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Centrifuge modelling of liquefaction under a partially-drained condition

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ABSTRACT: Liquefaction of sandy ground during earthquakes can cause severe damage to buildings and lifelines. The drainage condition of the near-surface layer significantly affects the behaviour of liquefied ground. In reality, the surface layer may be in a condition that is closer to undrained rather than fully drained. To reproduce this situation experimentally, this study proposes a centrifuge modelling method to simulate *partially-drained conditions (PDC)* using a high-viscosity fluid. Centrifuge model tests were conducted at Kansai University under an acceleration field of 50g. A high-viscosity Metlose solution was used to create an undrained surface layer above a liquefiable sandy layer, and three adjacent house models were installed on the ground. Excess pore water pressure (EPWP), acceleration, and settlement were measured and compared with those under drained conditions (DC). During shaking, a layer of water was observed at the interface between the undrained and liquefied layers, indicating that the undrained layer effectively restricted drainage. The dissipation time of EPWP in the PDC model was approximately two to three times longer than that in the DC model. These findings indicate that drainage conditions have a strong influence on the behaviour of the ground both during and after liquefaction, and they provide fundamental insight into liquefaction phenomena under partially-drained conditions.

1 INTRODUCTION

Liquefaction of sandy soils is a well-known phenomenon that occurs during earthquakes. The 2024 Noto Peninsula, Japan, earthquake caused severe liquefaction in a wide area. Residential houses and pipelines were heavily damaged. Particularly, in Uchinada town, many buildings and infrastructure were damaged by liquefaction (Hazarika et al. 2025).

Many studies on liquefaction have been conducted to date, and experimental investigations are often performed under fully drained conditions. However, in reality, the near-surface ground is often compacted or paved, resulting in conditions that are closer to undrained rather than fully drained. According to Minarelli et al. (2024), the presence of an undrained layer at the surface significantly prolongs the dissipation time of excess pore water pressure. As such, drainage conditions -ranging from drained to undrained- can greatly affect the behaviour of liquefied ground (e.g., Ben-Zeev et al. 2023). Tobita et al. (2024) have discussed the concept of a “partially drained condition,” which refers to a state closer to undrained and is reported to extend the duration of liquefaction. In this paper, the term “Partially-Drained Condition (PDC)” will be used to describe a situation where the near-surface ground restricts drainage, leading to prolonged liquefaction behaviour.

Furthermore, field observations during the 2018 Sulawesi earthquake in Indonesia revealed extensive lateral spreading and long-runout flow associated with liquefaction. One factor causing this large-scale movement was the presence of a low-permeability surface layer, which hindered the dissipation of pore water during shaking (Kiyota et al. 2025). It has also been reported that a layer of water formed near the interface of the low-permeability layers, facilitating lateral flow (Tobita et al. 2022). These findings

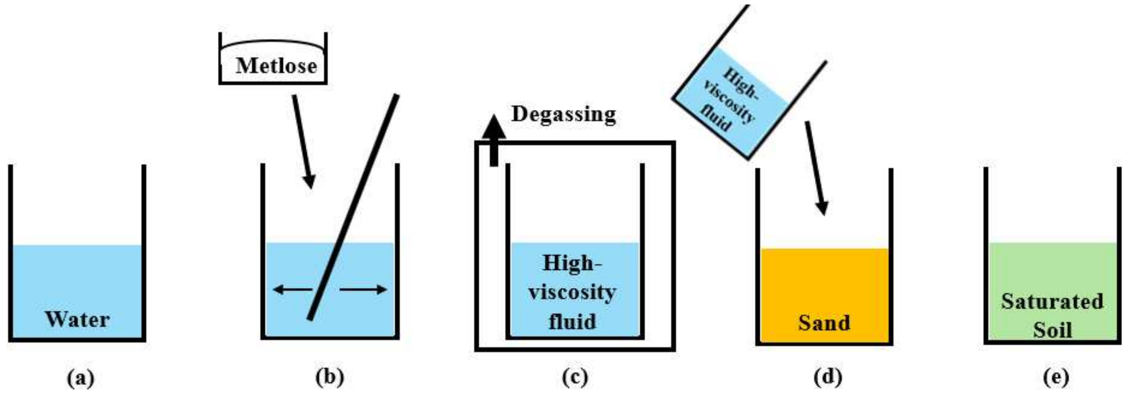


Figure 1. Basic step of the method to create an undrained layer. (a) water; (b) add metlose; (c) degassing; (d) add high-viscosity fluid to sand; (e) saturated soil (if needed, degassing again).

