Shaking table tests to investigate the influence of grain shape on the excess pore water pressure

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Abstract. Liquefaction that occurred in the Palu city in 2018 is the most devastating natural phenomena. The liquefaction phenomenon is a condition in which a saturated soil loses its strength due to an earthquake. This study aims to determine the increase in excess pore water pressure in solid particles and void particles after they are subjected to earthquake loading. Testing is done by shaking the table. Earthquake loads are modeled with cyclic loads, which are sine waves with acceleration amplitudes of 0.35g and 0.38g. The results showed that liquefaction conditions had not yet occurred in cyclic load applications with an acceleration amplitude of 0.35g and a time duration of 7s. At an acceleration amplitude of 0.38g with a time duration of 60 s, the sand model underwent liquefaction at 7s after the test began. Analysis of the results of transducer records installed at a distance of 0.10 m from the surface of the test model shows that the addition of pumice by 10%, 30%, and 50% can reduce pore pressures by 15%, 62%, and 85%, respectively.

1. Introduction
Liquefaction is a process in which sediment under the groundwater level suddenly loses its strength and tends to behave as a viscous material rather than as a solid material. When an earthquake occurs, seismic waves will propagate through the saturated soil layer, if the soil is less dense, the bond between soil particles will be reduced and the soil shear strength decreases. In this condition, the pore pressure between the soil particles will increase. Initial liquefaction is a condition where an increase in pore water pressure reaches the effective stress value of the soil.

According to [1] Indonesia has experienced 37 liquefaction events from 1967 to 2018. The liquefaction event that occurred in Palu in 2018 was the most devastating because it resulted in large mass displacement and submerged many houses including Petobo and Ballaroa villages. This phenomenon of liquefaction is then known as "nalodo".

This study aims to determine changes in pore pressure due to saturated soil masses subjected to earthquake loading. There are two types of material used, a material with solid shaped particles and material with void shaped particles. Tests are carried out using a shaking table, earthquake or seismic loading are modeled using sine waves.

2. Literature review
Fine sand having a relative density of 25% will be easier to experience liquefaction compared to those having $D_r = 60\%$ [2]. Toyoura sand with a relative density of 50% is more susceptible to liquefaction...
compared to pumice sand which has a relative density of 25%, [3], and [4]. Pumice sand mixed with Mercer river sand with a volume ratio of 1:1, the results of the cyclic test showed that the cyclic strength of the Mercer sand and pumice sand mixes was lower compared to the cyclic strength of pumice sand for the same relative density [3].

Shaking table test is one type of experimental test to evaluate the potential of liquefaction based on pore pressure reading data during testing. The use of shaking tables to model the liquefaction phenomena is considered to be able to describe the actual conditions in the field. The advantages of shaking tables as a test model include: large amplitudes can be controlled properly, input motion can be modeled from all directions, data retrieval is easier to do, and this test model is very well used to validate numerical models or to understand the failure mechanism [5].

The use of large test models such as the shaking table test provides several advantages, namely: loading on the ground can be simulated close to the conditions in the field, boundary conditions have little effect on the test model, it is easier to install gauges next to the test model, the size of the equipment used for measurements relatively small compared to the size of the soil model so that it has little effect on soil behavior, measurement values are evenly distributed in the soil, and changes that occur during testing can be obtained from equipment installed in different locations [13]. Several studies have been conducted using the shaking table test, including: [1], [6], [7], [8], [9], [10], [11], and [12].

3. The material used and experimental procedures

3.1. Materials
The material tested was Maguwo sand and Mataram pumice. According to [13] and [14], in the location of the Maguwo sand extraction, there was a liquefaction phenomenon during the 2006 Yogyakarta earthquake. The Mataram pumice was taken from the pumice deposit in Kebon Talo Village, Mataram City. The original characteristics of the two materials can be seen in Table 1. The dry density of Mataram pumice is smaller than Maguwo sand, and the void ratio of Mataram pumice is greater than Maguwo sand. This is due to Mataram pumice having many cavities in the particles as shown in Figure 1.

| No. | Properties          | Maguwo sand | Mataram pumice |
|-----|---------------------|-------------|----------------|
| 1.  | The specific gravity, $G_s$ | 2.69        | 2.28           |
| 2.  | Water content, $w$ %       | 26.33       | 114.37         |
| 3.  | Grain size            |             |                |
|     | • Gravel mm            | 3.67        | 22.23          |
|     | • Sand mm              | 89.32       | 69.75          |
|     | • Silt and clay mm     | 7.01        | 8.02           |
|     | • $D_{50}$ mm          | 0.45        | 1.20           |
| 4.  | Coefficient of uniformity ($C_u$) | 5.9          | 23.53          |
| 5.  | Coefficient of curvature ($C_c$) | 1.06         | 0.32           |
| 6.  | USCS Classification    | SW          | SP             |
| 7.  | Bulk density, $\rho_s$ gr/cm³ | 2.01        | 1.16           |
| 8.  | Dry density, $\rho_{s-dry}$ gr/cm³ | 1.59        | 0.54           |
| 9.  | Void ratio, $e$        | 0.69        | 3.22           |

Figure 1 shows the Scanning Electron Microscope (SEM) image of particles obtained from the Mataram city. This figure depicts scanning electron microscope photographs of the particles retained on #10 sieve. As shown in the figure, there is a dense network of fine interconnected holes, most of
them open to the surface, but others isolated inside the particle. All this results in a lightweight, rough surface and easily crushable particles.

