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Effect of Micro-Pile Mitigation on Seismic Performance of Liquefiable Ground

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ABSTRACT Soil liquefaction and its associated ground failures, pose a significant threat, causing damage to engineering structures during earthquakes, and one of the most effective methods used to mitigate liquefaction in liquefied soil is micro-pile (MP) method. Therefore, this study aims to examine the current state of MP method as liquefaction countermeasure in the soil of the Coal Fired Power Station in Central Java, an area with a high liquefaction potential. A three-dimensional finite element analysis, conducted with OpenseesPL software, uses a numerical method to yield information about ground lateral deformation and excess pore pressure generation caused by MP method during seismic shaking. This result examines important design parameters, including diameter, spacing, length of MP, and inclination of ground, to address these issues. MP method increases the stiffness of soil, reducing excessive pore pressure and thereby minimizing liquefaction risks. In general, MP remediation appeared effective for any sloping ground. This study provides valuable information for devising an efficient remediation solution by comparing relevant variables, such as diameter, spacing, MP length, and ground inclination, under the same conditions. Numerical simulation with OpenseesPL yields results such as stress and strain path, acceleration time histories, excess pore pressure, displacement time histories, and maximum lateral displacement, which are then compared with various diameter parameters. The diY6-ameter parameters were compared to test how the additional diameter dimension affects the performance of the micropile provided to the soil. This will be demonstrated based on the results shown on excess pore pressure and maximum lateral displacement. This comparison shows that increasing MP diameter is more effective in reducing the risk of liquefaction.

KEYWORDS Liquefaction; Micro-pile; Mitigation; Numerical Simulation; OpensessPL

1 INTRODUCTION

Liquefaction is a phenomenon that can lead to lateral spreading on slightly sloping ground during shocks such as earthquakes, causing significant damage to building infrastructure (Tang et al., 2015; Lu et al., 2019; Huang et al., 2008). This phenomenon is highly likely to occur when the soil is of a sandy type, saturated, and characterized by loose granular properties, making it prone to losing strength and exhibiting liquid-like behavior (Thevanayagam and Martin, 2002).

Liquefaction is caused by the loss of soil shear strength due to an increase in excess pore pressure during seismic shock (Bird and London, 2005). The level of vulnerability to liquefaction can be assessed using liquefaction factor of safety (FSL). Subsequently, the standards for soil stability during earthquakes should have a factor of safety greater than 1.25 to ensure resistance to seismic forces. Liquefaction is anticipated to occur when liquefaction factor of safety falls below 1, which can be calculated using the method proposed by Seed and Idriss (1971). FSL can be estimated by the ratio between cyclic resistance $(CRR)_N$ with N which represents number of cyclic and cyclic stress ratio *(CSR)*.

$$FSL = (CRR)_N / CSR \tag{1}$$

$(CRR)_N$ is estimated in:

$$(CRR)_N = (CRR)_{15} NCSF \tag{2}$$

$(CRR)_{15}$ is the equivalent magnitude of a 7.5 earthquake with a uniform cycle of 15 and *NCSF* a scaling factor based on the input cycle. According to Bird and London (2005), the value of CSR is calculated as follows:

$$CSR = \frac{\tau av}{\sigma' v} = 0.65 \frac{a_{max}}{g} \frac{\sigma v}{\sigma' v} \frac{\gamma d}{MSF} \tag{3}$$

There are several methods to reduce the threat of liquefaction, such as soil improvement, removal, and remediation of soils with low density, removal of excess water, grouting, and other methods (Forcellini and Tarantino, 2014). In this context, mitigation method to be discussed is the use of micropile (MP), which have proven to be effective in compacting sandy soil. However, it is important to note that its effectiveness may diminish as the fine-grained content in the soil increases (Ashford et al., 2000). Subsequently, column rock usually consists of coarse-grained soil, gravel, or pillar aggregate by compacting crushed stone, granular soil, or concrete embedded in drilled soil.

MP are small pile with internal reinforcement, constructed by drilling boreholes (Brier and Jayanti, 2020). They are built to carry large loads when vibrations occur and are widely used for seismic reinforcement, rehabilitation of sensitive structural foundations, overcoming expansive soils due to swelling and shrinkage, settlement reduction, and slope stabilization (Pitroda and Bhavsar, 2015).

