Effect of micro-pile, stone column, and encased stone column mitigation on seismic performance of liquefiable ground in the coal-fired power station in Central Java

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Abstract. Liquefaction is a disaster that can damage building infrastructure. This disaster is all too common in granular sandy soils. This is due to the subsidence and instability of the soil when subjected to shocks such as earthquakes. For this reason, mitigation efforts are needed to reduce the risk of liquefaction. This study will compare the effectiveness and influence of micro-pile, stone column, and densification mitigation methods on granular soils at the Central Java PLTU site in reducing the impact of liquefaction risk on land, which is dominated by silty sand soil types. Each type of method has its own advantages in each type of supporting soil layer and has some differences in results due to differences in the material used even in the same dimensions. The purpose of this study was to assess the most suitable use for soil types in the area of the Coal-Fired Power Station in Central Java. This model was analyzed using OpenSees PL software, considering the shocks obtained from the 2007 Niigata earthquake at PEER NGA-WEST2 by analyzing factors such as displacement and reduction in excess pore pressure.

1 Introduction

1.1 Liquefaction

The process of liquefaction involves turning saturated, non-cohesive soil into a liquid condition [1-2]. When there is vibration or water pressure, this phenomenon will rapidly happen in granular soils, causing loose each grain [3]. When liquefaction occurs, the soil will lose its strength significantly resulting in the structure not being properly supported [4].

The liquefaction phenomenon is triggered by the loss of saturated soil shear strength due to an increase in excess pore pressure during cyclic loading [5]. As a consequence, the soil is displaced, and buildings are damaged [6].

According to the results of the analysis [7], the value of the potential for liquefaction can be measured by the procedure developed by Seed and Idriss in 1971 using the value of the factor of safety for liquefaction, FSL (Equation 1), by estimating the value of the ratio between cyclic resistance ratio (CRR)\textsubscript{N} with N is number of cyclic and cyclic stress ratio (CSR).

\[ FSL = \frac{(CRR)_{N}}{CSR} \]  

The value of (CRR)\textsubscript{N} is estimated in Equation 2.

\[ (CRR)_{N} = (CRR)_{15} \times N \times CSF \]  

\( (CRR)_{15} \) is the correspondent value of an earthquake with a magnitude of 7.5 which is characterized by a uniform cycle equal to 15 and CSF is a scaling factor according to the input cycle. According to Bird and London [5], the value of CSR is estimated in Equation 3.

\[ CSR = \frac{\tau_{av}}{\sigma_{v}} = 0.65 \times \frac{a_{max}}{g} \times \frac{\sigma_{v}}{\sigma_{v}} \times MSF \]  

\( CSR \) is a cyclic stress ratio with respective values at the depth under review. \( A_{max} \) is a peak ground acceleration in surface, \( g \) is gravity acceleration, \( \sigma_{v} \) is total ratio \( f \) or effective vertical stresses in the soil layer considered, \( y_{d} \) is stress reduction coefficient, and MSF is a scale factor for earthquake magnitude for \( M = 7.5 \).

According to Karastanev and Tchakalova [8], the recommendation of safety factor value is more than 1.25. This value is a safe limit for estimating liquefaction will not occur. Meanwhile, a safety factor value that is below 1 indicates the potential for liquefaction when an earthquake occurs in that area.

1.2 Mitigation method

There are various ways to prevent liquefaction for areas on liquefiable ground. Some mitigation efforts that can be done are for example the installation of stone
columns, micro pile, and densification. These three are appropriate mitigation efforts for each soil condition.

Stone column is one of the mitigation techniques for infrastructure that is built in areas with new soil, especially coastal areas. Stone column is done by filling the cylindrical cavity with rock. This aims to accelerate consolidation by increasing the rate of vertical drainage due to differences in granular material that are stronger in the stone column area [9].

Micro pile is small piles that have internal reinforcement and are constructed by drilling boreholes [10]. Micro pile 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 [11-12].

Encased stone column is a form of stone column which is wrapped with a geosynthetic layer [13]. The purpose of wrapping it with geosynthetics is to increase the strength of the stone column, so that the pressure that can be received by the stone column becomes greater [14].

1.3 Objective and motivation

The object to be used in this study is the Coal-Fired Power Station in Central Java. This location was built in a coastal area with the composition of the soil shown in Fig. 1. With SPT-N as shown in Fig. 2, the soil data is analyzed to obtain the Factor of Liquefaction Safety value for each soil layer as shown in Fig. 3. This value indicates several depths that have the potential to experience liquefaction. Therefore, mitigation handling needs to be done in this area.

![Fig. 1. A cross-section of soil profile.](image1)

![Fig. 2. The distribution of typical formation profile SPT-N values.](image2)

![Fig. 3. The result of factor safety of liquefaction (FSL).](image3)
This paper focuses on comparing the results of the three mitigation methods, namely micro-pile, stone column, and encased stone column, in reducing risks due to liquefaction by using OpenSees PL software, which is capable of retrieving liquefaction data properly, or what is called built-in capability, by displaying a graphical user interface in each model input [15-17]. The purpose of the comparison of these values is to determine the most effective method for reducing risk due to shocks that result in disbursement. The things that are considered in this focus paper are the value of the decrease in lateral locking and excess pore water pressure due to the shocks given. A high value for excess pore pressure causes soil liquefaction, and displacement is the result of liquefaction, so high displacement values can cause great damage as well. This study was structured to determine which method was able to reduce the greatest amount of displacement and excess pore pressure.

