Effectiveness of earthquake drains in mitigating liquefaction-induced settlement

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Abstract. This study evaluates the effectiveness of earthquake drains in mitigating liquefaction and examines their performance at specific frequencies in loose and medium-dense sediments. Two lab-scale shake table single-axis test series were conducted to assess this: one without mitigation and another using earthquake drains. Both models were instrumented and subjected to consistent shaking sequences at 1 Hz and 1.2 Hz frequencies. The results revealed reduced excess pore-water pressure generation around the drains due to the rapid dissipation of pore pressures during shaking. Additionally, the excess pore water pressure increased more slowly with the drains, as they allowed partial dissipation of pressure through drainage. Earthquake drains significantly reduced liquefaction potential, particularly in the middle area, where conditions shifted from liquefied to non-liquefied. Furthermore, ground treated with drains exhibited less differential settlement than untreated ground. The use of drains resulted in settlements being retrieved by 2% to 15% more than untreated conditions. The drains effectively mitigated the post-shaking liquefaction-induced settlement mechanisms. While this study demonstrates earthquake drains as a reliable and efficient measure for reducing liquefaction-induced settlement, further research is necessary to optimize their design and application.

1 Introduction

Liquefaction during earthquakes significantly threatens infrastructure stability, leading to severe ground deformations and structural failures. Indonesia is a country located in the Pacific Ring of Fire. This region is prone to earthquakes, volcanic eruptions, and tsunamis due to the meeting of three world tectonic plates: the Indo-Australian, Eurasian, and Pacific.

Sandy Poor (SP) soils, known as loose sand, store more water than well-graded soils. Unconsolidated and water-saturated sandy soils have a large porosity, allowing water to infiltrate easily, making them susceptible to liquefaction. Liquefaction occurs when the soil loses its shear strength due to an earthquake, and the bearing capacity of the soil drops suddenly. The pore water stress almost entirely replaces the total stress because the soil decreases in volume, pushing the ground surface upwards or flowing like mud, which causes the collapse of buildings.

Excess Pore Water Pressure (EPWP) is the additional pressure exerted by water within soil pores, above normal hydrostatic pressure, typically caused by external forces like seismic activity or rapid loading. This condition reduces the effective stress between soil particles, weakening the soil and potentially leading to liquefaction, where soil behaves like a liquid. Managing excess pore water pressure is crucial in geotechnical engineering to prevent ground deformations and structural failures, especially in earthquake-prone areas. Techniques such as earthquake drains can accelerate the dissipation of this pressure, enhancing soil stability and infrastructure resilience [1, 2].

In overcoming one of the failures in the Sandy Poor (SP) soil structure or loose sand, an experimental analysis of liquefaction potential using an earthquake drain with shaking table testing was conducted. An earthquake drain is a vertical channel that provides a drainage path that accumulates pore water pressure to dissipate ideally before the surrounding soil reaches a state of liquefaction [3, 4].

Other vertical drains, such as Prefabricated Vertical Drain (PVD), accelerate the soil. The consolidation process speeds up water dissipation from the soil [5]. The general characteristics of PVDs are that they are flat and are used in fine-grained soils with low water flow rates while preloading loads are applied [6]. When it is necessary to address the discharge of excess pore water pressure during earthquakes, PVDs alone may not be sufficient. Therefore, the method is changed from PVD to earthquake drains, which have a similar drainage function but offer a larger capacity for removing water from the ground. While PVDs can be effective for dissipation, they require a higher capacity to handle the increased flow rate during such events [7].

Earthquake drains can be applied in sandy soils placed under shallow foundations and are expected to effectively reduce pore water pressure and mitigate impacts caused

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by liquefaction. Experimental analysis of liquefaction potential using earthquake drain is proactive research in improving the earthquake resistance of buildings and providing protection for residents and infrastructure in earthquake-prone areas [8].

In this research, relative density variations of 40% and 60% are employed, alongside vibration frequencies of 1 Hz and 1.2 Hz, to investigate the influence of these parameters on liquefaction potential. As highlighted by Salimah (2023), an increase in relative density percentage corresponds to a diminished likelihood of liquefaction and land subsidence, as denser soils exhibit greater resistance to shear stress and pore pressure build-up. Conversely, lower relative density percentages exacerbate the risk of liquefaction and subsidence, as looser soils are more susceptible to pore pressure accumulation during seismic activity. Liquefaction, which occurs when saturated soils lose their strength and behave as a viscous fluid due to elevated pore water pressure, poses significant risks to structural foundations and overall ground stability during earthquakes.

