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Numerical analysis of single rammed aggregate piers installed in stratified soil profiles

Zülal AKBAY ARAMA*

Istanbul University-Cerrahpasa, Engineering Faculty, Civil Engineering Department, Avcilar Campus, Istanbul

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Abstract

In this study, Rammed Aggregate Pier systems are analyzed according to the numerical analysis that are performed by two dimensional commercial finite element analysis software. The focus point of the paper is to identify the effects of pier dimensions, stratification of foundation soil profile and load applying levels on the deformation behavior of interacted rammed aggregate pier-surrounding soil system at the installation stage. Interpretations of the parametrical analyses are focused on the deformation change via loading levels. The relative displacement occurrence between pier and soil matrix is also checked.

Keywords: *Rammed aggregate pier, soil stratification, finite element analysis, pier installation, dimension effect.*

Tabakalanmış zemin profillerinde inşa edilen tekil kırmataş kolonların sayısal analizi

Öz

Bu çalışmada, Darbeli Kırmataş Kolon sistemlerinin sayısal analizi iki boyutlu ticari bir sonlu elemanlar programı kullanılarak yapılmıştır. Çalışmanın odak noktası; kazık boyutlarının, temel tabakalanma özelliklerinin ve kazık yükleme seviyesinin, inşa sırasında ve sonrasında etkileşimli kazık-semin sistemi içerisinde meydana gelen deformasyon davranışı üzerindeki etkilerinin araştırılmasıdır. Uygulanan parametrik analizlerin sonuçları düşey deformasyonların yükleme seviyesine bağlı değişimi olarak

* Zülal AKBAY ARAMA, zakbay@istanbul.edu.tr, https://orcid.org/0000-0001-8185-7329

incelenmiştir. Kazık ve zemin arasında meydana gelen rölatif deplasmanlar da ayrıca kontrol edilmiştir.

Anahtar kelimeler: *Darbeli kırmataş kolon, tabakalanmış zemin,* sonlu elemanlar *analizi, kazık inşası, boyut etkisi.*

1. Giriş

Selection of the appropriate structure and foundation supporting system for satisfying the envisaged construction requirements is still a basic problem in civil engineering applications. It is difficult to take into consideration both super and sub-structures action and reactions related to the complexity of multiple material usage and interacted behavior characteristics such as bearing capacity, short and long term settlement performance, seismic load effect and cost control. Heavy, high rise and large scaled structures like skyscrapers, embankments, storage tanks, bridges, wind turbines, earth walls and solar panels are some of the types of various important and frequently applied structures in the urbanization scheme. Due to the land limitation in the urban areas; landslide fields and soft soils that are characterized with their low bearing capacity and high deformability potential are used as foundation soils for these structures. In such situations shallow foundations are inadequate for bearing the loads of superstructure. Various stabilization techniques have been developed to overcome the bearing capacity and deformation problems of these kinds of weak soils under predicted structural loads. Fundamental concepts of soil stabilization such as drainage, densification, and reinforcement, cementation, drying and also heating were advanced hundred years ago. Even though the main principles of soil improvement are unchanged since the early years, the practices are changing with time owing due to the development of new materials, industry and technologies. Over the past century, soil stabilization techniques have mainly concentrated upon the development of new methods which benefits from vibratory methods for densification of granular materials, grouting materials and new concepts of soil improvement [1]. Selection and development of the appropriate type of stabilization technique is also depended on expected improvement ratio associated with the geometrical dimensions and structural load characteristics of superstructure and soil type, material properties, drainage conditions and stratification status of foundation. In this paper, an actual model of mechanical improvement technique called as Rammed Aggregate Pier (RAP) system is evaluated for soil stabilization purpose by performing different loading levels with multivariate parametric analyses done via finite element method in two dimensional space. Rammed aggregate pier systems have been used as an intermediate foundation system between conventional shallow footings and deep foundations for reducing intolerable settlements, increasing capacity of bearing, slope stabilization, uplift enhancement and liquefaction mitigation [2, 3, 4, 5, 6]. RAP construction is conceptually similar with compacted gravel column [7] but required special installation equipment. Piers can be constructed by various applications, such as replacement, displacement, vibrodisplacement, vibroreplacement and tamped methods [8]. The unique construction process of pier installation contains drilling an open hole to a desired depth (Fig. 1 (a)) or driving the pier directly to the soil media, replacing the weak soil with dense strong aggregate material (Fig. 1 (b)) or filling the hole with the same dense strong aggregate material. In the first stage, the bottom bulb is formed (Fig. 1 (c)) by vertically ramming strong aggregate using an impact hammer equipment (Fig. 1 (d)) with a specially designed high energy beveled tamper [9]. The RAP construction is followed by filling (Fig. 1 (e)) and ramming more thick stages of aggregate over the bottom bulb (Fig. 1 (f)) and compacting the material with the beveled tamper (Fig. 1 (g)). Energy of the tamper is applied to aggregates by a repeated impact process with frequencies range from 300 to 600 cpm [10]. Within the iterative ramming process compacted aggregate squeezed the matrix soil surrounded drilling cavity and forced the soil to move downward and outward. Horizontal stresses of matrix soil is increased due to the sensitivity of the soil medium and loading magnitude [3, 4]. Therefore this cycle contributes an increase of the soil stiffness and strength [11]. Taking into account the expected behavior characteristics of RAP installation and construction process, it can be said that the interaction between RAP element and surrounded soil matrix generated a complex phenomenon. Several experimental studies are conducted and numerical analyses are performed with different solution techniques to overcome the obscurity of these interacted system [6, 12, 13, 14, 15, 16, 17, 18, 19, 20].

(a) (b) (c) (d) (e) (f) (g)

Figure 1. The construction sequence of rammed aggregate piers.