In the assessment of mitigation method using MP, a three-dimensional simulation was conducted using OpenSeesPL software (Asgari et al., 2013). This software is specifically designed for seismic analysis of pile and includes features for accurately extracting liquefaction data (Rashma et al., 2022). Furthermore, it also offers a graphical user interface for each input model (Lu et al., 2019).

2 LITERATURE REVIEW

Several geotechnical experts have conducted several studies to test the effectiveness of MP mitigation for addressing liquefied soil. Several historical studies have been carried out to assess the effectiveness of MP parameters, including diameter, inclination, space, and length to evaluate their impact on MP performance. The analysis methods used for this assessment include the numerical analysis method, experimental test in the laboratory, and direct soil test. Subsequently, this study specifically focuses on investigating numerical analysis methods in OpenSeesPL using diameter as a parameter to be tested. Numerical analysis methods show that increasing the diameter reduces lateral displacement, and this is line with prior results (Fattah and Salim, 2018; Correia and Silva, 2010; Juran et al., 2001; Huang et al., 2020). The results of diameter enlargement also affect the decrease in bending moment (Juran et al., 2001), increase in efficiency and maximum load (Gogoi et al., 2014; Sharma et al., 2019), as well as increase in bearing capacity (Haghighy, 2017; Malik et al., 2021; Fan et al., 2020).