During liquefaction, water within the soil pores experiences an increase in excess pore water pressure, reducing the soil's effective stress to nearly zero. This causes the soil to lose its strength, behaving like a liquid and allows soil particles to settle back into a denser condition once the earthquake ends [9].

Several drainage techniques, such as earthquake drains, vertical drains, and sand drains, have been developed to facilitate the rapid dissipation of excess pore water pressure generated during seismic events to mitigate these hazards [10]. These systems work by enhancing soil drainage capacity, thus accelerating the stabilization of soil layers and minimizing the risk of liquefaction. By allowing water to escape more efficiently from the soil matrix, these drains play a critical role in reducing soil deformation, preserving structural integrity, and preventing catastrophic ground failure in earthquake-prone regions.

2 Research significance

This study demonstrates the effectiveness of earthquake drains in mitigating liquefaction in loose and medium-dense sediments during seismic events. This experiment hypothesizes that seismic drainage significantly reduces excess pore water pressure by facilitating rapid dissipation. The accelerated dissipation of pore water pressure prevents it from exceeding the effective stress of the soil, thereby reducing the liquefaction potential. The reduced liquefaction potential is also expected to decrease settlement events. These findings highlight the practical benefits of earthquake drains, providing a foundation for further research to optimize their design and application, hopefully enhancing infrastructure resilience in seismic regions.

3 Methods

The research was conducted at the Civil Engineering Laboratory, Politeknik Negeri Jakarta. The test box is 40 cm long and 40 cm wide, with a depth of 60 cm, where the depth of sand sediment is 40 cm. The test box is equipped with a one-way automatic drive to model the occurrence of an earthquake. Sample preparation using a rainer box system to drop sand into the sandbox, as seen in Fig. 1. This tool has a sand filter with a diameter of 0.6 mm. The sand rainer box is equipped with a pulley system to control the height of the sand drop, which helps regulate the relative density of the soil. Controlling the rainer box is essential to ensure the uniformity of the soil sediment [11]. Figure 2 shows a shaking table system using seismic control. Seismic input as 1 Hz and 1,2 Hz equal to 0,1 g and 0,18 g for this scale. Seismic input as 1 Hz frequency equal to 0,1 g for this scale. Seismic response was observed for 30 seconds for each test. Presentation of data 30 seconds before shaking, during 30 seconds of shaking, and 30 seconds after shaking, ensuring the observation covers the entire period before, during, and after the shaking event.

