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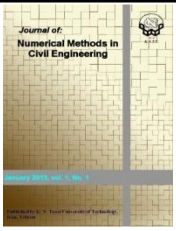

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Investigation of the effectiveness of deep mixing method on seismic response of liquefiable soils using 3D numerical simulation

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Abstract:

In recent decades, extensive studies have been conducted on mitigating the effects of liquefaction through various soil improvement methods. The Deep Mixing Method (DMM) is a widely used technique to improve the mechanical properties of loose soils and reduce liquefaction effects. This research investigates the performance of DMM columns in reducing liquefaction effects through a parametric study using the finite element software OpenSees PL. In this study, the soil and DMM columns are modeled as a continuous three-dimensional medium considering nonlinear elastoplastic behavior. The influence of area replacement ratio, layout placement of DMM columns, and shear modulus on excess pore water pressure, lateral displacement, horizontal acceleration, and stress-strain behavior in the liquefiable soil are investigated. Results show that an area replacement ratio of 20% or higher effectively reduces liquefaction effects. Furthermore, using DMM columns in a grid layout is more effective in reducing liquefaction effects compared to a single-column layout. However, employing DMM columns increases the acceleration transmitted to the superstructure at the ground surface.

1. Introduction

Liquefaction is a phenomenon where the stiffness and strength of saturated, loose, cohesionless soils decrease due to an increase in pore water pressure, causing the soil to behave like a fluid. Among conventional methods for liquefaction mitigation, in-situ soil mixing with cementitious materials such as lime or cement, known as the Deep Mixing Method (DMM), has garnered significant attention due to its simplicity, cost-effectiveness, and high efficiency. A common method to counter liquefaction involves creating a grid of DMM walls in the ground, which confines the liquefiable soil within cells of soil-cement walls. This approach limits the increase in shear strains in the liquefiable soil, preventing the rise in pore water pressure and reducing soil displacement in the improved area.

Design guidelines estimate shear stresses in improved soil, assuming shear strain compatibility between the DMM columns and the surrounding soil which was initially proposed by Baez (1995) [1]. In this theory, it is assumed that DMM columns, due to their higher stiffness, bear more shear stresses under loading compared to the surrounding soil which results in the reduction of shear stresses in the soil. It has been shown that DMM columns deform in both shear and flexural modes under seismic loadings [2-4], but due to the complex behavior of DMM columns in liquefiable soil, the actual deformation pattern of the columns has not been accurately determined.

Moreover, the effects of various design parameters, including the area replacement ratio, layout placement of DMM columns, and the shear stiffness ratio of the columns to the surrounding soil on the mechanical behavior of the

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liquefiable soil have not been thoroughly studied. This study aims to investigate the impact of the mentioned parameters on the behavior of DMM columns in liquefiable soil.

In this research, a series of three-dimensional numerical simulations are conducted on improved and unimproved soil under dynamic loading to investigate the effects of area replacement ratio, layout placement of DMM columns, and the shear stiffness ratio of the columns to the surrounding soil. The elastoplastic nonlinear PMDY02 constitutive model in OpenSees PL has been used for continuous modeling of liquefiable soil and DMM columns. This model, with pressure-dependent yield surfaces, can accurately simulate the dilative behavior of liquefiable soils under cyclic loading.

2. Literature review

The Deep Mixing Method (DMM) is a widely used soil improvement technique globally. It involves injecting stabilizing materials such as cement or lime into the soil using a hollow-shaft auger, mechanically producing soil-cement columns, and enhancing soil properties. Continuous soil-cement walls can be constructed beneath the ground surface by overlapping columns before complete cementation of the columns. Utilizing the deep mixing method, especially in a grid layout, significantly enhances the average shear strength of the soil, thereby reducing the liquefaction potential of loose, saturated soils.

The effectiveness of DMM columns in reducing liquefaction effects has been investigated in past studies using physical modeling by conducting centrifuge and shake table tests. These studies have shown that the effectiveness of DMM columns depends on the geometric layout of the columns [5,6] and their spacing and stiffness ratio [6-8]. The columns significantly reduce excess pore water pressure; however, using a single-column layout does not significantly impact settlement and shear stresses [9]. Using DMM columns in a grid layout effectively reduces shear stresses and settlements due to the confining effect of the column walls on the dynamic shear strain in the confined soil [6,10]. Another study showed that using DMM columns reinforced with steel rebars, even if not used in a grid layout, can reduce shear stresses and settlements [11].

Numerical studies have seen significant growth in recent years because of advancements in numerical modeling methods and the ability to investigate multiple parameters. Numerical models for simulating DMM columns can be divided into two categories: 2D FEM models (e.g., O'Rourke & Goh, 1997 [12]) and 3D FEM models (e.g., Namikawa et al., 2014 [13]). Although 2D simulations reduce computational costs, O'Rourke and Goh (1997) showed that these models might show unrealistic shear deformations. On the other hand, 3D effective stress analyses by Namikawa et al. [13] showed that the area replacement ratio and the average stiffness of the improved soil are the most important parameters controlling the effectiveness of DMM columns.

Several numerical studies have investigated the effect of DMM column groups on reducing liquefaction potential [14,15]. These studies have shown that the area replacement ratio and the shear modulus ratio of DMM columns are the most critical parameters in reducing shear stresses and excess pore water pressures under dynamic loading. Moreover, with a sufficient area replacement ratio, DMM columns effectively reduce settlements and lateral displacements caused by soil liquefaction. These studies also evaluated the effect of other parameters, such as the depth and layout of the columns.

Another group of studies has evaluated the effectiveness of using DMM walls in a grid layout to mitigate liquefaction effects [16-18]. These studies investigated parameters such as the spacing of the grid walls, thickness of the DMM walls, relative density of liquefiable soil, and ratio of the shear modulus of soil-cement walls to the surrounding soil. The results have shown that using the deep mixing method in a grid layout effectively reduces liquefaction potential, increases the bearing capacity of shallow foundations, and reduces settlements. The effect of DMM walls is because of preventing the buildup of excess pore water pressure and resisting lateral deformations. Furthermore, the spacing of the grid walls, the thickness of the DMM walls, relative soil density, and the shear modulus ratio of DMM walls to the confined soil are crucial factors in the ability to mitigate liquefaction effects.

3. Numerical modeling

3.1 Modeling of soil and DMM columns

In this study, three-dimensional numerical simulations of DMM columns in liquefiable soil were performed using the finite element software OpenSeesPL. The computational time required for solving three-dimensional models of liquefiable soils is significantly high due to the large number of degrees of freedom, the complexity of the constitutive models used, and the coupled interaction of solid and fluid phases in these models. To reduce the computational time, simplifying assumptions or selecting appropriate boundary conditions can be used. By assuming similar behavior of DMM columns in a group, only one DMM column can be simulated with periodic boundary conditions applied to the lateral boundaries.

Figure 1 shows the plan view of a group of DMM columns with periodic boundary conditions. In these boundary conditions, points located on lines i-l and j-k (soil boundary points) are constrained to have the same displacement in the x and z directions (longitudinal and vertical directions), while nodes on the bottom boundaries (base model or bedrock) are fixed in all degrees of freedom. Due to the application of the earthquake excitation along the longitudinal direction and symmetry of the model, only half of the model is simulated to reduce computational time. This modeling approach in a 3D continuous media has been used in the modeling of piles by [16,19,20,21] and in modeling stone columns and DMM columns by [15,17,22,23].