Although rammed aggregate piers are generally installed in groups, the behavior of the whole interactive system depends on investigations of individual pier behavior. The influential parameters of mono pier installation, construction and sustainable usage terms are mainly evaluated from previous investigators. By the way it can be summarized that the fundamental factors effective on the behavior that are determined in studies are installation sequence, materials of foundation - pier and geometric characteristics of the whole system. In this paper, it is aimed to discover the importance of foundation soil stratification on the behavior of mono pier with fictionalizing arbitrarily identified pier dimensions and pier loading levels. Stratified foundation profiles are obtained by defining a crust layer above soft clayey medium with different thicknesses. Pier installation is modelled with two dimensional numerical analysis and compressive load application procedures are simulated by finite element based commercial numerical analysis program Plaxis 2D.V2019. In addition to these, pier dimensions such as radius and length are investigated for analyzing the dimension effects of pier behavior. Interpretations of the parametrical results are focused on the deformation and stress characteristics of the interactive pier elements and adjacent soil matrix to make authors fully equipped for utilizing group pier behavior under the influence of different stratification characteristics of foundation soils. The relative displacement occurrence between pier and soil matrix is also checked and evaluations are obtained according to the stiffness of used material characteristics.

2. Numerical modeling of Rammed Aggregate Piers

In this paper, the performance of 27 different cases that are arranged according to the dimensions of single rammed aggregate piers is investigated by simulating axisymmetric finite element models with Plaxis 2D.V2019 under axial loading conditions. The pier diameter is selected 0.50, 0.80 and 1.0 meters and the length of pier is selected 2.0, 3.0 and 6.0 meters (Figure 2) respectively. In addition to this, three different foundation stratification profiles are fictionalized by utilizing the material properties that is used for the studies of White et al. (2002, 2003) under the influence of pier loading tests [21, 22]. The first profile of foundation soil consists of pure alluvial formation (SP1), the second and third foundation profile consists of a two layer matrix (Figure 2). Second profile includes a 1.0 meter thick crust layer at the surface of the ground (SP2) and in the third profile the crust thickness rises to 2.0 meters (SP3) and followed by alluvial material for both (Figure 2). In order to simplify the definition of variable cases some abbreviations are done. Pier length change is symbolized by using P letter and 1, 2, 3 numbers define 2, 3 and 6 meters length of piers respectively. Similarly the change of pier diameter is represented by D letter and 1, 2, 3 numbers define 0.50, 0.80 and 1.0 meters pier diameter respectively.

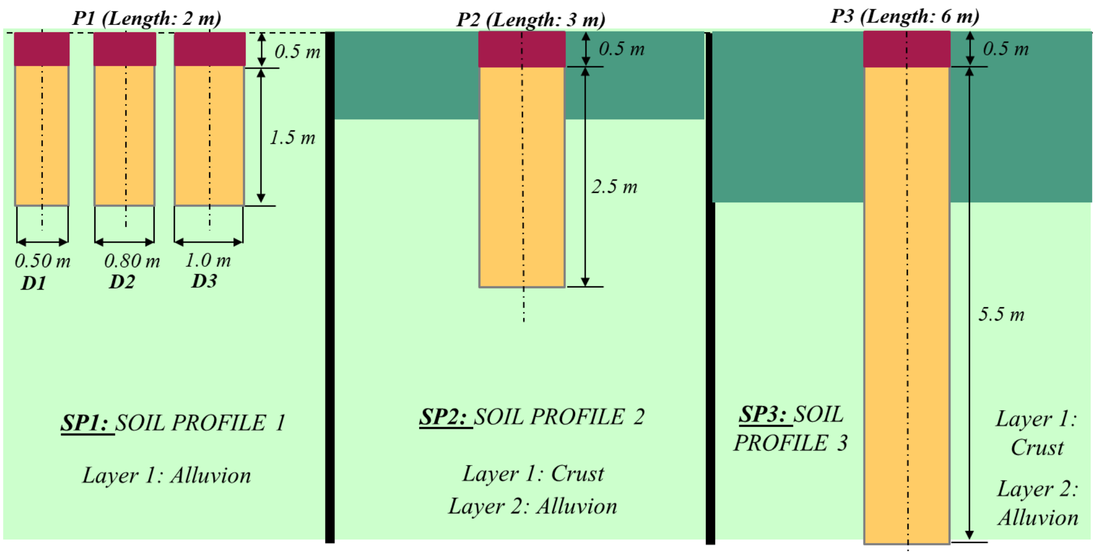


Figure 2. Pier and foundation soil characteristics used in numerical analyses.

It is aimed to throw light on the importance of foundation stratification to the response of pier-surrounding soil interaction under vertical loading conditions. Rammed aggregate piers and foundation soils are modelled with using Hardening Soil constitutive material model in numerical analysis. Material stiffness properties of hardening soil model include; the confining stress dependent secant modulus for primary deviator loading (E_{50}), the modulus for primary isotropic compression (E_{oed}) and the elastic unloading-reloading parameters (E_{ur}, ν_{ur}) and material strength properties are described in terms of effective stresses (c', ϕ'). The mentioned stress dependency amount is defined by the power parameter m. The stiffness and strength properties of piers and surrounding soil is given in Table 1. A rigid 0.50 meter thick cap at the top of the pier is modelled with linear elastic characteristics as a non-porous material. Perfectly rough condition is assumed throughout the interface between piers and surrounding foundation soil. Therefore the strength reduction ratio of the interface elements are entered 1.0 value. The pier construction process is modelled with four main phases by using plastic drained conditions. The implementation process is began with making a cavity with drilling along the shaft (Figure 3-1). For modelling pier ramming action, prescribed displacement application to skin and top of the pier is envisaged at the second phase (Figure 3-2). The observations that are acquired by the application of numerical analyses or the field investigations have shown that the prescribed displacements defined at the top of the pier occur two times bigger than the displacements occur at horizontal direction through the pier shaft and the value of the displacements at the shaft of the pier results in %5 of nominal diameter of the cavity [18, 23].