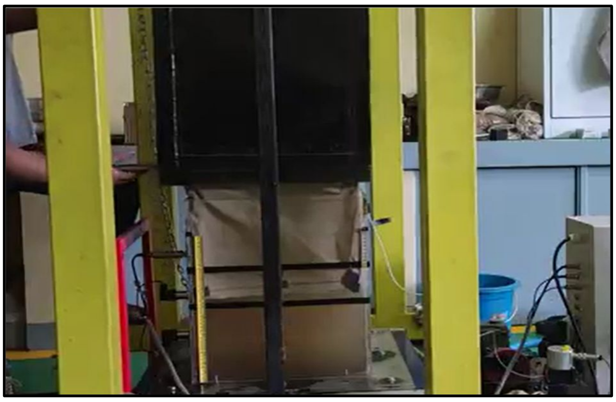

Fig. 1. Rainer box system

Fig. 2. Shaking table system

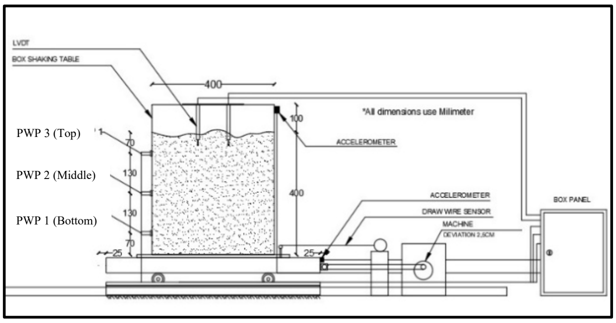

Fig. 3. Plan view of shaking table system

Figure 3 shows a plan view of the shaking table with the position of the sensor used in the measurement. Pressure transmitters are located at three levels to analyze the excess pore water pressure at each level and assess its significance. The data obtained is the value of the change in pore water pressure (Δuo) read in the layer at depths of 32 cm (bottom transmitter) for first elevation, 20 cm (middle transmitter) for second elevation, and 8 cm (top transmitter) for third elevation. An inverter is used in the machine motor to control acceleration, while an accelerometer sensor is placed on the table base to measure the actual acceleration. Linear Variable Differential Transformer (LVDT) used to measure settlement. There are 4 LVDT placed on the top of shallow foundation. Electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal.

This research used clean sand as a base material. Due to its purity and consistent grain size, silica sand is specifically used to ensure good results, making it ideal for applications requiring precision and durability, with particle sizes ranging from 0.15 mm to 0.5 mm. Properties of soil in Table 1 show uniform grain gradation Cu < 6, which means poorly graded soil. Study variations on shallow foundations include without and with mitigation using earthquake drains. Soil properties details are shown in Table 2.

Table 1. Soil properties

Properties	Value	Unit
γd_{max}	14,47	kg/m^3
γd_{min}	13,33	kg/m^3
Gs	2,65	
e_{max}	0.950	
e_{min}	0.796	
C_u	2,056	
C_c	0.794	
c	0.017	
φ	29.28	°

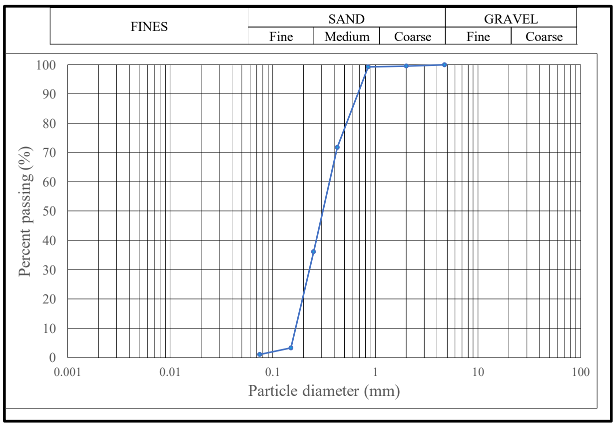

Fig. 4. Grain size distribution

Figure 4 shows the grain size gradation of the soil samples used. The distribution appears steep around the medium sand size, indicating that the sand grains are uniformly graded. This uniformity is essential to meet the requirements for preparing liquefaction soil samples.

Table 2. Experimental variations

Mitigation	Symbol	Density relative (%)		Frequency (Hz)
Shallow foundation	No ED	40	60	1
Shallow foundation with earthquake drain	ED	40	60	1

Table 2 presents the experimental variations used in this study. The 'NO ED' symbol represents tests without mitigation, while the 'ED' symbol indicates tests with mitigation, where earthquake drains were used to reinforce the shallow foundation. The data analysed includes pressure transmitter readings from the top, middle, and bottom elevations.

4 Results

4.1 Excess pore water pressure (EPWP)

Excess Pore Water Pressure (EPWP) must be carefully managed in geotechnical engineering to prevent soil weakening and liquefaction, particularly in earthquake-prone areas. Techniques like earthquake drains help dissipate this pressure, improving soil stability and protecting infrastructure. In this study, EPWP measurements show the differences in pore pressure at various elevations before, during and post shaking. Figs. 5- 8 illustrates the variation in excess pore water pressure (EPWP) over time, comparing tests without earthquake drains (No ED) and with earthquake drains (ED) across different elevations (1, 2, and 3). The x-axis represents time, while the y-axis represents EPWP levels.