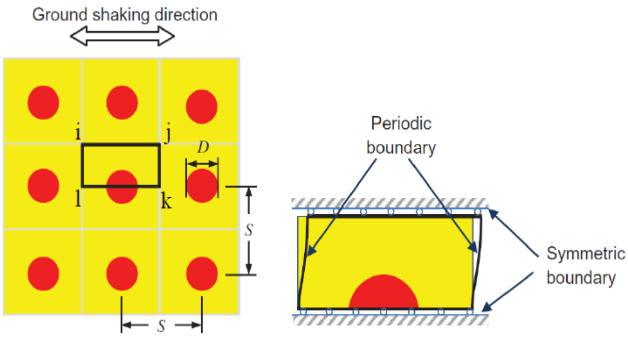


Fig. 1: A schematic view of a group of DMM columns with periodic boundary conditions

In this research, DMM columns are modeled in two layouts of grid and single-column to evaluate the effectiveness of the geometric pattern of columns. In these models, the area replacement ratio (A_{rr}) is equal to the ratio of the improved area ($A_{improved}$) to the total area (A), as schematically shown for both grid and single-column layouts in Figure 2. The area replacement ratio in the models of this research is chosen as 5%, 10%, 20%, 40%, and 50% for both grid and single-column layouts to examine the efficiency of each layout in mitigating liquefaction effects. Table 1 presents the geometrical specifications of each layout for different area replacement ratios. Figure 3 shows numerical models of DMM columns in grid and single-column layouts for different area replacement ratios.

In recent years, advanced constitutive models have been developed to simulate liquefiable soil under dynamic loading, effectively replicating the behavior of liquefiable soil under such loads. In this study, a nonlinear elastoplastic constitutive model is used to simulate the behavior of liquefiable soil. This model, known as PressureDependMultiYield02 (PDMY02) in the OpenSeesPL material library, has pressure-dependent yield surfaces and can simulate the dilative behavior of liquefiable soils under cyclic loading.

The hardening law, yield function, and flow rule are key components in the PDMY model. The yield function is conical in the principal stress space, with its apex along the hydrostatic axis. Additionally, multiple similar yield surfaces, each with defined apices and varying sizes, form the hardening region, which encloses the failure envelope. For saturated soils, this constitutive model is based on Biot's theory (1963), which treats the soil as a two-phase porous medium, where the deformations of the solid and fluid phases are coupled.

Values of parameters of the PDMY model are selected from the study of Rayamajhi et al. (2014) [22] which calibrated these parameters based on the results of centrifuge tests on DMM columns.

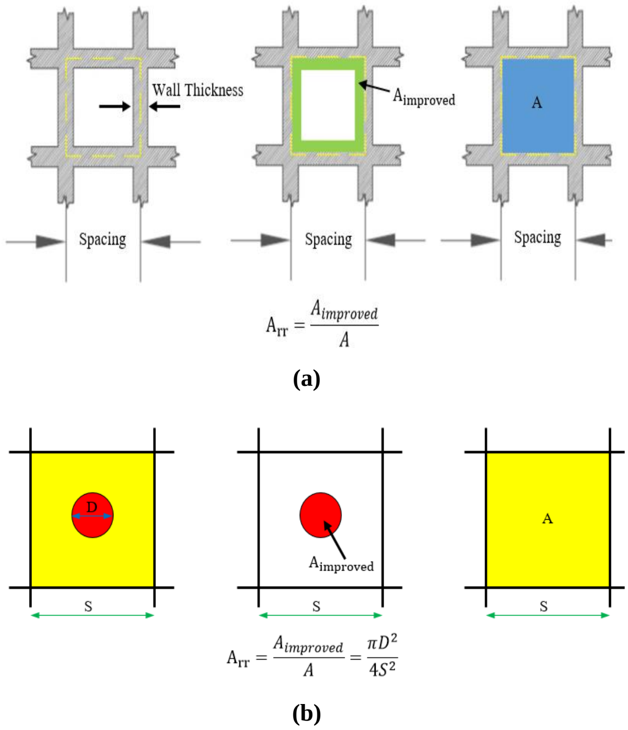


Fig. 2: Area replacement ratio (A_{rr}) for (a) grid and (b) single-column layouts

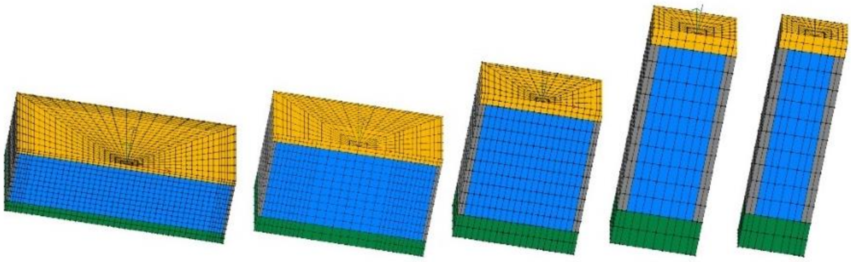
3.2 Soil Constitutive Model

3.3 Soil profile

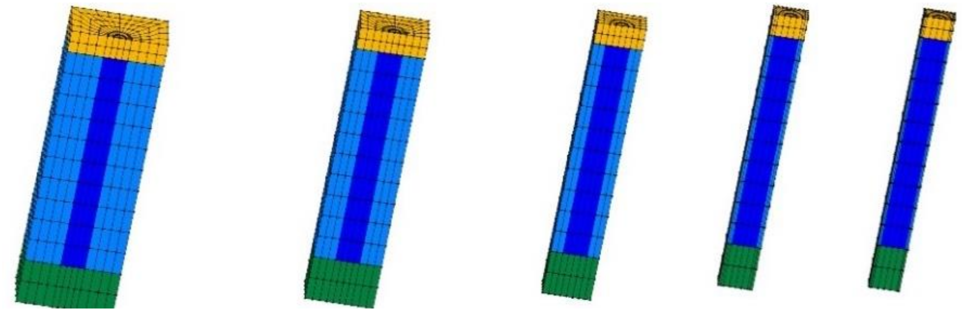
The soil profile used in all models of this research consists of three layers and is fully saturated. The top and bottom layers consist of dense sand with thicknesses of 1 meter and 2 meters, respectively, while the middle layer consists of loose sand with a thickness of 10 meters. The liquefiable layer has a relative density of 40%, an internal friction angle of 33°, and a low-strain shear modulus of 40 MPa. Thickness of the DMM walls in grid layouts or diameter of the DMM columns in single-column layouts are equal to 1 meter in all models, as represented in Table 1. Figure 4 shows an example of the simulated soil profile with DMM columns in both grid and single-column layouts.