suggest that partial drainage and permeability contrast at shallow depths play a crucial role in controlling the liquefaction behaviour of the ground.

In this study, centrifuge model tests were conducted to reproduce partially-drained conditions and to investigate the dissipation behaviour of excess pore water pressure under these conditions. The viscous fluid was utilized to create an undrained layer, enabling experiments under partially-drained conditions. In the model, three adjacent house structures were arranged on the ground surface, allowing for the observation of interactive behaviour among buildings. In addition to the pore pressure response, the settlement and tilting behaviour of each building were also examined to clarify how partial drainage affects the deformation characteristics of structures on liquefied ground.

2 PDC METHOD

In centrifuge model tests, a viscous fluid has traditionally been used to satisfy similitude laws under centrifuge acceleration (Stewart et al. 1998, Adamidis et al. 2015). Gonzalez et al. (2010) investigated the influence of permeability on soil-structure response using viscous fluids with different viscosities to vary the hydraulic conductivity of the model ground. Following this approach, the present study proposes a method to reproduce partially-drained condition (PDC) by increasing the viscosity of the fluid conventionally used in centrifuge experiments, thereby forming an undrained surface layer artificially reproduced by a high-viscosity fluid.

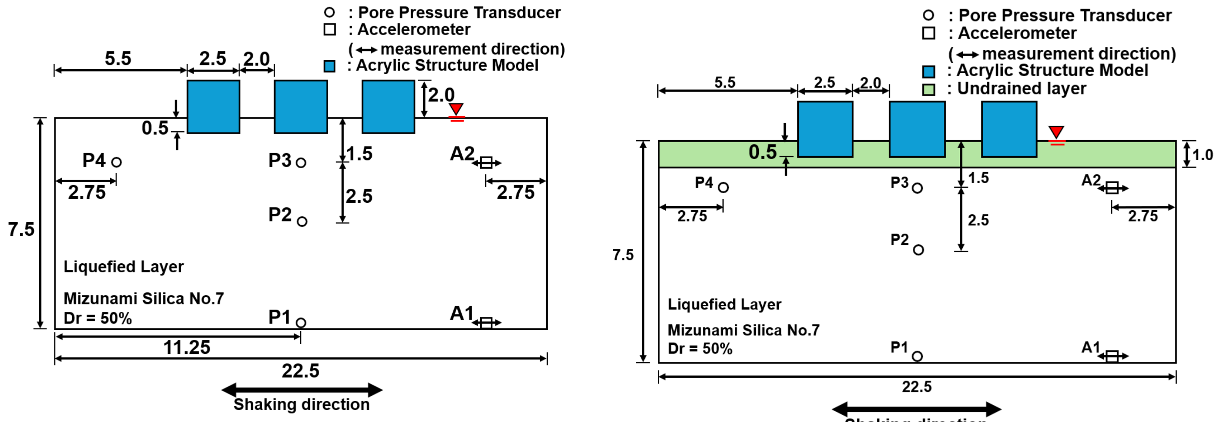
In these experiments, Metlose (methyl cellulose, manufactured by Shin-Etsu Chemical Co. Ltd.) was used to saturate both the model ground and the undrained surface layer. The preparation procedure for the viscous fluid and the construction of the undrained layer are shown in Figure 1. First, Metlose powder was dissolved in water and then de-aired. Because the removal of air bubbles becomes more difficult as viscosity increases, a longer degassing time was required. Hot water was found to facilitate the dissolution of Metlose. Subsequently, the de-aired high-viscosity fluid was used to saturate the sand. In high-viscosity cases, infiltration was slow; therefore, the sand and fluid were mixed directly to ensure uniform saturation. After saturation, the specimen was again de-aired to remove residual air trapped in the saturated soil. The kinematic viscosity of the fluid used for the surface layer was approximately 100 thousand cSt (centistokes; $1\ \text{cSt} = 1 \times 10^{-6}\ \text{m}^2/\text{s}$). By placing this high-viscosity saturated layer on top of the model ground, a centrifuge model representing a partially-drained condition was successfully created.