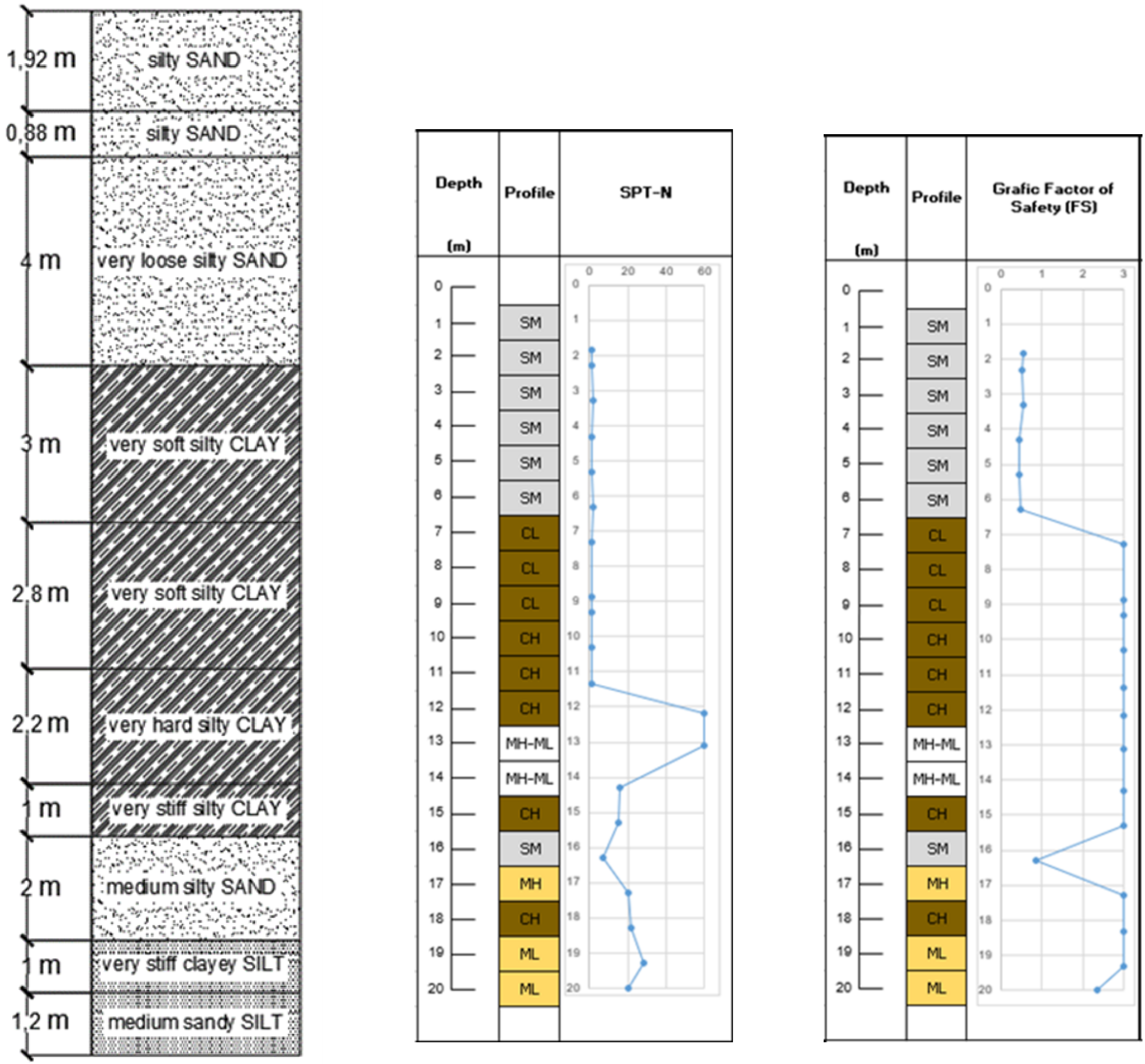
3 NUMERICAL SIMULATION

3.1 Computation Framework

The effectiveness test discussed was analyzed on the soil of the Coal Fired Power Station in Central Java area, based on drilling data carried out at coordinates 443.333 N and 1343.000 E with drilling number PBA – 23, TJB Unit 5 6 CFPP Project, situated at an elevation of 2,628 meters, as shown as Figure 1a and SPT-N value as shown in Figure 1b. The soil has a high potential of liquefaction during earthquake as shown in the graph in Figure 1c. The drilling soil data was analyzed to assess its liquefaction susceptibility, and subsequently, various MP parameters were tested for liquefaction disaster mitigation. The parameters included are diameter in the same as inclination, space, and length. It was assumed that the soil is liquefied in order to investigate effect of using MP.

The data analysis process included taking the soil data and subjecting it to seismic data from the 2007 earthquake in Niigata at the NIG010 station, with the EW component. Subsequently, DeepSoil software was used to analyze seismic effect at a specific depth using deconvolution and convolution tests with a linear analysis method and a frequency domain solution. Seismic data used in this analysis included vibrations with a maximum acceleration value of 0.21g, which were applied from the soil surface to the bedrock during the deconvolution test, and then vibrated again from the bedrock to the surface during the convolution test. From these results, the acceleration value of the deconvolution process is then obtained. Data is taken from the acceleration of the deconvolution process at a depth of 20 m with a maximum value of 1.02g and then inputted into the OpenSeesPL software for numerical analysis.

The data input into OpenSeesPL includes two phases. First, field tests are conducted with variations in the slope component for three trials. Af-



(a) A cross-section of soil profile

(b) The distribution of typical formation profile SPT-N values

(c) The result of factor safety of liquefaction (FSL) analysis

Figure 1 A cross-section of soil profile; The distribution of typical formation profile SPT-N values; The result of factor safety of liquefaction (FSL) analysis. Reference: Data Processing from SPT-N values

ter this, MP simulations are carried out by varying the diameters, in the same distance, length, and inclination. The data taken in this software are the values of acceleration, displacement, excess pore pressure, strain path, and strain.

The vibration data used in this test is based on earthquake data with a maximum acceleration of 0.21g, which recorded as shown in Figure 2. The acceleration is then processed using DeepSoil software to analyze seismic effect at a depth of 20 meters as shown in Figure 3. The chosen depth for analysis is considered ideal and has been adjusted based on the available soil data. This depth is crucial for the study because it corresponds to the soil showed to be susceptible to liquefaction according to liquefaction factor safety analysis. The objective of study is to assess the effectiveness of MP treatments with various diameters at this specific depth. MP parameters used when entering data into OpenSees as shown in Table 1 are conditioned by the soil being used, which is characterized as

Table 1. Analysis framework for MP

Description	Unit	Reinforced concrete		
		0.15	0.30	0.45
Flexural rigidity, EI	kNm^2	8.6E+02	1.4E+04	7.0E+04
Plastic moment, Mu	m^2	1.8E-02	7.1E-02	1.6E-01
Shear rigidity, GA	kN	2.6E+05	1.0E+06	2.3E+06
Torsional rigidity, GJ	kNm^2	7.2E+02	1.2E+04	5.8E+04
Axial rigidity, EA	kN	6.1E+05	2.5E+06	5.5E+06