Table 1: Geometrical specifications of grid and single-column layouts for different area replacement ratios

Grid layout					
Area replacement ratio A_rr (%)	5	10	20	40	50
Wall thickness (m)	1.0	1.0	1.0	1.0	1.0
Wall spacing (m)	39.5	19.5	9.5	4.4	3.4
Single-column layout					
Area replacement ratio A_rr (%)	5	10	20	40	50
Column diameter (m)	1.0	1.0	1.0	1.0	1.0
Column spacing (m)	4.0	2.8	2.0	1.4	1.3



(a)



$A_{rr}=5(\%)$ $A_{rr}=10(\%)$ $A_{rr}=20(\%)$ $A_{rr}=40(\%)$ $A_{rr}=50(\%)$

(b)

Fig. 3: 3D view of (a) grid and (b) single-column layouts simulated in the OpenSeesPL for different area replacement ratios

To simulate soil and DMM columns, eight-node solid elements based on a coupled formulation considering fluid-solid interaction for saturated soils are used. Each node of these elements has four degrees of freedom: three translational degrees of freedom and one degree of freedom for the calculation of pore water pressures. Also, DMM columns are directly connected to the surrounding soil without any interface elements.

3.4 Elements dimension in the finite element mesh

The finer the element dimensions, the greater the number of elements are, leading to a more accurate analysis. However, when the number of elements exceeds a certain limit, the time required for the analysis of models increases significantly. The element dimensions should be proportionate to the wavelength of the seismic waves; if the element dimensions are too large, they cannot capture the wave variations. In other words, the element dimensions should be small enough so that seismic waves can pass through the elements without being filtered out. The frequency and velocity of the propagating waves are the key parameters in this regard. Generally, for proper transmission of seismic waves through the elements, the dimension of the elements should be equal to or smaller than approximately one-eighth of the wavelength of the seismic waves (Kuhlemeyer & Lysmer, 1973 [24]) according to the equation (1):

$$\Delta l \leq \frac{\lambda}{8} = \frac{V_{s,min}}{8 f_{max}} \qquad (1)$$

where Δl is the element size, λ is the wavelength of the seismic wave, f_{max} is the maximum input excitation frequency, and $V_{s,min}$ is the minimum shear wave velocity. To determine the element size in the finite element mesh, the values of f_{max} and $V_{s,min}$ are taken as 10 Hz and 80 m/s, respectively. Based on these values, the element size of 1 meter is obtained using the equation (1). The obtained dimension is used for mesh generation in all FEM models of this study.

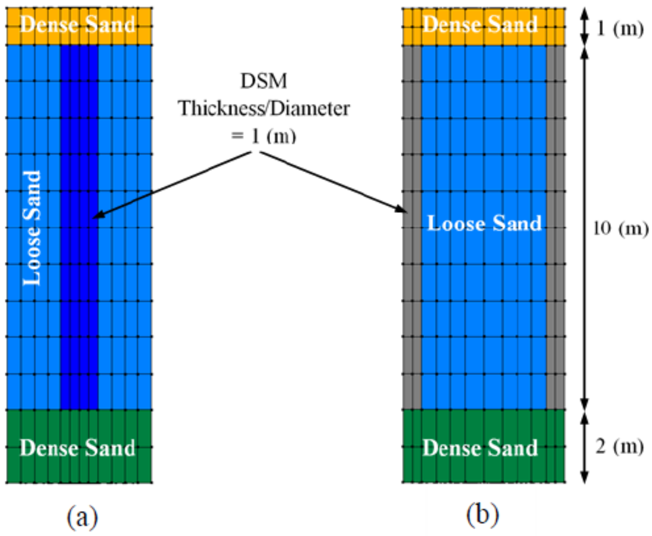


Fig. 4: An example of the simulated soil profile with DMM columns in both (a) single-column and (b) grid layouts

3.5 Boundary conditions

The following boundary conditions are used in the numerical model:

- Nodes on the symmetry boundaries and the bottom of the model (bedrock) are considered impermeable, allowing drainage only from the soil surface.
- Nodes on the bottom of the model (z= -13m) are constrained against any translational movement, and nodes on the lateral boundaries (x=±S/2 and y=+S/2) are constrained in x and y directions.
- With periodic boundary conditions, nodes on the lateral boundaries (x= -S/2 and y=+S/2) are constrained to a specific elevation level in the x and y directions and exhibit the same displacement.
- Nodes on the symmetry boundary (y=0) are constrained in displacement perpendicular to the plane (y direction, rotation around the x and z axes) but can displace within the plane.

3.6 Applied excitation to the models

In this study, a scaled acceleration time history (PGA = 0.1g) from the Kocaeli earthquake recorded at the Izmit 090 station is applied to the models (Figure 5). The predominant period of this excitation is about 0.28 seconds.

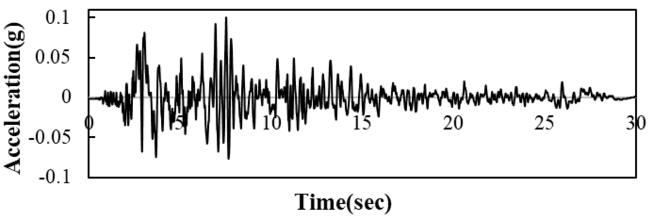


Fig. 5: Acceleration time history of the Kocaeli earthquake scaled to a PGA of 0.1g

4. Model verification

To ensure the accuracy of the numerical model, centrifuge test No. 2 from the VELACS project [25] is first simulated in OpenSeesPL, and the results are compared. Subsequently, the numerical model presented by Rayamajhi et al. [22] is simulated, and the results are compared.

4.1 VELACS centrifuge test

The objective of the VELACS project [25] was to perform dynamic centrifuge tests on various saturated soil models to investigate liquefaction mechanisms and use the results to verify various numerical models. The second centrifuge test from the VELACS project is selected to verify the numerical model of the present study. The liquefiable soil profile in the VELACS No. 2 model consisted of a layer of Nevada sand with a relative density of 40%. Figure 6 shows the experimental model and the simulated model in OpenSeesPL. The parameters of the PDMY02 constitutive model are selected based on the loose sand used in the test. Figures 7, 8, and 9 respectively show the time history of excess pore water pressure, lateral displacement of the ground surface, and horizontal acceleration of the soil obtained from the experimental test and numerical simulation. As observed, there is a good agreement between the results of the centrifuge test and the numerical simulation.

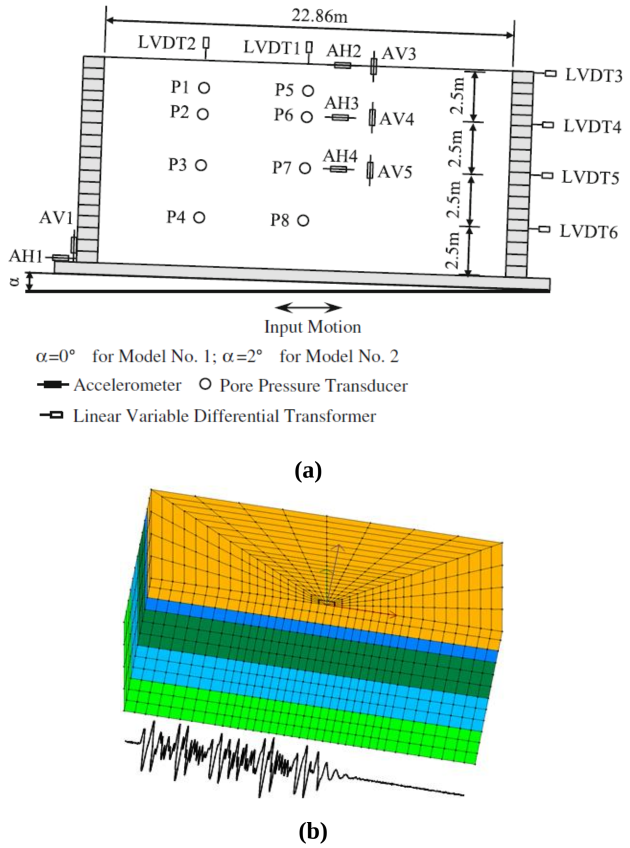


Fig. 6: Details of VELACS No.2 test: a) experimental model b) Numerical model in OpenSeesPL

