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# Composite vertical drains for liquefaction mitigation- A laboratory study

M.P. Kompala
*National Institute of Technology Warangal, Warangal, India, km22cer1r19@student.nitw.ac.in*

S.K. Yamsani
*National Institute of Technology Warangal, Warangal, India, skyamsani@nitw.ac.in*

**ABSTRACT:** Liquefaction-induced excess pore water pressure generation and seismic amplification significantly influence the response of saturated loose sand deposits during earthquakes. This study investigates the effectiveness of Prefabricated Vertical Drains (PVDs) and Composite Vertical Drains (CVDs) in mitigating liquefaction through a series of shaking table tests. Saturated sand models were tested under input base accelerations of 0.1 g, 0.2 g, and 0.3 g for soil-alone, PVD-treated, and CVD-treated conditions. Excess pore water pressure was measured at different depths, and acceleration amplification factors (AAF) were evaluated along the soil column. Results indicate that excess pore pressure increased with depth and input acceleration, with untreated soil reaching liquefaction conditions at higher acceleration levels. PVDs reduced peak pore pressure and delayed liquefaction through enhanced drainage, although their effectiveness decreased under strong shaking. CVDs consistently exhibited lower pore pressure ratios and reduced acceleration amplification, demonstrating superior liquefaction mitigation due to combined drainage and damping effects.

## 1 INTRODUCTION

During the time of an earthquake, permeable soils such as gravelly sands or coarse sands will be able to dissipate the increased pore water pressures. However, in semi-permeable soils such as silty sands and fine sands, the time for increasing pore water pressure is shorter than the time for dissipation [Hakam, 2020; Florin, 1961; Haigh et al., 2000]. The condition of increased pore water pressure will reduce the effective stress in soil mass which causes liquefaction. For this reason, it is necessary to carry out mitigation efforts to prevent the risk of liquefaction disasters. By densifying the soil in-situ through methods like vibro-compaction, deep soil mixing, dynamic compaction, or explosive compaction, liquefaction risks have often been reduced. These methods are often ineffective for sands with greater fines contents, despite their general effectiveness in clean sands. Providing drainage is an option to densifying the sand because it allows the extra pore water pressures created by the shaking caused by earthquakes to quickly dissipate preventing liquefaction. The idea of liquefaction mitigation by the use of vertical gravel drains was first proposed by Seed and Booker (1977).

Prefabricated drains were recently erected for liquefaction mitigation at some sites, although no significant earthquakes have occurred at these sites. There are no case histories available to validate the usefulness of prefabricated drains against liquefaction. Recent field experiments evaluated the performance of prefabricated products. In order to test prefabricated drains constructed at two locations with liquefiable soils, Rollins et al., (2003) used controlled blasting. According to the findings, there were 40–80% fewer settlements in the treated region than in the untreated area, and the treated area's rates of dissipation were noticeably faster than those of the untreated area. However, the vibratory methods used to install the drains for these tests caused some densification of the soil (3–4% volumetric strain). As a result, these tests were unable to assess how well drainage worked alone to reduce the development of pore pressure and liquefaction-induced settlement.

In the present study, conventional prefabricated vertical drains (PVDs), which are widely used to accelerate soil consolidation, and composite vertical drains (CVDs) were evaluated for their effectiveness in mitigating soil liquefaction under dynamic loading conditions. The investigation focuses on a comparative assessment of PVDs and CVDs with respect to the soil-alone condition. The evaluation was carried out based on the dissipation characteristics of excess pore water pressure and the influence of the installed drains on the acceleration amplification factor, thereby examining their role in improving the overall seismic performance of saturated soil deposits.

## 2 MATERIALS AND METHODOLOGY

### 2.1 Prefabricated Vertical drains (PVD)

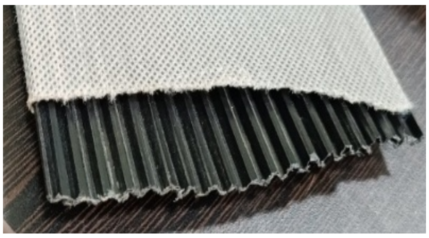
Prefabricated Vertical Drains (PVDs) are geosynthetic drainage elements consisting of a polymeric core wrapped with a geotextile filter as shown in Fig. 1(a), primarily used to accelerate consolidation by shortening drainage paths in saturated soils. In liquefaction mitigation studies, PVDs act as preferential drainage channels**,** facilitating partial dissipation of cyclically generated excess pore water pressure during seismic loading. This helps in maintaining higher effective stress, reducing soil softening, and delaying the onset of liquefaction (Rollins et al., 2003; Padmanabhan and Shanmugam, 2024).