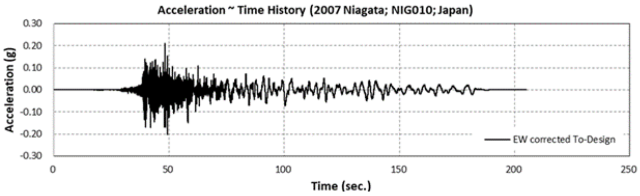


Figure 2 Magnified EW a-t with a design using Niigata Earthquake (a$_{max} = 0.210g$)

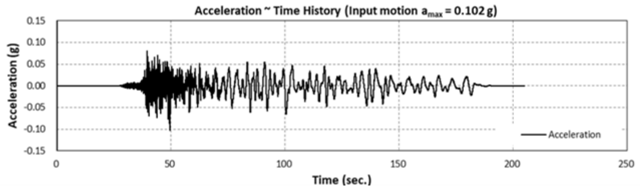


Figure 3 Deconvolution a-t history at Depth = 20 m as the input motion for OpenSeesPL analyses (a$_{max} = 0.102g, NIG010, EW Direction$)

plastic elastic and the boundary condition used includes the soil without any surrounding stress as shown in Figure 4.

The testing framework is carried out according to the data in Table 2, which includes the following codes OG-i1, MP-d1s2L2i1, MP-d2s2L2i1, and MP-d3s2L2i1. Subsequently, OG-i1 represents the original ground with the soil used, situated at a slope of 0 degrees according to the conditions in the area. The analysis of the original ground is essential to assess liquefaction potential and determine the most effective depth for comparing liquefaction potential. Subsequently, MP test is carried out with consistent treatment regarding spacing, length, and slope, and the main focus of the test is to vary the diameter value. Therefore, the code used in the test is only distinguished based on the diameter, with the code MP-d1s2L2i1, representing diameter 1, MP-d2s2L2i1 representing diameter 2, and MP-d3s2L2i1 representing diameter 3. These codes correspond to the testing framework as shown in Table 2.