Solid line at Fig. 5 shows curves without earthquake drain used to mitigation. No ED 1 (blue solid line) shows the highest peak of EPWP, indicating significant pore pressure buildup and slow dissipation. The orange solid line reaches a moderate peak but is considerably lower than No ED 1, suggesting less EPWP buildup. No ED 3 (green solid line) shows the lowest EPWP, indicating minimal pressure buildup at this elevation. Dash line shows curves with earthquake drain used to mitigation. ED 1 (blue dashed line) shows a noticeable reduction in peak EPWP compared to No ED 1, demonstrating that earthquake drains effectively mitigate pore pressure. ED 2 (orange dashed line) also shows a reduction in EPWP compared to its No ED counterpart, though the reduction is less dramatic than in ED 1. ED 3 (green dashed line) shows the smallest peak EPWP and remains relatively flat, confirming effective mitigation at this elevation. In general, for relative densities 40% shows trend that EPWP rises rapidly 5 until 10 second after shaking begins and soon dissipate after end of shaking.

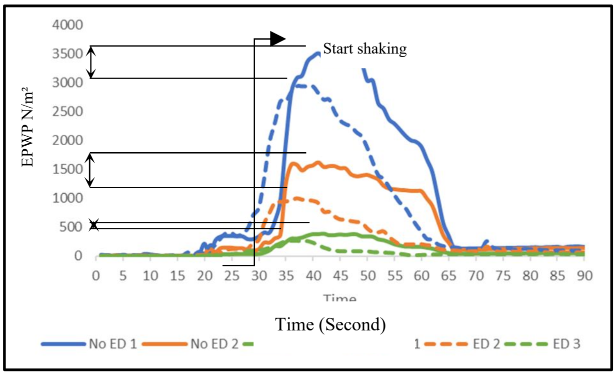

Fig. 5. EPWP for RD 40%, 1 Hz frequency

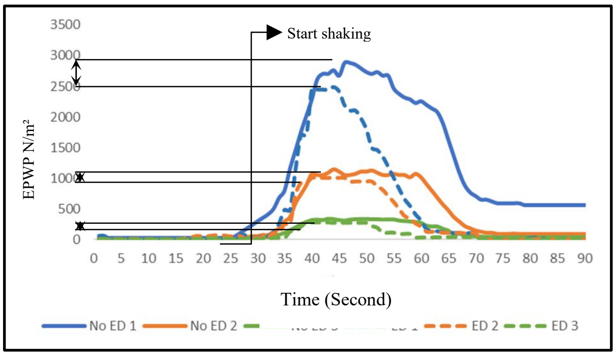

Fig. 6. EPWP for RD 60%, 1 Hz frequency

Similar to Fig. 5, Figure 6 illustrates the time series values of excess pore water pressure (EPWP) for sedimented soil with 60% relative density (RD), representing medium-density sand. The trend of the curve is comparable to that observed at 40% RD. However, upon closer examination, Figure 6 shows that EPWP increases 5 seconds longer than in Fig. 5 immediately after shaking begins, dissipating rapidly once shaking stops. This indicates that denser soil conditions result in a slightly longer duration for excess pore water pressure to dissipate.

Figure 7 shows the excess pore water pressure (EPWP) for 40% Relative Density (RD) at a frequency of 1.2 Hz. The solid line represents EPWP without mitigation, while the dashed line represents EPWP with earthquake drains as a mitigation measure. The curves demonstrate that the use of earthquake drains reduces EPWP effectively. Similarly, Figure 8 presents the EPWP results for 60% RD at the same frequency of 1.2 Hz, showing comparable outcomes. The use of earthquake drains accelerates water dissipation, thereby reducing pore water pressure during seismic events.