Table 1. Geotechnical properties of foundation soil and pier [21].

Type of Material	Alluvion	Crust	Aggregate
ϕ' (°)	24	35	47
c'	2	2	4
ψ(°)	0	0	12
γ (kN/m³)	19.24	19.24	21.00
E_{50ref} (kPa)	3000	9000	61000
E_{oedref} (kPa)	1500	4500	61000
E_{urref} (kPa)	9000	27000	1220000
m	1	1	0.48
v_{ur}	0.2	0.2	0.2
p_{ref}	25.5	25.5	34.5
R_f	0.96	0.96	0.88
$K_{0,NC}$	0.59	0.43	0.27
e_{ini}	1	1	1
σ_{ten} (kPa)	0	0	0

From this point of view, prescribed displacements which are defined at the top of the pier is taken two times bigger than the horizontal direction prescribed displacements and the value is taken %10 of nominal diameter of the cavity for all cases that are identified. The third phase consists of the replacement of pier properties with improved material properties (Figure 3-3) and the test loads are applied incrementally at the vertical direction in the last phase (Figure 3-4).

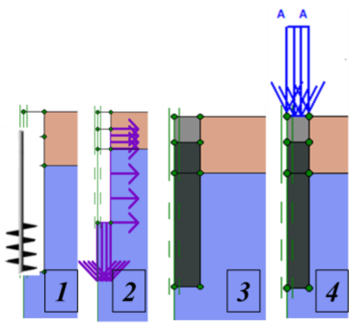


Figure 3. Phases of pier installation.

A selected reference model is calibrated with the field studies of White et al. (2002) for the verification of modelling phases [21]. The physical boundaries of the model is extended throughout the depth and width not to effect the distribution of stresses. Axial rollers are modelled along the symmetry axes of the system and full fixity condition is constituted for all other boundaries. For the simulation of long term usage conditions after the installation process, the expansion of the cavity is modelled drained with the use of effective stress parameters. Analysis results are evaluated in terms of deformations which are transferred from finite element software by a written excel macro code to exhibit more understandable illustration of the dimension and stratification effect on the behavior of pier. Deformation values are obtained from the points that are located at the vertical symmetry axes of pier (within the pier as called pier element and abbreviated PE) and the points that are situated on the tangent vertical axes of pier-surrounding soil interface (within the soil as called soil element and abbreviated SE). The locations and abbreviations of reference displacement measurement data points are given in Figure 4. Totally 108 data points are examined and these mentioned data points are available for all foundation soil stratifications and for all pier geometries. It is aimed to find relative displacement change between pier and surrounding soil matrix by using the selected data points. In Figure 4 the increase of consecutive number values defines the increasing depth throughout the foundation profile for all types of piers.

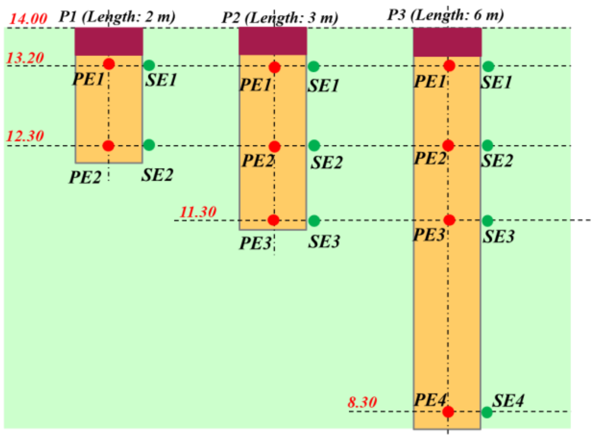
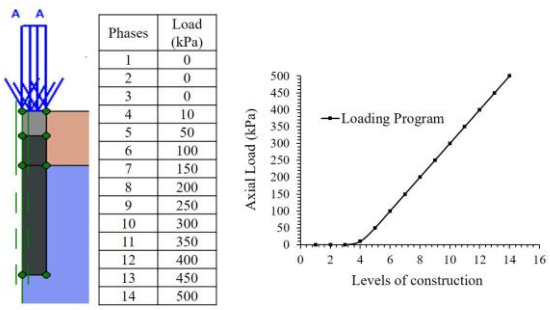


Figure 4. Deformation measurement points.

The loading program of mono pier is also given in Figure 5. The loading sequence is modelled by using staged construction technique and incremental load values are only applied in vertical direction to the cap of the pier as a distributed uniform load.



Phases	Load (kPa)
1	0
2	0
3	0
4	10
5	50
6	100
7	150
8	200
9	250
10	300
11	350
12	400
13	450
14	500

Figure 5. The loading program of mono pier.

3. Numerical analysis of Rammed Aggregate Piers

Numerical analyses are conducted for all the fictionalized cases of pier installation and the results are denominated via load increment-vertical displacement curves between Figures 5-15. The effects of rammed aggregate pier length and diameter and foundation stratification on the installation process of the mono system is explained using the identified pier and soil elements that are located in different coordinates. By the way, pier and soil deformations at the same horizontal plane which are occurred during the installation sequence can be observed. The analysis results are taken from 108 different points therefore vertical displacement change via loading levels can be defined by remarkable amount of graphs and different combination of data's. Selection of specific cases which describes the significant characteristics of interacted rammed aggregate pier-surrounding soil system eases to understand and interpret the main behavior of whole influenced structure with different pile dimensions and foundation soil profiles. Therefore in this study, selected significant cases are evaluated not to cause informational convergence.