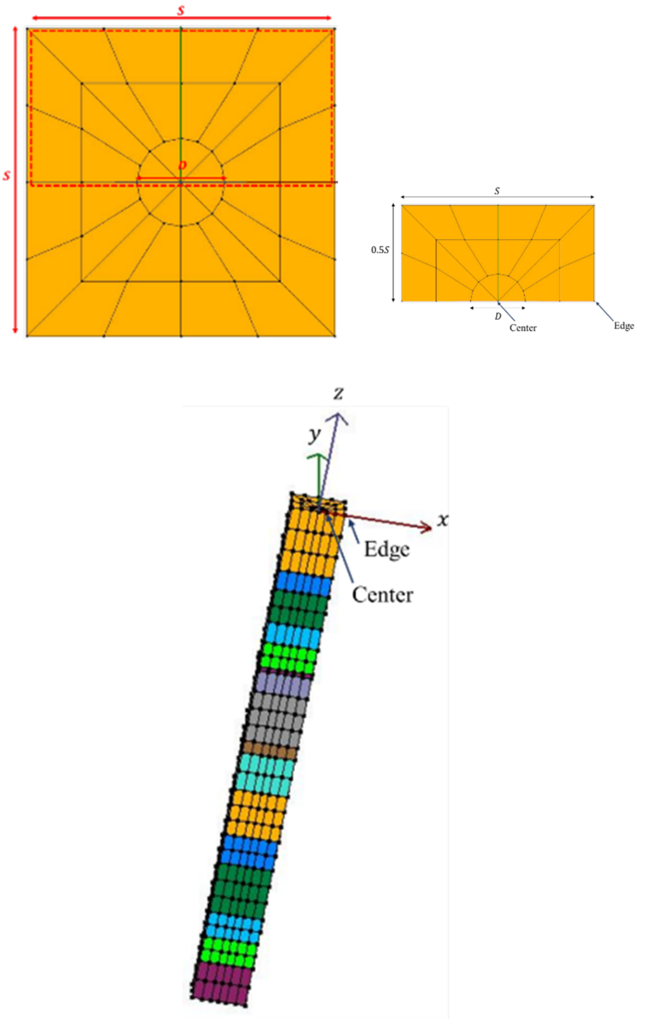


Figure 4 Schematic plan and 3D views of numerical simulation

3.2 Simulation Result

Based on experiments carried out by installing MP using Open Sees PL software, several results were obtained such as stress path, stress-strain, acceleration, excess pore pressure, and displacement. Stress path and stress-strain data help assess soil strain caused by vibrations, while acceleration measurements determine earthquake forces at specific depths. Excess pore pressure is the most important factor to consider in liquefaction analysis to determine the potential for air to rise above ground surface during shaking. Displacement measurements gauge building displacement during seismic shock and assess damage reduction potential caused by liquefaction.

The initial step includes testing the original soil to determine the appropriate depth for liquefaction observations. This depth can be found by