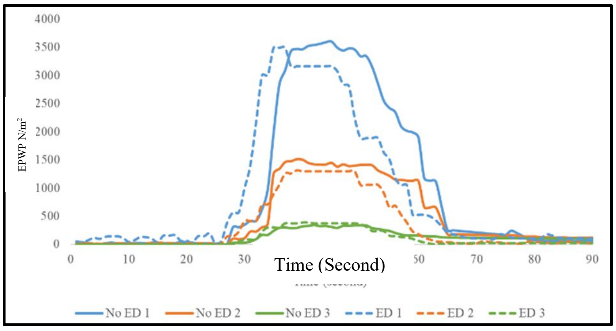

Fig. 7. EPWP for RD 40%, 1.2 Hz frequency

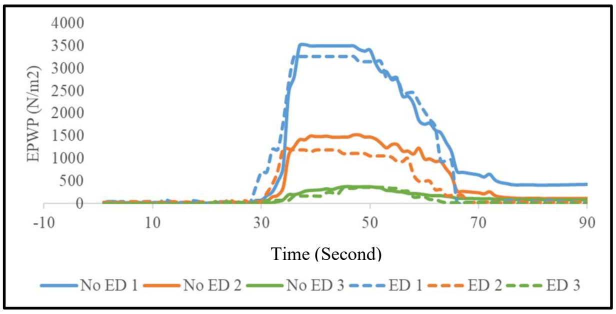

Fig. 8. EPWP for RD 60%, 1.2 Hz frequency

The key findings from Figs. 5-8 demonstrate earthquake drains significant role in reducing Excess Pore Water Pressure (EPWP) in soils subjected to dynamic loading. One of the most notable observations is the reduction of EPWP in both loose (40% relative density) and denser (60% relative density) soils. Earthquake drains allow excess water to dissipate from soil pores, thus preventing the buildup of excessive pressure that can weaken the soil structure during seismic activity.

The data further show the impact of relative density on EPWP. In looser soils with a relative density of 40%, the EPWP is higher due to the soil's tendency to compress more during loading. This compression causes a more significant accumulation of pore water pressure. In contrast, soils with a higher relative density of 60% exhibit lower initial EPWP. The denser arrangement of soil particles provides more excellent resistance to compression, resulting in less volume change and a more minor increase in pore water pressure. This demonstrates that soil density is critical in how pore water pressure develops under seismic conditions.

Moreover, earthquake drains effectively minimize the gap between EPWP and the effective stress within the soil. Since effective stress is the force that holds soil particles together, a smaller gap means that more stress is available to maintain the soil's strength. By controlling the rise in EPWP, earthquake drains help preserve soil stability during seismic events, reducing the risk of liquefaction and ground deformation. As a result, using earthquake drains enhances the seismic resistance of buildings and infrastructure, ensuring greater resilience and safety during earthquakes.

This study shows earthquake drains can effectively reduce the excess pore water pressure that occurs, thereby minimizing the gap between excess pore water pressure and effective soil stress. Which means that the earthquake drains play effectively in stabilizing the soil structure during an earthquake, thereby improving the safety and seismic resistance of the building.

4.2 Potential liquefaction

The ratio of excess pore water pressure to initial effective stress, denoted as r_u, plays a critical role in assessing liquefaction potential. The analysis of potential liquefaction ratio (r_u) values in relation to variations in Relative Density (RD) and earthquake frequency reveals that ru values increase significantly with higher RD and earthquake frequency. At lower relative densities, the ru values are greater, indicating that the soil is more susceptible to liquefaction. Additionally, higher earthquake frequencies can further elevate r_u values, as faster seismic waves are more likely to trigger liquefaction. This analysis provides valuable insight into soil behavior under seismic conditions and its potential for liquefaction. The image below shows two graphs labeled Fig. 9 and 10, both depicting the potential liquefaction (r_u) over time for soil samples with varying Relative Densitiy (RD) and subjected to seismic frequencies. The x-axis represents time in seconds, while the y-axis represents the r_u value. The $r_u > 1$ shows high potential liquefaction.