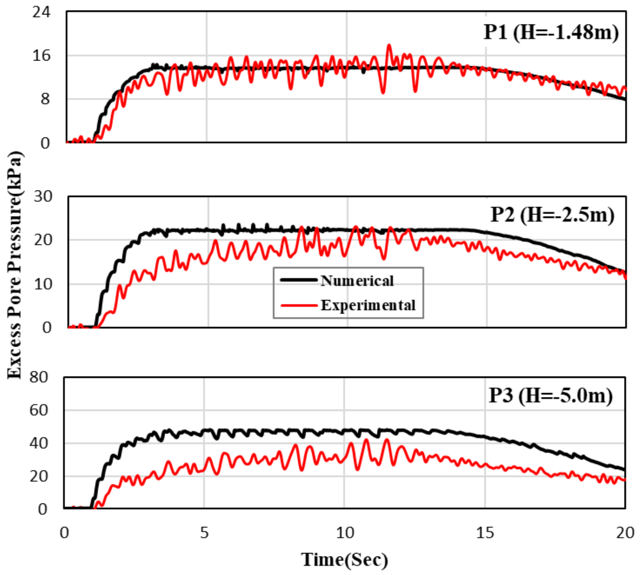


Fig. 7: Comparison of excess pore water pressure at different depths obtained from experimental test [25] and numerical simulation

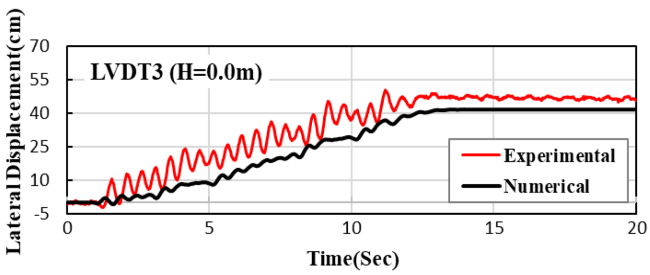


Fig. 8: Comparison of lateral displacement of the ground surface obtained from experimental test [25] and numerical simulation

4.2 Study by Rayamajhi et al (2014)

Rayamajhi et al. (2014) [22] conducted a series of numerical simulations using OpenSeesPL to evaluate the effectiveness of DMM columns in liquefiable soil. The soil profile consisted of three layers: the top and bottom layers were made of dense sand, and the middle layer was composed of loose liquefiable sand. The liquefiable sand was improved with an area replacement ratio of 20% using individual DMM columns having a diameter of 1 meter and a shear modulus ratio of 10. The model was subjected to a sinusoidal record with an amplitude of 0.2g and a frequency of 15 Hz. The specified model was re-simulated using the numerical model presented in the current study. Figure 10 compares the shear strain ratio results obtained from the numerical model of this study with those of Rayamajhi et al. which shows a good agreement.

Overall, the presented comparisons demonstrate the efficiency and accuracy of the proposed model for the simulation of liquefiable soils and soil improvement with the deep mixing method.

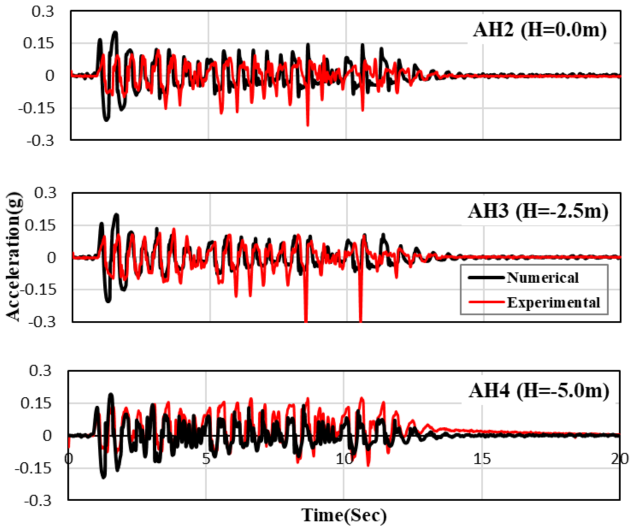


Fig. 9: Comparison of horizontal acceleration of soil obtained from experimental test [25] and numerical simulation

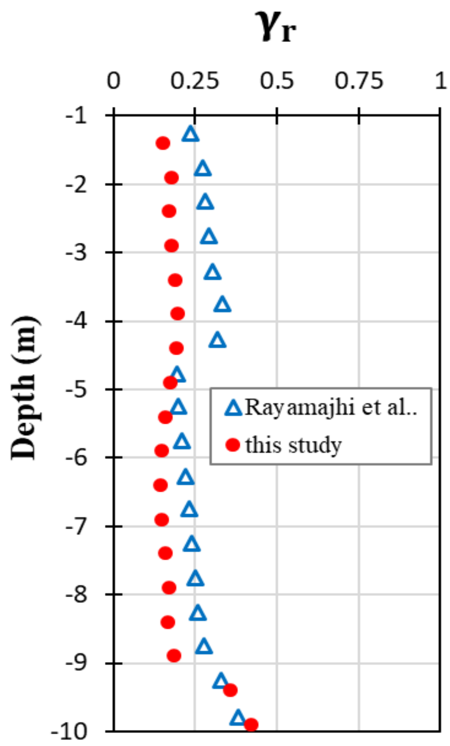


Fig. 10: Comparison of the ratio of shear strain obtained from numerical simulation of the current study and Rayamajhi et al. (2014) [22]

5. Results and discussion

In this study, the performance of Deep Mixing Method (DMM) in liquefaction mitigation is investigated using 3d FEM modeling considering the nonlinear behavior of soil and DMM. A parametric study is conducted to compare the efficiency of DMM in grid and single-column layouts at area replacement ratios of 5%, 10%, 20%, 40%, and 50%.

Table 2: Details of simulated models in present study

Model Type	G_r	A_{rr}	Number of models
Single DMM columns (SD)	13.33, 26.66	5%, 10%, 20%, 40%, 50%	10
Grid DMM walls (GD)	13.33, 26.66	5%, 10%, 20%, 40%, 50%	10
FreeField (FF)	-		1

Each of these models simulated with two different shear modulus ratios G_r(=shear modulus of DMM columns to the soil). The details of the models are presented in Table 2.