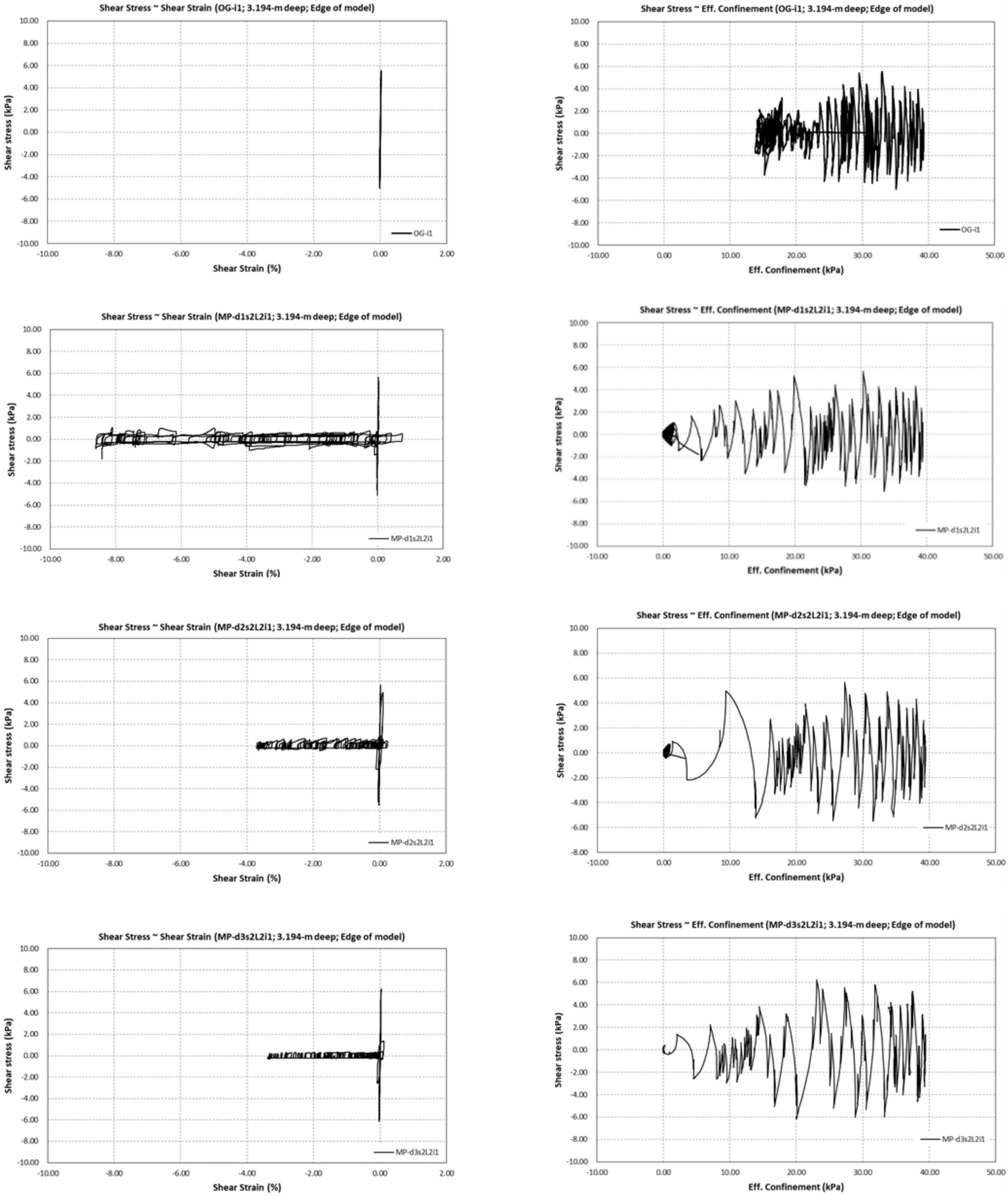


Figure 5 Stress-strain and stress path relationships with various diameters on ground with i1=0 deg. (OG-i1, MP-d1s2L2i1 (d=0.15), MP-d2s2L2i1 (d=0.30), MP-d3s2L2i1 (d=0.45)) of soils at 3.194 m deep for soils at the edge of the model

analyzing the excess pore pressure results from OpenSees PL software, specifically identifying the highest value. The highest excess pore pressure signifies a significant risk of water rising

Table 2. Properties of diameter

Analysis No.	Diamater/ d (m)	Spacing/ s (m)	Length/ L (m)	Ground inclination/ i (deg.)
MP-d1s2L2i1	0.15	0.9	10	0
MP-d2s2L2i1	0.30	0.9	10	0
MP-d3s2L2i1	0.45	0.9	10	0

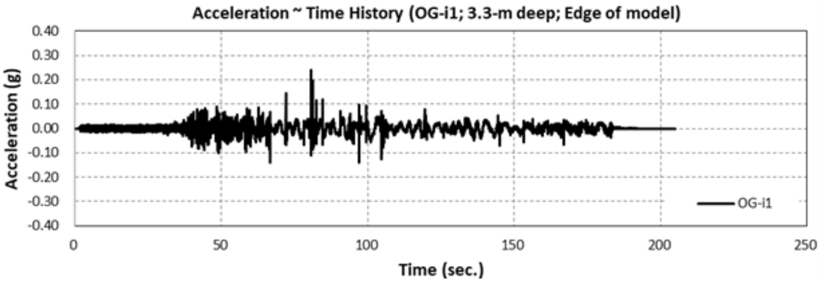


Figure 6 Acceleration time histories of 0 deg. (OG-i1) of soils at 3.3-m deep for soils at the edge of model $a_{max} = 0.241g$)

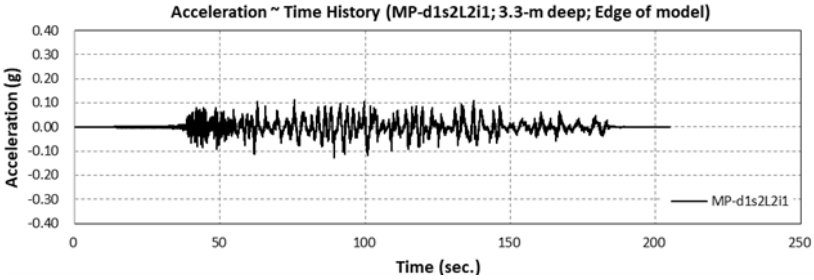


Figure 7 Acceleration time histories of 0 deg. (MP-d1s2L2i1) of soils at 3.3-m deep for soils at the edge of model ($a_{max} = 0.125g$)

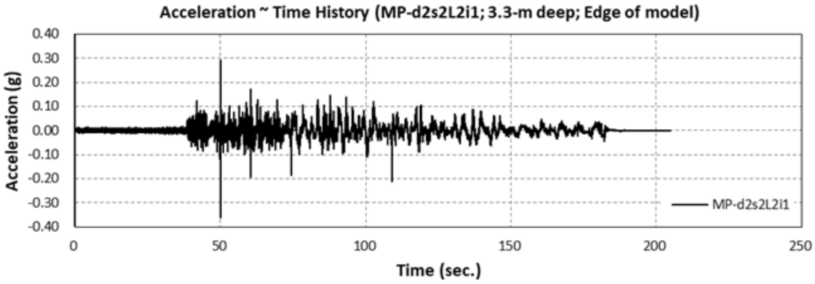


Figure 8 Acceleration time histories of 0 deg. (MP-d2s2L2i1) of soils at 3.3-m deep for soils at the edge of model ($a_{max} = 0.358g$)