![SEM image of mataram pumice.](image)

Figure 1. SEM image of mataram pumice.

To achieve the research objectives, the sand and pumice used in this study were designed to be in a zone of potential liquefaction based on the grain distribution curve of Tsuchida. In Figure 2, the grain size distribution of sand is in the most potential liquefaction zone (curve a - a'), while the grain size distribution of pumice is in the potential liquefaction zone to the most potential liquefaction (curve b - a').

![Particle size distribution of Maguwo sand and Mataram pumice used in this study.](image)

Figure 2. The grain size distribution of Maguwo sand and Mataram pumice used in this study.

### 3.2. Experimental setup and procedures

The shaking table test was carried out at the Structural Engineering Laboratory of the Department of Civil and Environmental Engineering, Gadjah Mada University. The shake table is a type of R-141, was produced by ANCO Engineers (Boulder, Colorado, USA). It has a gross weight of 1608.5 kg, the top of the shake table is made of steel with dimensions of 1.5 m × 1.5 m (Figure 3). Shake table specifications can be seen in table 2. Shaking table operations use DANCE software.
Figure 3. Shaking table test in the Structural Engineering Laboratory of the Department of Civil and Environmental Engineering, Gadjah Mada University.

The sample box is made of acrylic with a thickness of 5 mm. Its dimensions are $0.40 \times 0.40 \times 0.65$ m (length × width × height), while the sample height is 0.50 m. On the two sides of the sample box, in the direction of the shake table movement, there are three holes to install pore pressure gauge and pipe for the saturation stage.

Table 2. Operational specification of the shake table of type R-141.

| Operational              | Limits                      |
|--------------------------|-----------------------------|
| Frequency limit          | 0 – 35 Hz                   |
| Payload weight           | 3 tons                      |
| Movement direction       | Horizontal uniaxial         |
| Maximum displacement     | ± 10 cm                     |
| Maximum velocity         | ± 0.4 m/s                   |
| Maximum acceleration     | 1.5g                        |
| Maximum actuator static stress | 50 kN at 3000 psi          |

The evaluation of liquefaction potential using a shaking table is conducted by measuring the pore water pressure increment of the sample which is placed in the box on the shake table. To determine the development of excess pore water pressure, there are three pore pressure transducers, abbreviated as PPT, placed on the side of the sample box at a distance of 0.10 m (Upper PPT), 0.25 m (Middle PPT), and 0.40 m (Base PPT) from the bottom of the sample box. The pore pressure transducer is connected to a datalogger then to a computer to record every time change in pore pressure. Records are made before the test begins, during the shaking test, and after the shaking test is complete.

The entire sample is prepared using the dry pluviation method with a relative density of 30%. The pluviator tool is designed so that it can be taken in and out of the sample box. The dimensions of the pluviator base are $0.34 \times 0.34$ m, consist of two filters with a 10 mm opening hole diameter with a distance of 0.50 m. At a distance of 0.40 m from the base of the pluviator, there are openings made of iron plate. Several tests were carried out to determine the position of the pluviator so that the relative density of 30% was obtained. For this purpose, the basic pluviator position is preserved to be at a distance of 0.40 m from the material to be poured out. The saturation process is carried out by
inserting water into the sample box through a small pipe placed at a distance of 10 cm, 25 cm, and 40 cm from the bottom of the sample box. Saturated conditions can be seen if water has reached the sample surface and the water level on the pipeline does not experience up and down movement.

A total of two tests are conducted on Maguwo sand with a relative density of 30%, the sample is subjected to two acceleration level viz. 0.35g and 0.38g. There are three samples of sand containing pumice with variations of 10%, 30%, and 50% pumice. Sand samples containing pumice receive an acceleration level of 0.38g. Table 3 shows the test sequence in shaking table tests.

**Table 3.** Test matrix and dynamic loading.

| Variation of the soil model | $D_r$ | Amplitude (%) | Frequency, $f$ (Hz) | Acceleration (g) | Duration (s) |
|-----------------------------|-------|---------------|---------------------|------------------|--------------|
| %Sand %Pumice               |       |               |                     |                  |              |
| 100 0                        | 30    | 35            | 1.428               | 0.35             | 7            |
| 100 0                        | 30    | 24            | 2.071               | 0.38             | 60           |
| 90 10                        | 30    | 24            | 2.071               | 0.38             | 60           |
| 70 30                        | 30    | 24            | 2.071               | 0.38             | 60           |
| 50 50                        | 30    | 24            | 2.071               | 0.38             | 60           |

4. Results

4.1. Excess pore water pressure at an acceleration of 0.35g

The first shaking table test was performed on the sand model using an acceleration amplitude of 0.35g with a shock duration of 7 seconds. In this test, the pore pressure recorded by the transducer tends to increase. But when the duration of the shock has finished, the pore pressure value decreases for a moment and then increases again and reaches a maximum value.

