Liquefaction Resistance of Sand Mixed with Fines-Grained for Reclaimed Land

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Abstract. Liquefaction due to earthquakes can cause collapse, subsidences, landslides, lateral spreading, and sand boiling. The damage is commonly occurred at layer of water-saturated granular sediments with low relative density. Reclamation areas formed by loose sands are areas with high risk to liquefaction, such as damages occurred in the reclamation area of Tokyo Bay Area (Fukushima Earthquake, 2011) and Wellington Port (New Zealand Earthquake, 2016). Some researches have stated that the gradation of soil grains, relative density and maximum acceleration of an earthquake affect the soil's resistance to liquefaction. This paper presents the results of the experimental studies about the influence of fines-grained in the sand that has liquefaction potential which is used as a reclamation material to review its resistance to liquefaction. The experimental studies were carried out by adding fines-grained. A mixture of sand with fines-grains was made at a relative density of 25%, 50% and 75% under earthquake load with a maximum acceleration of 0.3g. Experimental results show that the increase in the fines content up to 30% and the relative density up to 75% reduces the resistance to liquefaction of the sand–fines mixture. The liquefaction resistance increases well as the increase of fines-grained and relative density.

1. Introduction

Liquefaction is a phenomenon where the soil changes from a solid phase to a liquid phase because of effect of increase pore water pressure in the pore soil [1]. From previous liquefaction research, it is known that liquefaction generally occurs in areas formed by granular layers of water-saturated sediment with low relative density [2]–[4]. This incident caused damage to buildings, moving land, lateral spreading, and landslides. Indonesia is not spared from liquefaction events, such as those occurred in Nias earthquake (2005), Yogya (2006), Padang (2009), and Palu earthquake (2018). Reclamation area is one area that is vulnerable to liquefaction because it is usually built in a coastal or waterlogged area. Besides that, embankment material generally uses levels of sand a minimum of 80%. Such conditions have led to liquefaction in reclamation areas such as Tokyo Bay Area (Fukushima Earthquake, 2011) and Wellington Port (New Zealand Earthquake, 2016) [5]–[7]. Reclamation is not only done abroad, some regions in Indonesia have already carried out reclamation, such as Jakarta Bay, Mamuju Beach, Denpasar, Manado, Semarang, Tangerang, and also in Makassar [8]. Based on condition of Indonesia's earthquake-prone areas, it is necessary to conduct research
related to the liquefaction problem, especially in the reclamation area. Analysis of relative density is needed to prevent liquefaction by providing additional requirements that must be included in the reclamation work process to achieve the specified relative density [9]. The fine grain content affects the strength of the reclaimed soil against liquefaction, where its strength increases with the increase of fine grains content and relative density [10]. Chien, LK, et.al [11] in research for land reclamation, state that the increase of fine grain content under constant relative density will decrease of liquefaction strength. According to research conducted by Hakam (2016) [10], it stated that there is a limit value of relative density respect to its mean grain size associated with liquefaction resistance. This study was conducted to review the effect of density relative and levels of fines content by using shaking table against the resistance of liquefaction. The sand used in this study was taken from Lampung area in which it was usually used as material for land reclamation in Indonesia. Therefore, these results might be used as a reference for reclamation material planning and ensure the safety and stability of reclaimed land from potential liquefaction.

2. Methodology

This research uses an experimental method by providing several sample specimens modeled as reclamation soils that have liquefaction potential. The test specimens were made of 12 samples, namely with a mixture of fine grain content of 0%, 10%, 20%, and 30%, and have a relative density of 25%, 50%, and 75%.

2.1 Research Materials

2.1.1 Sand sample. Selected soil sample used in this study is disturbed soil, originated from Lampung. It is one of the materials used for reclamation in Indonesia, especially in Jakarta Bay. The early stages of the test are conducted prior weeks to look at the criteria of this sand soil liquefaction of its potential as given by Tsuchida [12], shown in Figure 1.

![Figure 1. Gradation of Lampung sand soil and potentially liquefaction soil chart [12].](image)

Figure 1. Shows that the distribution of Lampung sand grains is within the most potentially liquefied land boundary according to Tsuchida graph [12]. In addition to the grain size analysis test, the specific gravity and relative density tests are also carried out referring to ASTM D 1989, the results of which can be seen in Table 1.
Tabel 1. Index Properties of Lampung Sand

| Parameter | Results | Unit |
|-----------|---------|------|
| $\gamma_{d_{max}}$ | 1827 | kg/m$^3$ |
| $\gamma_{d_{min}}$ | 1456 | kg/m$^3$ |
| $G_s$ | 2.66 | |
| $e_{max}$ | 0.842 | |
| $e_{min}$ | 0.49 | |
| $D_{50}$ | 0.4 | Mm |
| $D_{10}$ | 0.23 | Mm |
| $D_{60}$ | 0.45 | Mm |
| $D_{30}$ | 0.2 | Mm |
| $C_u$ | 1.97 | |
| $C_c$ | 0.38 | |

According to the USCS classification, this type of soil is categorized as fine-grained soils with a percentage of granules passing filter No.200 with an amount of more than 50%, and a liquid limit > 50, so this land is classified as MH (inorganic silt).