3 MODEL DESIGN

3.1 Centrifuge facility

The centrifuge tests were conducted using the centrifuge apparatus at Kansai University. The facility has an effective radius of 1.5 m and is capable of applying centrifugal accelerations of up to 50g. A photograph of the centrifuge device is shown in Figure 2. The centrifuge is equipped with a rigid model container and a shaking table system, allowing dynamic loading tests to be performed under controlled acceleration fields.

Figure 2. Kansai University Centrifuge.



Drained Condition (DC)

Partially-Drained Condition (PDC)

Figure 3. Schematic view of experimental setup (Model size unit: m, prototype scale).

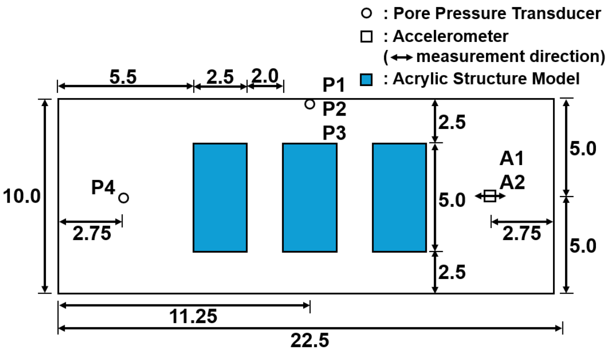


Figure 4. Schematic top view (unit: m, prototype scale).

3.2 Model geometry

Figure 3 and 4 show schematic diagrams of the experimental model. In the drained condition (DC) model, a loose sandy ground (Mizunami Silica No. 7, relative density = 50%) with dimensions of 450 mm (width) × 200 mm (depth) × 150 mm (height) was prepared in a rigid container and tested under a centrifugal acceleration of 50g. Under centrifugal acceleration, the gravity field acts in the radial direction from the rotation centre, and therefore the ground surface and layer boundaries in the model were formed as circular arcs. The ground was saturated up to the surface using a Metlose solution with a viscosity that satisfies the similitude law under centrifuge conditions. The physical properties and grain-size distribution curve of Mizunami Silica No. 7 are shown in Table 1 and Figure 5, respectively. In the partially-drained condition (PDC) model, the surface PDC was reproduced by creating a 20 mm-thick surface layer of saturated sand prepared with a high-viscosity Metlose solution (viscosity ≈ 100 thousand cSt). In addition, three acrylic house models (50 mm wide × 100 mm deep × 50 mm high) were installed at the centre of the specimen, spaced 40 mm apart, with an embedment depth of 10 mm. These house models were designed to exert a contact pressure of approximately 25 kPa under a centrifugal acceleration of 50g. In the PDC model, the foundations of the house models were embedded within the undrained layer.

The input acceleration consisted of 40 cycles of a sinusoidal wave at a frequency of 50 Hz (equivalent to 1 Hz in prototype scale) with a single amplitude of 2.5 mm. All depths, accelerations, and time scales mentioned hereafter are presented on the prototype scale.

Table 1. Properties of Silica No. 7 (Mizunami Silica).