5.1 Excess pore water pressure

Figure 11 shows the variation in the ratio of excess pore water pressure to the effective stress ($r_u = \frac{\Delta u}{\sigma'}$) along depth for grid (GD) and single-column (SD) layouts at a shear modulus ratio of 13.33 and different area replacement ratios. It can be observed that using DMM does not result in a significant reduction in r_u at low-area replacement ratios compared to the unimproved soil. When the area replacement ratio exceeds 20%, the effectiveness of using DMM becomes apparent, and r_u values decrease compared to the unimproved soil for both DMM layouts. This behavior can be attributed to the barrier effect of DMM columns at higher area replacement ratios. Moreover, it is observed that the DMM grid walls perform better in reducing excess pore water pressure than the single-column layout.

Figure 12 shows the time history of excess pore water pressure at a depth of 6 meters (middle of the liquefiable soil layer) for models improved with grid and single-column layouts at different area replacement and shear modulus ratios. It is observed that using DMM in both layouts reduces the generation of excess pore water pressure compared to the unimproved soil, and the reduction becomes more pronounced as the area replacement ratio increases. For example, for $G_r = 13.33$, the excess pore water pressure values decrease by approximately 7%, 11%, and 15% at area replacement ratios of 20%, 40%, and 50%, respectively, compared to the unimproved soil. It is also observed that increasing the shear modulus ratio from $G_r = 13.33$ to $G_r = 26.66$ slightly enhances the effectiveness of DMM columns in reducing excess pore water pressure at different area replacement ratios.

5.2 Shear strain ratio

Currently, the design approach for the deep mixing method in guidelines is typically based on the assumption of strain compatibility. In other words, it is assumed that the DMM columns and the surrounding soil have the same shear strains.

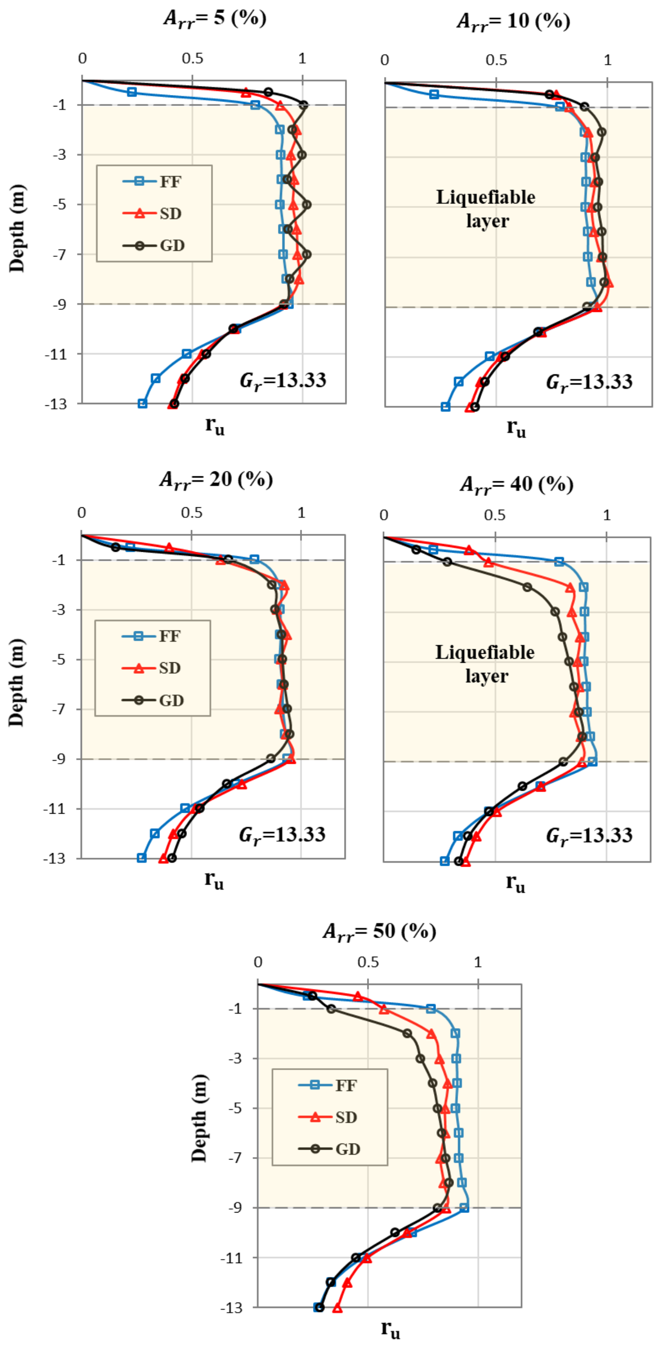


Fig. 11: Variation of the r_u along depth for grid (GD) and single-column (SD) layouts at a shear modulus ratio of 13.33 and different area replacement ratios