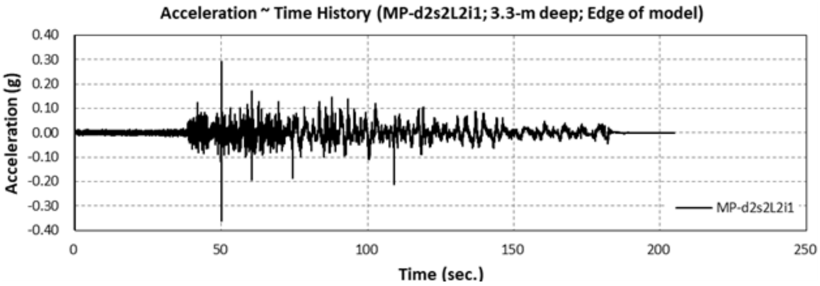


Figure 9 Acceleration time histories of 0 deg. (MP-d3s2L2i1) of soils at 3.3-m deep for soils at the edge of model ($a_{max} = 0.290g$)

during seismic activity. To ensure safety, this depth should also consider liquefaction safety factor (FSL), aiming for FSL values less than 1. The results of the analysis show that the best depth to observe liquefaction potential is 3.3 meters below the soil surface. This depth is used for each experiment in analyzing each result due to differences in the diameter size of MP.

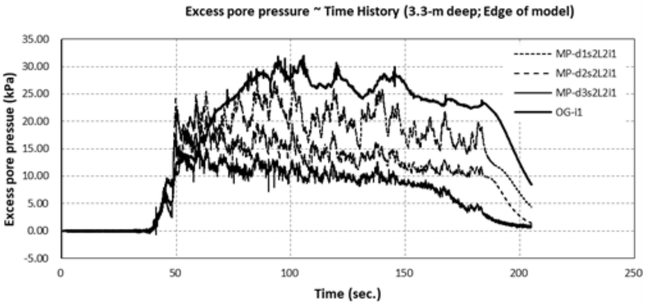


Figure 10 Excess pore pressure time histories with various diameters on ground with i1=0 deg. (OG-i1, MP-d1s2L2i1 (d=0.15), MP-d2s2L2i1 (d=0.3), MP-d3s2L2i1 (d=0.45)) of soils at 3.3 m deep for soils at the edge of the model

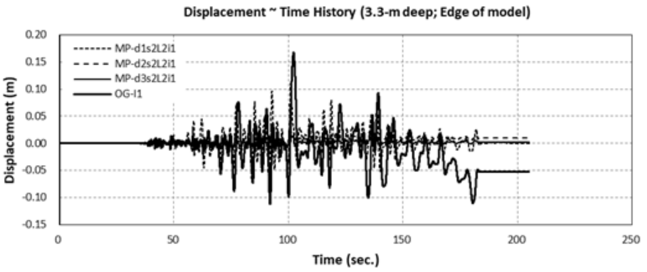


Figure 11 Displacement time histories with various diameters on ground with i1=0 deg. (OG-i1, MP-d1s2L2i1 (d=0.15), MP-d2s2L2i1 (d=0.3), MP-d3s2L2i1 (d=0.45)) of soils at 3.3 m deep for soils at the edge of the model

The analysis of shear strain and shear paths at a depth of 3.194 meters, as shown in Figure 5, shows that in the original soil, both peak shear strain and shear paths are significantly smaller when compared to soils with MP. These differences can be attributed to the greater soil shear interaction between the soil and MP, resulting from the surface area of MP causing abrasion on ground. Subsequently, it is important to note that a larger MP diameter shows reduced shear strain. This shows that the larger diameter will strengthen MP used and can mitigate the stress caused by the earthquake shaking.

Figure 6, 7, and 8 shows the acceleration analysis at a depth of 3.3 meters. Before the administration of MP, the resulting peak ground acceleration was 0.241g, while using MP with different diameters (1, 2, and 3) yielded peak ground accelerations of 0.125g, 0.358g, and 0.29g, respectively. Overall, the addition of MP does not appear to significantly affect the earthquake acceleration.

The analysis of excess pore pressure, as presented in Figure 10, shows the impact of using MP with different effective diameters. In natural soil, the resulting excess pore pressure is 31.97 kPa, and then after MP application, it shows a decrease in excess pore pressure in the diameter of 1 to 27.63 kPa, diameter 2 with excess pore water pressure of 24.22 kPa, and diameter 3 with excess pore water pressure of 17.87 kPa.