2 Literature review

The phenomenon of liquefaction can cause many building collapses, as was the case in Palu due to an earthquake measuring 7.4 on the Richter scale which caused liquefaction covering an area of 4,95 km² [18-19]. Their locations in other hemisphere areas have also experienced similar things, for example in the Olfus earthquake that occurred in Hvergerdi, Selfoss, and Eyarbakki which was able to destroy around 2000 buildings [20].

This study will practice simulations of three soil mitigation methods that have been developed by several experts as they have been tested by several experts with several software. The results stated that the stone column is able to reduce the lateral displacement due to loading [15, 21-22] and can help drainage vertically so that excess water on the surface can be channeled more quickly to deeper soil [23]. Research discussing the encased stone column was carried out by Tang et al. [24] and Geng et al. [25] produces the result that the use of geosynthetics in the stone column is able to reduce the lateral displacement values. Micro pile according to some researchers according to Lekshmi et al. [26] who tested experimentally and found that the micro pile was able to reduce displacement.

From several discussions regarding the micro pile, stone column, and encased stone column methods, it proves that the three methods are used to reduce displacement due to shocks. However, there are more benefits to the stone column and encased stone column which are able to assist vertical drainage so that the pore water pressure value can decrease. For this reason, this study was designed to determine the effectiveness of these three methods in reducing the potential for liquefaction.

3 Numerical simulation

3.1 Numerical framework

The research designed is a comparison between the three methods using the middle parameter for each type of mitigation according to the size used in general. Parameters are designed using detailed values of diameter, depth, distance between piles, and slope in the center position. This is a method designed to find out the average value generated by the use of each mitigation so that later the results of the experiment will be compared to find out which mitigation is most effective in the Coal-Fired Power Station in Central Java area to reduce the potential for liquefaction.

The procedure designed in this study begins with preparing earthquake data through PEER NGA WEST2 by combining the strength of the planned earthquake based on the geological structure data of the area being reviewed, the distance between the location and the epicenter of the possible earthquake, and the depth of the source of the earthquake that might occur. From matching these values, the design earthquake value used in that area was obtained, namely the 2007 Niigata earthquake with the NIG010 station with an EW component. The use of earthquake data is selected based on the history of the largest earthquake that has ever occurred in the area by connecting the distance between the epicenter and the area studied and then adjusting it to the Indonesian spectral design data at the point studied, namely PBA-12 with coordinates 506.333 N and 13151.000 E. The data is then inputted into PEER NGA WEST 2 to look for histories of earthquakes that have recorded earthquake values. The values for the distance and strength of the earthquake are the same as those that have occurred in the area under study, the Niigata earthquake that occurred in Japan in 2007. The value taken from the data is the acceleration time history value. The acceleration data is then edited in the baseline correction using Deep Soil software to set the final acceleration at zero or until the earthquake ends. This value is then scaled to achieve the planned acceleration value with the correct peak ground acceleration based on the spectrum design at this location of 0.21 g, as shown in Fig. 4. The acceleration data is then edited in baseline correction using Deep Soil software to set the final acceleration to zero or until the earthquake ends.

To obtain the acceleration vibration value at the intended depth, deconvolution and convolution processes are carried out as illustrated in Fig. 5 using Deepsoil software. This software is able to calculate the value of the vibrations flowing through the ground and will have a constant value when it is vibrated downwards first, namely deconvolution and again when it is vibrated upwards or convolution. The design depth to be used is adjusted to the available soil data, so we use a depth of 20 meters to obtain a deconvolution value at a depth of 20 meters, which is as shown in Fig. 6 with a peak ground acceleration value of 0.83 g.

The data that has been planned is then calculated in the OpenSees PL application by inputting the planned
parameter, framework, and vibration values at a certain depth which will later be run and analyzed by the software so that several values are produced which are indicators of liquefaction. The initial thing to do is to ensure that there is liquefaction at the depth to be reviewed in accordance with the Safety Factor of Liquefaction value that has been calculated previously using a comparison of the Excess Pore Pressure Ratio value where if the value shows a number less than 1, liquefaction at that depth has the potential to occur because excess pore pressure value is the main review by comparing the presence or absence of liquefaction. Therefore, the results that need to be observed carefully are the decrease in excess pore pressure in each method but still display the displacement value as a reference if liquefaction occurs.

Fig. 4. Magnified EW a–t with a design from Niigata Earthquake (a_max = 0.210 g).

Fig. 5. Illustration of convolution and deconvolution procedures [27].

Fig. 6. Deconvolution a–t history at depth = 20m as the input motion for OpenSeesPL analyses (a_max = 0.83 g, NIG010, EW direction).