3.1. Data point location effect

Rammed aggregate piers are special soil improvement structures that are constructed by soil based materials. This property causes piers to behave more flexible than bored concrete or reinforced concrete piles. In addition to this, during the installation of piers the ramming actions changes alignment of pier materials and squeezes pier matrix elements in a limited area with gaining a new strength value. This condition of flexibility and strength increase of pier made it necessary to investigate the internal behaviour of piers and soil matrix both. The relative displacement between pier and soil matrix under the applied loads, generates a soil resistance throughout the interaction plane of associated system. In field applications, tell-tale plates are applied while the construction of pier to control the deformation behaviour of pier elements and extensometers and inclinometers are placed into the foundation soil to control the deformations of surrounded soil matrix. Beside this, in numerical analysis it is possible to evaluate the displacements inside the pier for all phases of installation and during the loading procedure of pier. By the way it may be possible to analyse the modes of deformations that is composed under different load levels subjected to the relative displacements of pier and soil.

In this study, the relative vertical displacements between pier and soil matrix are investigated according to the chosen data points with the analyses of fictionalized cases. In general manner, the analyses results shows that the vertical displacement of pier elements are bigger than soil element displacements for the first pier in all soil profile conditions and all defined pier geometries at the near points of pier cap. But this condition changes at the points near the base of pier. Soil displacements become bigger than piers' at the tip. A different situation occurs for relatively small pier diameters for the piers which are embedded in soil profile 2. The soil displacements exceed pier displacements. The existence of crust layer in the soil profile leads to decrease the relativity degree of displacements throughout the foundation soil layer. Relative displacement change via loading level is illustrated in Figure 6 in order to clarify the effects of mentioned comparative evaluations. Figure 6a and Figure 6d represents the relative change of vertical displacements according to vertical loading increments for homogenous alluvial soil profile. The uniform distributed load is applied from pile cap and data analysis are evaluated for the pier element 1 & soil element 1 (PE1-SE1) and pier element 2 & soil element 2 (PE2) respectively. The displacements are decreased at the deeper points inside pile section. Maximum values of relative displacement occur at the first loading levels. Figure 6b and 6e represents the change of relative displacements of soil and pier elements for soil profile 2 and Figure 6c and 6f shows the change of relative displacements of soil and pier elements for soil profile 3. The degree of relative displacement change according to the rise of crust layer thickness causes to decrease relativity. Homogenous soil profile exhibits deformable characteristics than other profiles of analyses as expected. Minimum relative deformation difference is obtained at the tip points of selected pier embedded in the profiles that are including crust.

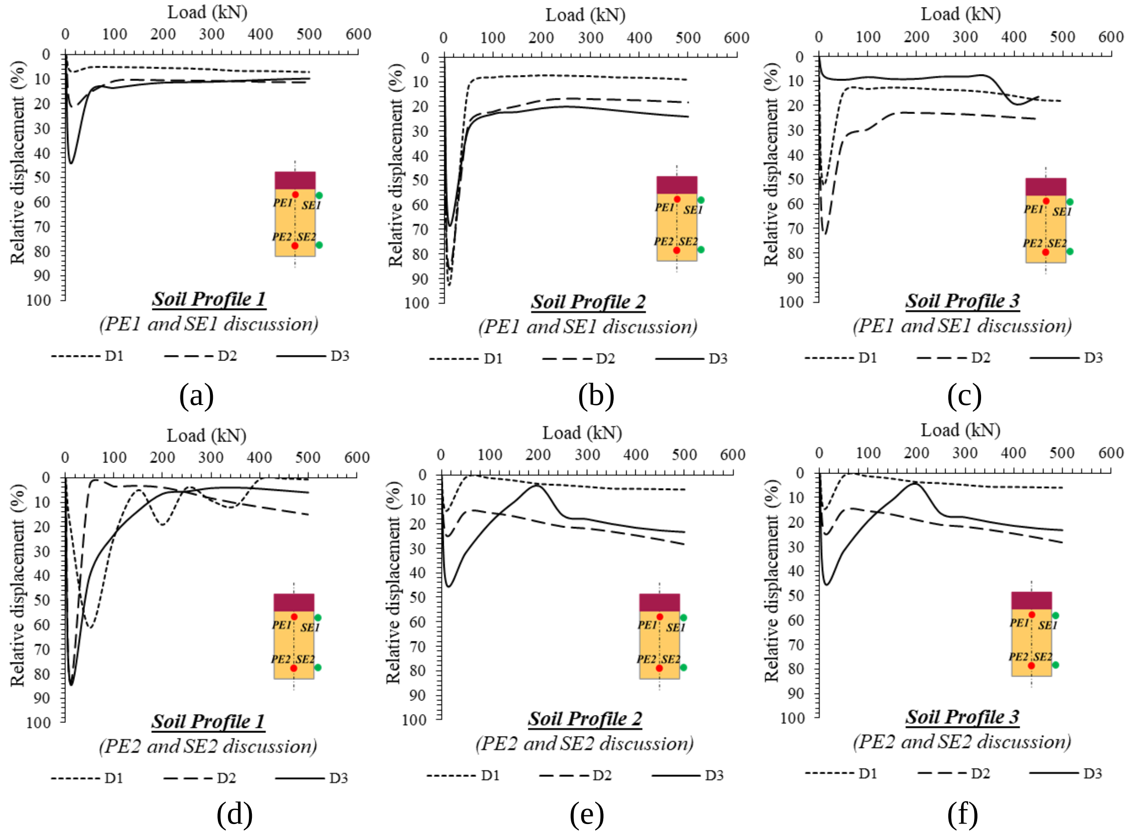


Figure 6. Relative displacement via loading level.

Vertical displacement change according to the load increment is given in Figure 7 for the first pier (P1) embedded in soil profile 1 (SP1). Figure 7a illustrates the displacement change of pier element 1 (PE1) via different diameters of pier. Figure 7b shows the displacement change of pier element 2 (PE2) via different diameters of pier. The vertical axes of the charts are fixed at the same maximum values for simplifying comparison. The increase of the data point depth leads to decrease vertical displacements in all loading levels. The decrease amount of vertical displacements is nearly one third of each other. Figure 8a and 8b represents the vertical displacement change of soil elements 1 and 2 respectively. The vertical axes of the chart is fixed at the same deformation value as the graphs of Figure 7. The deformations exhibited same manner as Figure 7 and decreases along the depth. The difference between soil and pier elements is relatively small for soil profile 1 (SP1)-pier 1 (P1) than other fictionalized cases of analyses.