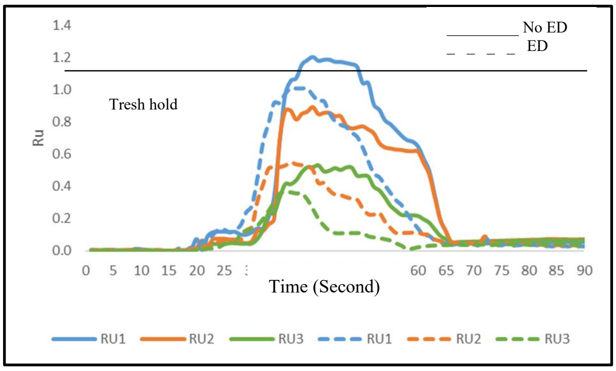

Fig. 9. Potential liquefaction (r_u) RD 40%, 1 Hz frequency

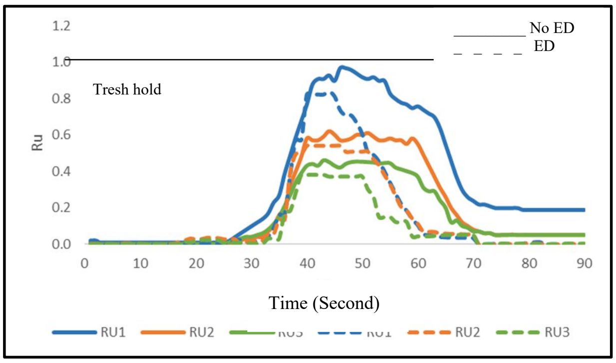

Fig. 10. Potential liquefaction (r_u) RD 60%, 1 Hz frequency

Figure 9 highlights a significant difference in the change of r_u values between the shaking table tests with and without the use of earthquake drains. The solid line represents the ru values without mitigation, while the dashed line represents the r_u values with earthquake drains. The dashed line is consistently lower than the solid line, demonstrating that earthquake drains effectively mitigate the increase in excess pore water pressure (EPWP).

Figure 10 follows a similar trend to Fig. 9, but the denser soil (60% RD) results in slightly lower ru values, indicating reduced liquefaction potential compared to the 40% RD case. Overall, the use of earthquake drains significantly reduces the r_u values, particularly at the peak, effectively mitigating liquefaction potential.

A comparison between the two figures shows that Fig. 9 (40% RD) presents higher r_u values, indicating that the soil is more prone to liquefaction compared to Fig. 10 (60% RD), where denser soil decreases the risk of liquefaction. In both figures, the effect of earthquake drains consistently lowers r_u values, demonstrating their effectiveness in reducing liquefaction risk.

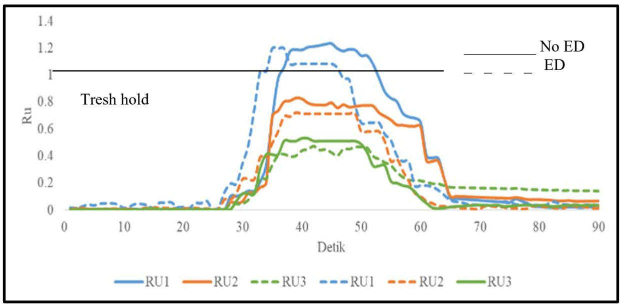

Fig. 11. Potential liquefaction (r_u) RD 40%, 1.2 Hz frequency

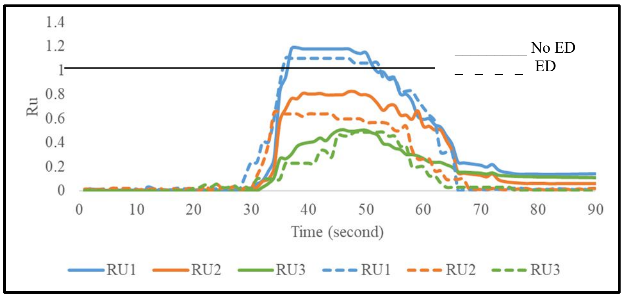

Fig. 12. Potential liquefaction (r_u) RD 60%, 1.2 Hz frequency

Figs. 11 and 12 show the r_u values where the relative density of 40% loose shows a r_u value higher than the relative density of 60%. The curves in both figures clearly show that higher relative densities and the use of earthquake drains significantly reduce liquefaction potential, with the denser soil in Fig. 12 showing a more pronounced reduction in r_u values.

This shows that soil density conditions significantly affect the liquefaction potential. In addition, looking at Figs. 11 and 12 one by one, it shows that liquefaction occurs in the top of transmitter positions. In contrast, after mitigation using an earthquake drain, mitigation only occurs in the top layer, with a value that decreases from before, and the time of liquefaction is narrower. This shows that the earthquake drain can effectively quickly distribute pore water pressure so that liquefaction does not occur in specific layers.

4.3 Liquefaction-induced settlement

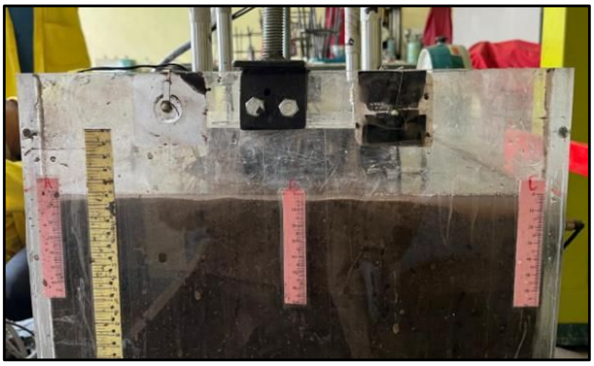

Fig. 13. Initial condition before shaking

The measurement of the foundation settlement that occurs using 4 LVDT sensors placed on the foundation will measure the settlement and be analyzed for settlement differences.