**Figure 4.** Excess pore water pressure with time for Maguwo sand at an acceleration of 0.35g and time duration of 7 seconds.

Figure 4 shows that the three transducers recorded an increase in maximum pore pressure after 9s of the test began, and Base PPT recorded the greatest pore pressure value. Upper PPT, Middle PPT, and Base PPT record the maximum pore pressure values are 0.7 kPa, 1.3 kPa, and 1.5 kPa respectively. After reaching the maximum value, the pore pressure begins to dissipate. This condition occurs because the duration of the shock is over. Measurement of the pore pressure value was stopped
after two transducers (Middle and Base PPT) reached a value of 0 kPa. Upper PPT is still recording pore pressure values of 0.1 kPa until the measurement is stopped. The maximum excess pore pressure ($\tau_\text{u}$) ratio produced by the Upper PPT is 0.84 and the effective stress value at this elevation is 0.83 kPa.

### 4.2. Excess pore water pressure at an acceleration of 0.38g

Figure 5 shows the increase in excess pore water pressure in the sand model with an acceleration amplitude of 0.38g of 60s duration. Upper PPT records an increase in maximum excess pore water pressure of 1.3 kPa after 7s of shaking table test begins, Middle PPT records an increase of 1.7 kPa after 11s and Base PPT records an increase of 1.9 kPa after 11s. Maximum excess pore water pressure of Upper PPT occurs at the 12th cyclic and begins to dissipate at $t = 27s$, Middle PPT occurs at the 20th cyclic and begins to dissipate at $t = 21s$, and Base PPT occurs at the 20th cyclic and is dissipated at $t = 19s$. After the shaking test is complete, the pore pressure is relatively constant until the measurement is finished.

![Figure 5. Excess pore water pressure with time for Maguwo sand at an acceleration of 0.38g and time duration 60 seconds.](image)

In this test, the increase in excess pore water pressure of Upper PPT exceeds the value of the effective stress at this depth ($\sigma_\text{v}' = 0.84$ kPa). This condition illustrates that liquefaction occurs shortly after the shaking test begins. But the other two PPTs (Middle and Base PPT) do not show the same conditions.

### 4.3. The effect of pumice content to excess pore water pressure

Figure 6 explains the effect of adding pumice to the reduction of excess pore water pressure in the Upper PPT. In the sand model test, the Upper PPT records a maximum pore water pressure of 1.3 kPa after the shaking test lasts for 7s. The addition of 10% pumice can reduce pore pressure increase by 23%. The maximum pore pressure due to the addition of 10% pumice is 1.1 kPa which is achieved after 10 seconds of shaking test begins. The addition of 30% pumice can reduce the increase in pore pressure by 62%. The maximum pore pressure due to the addition of 30% pumice is 0.5 kPa which is achieved after 6 seconds of shaking test taking place. The addition of 50% pumice can reduce the increase in pore pressure by 85%. The maximum pore pressure obtained due to the addition of 50% pumice is 0.3 kPa.
Figure 6. Effect of pumice content on the reduction of excess pore water pressure in Upper PPT ($D_r = 30\%$, an acceleration of $0.38g$, a time duration of the 60s).

As explained earlier that the addition of 10% pumice can still result in liquefaction in this test model. Liquefaction starts at $t = 4$ s since the shaking test begins, the value of pore water pressure at Upper PPT is 0.80 kPa and the effective stress at this depth is 0.78 kPa. At $t = 38$ s the pore pressure value that occurs in sand and sand containing 10% pumice is 1.1 kPa. By the end of the shaking test, at $t = 51$ s to $t = 58$ s the value of the pore pressure of sand and sand containing 10% pumice is 1.0 kPa. The sand pore pressure value is still higher until the measurement ends.

Figure 7 shows the tendency for excess pore water pressure reduction in the Upper PPT taken at $t = 10s$ to $t = 20s$. At this duration, the addition of pumice by 10%, 30%, and 50% can reduce the pore pressure in the sand model containing pumice by 15%, 62%, and 85%. The tendency pattern formed due to the addition of pumice is a linear regression with the equation $y = -0.0229x + 1.2898$. Where $x$ is the percent pumice and $y$ is the increase in excess pore water pressure.

Figure 7. Effect of pumice content on pore water pressure reduction in Upper PPT.
5. Conclusion
The following conclusions are drawn from the present study.
1. The sand model has not shown the liquefaction conditions in the shaking test with an acceleration amplitude of 0.35g with a time duration of 7 seconds.
2. The sand model experiences liquefaction at an acceleration amplitude of 0.38g and a time duration of 60 seconds.
3. The addition of pumice by 10%, 30%, and 50% can reduce the excess pore water pressure in the sand model containing pumice by 15%, 62%, and 85%, respectively.
4. The percentage increase in pumice (x) to the increase in excess pore pressure (y) results in a linear regression model. The reduction of maximum excess pore water pressure is obtained by adding 50% pumice. The tendency pattern formed is $y = -0.0229x + 1.2898$.

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