In order to clarify the effects of pier length to the data points, another case is illustrated by Figure 9 and 10. Pier elements 1-2-3 and soil elements 1-2-3 is addressed in Figure 9 and 10 respectively. The case is modelled for pier 2 (P2) embedded in soil profile 3 (SP3). Generally, pier displacements are bigger than soil element displacements in all loading levels. The decrease of pier diameter decreases the relative change of displacements of pier and soil elements. The relative displacement change for elements 2 and 3 is very smaller than first elements of pier and soil.

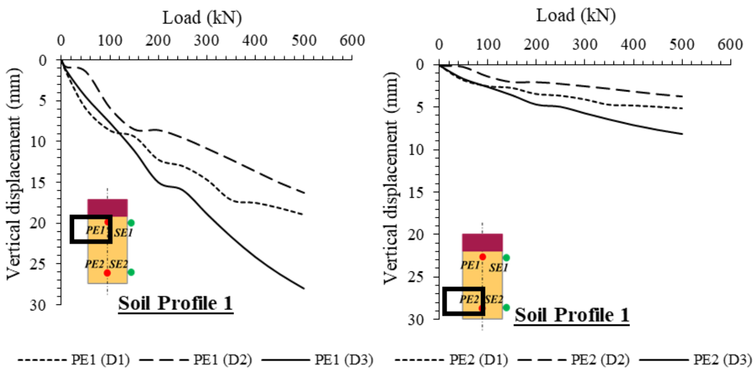


Figure 7. Vertical displacement change via loading level for Pier 1 in Soil Profile 1 according to the data point condition (PE1-PE2).

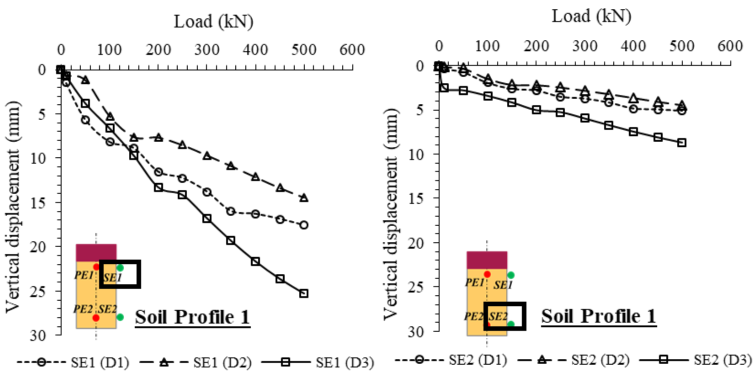
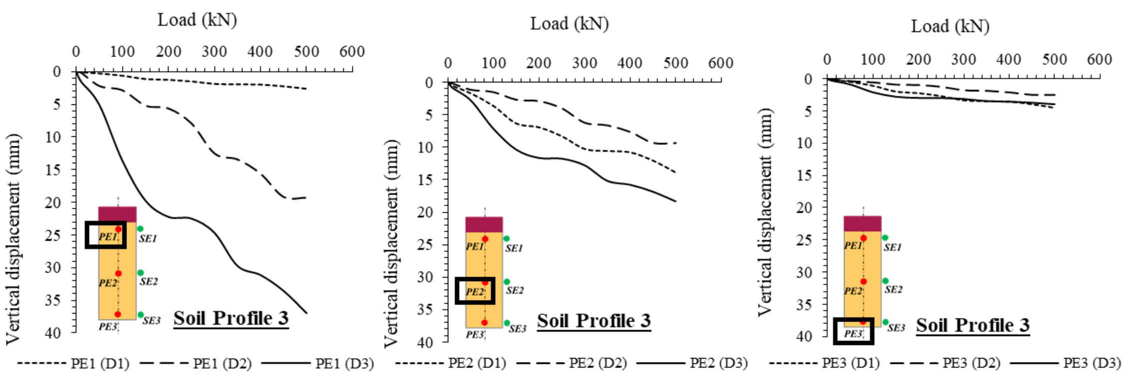
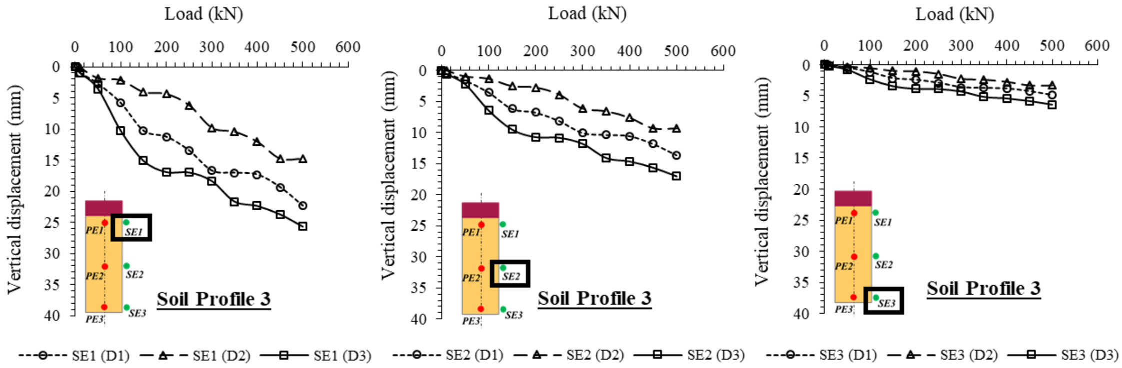


Figure 8. Vertical displacement change via loading level for Pier 1 in Soil Profile 1 according to the data point condition (SE1-SE2).



(a) (b) (c)

Figure 9. Vertical displacement change via loading level for Pier 2 in Soil Profile 3 according to the data point condition (PE1-PE2-PE3).