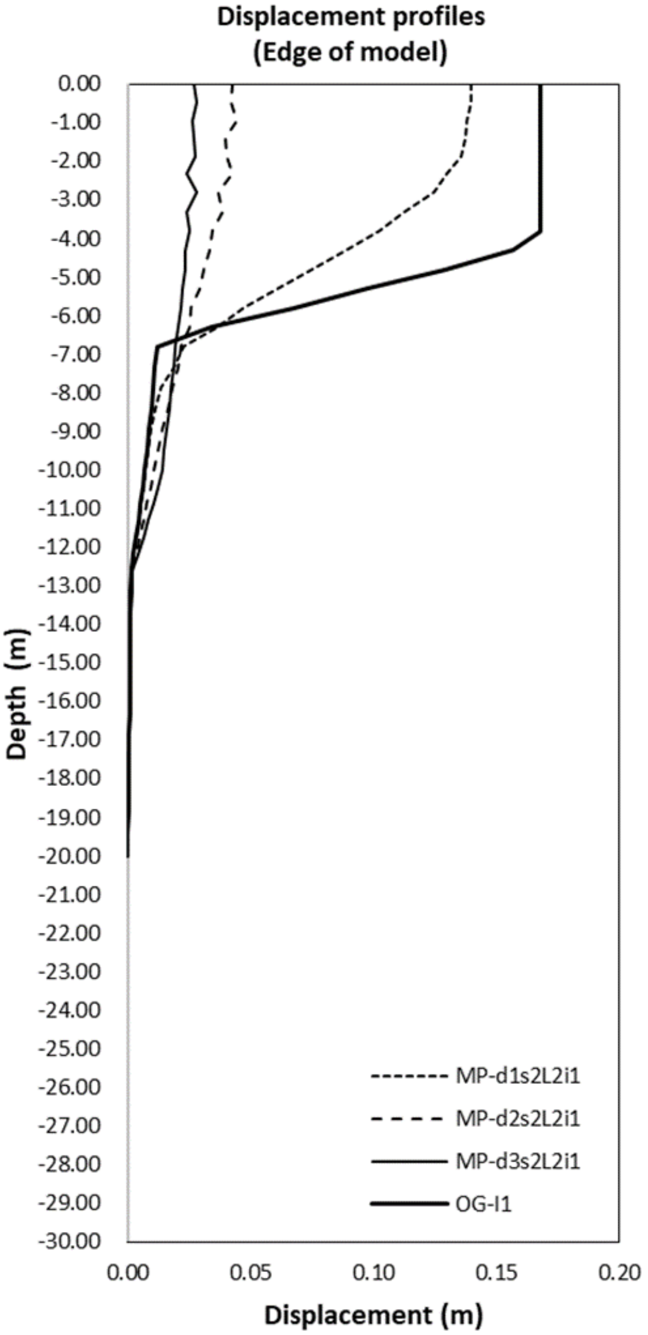


Figure 12 Maximum lateral displacement profiles during shaking with various diameters on ground with i1=0 deg. (OG-i1, MP-d1s2L2i1 (d=0.15), MP-d2s2L2i1 (d=0.3), MP-d3s2L2i1 (d=0.45)) of soils at 3.3 m deep for soils at the edge of the model

OpenSees PL software presents two types of displacement data: displacement history (Figure 11) at a depth of 3.3 meters and displacement profile (Figure 12) showing the maximum displacement at various depths. Before MP installation, the maximum displacement that occurred was 0.168 meters, then the appearance was reduced to 0.113 meters for diameter 1, 0.038 meters for diameter 2, and 0.024 meters for diameter 3. The addition of MP shows a reduction in displacement which then decreases with the addition of diameter.

4 CONCLUSION

In conclusion, the results obtained at the Coal Fire Power Station indicated that the use of MP could have reduced the potential for liquefaction by decreasing excess pore pressure. It also appeared to have lessened the potential for damage due to ground displacement during an earthquake by reducing overall displacement. The influence of the parameters discussed focused on the impact of the diameter on the effectiveness of using MP. The results showed that the larger the diameter used in MP, the better the results, with a noticeable reduction in excess pore pressure, displacement, and shear strain.

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