Specific gravity	Gs	2.65
Mean grain size	D_{50} (mm)	0.26
Effective grain size	D_{10} (mm)	0.13
Maximum void ratio	e_{max}	1.09
Minimum void ratio	e_{min}	0.69

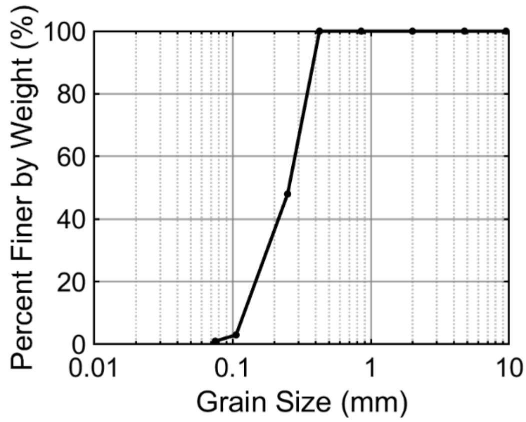


Figure 5. Particle size distribution of Silica No. 7.

4 RESULTS AND DISCUSSION

4.1 Acceleration response

Figure 6 shows the input and measured acceleration time histories of DC and PDC. At observation point A2, the amplitude of acceleration rapidly decreased soon after the start of shaking, indicating that liquefaction occurred and energy dissipation progressed within the soil layer. This reduction in acceleration amplitude confirms the corresponding loss of stiffness in the ground.

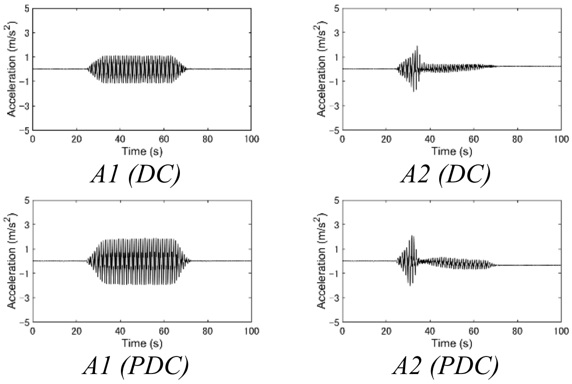


Figure 6. Acceleration time histories.

4.2 Pore pressure generation and dissipation

Figure 7 shows the PDC model before and during shaking. During shaking, a layer of water was observed to form at the interface between the undrained layer and the liquefiable layer. Previous studies on sand boiling (Okawa 1997) have reported that when an impermeable layer exists within a sand layer, a thin layer of water tends to form between the impermeable layer and the underlying liquefied sand. In this experiment, the undrained layer appeared to act as such an impermeable layer, resulting in the formation of a layer of water film. This observation indicates that the undrained layer made of high-viscosity fluid effectively restricted the drainage paths of pore water.

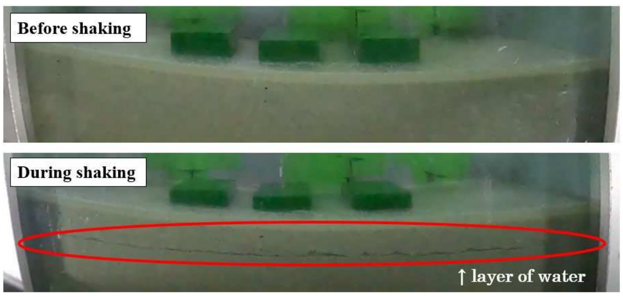


Figure 7. Comparison of the PDC model before and during shaking.

The maximum excess pore water pressures (EPWP) at sensors P1 to P4 were 23.4, 20.8, 4.0, and 7.5 kPa for the DC model, and 39.3, 23.7, 4.2, and 10.5 kPa for the PDC model, respectively. Figure 8 presents the time histories of EPWP. In both models, pore pressures increased with shaking and subsequently dissipated after the end of excitation. The horizontal dashed lines in the figure indicate the initial effective overburden stress. At P1 and P3, the pore pressures did not reach the initial effective overburden stress, while at P2 and P4 they rose to that level, indicating full liquefaction at those depths.

