs and the distance between RAPs are given in Table 7. The values of settlement varying according to the length of RAPs with a constant spacing of 1.5 m and the distance between RAPs with a constant RAP length of 6.5 m are given in Fig. 11. The values of bearing capacity varying according to the length of RAPs with a constant spacing of 1.5 m and to the distance between RAPs with a constant RAP length of 6.5 m are given in Fig. 12.

Table 6. Settlement values with and without RAPs both under earthquake effect (k_h=0.5)

Settlement Without RAPs (mm)	Settlement With RAPs (mm)					
	RAPs Diameter (cm)	RAPs Length (m)	Distance between RAPs (m)			
			s=2.5	s=2	s=1.5	s=1
20	50	L= 4.5	17.74	18.65	18.63	18.70
		L= 6.5	18.42	18.49	17.88	18.01
		L= 8.0	20.34	17.30	17.77	18.17
		L= 10.0	22.10	17.97	17.65	17.50



Figue 11: Settlement of soil with earthquake effect (k_h=0.5): (a) without RAPs and depending on the distance between RAPs of 6.5 m in length, (b) without RAPs and depending on the length of RAPs with 1.5 m spacing

Table 7: Bearing capacities with and without RAPs both under earthquake effect (k_h=0.5)

Bearing Capacity Without RAPs (kN/m²)	Bearing Capacity With RAPs (kN/m²)					
	RAPs Diameter (cm)	RAPs Length (m)	Distance Between RAPs (m)			
			s=2.5	s=2	s=1.5	s=1
239.50	50	L= 4.5	361.80	359.05	354.70	464.50
		L= 6.5	369.90	380.95	378.35	450.50
		L= 8.0	375.50	381.05	380.00	484.00
		L= 10.0	377.00	383.35	397.40	505.00

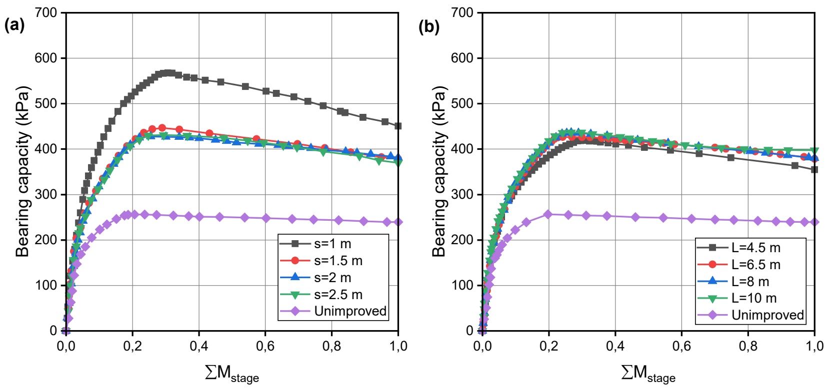


Figure 12: Bearing capacity of soil with earthquake effect (kh=0.5): (a) without RAPs and depending on the length of RAPs of 6.5 m in length, (b) without RAPs and depending on the distance between RAPs with 1.5 m spacing

As seen in the above tables and figures obtained by various analyses, it was found that the seismic settlement value of soils improved with RAPs decreased compared with the soils unimproved. Further, the values of bearing capacity of the soils improved with RAPs increased compared to the soil unimproved.

4. CONCLUSION

In this study, the behavior of RAPs, which is one of the soil improvement methods, under earthquake effect was investigated in detail by FEM. It has been found that settlement of soils improved with RAPs, is lower than those without RAPs. The decrease in the settlement becomes more evident depending on the increase in length of RAPs with and without considering an earthquake. Besides, the bearing capacities of soils improved with RAPs increase compared to soils without RAPs. The results acquired from the study are specified below.

- The bearing capacities of soils improved with RAPs increase by 1.5 to 3 times on average according to the bearing capacities of soils without RAPs. On the other hand, the bearing capacity values of soils with RAPs affected by the earthquake were 1.5 to 2.4 times higher than soils without RAPs.
- In the analyses carried out an earthquake, the settlements of the soils improved with RAPs is 1.2-2.3 times less than those without RAPs. In addition to this, in the analyses carried out with earthquake effect, settlement values with RAPs were decreased 1.2-2.4 times compared to soil models without RAPs.
- Bearing capacities of the soils improved with RAPs increased due to the increasing length of the RAPs (4.5 m, 6.5 m, 8 m, 10 m) and a decrease in settlement occurred due to the increase in length of RAPs.
- RAPs implemented in the soil models were applied with various spacings (1 m, 1.5 m, 2 m, 2.5 m), and depending on the increase in the distance between RAPs, increasing settlement values and decreasing bearing capacity were observed. As a result of increase in spacing, decrease in bearing capacity and increase in the settlement were observed under the earthquake effect.
- For different seismic loads applied to the soil models improved with RAPs, it was found that bearing capacity decreases and settlement increases due to the increase in the intensity of earthquake. In other words, when k_h=0.2 is applied to the soil, on an average of 6% decrease and when (k_h=0.5) is applied, on an average of 16% decrease was observed in the bearing capacities compared to cases without earthquake effect.

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