2.1.2 Fine Grain Soil Sample. Fines-grain soil used is the soil taken from the East Canal area, East Jakarta at a depth of -7.50 m with the undisturbed sample. Then several tests are carried out to get the soil property index. Index properties of fines-grain can be seen in Table 2.

Tabel 2. Index Properties of Fines-Grain

| Parameter | Notation | Result | Unit |
|-----------|----------|--------|------|
| Specific Gravity | Gs | 2.56 | - |
| Liquid Limit | LL | 58.53 | % |
| Index Plasticity | IP | 23.34 | % |

2.1.3. Mixed Sand + Fine Content (FC) Sample. Research carried out as experimental research on potential liquefaction sand mixed with fine-grained soil and the fine grain content of 0%, 10%, 20%, and 30%. Samples were prepared by mixing sand and fine grain soil that has been dried, and each was weighed its dry weight according to the relative density of 25%, 50%, and 75%. The results of the relative density testing of each mixture can be seen in Table 3.

Table 3. Results of Relative Mixed Soil Density Tests

| Fine Content FC (%) | $\gamma_{d_{max}}$ kg/m$^3$ | $\gamma_{d_{min}}$ kg/m$^3$ |
|---------------------|------------------------------|------------------------------|
| 0%                  | 1827                         | 1456                         |
| 10%                 | 1762                         | 1417                         |
| 20%                 | 1750                         | 1408                         |
| 30%                 | 1710                         | 1406                         |
From the test results above, the calculation is carried out to get the weight of the mixture from mixed soil samples. After obtaining the dry weight of the mixed soil samples, the value of the dry weight of the sample to be tested into the shaking table can be obtained.

2.2. Research Procedure

2.2.1. Soil Sample Mode. Soil modeling was made like a sample box with a size of 400 x 400 x 400 mm\(^3\). The sample box was made from acrylic material with its sides glued together well so that it allows the researcher to see firsthand the conditions that occur in the sample at the time of testing and after testing. The walls of the sample box were perforated on one side for the transmitter (measuring the pore tension). The sample box is equipped with two pore water transmitters that are installed on one side of the sample box. Installation of pore water transmitter is placed in the middle (200 mm) and bottom (320 mm) measured from the surface of the sample. The bottom side of the container was given a 5 cm thick rubber layer to allow for permanent shear deformation during vibrations, as well as improvements to avoid errors that occur in testing. The disturbed samples were tested by using shaking table testing:

a) Sand soil samples are poured carefully into a sample box that has a thickness of 12 mm and is leveled to a specified height. Then the water is put into the sample box until the surface of the water is at equal level as the sand.

b) In the pouring process, the condition is almost saturated when the water level above the sample is constant.

2.2.2. Loading. In potential liquefaction testing, the concept of loading carried out is dynamic loading. Some loading applications used in this study include the maximum earthquake speed of 0.3 g, the frequency of earthquake vibrations 1.1 Hz, and the dynamic loading time of 100 seconds.

2.2.3. Shaking Table Testing Procedure

1. Insert sand samples according to the sample preparation procedure.
2. When filling the sample take the excess water on the surface, so that the water level is the same as the sand level.
3. Shaking table is driven using an electric motor by following with the specified earthquake load ie \(a_{\text{max}} = 0.3 \, \text{g}\) and 1.1 Hz frequency, same with Yelvi (2018) research [13]
4. The increase in pore pressure at dynamic loading times is recorded second by second until 100 seconds.
5. The test results are in the form of a pore pressure reading which is a function of time plotted in a graphic so that it can be evaluated whether or not liquefaction occurs.