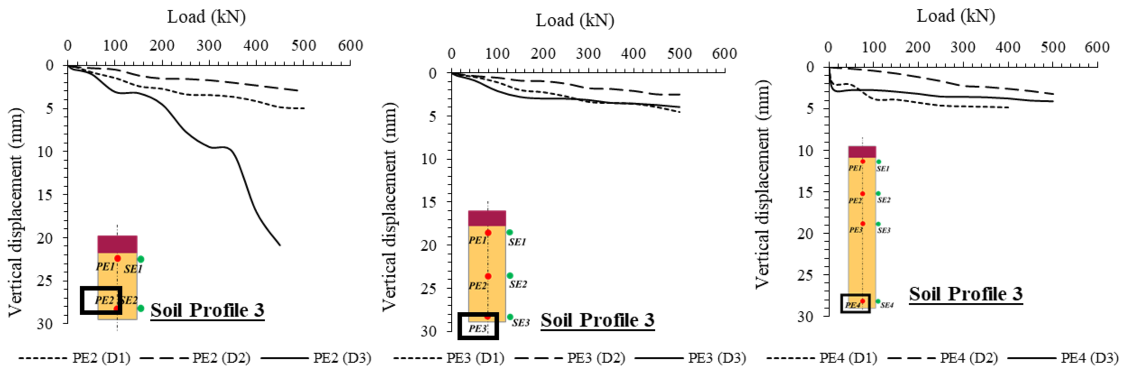


(a) (b) (c)

Figure 10. Vertical displacement change via loading level for Pier 2 in Soil Profile 3 according to the data point condition (SE1-SE2-SE3).

3.2. Pier diameter effect

In Figure 11 vertical displacement change via loading level according to the pier diameters is given respectively for pier 1, 2 and 3 when they are embedded in soil profile 3 (SP3). The tip points of piers are used as data points for the evaluation. Soil profile 3 consists of 2 meter crust layer above alluvial soil medium. Therefore for pier 1 (P1) the pier is fully embedded in crust layer. The rise of pier diameter causes to deform crust layer bigger than other cases but at the other cases (P2 and P3) deformation levels remain as the same at the pier tip. But it is remarkable that the pier which has 0.8 meters diameter exhibits less deformable characteristics than other cases.



(a) (b) (c)

Figure 11. Vertical displacement change via loading level according to the pier diameter change for pier elements.

Vertical displacement change via loading levels according to pier length and diameter is given in Figure 12 for the soil elements located at the tip of pier. The only contrarian case is evaluated for pier 1 (P1), soil element 1 (SE1). The other amounts of displacements remain the same for cases and the increment of pier diameter leads deformations to rise instead of the pier that has 0.8 meters diameter.

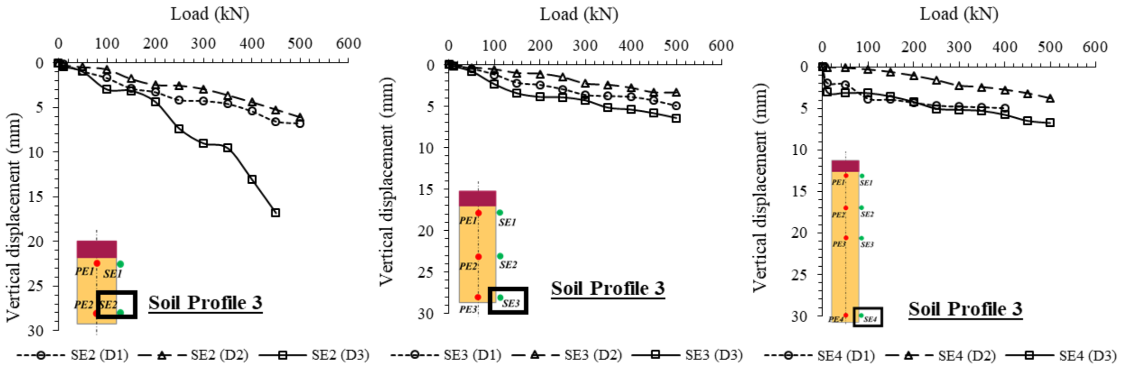


Figure 12. Vertical displacement change via loading level according to the pier diameter change for soil elements.

3.3. Pier lenght effect

In Figure 13, pier 1-2 and 3 are presented respectively with their resultant displacements for the pier diameter 0.5 (D1) meters in the soil profile 1 (SP1). Data points are marked on the illustrations for the selected cases. Pier displacements are increased according to the increasing length of pier for pier elements in both cases shown in Figure 13a and 13b. The increase amount is decreased with the increment of embedment depth. Figure 14 shows the effects of pier length according to the soil element displacements. Similar manner is evaluated for pier and soil elements for the case of increasing pier length.

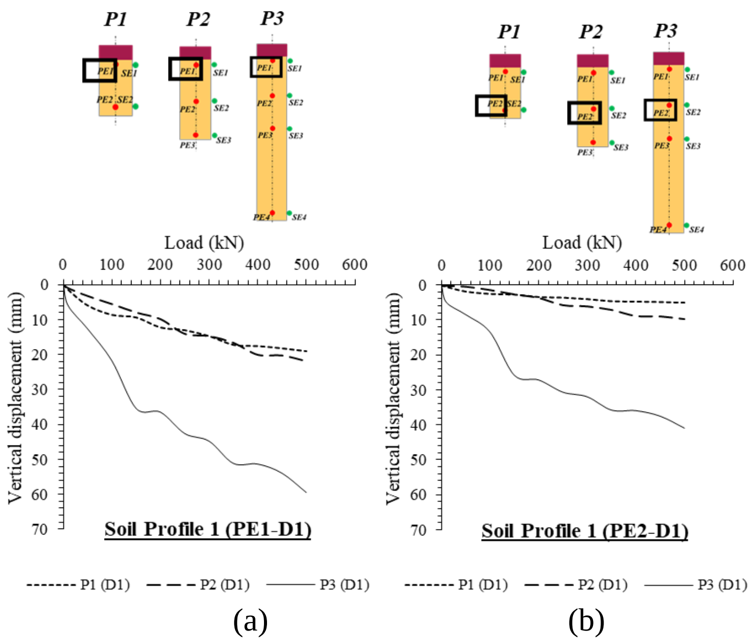


Figure 12. Vertical displacement change via loading level according to the pier length change for pier elements.

