Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 55(3) (2023) 129-132
DOI: 10.22060/ceej.2023.21772.7821

Investigating the dynamic response of deep mixing columns and gravel columns in liquefiable layer with different thickness

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ABSTRACT: Liquefaction is one of the most devastating Geotechnical phenomena that severely damage vital structures and lifelines. An accurate understanding of the dynamic response of the site prone to liquefaction and improved with different modern methods and comparing it with the unimproved site improves the ability of engineers to choose the appropriate improvement method. Before construction, it is necessary to solve the geotechnical problem. Among the methods of land improvement to deal with liquefaction, gravel columns and deep mixing columns can be mentioned. In this study, the results of 1g shaking table tests by a flexible box on the foundation located on the liquefiable ground surface and reinforced with the aforementioned techniques have been investigated. The dynamic responses of the reinforced ground in different thicknesses of the liquefiable layer and the different frequencies of the input movement have been investigated based on stress-strain behavior, secant shear modulus of the soil and excess pore water pressure versus shear strain. The results of the tests show that the thickness of the liquefiable layer has a considerable effect on the dynamic responses of the soil, including the shear behavior and the shear modulus of the soil. By increasing the thickness of the liquefiable layer, the values of the secant shear modulus and shear strain of the improved mass decrease and increase respectively. Also, the dynamic performance of deep mixing columns in thicker layers is more suitable compared to gravel columns, and at lower thicknesses, the dynamic behavior of gravel columns approaches that of deep mixing columns.

Review History:

Received: Sep. 14, 2022
Revised: Feb. 08, 2023
Accepted: Feb. 09, 2023
Available Online: Feb. 15, 2023

Keywords:

Deep soil mixing
Gravel drain
Thickness of the liquefiable layer
Input motion frequency
Secant shear modulus

1- Introduction

Liquefaction-induced ground deformation is one of the major seismic hazards that cause damage to buildings, infrastructure, roads, bridges, and even loss of human life, as reported in previous seismic events [1]. Liu and Dobry (1997) carried out eight centrifuge tests to investigate settlement features of circular foundations situated on liquefiable soils [2]. The result of their study indicated that settlement percentage is dependent upon the width of the foundation and the thickness of the liquefiable layer. Therefore, the liquefiable layer thickness is one of the governing factors in the adopted countermeasure technics. When choosing land reclamation methods to deal with liquefaction, factors such as effectiveness, reliability, cost-effectiveness, time, construction conditions, soil type, and environmental compatibility should be considered [3, 4]. Among the soil improvement methods, deep soil mixing (DSM) columns and gravel drain (GD) columns can be highlighted, especially in urban areas. These techniques have a short construction time and low cost. They also have much less vibration and noise pollution than compacting methods [5, 6]. DSM is one of the most effective methods for improving liquefiable soil [7-9]. Esmaeili et al. (2014) investigated the effectiveness of DSM in loose sandy soils using laboratory experiments. The results show that the effectiveness of DSM depends on various parameters such as sand density and the water-to-cement ratio of mortar [10]. Asadzadeh and Bahadori (2009) investigated the effect of inlet movement and the arrangement of stone columns to deal with liquefaction. In this study, a PVC pipe with a diameter of 5cm was used to model the stone columns. The results show that the triangular arrangement of the columns has a better performance to deal with liquefaction [11]. Therefore, it is necessary to evaluate the response and deformation of reinforced soil against strong movements for critical structures in order to choose the most appropriate improvement method.

However, almost few comprehensive studies have been performed on the effect of different liquefaction layer thicknesses on the seismic performance of DSM and GD columns so far. In order to fully understand the performance of columns, it is necessary to study the dynamic behavior of columns at different thicknesses of the liquid-prone sand layer. In this study, a shaking table model test with a flexible

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box was used to analyze the seismic responses of free-field, GD and DSM columns containing soil layers. Models were implied harmonic loads with different frequency domains. The effects of the DSM and GD columns on the nonlinear dynamic response of different thicknesses of the liquefaction-prone sand layer were investigated by using parameters such as stress-strain response, excess pore water pressure ratio and the shear modulus of the whole system. Furthermore, the rupture of the columns in a similar area replacement ratio (Ar=18.2%) is focused.

2- Methodology

A flexible tank on the shaking table was designed for testing. The model tank was a rectangular laminar shear box with internal dimensions of 135.5 cm in length, 85.6 cm in width, and 72 cm in height. This tank was made of 18 single laminates supported by each other and made of aluminum profile pieces. The cross-section of the laminates was rectangular, with dimensions of 40 mm by 66 mm. The laminates were stacked one on top of the other and separated by ball bearings. The flexible box was free to move only along one direction and along the horizontal plane.

2- 1- Material

Firoozkuh Sand No. 161, which is clean and uniform sand, has been used in this study. The stone columns have a special particle distribution that is designed according to the studies of Seed and Booker (1977). The materials used to build DSM columns include ambient soil (Firoozkuh sand#161) and Portland cement type II, which have been created in situ with a water-to-cement ratio of unity and cement content of 110 kg/m^3.

In the present study, the construction of columns in the sand was not feasible without special arrangements. Thus, for this purpose, PVC pipes with an outer diameter of 5 cm were used in compliance with the simulation rules.

3- Results and Discussion

In these experiments, the effect of liquefiable soil layer thickness on the performance of two improvement methods (GD and DSM columns) was investigated. The peak input acceleration for all tests was approximately 0.2 g and was applied at frequencies of 1, 2, and 3 Hz. The secant shear modulus is usually used to estimate the shear stiffness of the soil under periodic loading. Soil shear modulus is estimated from stress-strain hysteresis curves and calculated as follows:

$$G = \frac{\tau_{max-}\tau_{min}}{\gamma_{max-}\gamma_{min}} \quad (1)$$

The changes of hardness with shear strain (G-ɤ) can be properly evaluated as a basic input parameter for dynamic analysis. The secant shear modulus in terms of shear strain has been obtained in all tests for different depths and in two sites reinforced with a tone column and deep mixing column. The results show that the higher thickness of the liquefiable layer leads to a decrease in the values of the secant shear modulus. The values of shear strain in the thicker liquefiable layer are higher than the thinner layer.

The results in this study show that in both methods of land improvement, in general, by reducing the thickness of the layer prone to liquefaction, the amount of shear strains and the generation of excess pore water pressure in the model also decreases. This shows that the thickness of the layer prone to liquefaction has a significant effect on the seismic performance of the soil and the effectiveness of the improvement methods.

The amount of input frequency in the soil system and foundation at different thicknesses in liquefiable soil also has diverse effects on the subsidence behavior of the foundation

Fig. 1. A view of the shaking table and laminar shear box

4- Conclusions

Ten tests were carried out, one of which was unmodified and nine of which were modified with columns. The main results of the experiments are as follows:

In the unimproved soil model, after a small number of applied loading loops, the loops quickly tilt horizontally, which indicates the rapid reduction of the shear modulus of the soil, which is caused by the occurrence of liquefaction in the unreinforced soil layer, but in reinforced models, the tendency of the stress-strain loops to become horizontal decreases.

The additional pore pressure values of the reinforced model have decreased significantly compared to the unreinforced model, in other words, soil reinforcement has improved the shear modulus of the reinforced soil mass.

Among the two improvement methods mentioned, the technique of deep mixing columns in thicker layers has a better performance than stone columns and has significantly preserved the shear modulus and reduced the shear strain of the soil mass.

Based on the results of this research, the behavior of stone columns and deep mixing columns is closer to each other in smaller thicknesses.

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HOW TO CITE THIS ARTICLE

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