3. Experimental Results
Tests were carried out for every 12 variations in relative density and fine content, with 25%, 50%, 75% for relative density, and 0%, 10%, 20%, 30% for fine content. Loading criteria used in this study was the maximum acceleration of the earthquake of 0.3 g, and the vibration frequency of 1.1 Hz, the loading time of 100 seconds. The number of vibration cycles that occur every 100 seconds is 110 times. This research was conducted at the same water level as the soil surface. The data obtained is the value of the change in air pressure (\(\Delta u_0\)) which is read at the layer at a depth of 20 cm (middle transmitter) and 32 cm (bottom transmitter). Evaluation of the test results is done by making a graph of the relationship between the ratio of pore pressure to the number of cycles. To measure the liquefaction resistance, a parameter \(r_u\) is defined as the ratio of excess pore water pressure due to shaking to effective overburden pressure. The relationship graph is stated in Figure 2.
Figure 2. Correlation of Pore water pressure ratio (ru) and Number of cycles for various relative density and fine content chart
Figure 2 shows that the pore water pressure ratio (ru) in middle level greater than the bottom level for all the test results. This result shows that the development of an increase in pore water pressure occurs in the middle first and followed by the bottom. This shows that in the middle the resistance to liquefaction is lower than the bottom. This behavior can be explained by the fact that the middle part of the drainage path is shorter than the bottom. Likewise, the results obtained from studies conducted in [13]–[16]. Pathak, et.al [14], explained that liquefaction initially developed from the top to bottom in a laboratory shaking table that was in accordance with previous research conducted with other laboratory tests. Figure 2 also shows that the difference between the middle and lower ru decreases due to the addition of fine grains. The addition of fine sand from 20% to 30% ru difference decreases. But the increase in relative density does not greatly affect the difference in ru values. Overall it can be concluded that the increasing levels of fine content and relative density increase resistance liquefaction of soil. For more details on each of these graphs taken ru maximum value at every level of fine-grain variety and relative density are presented in Table 4 and Figure 3.

**Table 4. Maximum Pore Water Pressure Ratio (ru)**

| Fine Content | Relative Density, Dr % | Max Pore Water Pressure Ratio, ru |
|--------------|------------------------|----------------------------------|
|              | 25%        | 50%        | 75%        | 25%        | 50%        | 75%        | 25%        | 50%        | 75%        |
| %            | Middle | Bottom | r_u(avg) | Middle | Bottom | r_u(avg) | Middle | Bottom | r_u(avg) |
| 0%           | 1.765  | 1.170  | 1.468    | 1.375  | 1.079  | 1.227    | 1.309  | 1.114  | 1.227    |
| 10%          | 1.547  | 1.249  | 1.398    | 1.264  | 0.942  | 1.102    | 1.145  | 0.828  | 0.986    |
| 20%          | 1.349  | 1.089  | 1.219    | 1.153  | 0.955  | 1.053    | 1.039  | 0.787  | 0.913    |
| 30%          | 1.091  | 0.821  | 0.956    | 0.911  | 0.770  | 0.841    | 0.659  | 0.628  | 0.641    |

**Figure 3. Correlation relative density (Dr) with maximum pore water pressure ratio (ru)**

Figure 3 shows the results of a cyclic test performed on a fine-grained sand mixture with FC 0%, 10%, 20%, 30%. Tests were carried out for three values of relative density of 25%, 50%, and 75%. It can be observed that FC 0%, 10%, and 20% for Dr 25% and 50%, respectively, cause full liquefaction. It can be seen from Figure 3 that an increase in relative density can reduce the ru maximum value. This means that the denser soil will reduce the potential of the land to experience liquefaction. In this case the value of the liquefaction potential of small to relative density 75%. It is appropriate with research Chien, LK, liquefaction resistance increases well as the increase of relative density. However, at the constant relative density, liquefaction strength decreases as the fines content increase. Likewise with the results obtained by Porcino, D, et.al in [17].
Figure 4. Correlation of Fine Content (FC) and pore water pressure ratio (ru)

Figure 4 shows that increasing levels of fine grains will reduce the max ru value. This means that the added level of fine-grains, will reduce the potential for experiencing soil liquefaction. In this case the least liquefaction potential value is at 30% fine grain content. In contrast to the results obtained from Chien, LK et al, who stated that resistance resistance increases to FC = 10% and decreases significantly if FC is greater than 10%. Karim, et.al in [18] states that the resistance of liquefaction increases to the level of fine grain boundary (LFC) and there after it is constant even though the level of fine grain increases. Different research methods and types of sand and fine grains used in the investigation can cause differences in the results obtained.

4. Conclusion

Research on liquefaction resistance in sand which is usually used as a reclamation material by adding fine grains has been carried out. The level of relative density is observed to see its effect on the resistance of liquefaction. The results obtained indicate that the liquefaction resistance will increase according to the increase in fine grain content and relative density. The difference in results obtained from other researchers is likely due to the method and type of soil used. For more accurate results, further research needs to use various methods and other types of soil so that specific conclusions can be drawn. It is expected that for areas which are prone to earthquakes, the development of the reclamation area will be well planned in order to avoid liquefaction.

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