3.4. Foundation soil stratification effect

In Figure 15, vertical displacement change according to the loading levels are given with respect to the change of soil profile. Figure 15a, 15b, 15c represents pier element 1 (PE1), 15d, 15e, 15f represents pier element 4 (PE4) for soil profile 1 (SP1), soil profile 2 (SP2) and soil profile 3 (SP3) respectively.

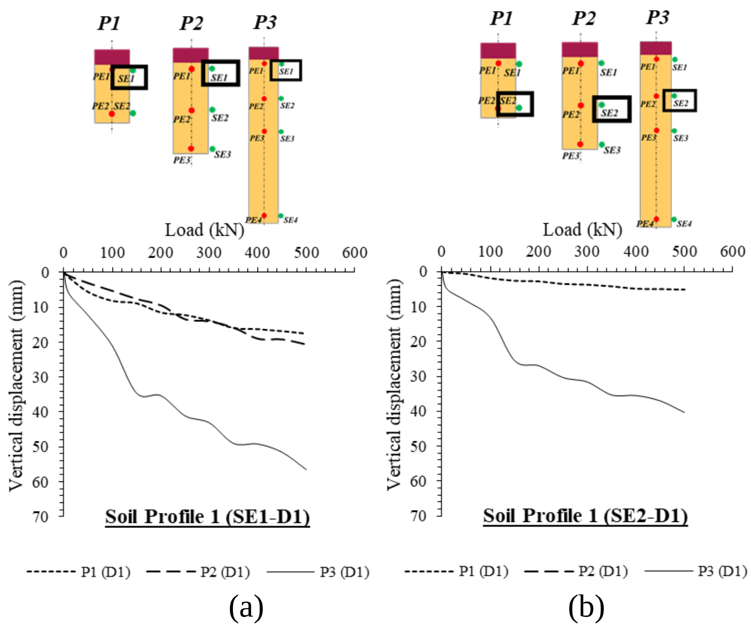


Figure 14. Vertical displacement change via loading level according to the pier length change for soil elements.

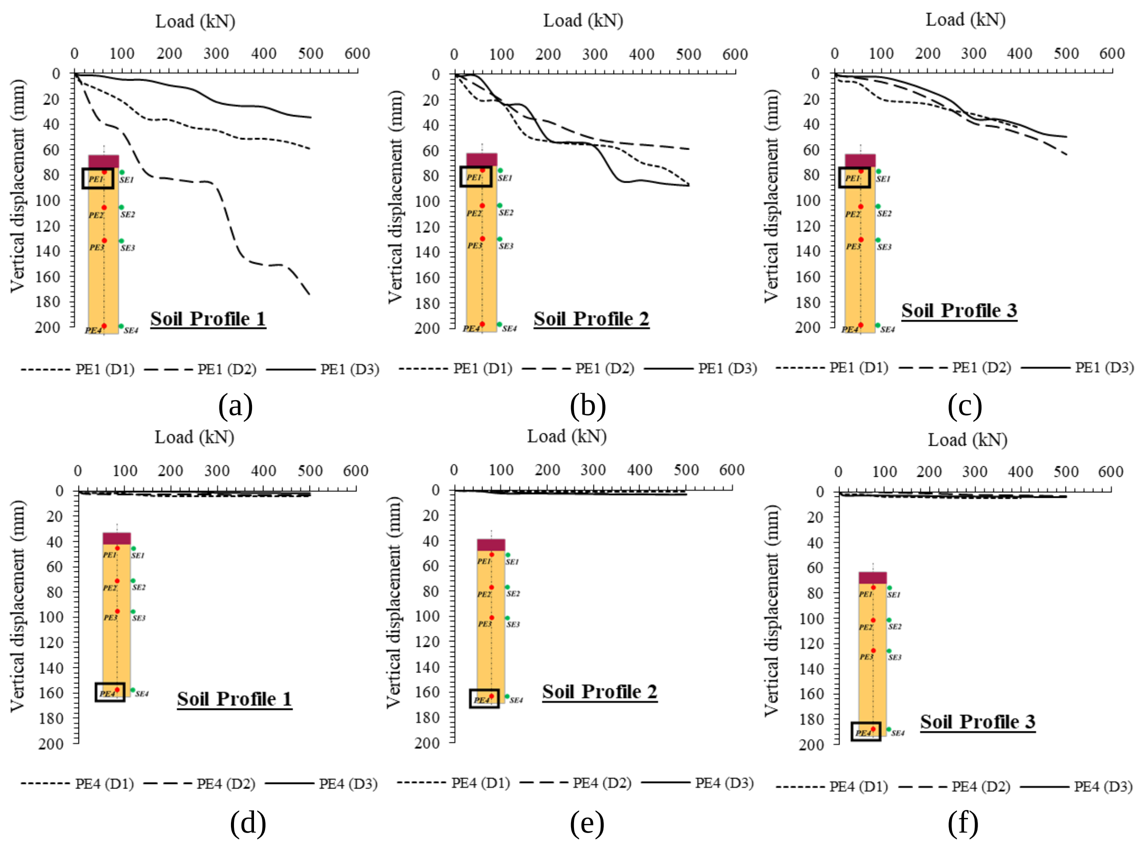


Figure 15. Vertical displacement change via loading level according to the pier length change for soil elements.