Overall, the PDC model exhibited a longer dissipation time of excess pore water pressure compared to the DC model. To evaluate this quantitatively, the dissipation time was defined as the time required for the EPWP to decrease by 20% from its maximum value. The dissipation times for the DC model were 23.6, 41.7, 49.0, and 42.5 s for P1 to P4, whereas those for the PDC model were 57.0 and 111.7 s for P1 and P2. At P3, a 20% reduction was not reached during the observation period, and at P4, the dissipation time was 144.1 s. Thus, the dissipation times in the PDC model increased by a factor of approximately 2-3 compared to those in the DC model. At the near-surface location (P4), the PDC model exhibited a 339% increase in dissipation time relative to the DC model, demonstrating that the effect of the undrained layer is most pronounced near the surface. Moreover, at deeper locations such as P1 (GL ≈ -4 m) and P2 (GL ≈ -7.5 m), the dissipation time also more than doubled, suggesting that the influence of the PDC extends beyond the surface layer to deeper parts of the liquefied ground.

4.3 Settlement and tilting of houses

In both the DC and PDC models, the houses experienced settlement due to liquefaction. Figure 9 shows the appearance of the houses after shaking. The settlement of each house was evaluated based on the measured displacements at the four corners of the houses, and the average settlement on the left and right sides was calculated. The average settlements of the left, center, and right houses were 0.69, 0.48, and 0.65 m in the DC model, and 0.78, 0.95, and 1.10 m in the PDC model, respectively. The settlements were generally larger in the PDC model, which can be attributed to the prolonged liquefaction duration (i.e., longer excess pore pressure dissipation time). In particular, the central house in the PDC model exhibited nearly twice the settlement observed in the DC model.

The inclination angles of the houses were estimated from the difference in settlement between