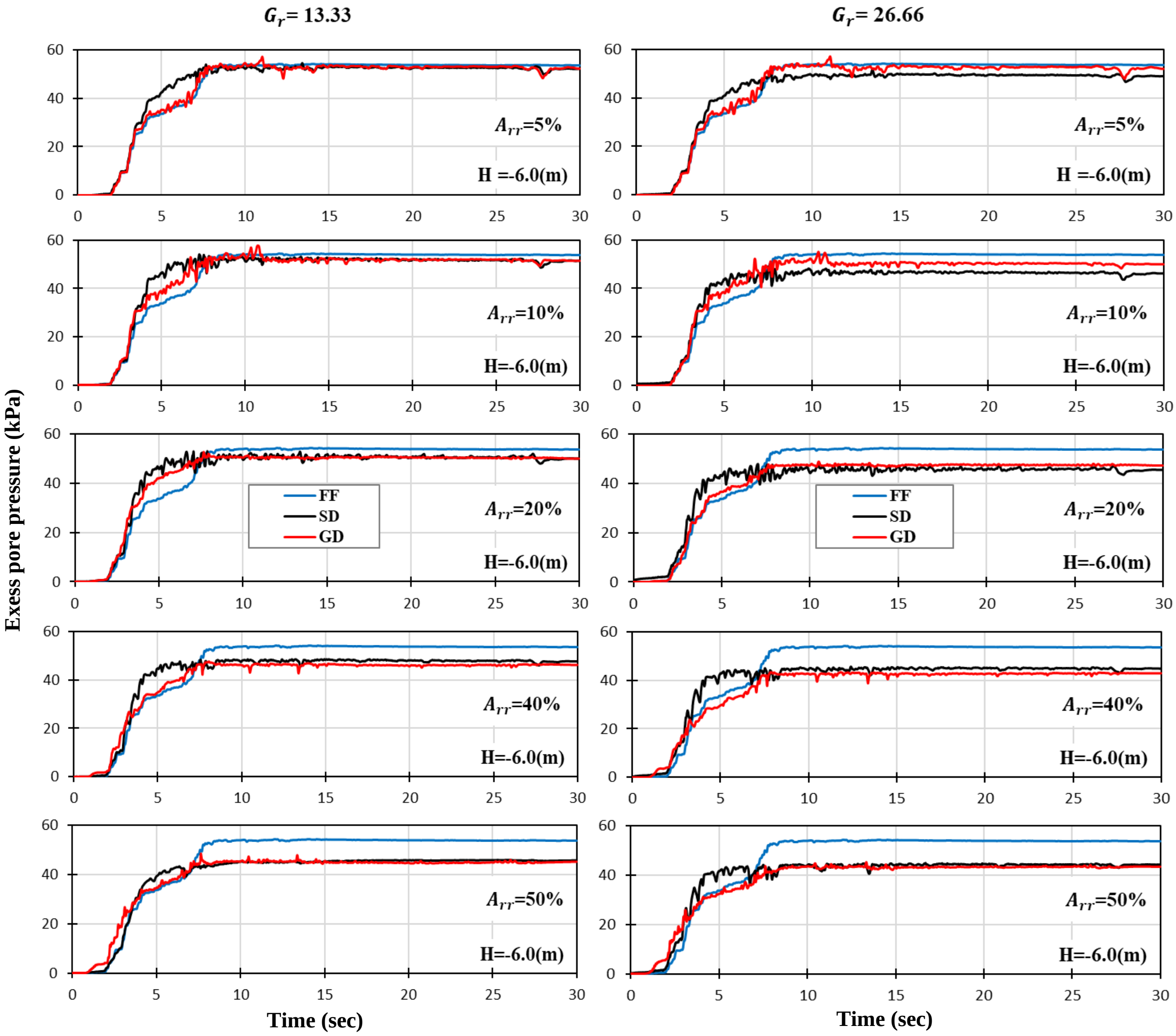


Fig. 12: Time history of excess pore water pressure at a depth of 6 meters for models improved with grid and single-column layouts at different area replacement ratios and shear modulus ratios

To investigate the distribution of shear stains in soils improved with DMM columns, the ratio (γ_r) of the shear of the DMM columns and the surrounding soil from the numerical results is used to calculate the shear strain ratio (γ_r). The shear strain ratio profile for grid and single-column layouts at different area replacement and shear modulus ratios is shown in Figure 13. As observed, for various area replacement ratios, the shear strain ratio, except for the upper and lower sections of the liquefiable layer, is less than 1. This finding indicates inconsistency between the shear strains of the DMM columns and the surrounding soil. Additionally, the results presented in Figure 13 show that as the area replacement and shear modulus ratios increase, this inconsistency intensifies, violating the assumption of shear strain compatibility. Furthermore, on average, the strain incompatibility is greater in the single-column layouts than in the grid layouts.

The presented results show that the assumption of shear strain compatibility might be conservative, as the DMM columns can undergo bending deformation, causing a gap between the soil and the DMM columns which results in unequal shear strain between the soil and the columns.

5.3 Lateral displacement

Figure 14 shows the profile of soil lateral displacement along depth for grid and single-column layouts at different area replacement ratios. As can be seen, when the area replacement ratio exceeds 20%, the maximum lateral displacement of the soil decreases compared to the unimproved model. This reduction in displacement is more significant for the grid layout compared to that for the single-column layout. For example, at a 40% area replacement ratio, the maximum reduction in lateral displacement of the soil using DMM columns in grid and single-column layouts is approximately 68% and 20%, respectively. Therefore, the results show that with an area replacement ratio exceeding 20%, using the deep mixing method can effectively reduce soil lateral displacements. These findings are in agreement with the results of experimental studies of Bahmanpour et al. (2019) [26] and Badanagki et al. (2019) [27].

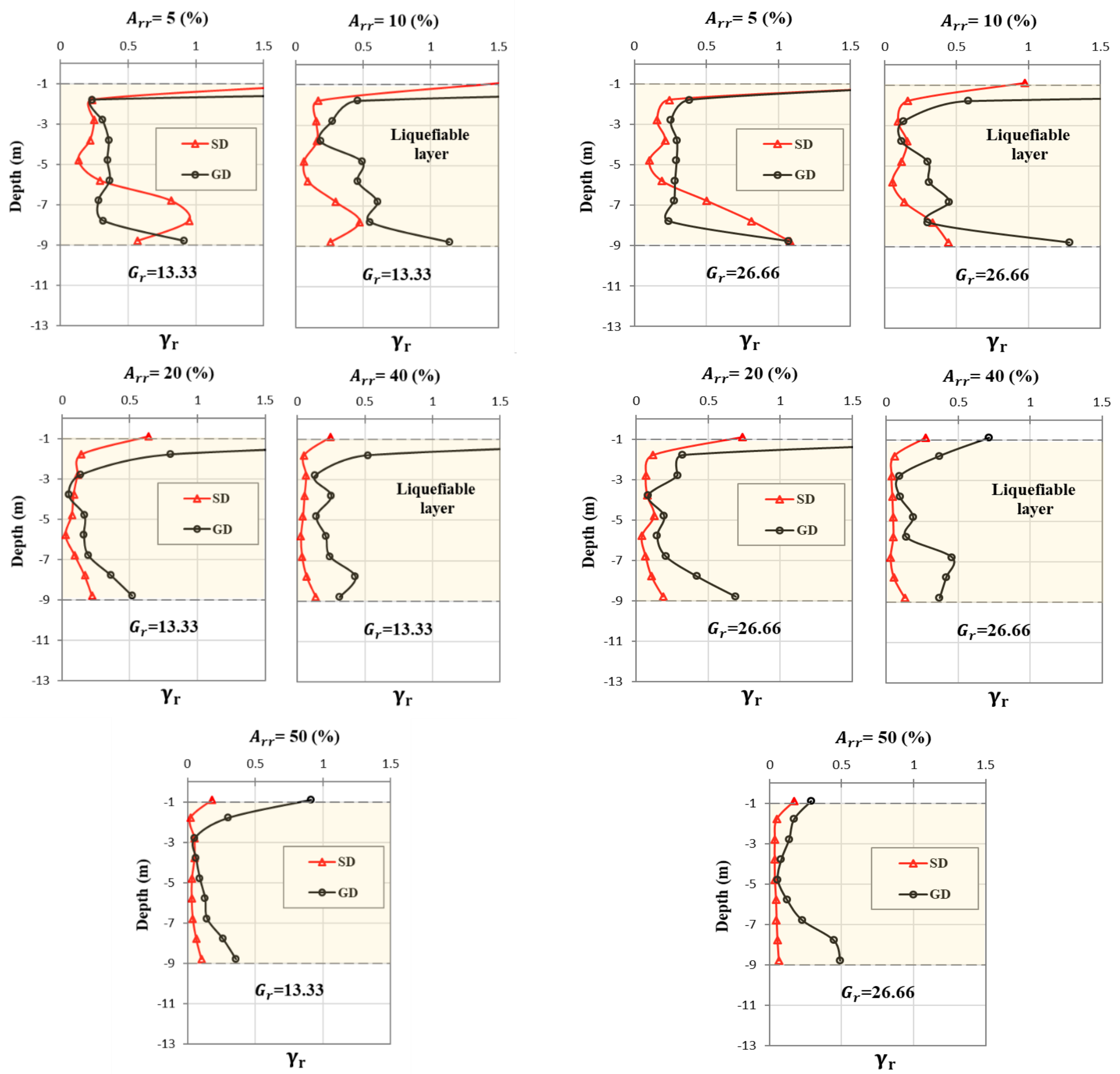


Fig. 13: Shear strain ratio profile for grid and single-column layouts at different area replacement and shear modulus ratios