Figure 16 shows the displacement-loading level change with respect to soil elements of same case as Figure 15. Relatively bigger displacements are occurred at homogenous soil profile at the data point PE1. Thickness of crust layer effects deformation occurrence mostly for the case of 0.8 meters diameter and the rise of crust thickness causes pier to decrease displacements half of the displacements occurred in homogenous soil profile. The deformations are decreased at the data point PE4 as the same level for all evaluated cases. Figure 16 shows the same manner as Figure 15 but the degree of deformations are much bigger than the deformations evaluated at the soil element located at the tip of the pier-soil interface.

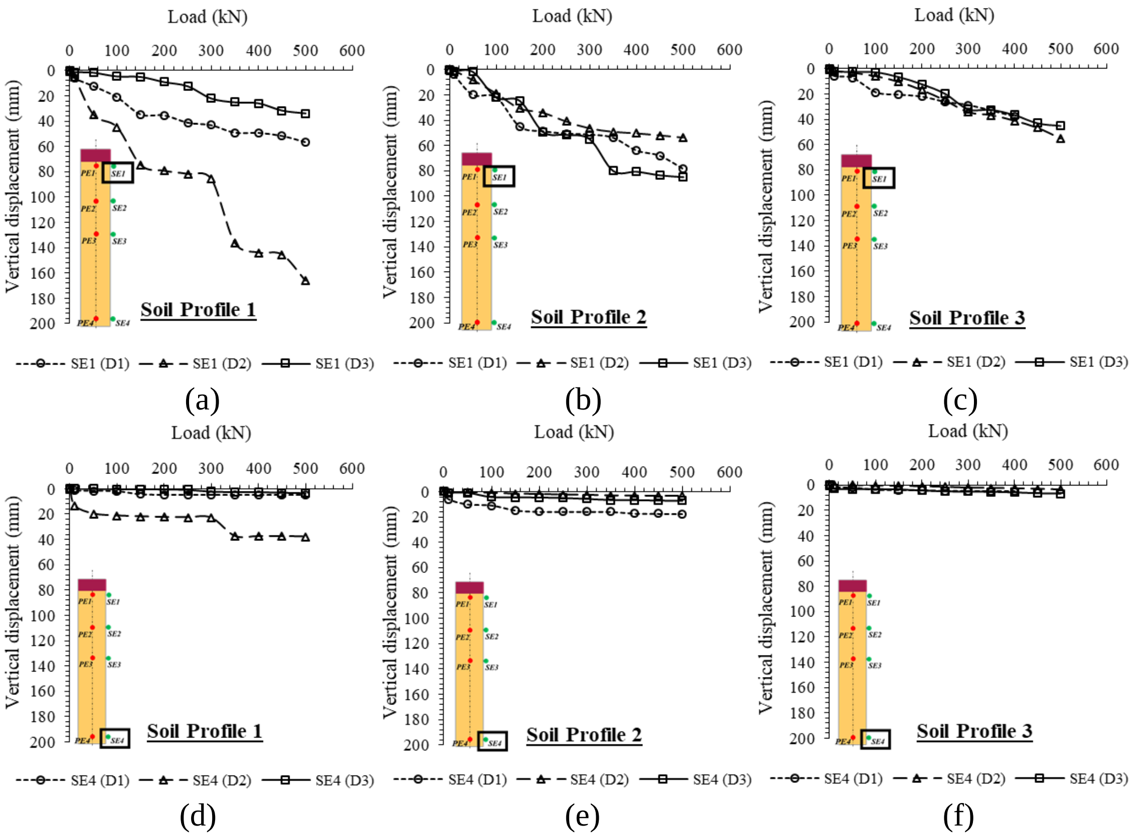


Figure 16. Vertical displacement change via loading level according to the pier length change for soil elements.

3. Evaluations and results

In this paper, numerical analyses are conducted in order to clarify the effects of soil stratification on the behavior of piers that has variable geometrical characteristics. Numerical analysis are illustrated in the previous section with respect to vertical displacement change via loading levels. The case of building rammed aggregate piers is quite different from installing traditionally drilled in situ concrete, reinforced concrete piles or stone columns. The ramming process generates excessive deformations and stresses inside the pier and also inside the soil matrix adjacent to pier. The increment of the loading magnitude in the application procedures of the tests causes to increase the deformations in the pier and in the soil both.

Numerical analyses results show that the main factor affecting relative displacement of pier and surrounding soil matrix is the pre-stressing of soil medium during the installation process. Relative displacement-loading level curves are shown that the bigger relative displacement occurrence is evaluated at the first stages of installation and at the top of the pier.

The results of the analyses are shown that the deformations can be occurred with different modes subjected to compressive loads according to their degrees and soil conditions in relation with pier dimensions. The type of deformation can be identified by the evaluation of load-settlement charts. Tip movement and bulging is the most common types of deformations encountered in the fictionalized pier construction applications. Vertical displacement-loading level curves are shown that the type of tip movement can be seen in the cases that the length of pier is shorter than others (P1 and P2). For longer pile length (P3) bulging is dominant type of deformation. It can be seen by the comparison of top pier element settlement with top soil element settlements. Bulging type of deformation occurred when the difference of top element settlements of pier and soil is increased with the rise of loading level.

Increasing depth of data points in pier or in soil matrix leads to decrease evaluated displacement values as expected. The relative difference between the selected points displacements are raised according to the increase in pier length. The raise of vertical distance between data points increases the difference between consisted displacements.

It is found that the increase of pier diameter inspires decrement of the displacements at the same points in the pier but above a limited diameter value the displacements are increased. This situation maintains validity for the pier length. Because of these opposite behavior it is very important to check diameter and length values in the field. It will be appropriate to use optimization algorithms to find the optimal design.

The change of foundation stratification influences the whole behavior with the interaction takes common place for the thickness of crust layer and length of pier. The presence of crust layer significantly affected resultant deformations independently of the thickness of crust for the selected soil profiles and applied cases.

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