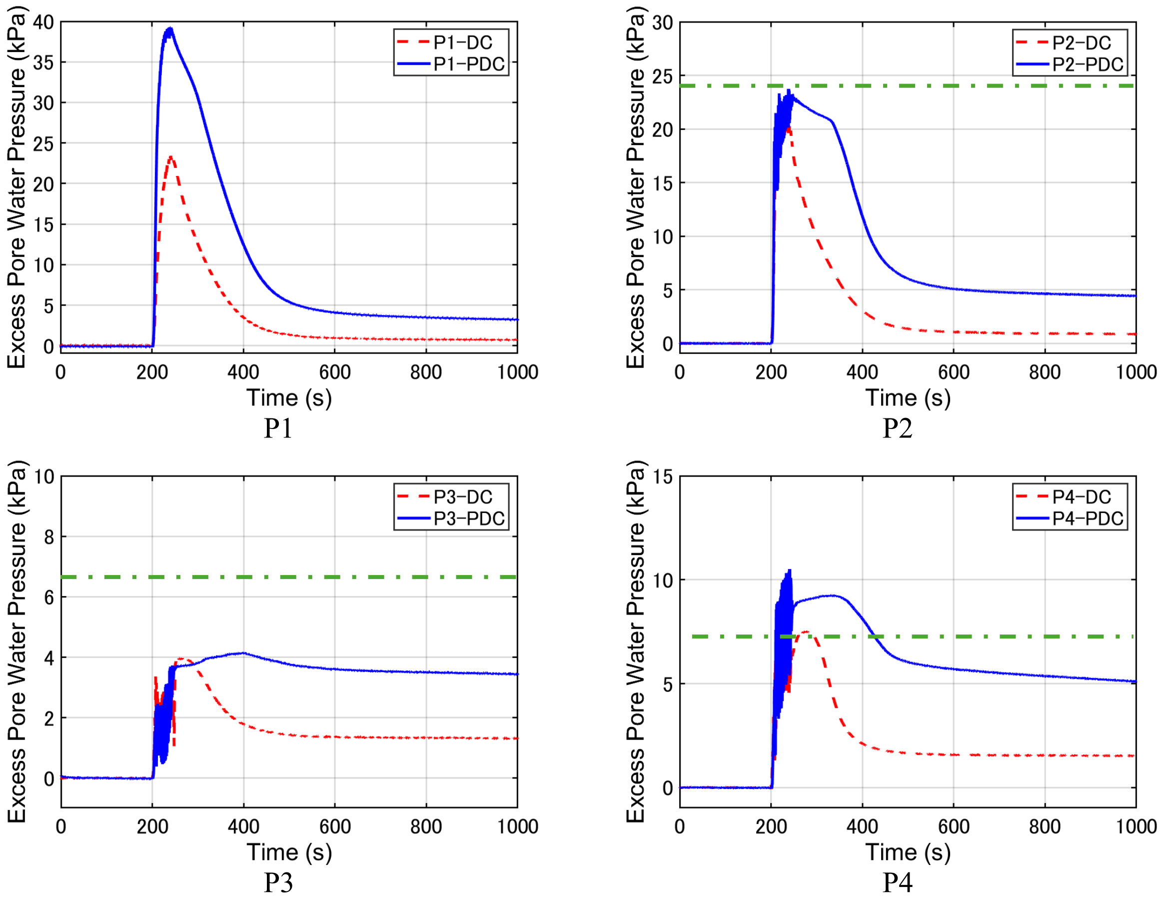


Figure 8. Excess pore water pressure time histories (the green dashed line represents the initial effective overburden stress).

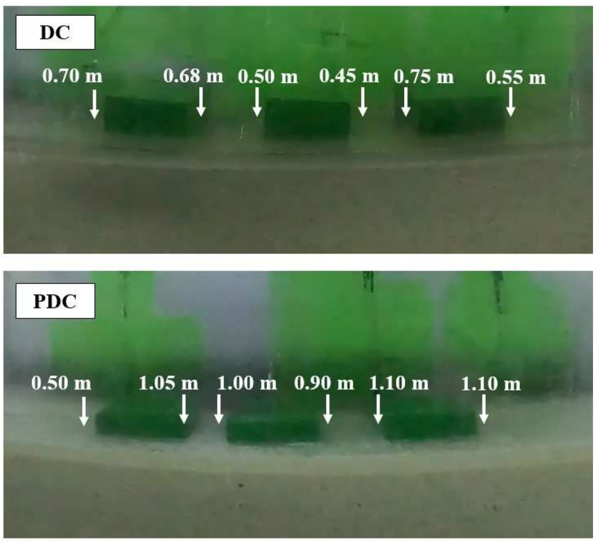


Figure 9. Settlement of house models after shaking.

the left and right sides, divided by the house width (2.5 m), assuming positive values for tilting to the left. The inclination angles were 0.458°, 1.146°, and 4.574° for the left, centre, and right houses in the DC model, and -12.407°, 2.291°, and 0.000° in the PDC model. Pronounced tilting was observed in the right house of the DC model and the left house of the PDC model. These results suggest that the interaction between adjacent houses affected the ground deformation due to stress interference caused by house loads within the ground, leading the houses to tilt toward the centre. Previous studies on liquefaction-induced settlement of adjacent structures (e.g., Yasuda et al. 2014, Kunisawa et al. 2024) have reported that when buildings are closely spaced, differential settlement tends to occur toward adjacent structures. The results of this study are considered to show partially similar behaviour.

5 CONCLUSIONS

In this study, a partially-drained condition (PDC) model was developed using a high-viscosity fluid, and centrifuge model tests were conducted to investigate the liquefaction behaviour of three adjacent houses under PDC. The main findings are summarized as follows:

1. A method for preparing an undrained surface layer, reproduced by saturating sand with a high viscosity fluid, was presented.
2. During shaking, a layer of water was observed to form at the interface between the undrained and

liefied layers, indicating that drainage paths were restricted by the undrained surface layer.

3. The dissipation time of excess pore water pressure in the PDC model was approximately 2-3 times longer than that in the DC model.
4. The effect of PDC was particularly pronounced near the surface, where the dissipation time increased by up to 339%, but it also extended to deeper layers.
5. Owing to the prolonged liquefaction duration, the settlement of some houses increased by nearly twice compared with that under DC.

These results demonstrate the effectiveness of the proposed PDC model and clarify the influence of drainage conditions on the deformation behaviour of houses during liquefaction. Future work will include further centrifuge experiments on various ground and house configurations, as well as improvements in the control and characterization of high-viscosity fluids used to simulate partially drained conditions.

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