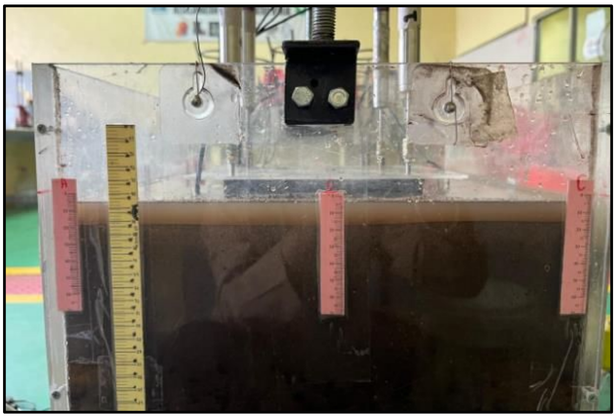

Fig. 14. Condition after shaking

Figure 13 shows the initial condition before shaking, where the sand is fully saturated. In contrast, Figure 14 illustrates the final condition after shaking. It is evident that water has risen to the surface, while the ground surface has subsided and become denser, causing the foundation to settle as it follows the ground's movement. This phenomenon is known as the change in relative density, which occurs immediately after the dissipation of water from soil pores due to cyclic loading.

Generally, settlement measure shows like the Figure 15, the denser the soil condition, the more the settlement will be reduced. Figure 15 shows the effect of using earthquake drains on settlement. The use can reduce the settlement by 2 % to 15% from the initial settlement without mitigation.

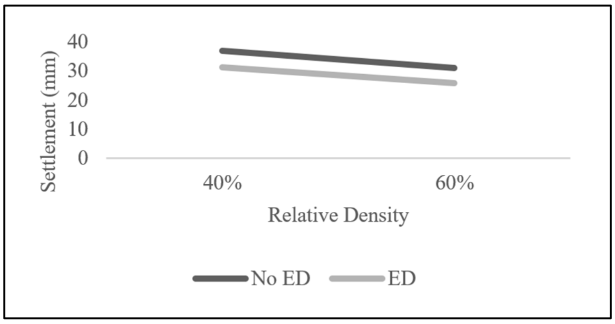

Fig. 15. EPWP for RD 60%, 1 Hz frequency

The subsidence value decreases as the relative density of the soil increases. Additionally, earthquake frequency plays a significant role in the extent of land subsidence—the stronger the earthquake, the greater the potential for subsidence. Besides these factors, the use of earthquake drains has been found to effectively mitigate the subsidence, reducing its severity even during seismic events.

5 Conclusion

The excess pore water pressure increase is highly dependent on soil depth, relative density, and seismic events. In samples with uniform relative density, the most significant excess pore water pressure occurs at the lowest position because pore water pressure trapped in deeper layers requires more time and pressure to escape. Lower relative density indicates looser soil, so if a seismic event occurs, the pore water pressure trying to rise will be more significant. Liquefaction potential is directly proportional to the increase in excess pore water pressure. However, in this assessment, a threshold determines whether the observed layer experiences liquefaction.

Mitigation using earthquake drains shows smaller excess pore water pressure values than without mitigation, and the liquefaction potential is also lower. Over time, earthquake drains can effectively dissipate water pressure from the lower layers directly to the upper layers, resulting in differences in the timing of excess pore water pressure increase. Earthquake drains can counteract the excess pressure that occurs. The reduction in excess pore water pressure positively impacts the soil-bearing capacity, helping to maintain the stability of the soil and the structures above it. Likewise, settlements can be reduced with mitigation using earthquake drains. The presence of earthquake drains (ED) consistently reduces EPWP across all elevations compared to the tests without mitigation (No ED), indicating the drains' success in dissipating excess pore water pressure during seismic events. This study demonstrates earthquake drains as a reliable and efficient measure to reduce liquefaction-induced settlement. However, further research is needed to optimize their design and application.

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