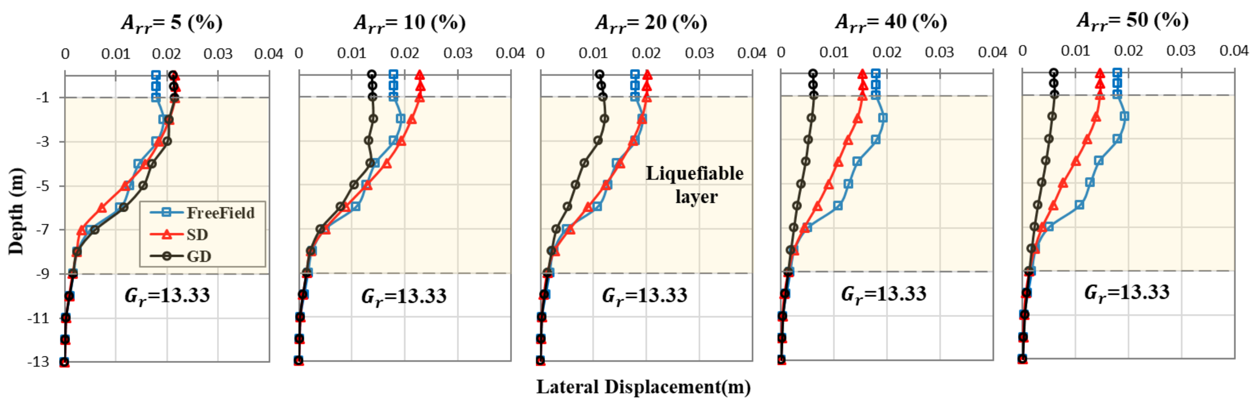


Fig. 14: Profile of soil lateral displacement along depth for grid and single-column layouts at different are replacement ratios

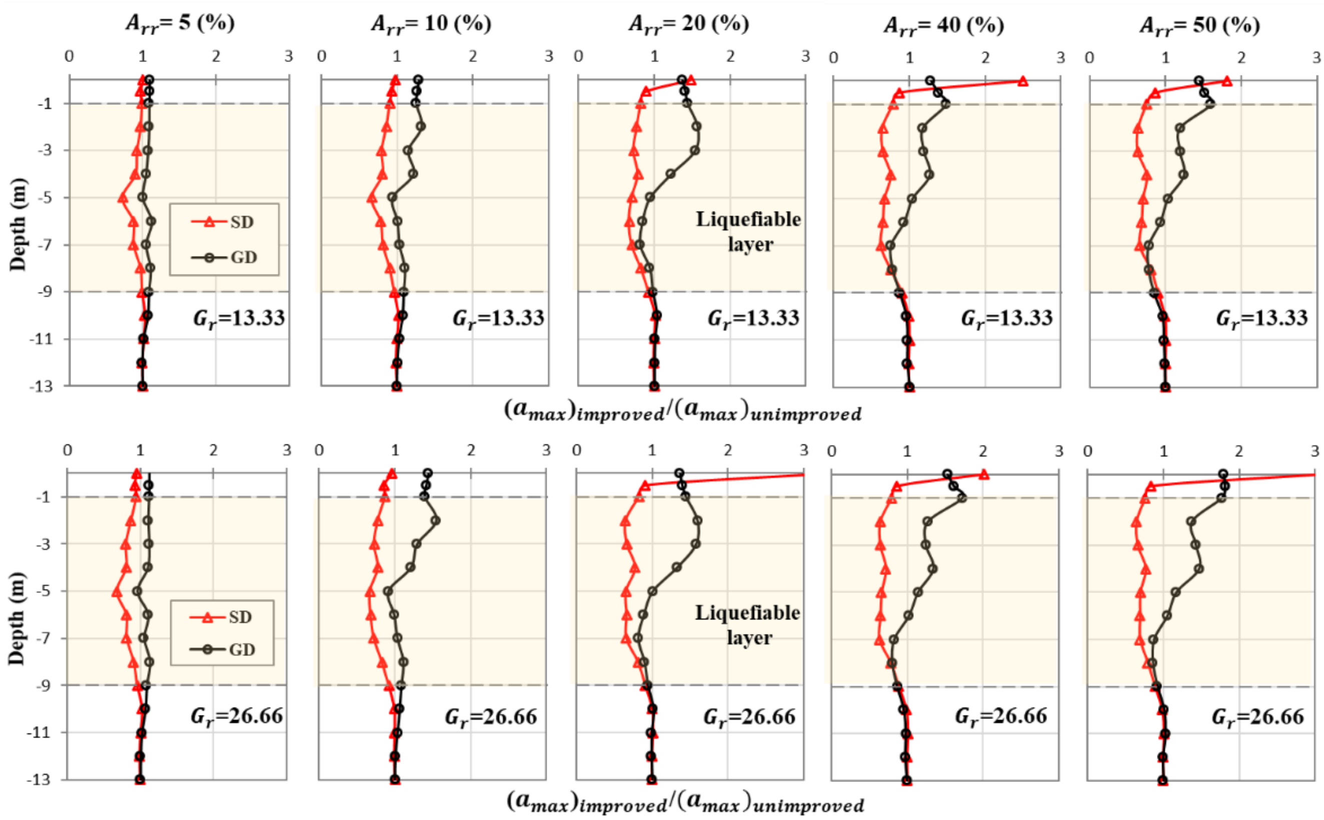


Fig. 15: Ratio of maximum horizontal acceleration of improved soil to unimproved soil at different area replacement and shear modulus ratios for grid and single-column layouts