This study will assess the effect of using micro piles, stone columns, and encased stone columns by comparing the original ground that has not been given mitigation with the treatment of providing mitigation from the three methods, micro-pile, stone column, and encased stone column. The original ground needs to be analyzed to see how much influence each mitigation method has on the soil being analyzed. The condition of the original ground used is at a slope of 3% according to the conditions of the area being studied and drawed as shown in Fig 7.

The input values in the analysis procedure using OpenSees PL include the framework values used such as micro pile, stone column, and encased stone column data as shown in Table 1. And the input parameters are shown in Table 2. which details the value when input the parameter in OpenSees software for each method used. But, before carrying out an analysis using the mitigation method, it is necessary to carry out an analysis on the original ground to compare the effect of each mitigation method on the observed factors.

The difference in micro-pile, stone column, and encased stone column modeling in OpenSees PL software is that when modeling a micro-pile, the piles are activated with adjusted parameters and their
The material used in each mitigation method is adjusted to Table 2, which is the general micro-pile, stone column, and encased stone column data used in mitigation projects. Meanwhile, for the analysis framework, Table 1 is used with an equated framework for each mitigation method with the aim of assessing effectiveness when compared using the same framework. However, there are exceptions to the micropile framework because the shape has a much smaller maximum value than other methods, so a different diameter is used for the micro-pile.

![Fig. 7. Original ground modelling in OpenSees Software.](image)

![Fig. 8. Micro-pile modelling in OpenSees software.](image)

![Fig. 9. Stone column modelling in OpenSees software.](image)
3.2 Simulation result

From the experiments carried out on the soil with the treatment of micro-pile, stone column, and encased stone column, there are several results showing the different effects of the three methods. The results compared in this study are focused on the results of reductions in acceleration, displacement and excess pore pressure. Excess pore pressure is a parameter that influences the potential for liquefaction in the soil. The higher the value of excess pore pressure, the higher the potential for water to rise to the surface of the ground when shocks occur and liquefaction occurs. While displacement is the amount of displacement due to liquefaction occurring. The shifts that occur can result in the displacement of existing buildings on the ground, causing great damage according to the scale of the earthquake that occurred. Acceleration is observed to measure the magnitude of the earthquake acceleration that occurs by comparing it at a certain depth and distance from the pole used.

The difference in results obtained for each use of the mitigation method indicates a change before and after the provision of mitigation. In the original ground analyzed, it was found that at a depth of 3.192 meter it has an excess pore pressure ratio of more than 1 which means that at that depth liquefaction will occur when given a vibration input of 0.21 g. Excess pore pressure ratio shows the ratio between excess pore pressure and normal voltage. This depth is used as the reference depth in this analysis. While the horizontal analysis used as a reference for this research analysis is the edge model.

Based on the acceleration results obtained from the modeling, it was found that the peak ground acceleration value on the original ground was 0.443 g as shown in Fig. 11, then the value decreased when providing mitigation to reach a peak ground acceleration of 0.217 g on the micropile as shown in Fig. 12, 0.263 g on the stone column as shown in Fig. 13, and 0.262 g on the stone column as shown in Fig. 14. The provision of relative mitigation reduces the peak ground acceleration to 50 percent compared to the original ground. The smallest acceleration is produced by using a micro-pile with a peak ground acceleration of 0.217 g.
Based on the excess pore pressure value obtained from the modeling, it was found that the original ground had a high excess pore pressure of 102.37 kPa and it decreased with the use of mitigation, 89.79 kPa for using micro-pile, 93.44 kPa for using stone column, and 93.39 kPa for using encased stone column as shown in Fig. 15.

Overall, the use of mitigation methods reduces excess pore pressure by up to 11 percent compared to the original peak ground. Micropile is the method that reduces excess pore pressure the most compared to other methods.

Another result observed is the effect on displacement. The results displayed by the displacement are shown in Fig. 16, which is the displacement history by showing the effect of time on the displacement value. The displacement profile results are also shown in Fig. 17, to assess the effect of depth on the maximum displacement at that depth. Based on the displacement history, the maximum displacement is shown at the time of recording the end of the time history and shows that the use of mitigation methods can reduce the displacement that occurs. On the original ground, the soil has a displacement of 1.39 meters and its value is
reduced by using the micro pile mitigation method which produces a displacement of 0.19 meters, a stone column has a displacement of 0.89 meters, and an encased stone column of 0.93 meters. Overall, significant reductions were obtained with the use of the micro-pile.

Fig. 16. Result of displacement time histories of 3 deg. (OG-i2, MP-d2s2l2i2, SC-d2s2l2i2, ESC-d2s2l2i2) of soils at 3.192-m deep for soils at the edge of model.

Fig. 17. Result of maximum lateral displacement time histories of 3 deg. (OG-i2, MP-d2s2l2i2, SC-d2s2l2i2, ESC-d2s2l2i2) of soils at 3.192-m deep for soils at the edge of model.
4 Conclusion

The results of all experiments give a better impact on soil quality by reducing excess pore pressure and displacement. Because the dimensions used in each method are the same, the results obtained do not show a significant difference. The most suitable method used for the type of soil in the area under study is the micro pile. Micro-pile is able to reduce displacement and excess pore pressure optimally compared to other methods.

References

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