5.4 Horizontal acceleration

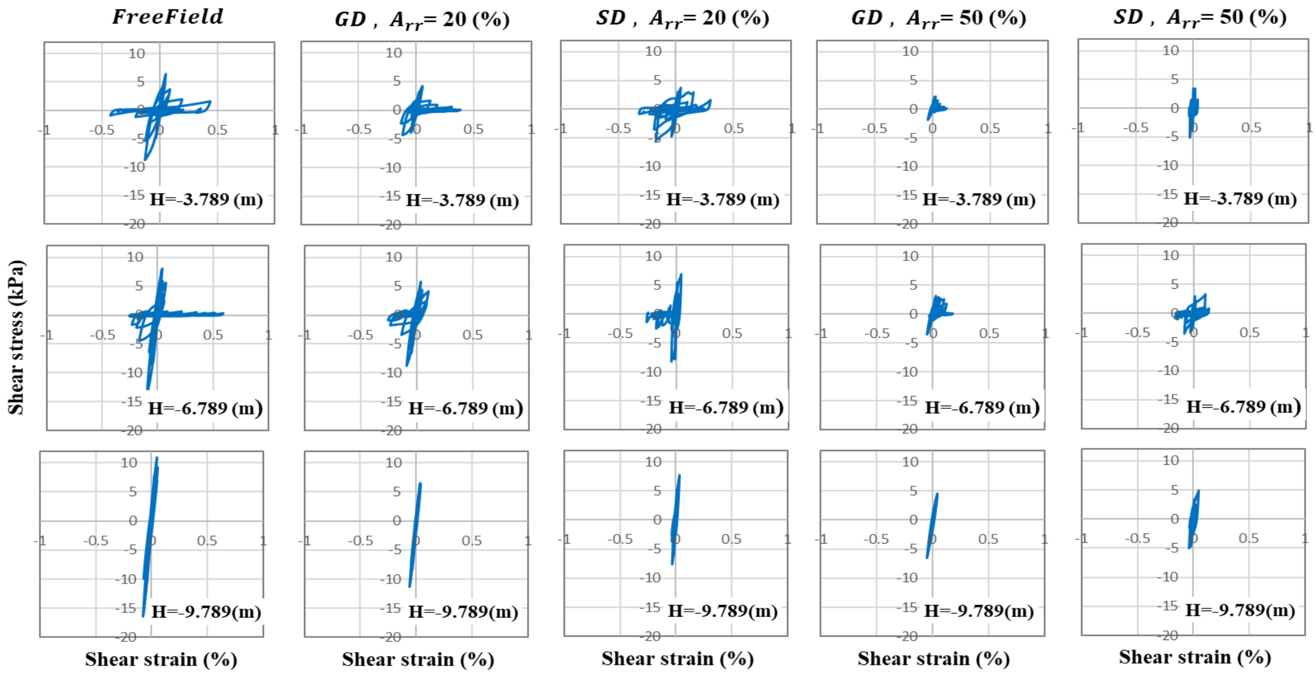
The profile of the ratio of the maximum horizontal acceleration of the improved soil to the unimproved soil at different area replacement and shear modulus ratios for grid and single-column layouts is shown in Figure 15. As seen, the ratio of the maximum horizontal acceleration increases near the ground surface for all area replacement ratios in both grid and single-column layouts. In other words, using the deep mixing method results in amplified accelerations in the near-surface to the ground surface. This finding has been also observed in previous experimental studies [26, 27]. Since accelerations transferred to the superstructure had a significant effect on the behavior of the structure under seismic loading, the effect of using the deep mixing method on amplification of accelerations should be further investigated.

Results shown in Figure 15 indicate that using the deep mixing method in a grid layout results in higher horizontal accelerations in the liquefiable and crust layers compared to that in a single-column layout. Also, it can be seen using DMM in a single-column layout reduces the accelerations in the liquefiable layer compared to that in the unimproved soil.

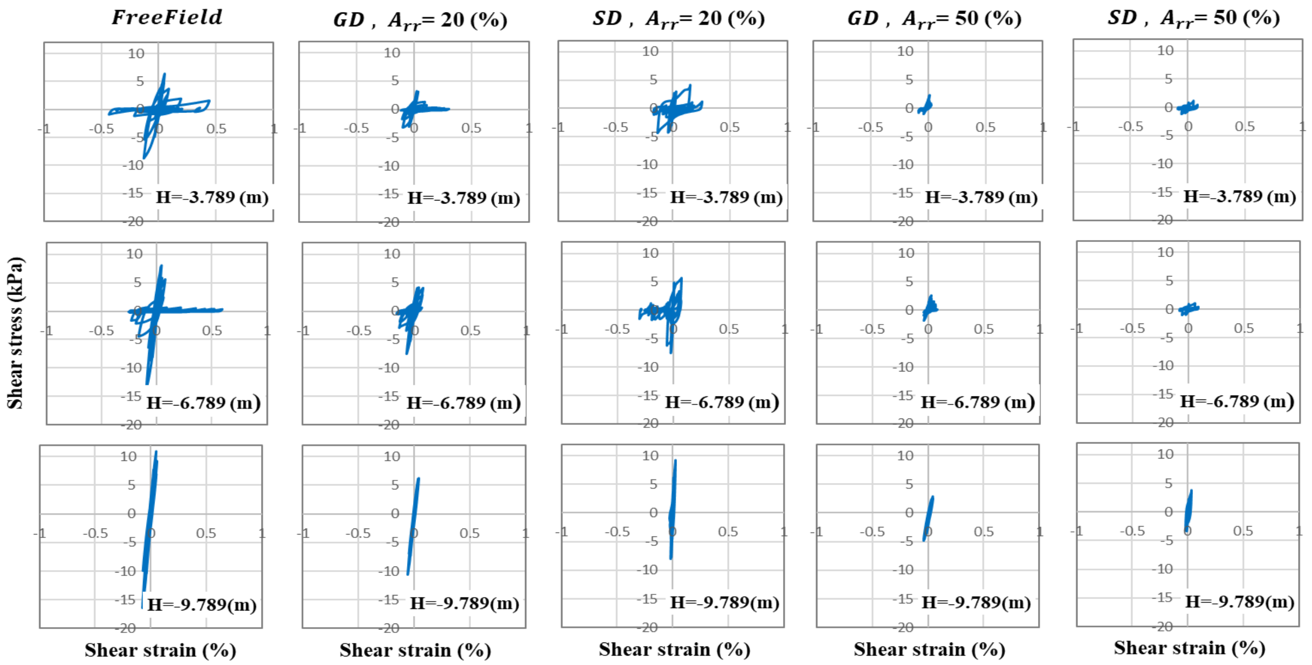
5.5 Stress-strain behavior

Figure 16 shows the shear stress-strain cycles for the unimproved and improved soils with 20% and 50% area replacement ratios at different depths. According to the figure, as the area replacement ratio increases in both single-column and grid layouts, the values of shear stress and strain decrease significantly. For example, in the grid layout and for a shear modulus ratio of $G_r = 13.33$ at a depth of 3.789 meters, the shear stress values for area replacement ratios of 20% and 50% decrease by approximately 50% and 73%, respectively, and the shear strain values decrease by 13% and 72%, respectively, compared to the unimproved soil. It can be observed from Figure 16 that soil improvement using DMM causes a decrease in the nonlinearity of stress-strain behavior under loading.

Furthermore, it is seen that using DMM in the grid layout is more effective in reducing stress and strain compared to that in the single-column layout. As expected, increasing the shear modulus ratio of the DMM columns leads to a reduction in shear stress and strain values at all depths in the improved soil.



(a)



(b)

Fig. 16: shear stress-strain cycles for the unimproved and improved soils with 20% and 50% area replacement ratios at different depths for (a) $G_r = 13.33$ and (b) $G_r = 26.66$

6. Summary and Conclusions

In this study, a series of 3D parametric numerical analyses are conducted in OpenSeesPL to investigate the performance of the Deep Mixing Method (DMM) in liquefaction mitigation, considering the nonlinear elastoplastic behavior of the soil. The effects of the area replacement ratio, layout placement of DMM columns, and shear modulus ratio on the behavior of liquefiable soil are examined. The summarized results are as follows:

- An area replacement ratio of 20% and above effectively reduces liquefaction effects, leading to decreased excess pore water pressures, displacements, and stresses in the soil.

- Using DMM in a grid layout is more effective than a single-column layout in reducing displacements shear stresses and strains.
- Using columns with a higher shear modulus enhances the performance of DMM columns in reducing shear stresses and strains.
- The assumption of strain compatibility in design might be conservative, as the DMM columns can undergo bending deformation, which results in unequal shear strain between the soil and the columns. Strain incompatibility between the soil and the DMM columns is greater in the single-column layouts than in the grid layouts.

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