Recent experimental and numerical investigations have shown that PVDs can reduce peak excess pore pressure ratios and post-shaking settlements, particularly in loose to medium dense sands (Liu et al., 2020). However, their effectiveness under strong shaking is limited, as rapid pore pressure generation may exceed the drainage capacity of the drains (Huang and Wen, 2015). Moreover, PVDs do not contribute significantly to seismic energy dissipation or acceleration reduction, and their influence on seismic response is mainly indirect, through pore pressure control rather than dynamic isolation.

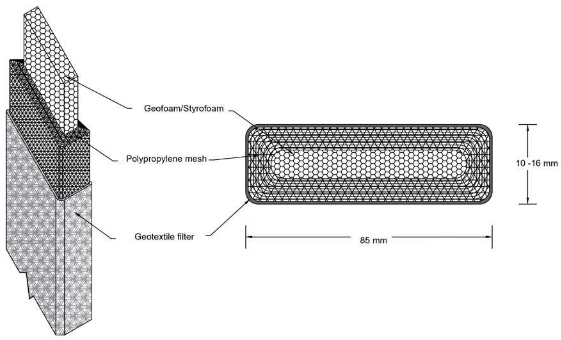
### 2.2 Composite vertical drain (CVD)

Composite vertical drains with geofoam cores (CVD) were fabricated in the laboratory using geofoam, polypropylene mesh (PPM), and geotextile filter materials as shown in Fig. 1(b). In these drains, the conventional corrugated polymeric core of prefabricated vertical drains (PVDs) was completely replaced by a composite core consisting of a thin geofoam sheet wrapped with PPM. Geofoam was selected as the core material due to its excellent compressible inclusion properties, which enable it to accommodate lateral soil deformations (Aytekin, 1997; Selvakumar and Soundara, 2019).

The schematic representation of the core and filter components of the CVD and conventional PVD is shown in Fig. 1(c). The geofoam core was prepared by cutting the material into strips of 80 mm width and 5 mm thickness using an electric hot knife. The prepared composite core was subsequently encased within a geotextile filter to form the CVDG. The PPM wrapping in the CVDG facilitates drainage through its interconnected pore structure and high transmissivity characteristics. The strength and hydraulic properties of PVD and CVD are summarized in Table 1.



*(a)*




*(b)* *(c)*

*Figure 1. Pictures of (a) prefabricated vertical drain (PVD), (b) composite vertical drain (CVD) and (c) schematic view of CVD*

*Table 1. Properties of PVD and CVD*

| Property | Code adopted | PVD | CVD |
|---|---|---|---|
| Drain Configuration | | Corrugated channels | Polypropylene mesh (PPM) layers |
| Discharge Capacity at 200 kPa, i=0.5 Straight condition ($cm^3/s$) | ASTMD 4716 | 80 | 82.6 |
| Tensile Strength (kN) @ 10% strain | ASTMD 4595 | 1.5 | 1.59 |
| Thickness (mm) | ASTM D 5199 | 3 | 13 |
| Width (mm) | ISO 22198 | 100 | 85 |
| Filter Apparent opening Size (μm) | ASTM D 4751 | 75 | 75 |
| Equivalent radius of drain (mm) | Hansbo (1979) | 33.12 | 31.21 |
| Water absorption Capacity (%) | ASTM D 1117 | 1.1 | 2.78 |

## 2.3 Experimental setup

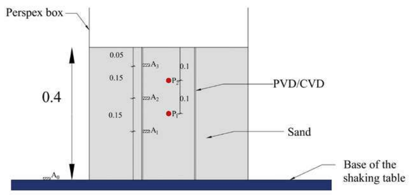
The setup involves a Perspex box, as showed in Figure 2, alongside a shake table for liquefaction simulation. The box dimensions measure 0.6 meters in height and 0.8 x 0.6 meters in length and width. To reflect real-world conditions, a geofoam sheet of equal size to the box is placed inside to prevent wave reflection and ensure sand saturation for sand deposition, a back-water pressure approach is employed. Initially, one-third of the tank is filled with water, followed by the pouring of sand by using pluviation method so that the required relative density of about 50% in the form of a slurry from a holding tank, is pumped into the box. To maintain consistent sand density, the water level is kept at a uniform height above the sand, the sand typically reaches a final height of 0.4 meters. Throughout the filling process, small buckets are placed within the box and weighed after filling to measure sand density at various depths. This allows for density assessment as the box is gradually filled with sand.

PVDs were hung into the rigid box and their tops were fitted with steel array mesh after the box was placed on the shaking table. Afterwards, using the pluviation process, water and sand were gradually added to the rigid box to reach the desired density. Because the drains were installed before sand pluviation, their installation did not induce any soil densification. Consequently, the test results isolate the effect of drainage, making it the sole parameter of interest in this study (Chang et al., 2004). Figure 3 illustrates the schematic of the experimental setup and the plan view of the PVD configurations.

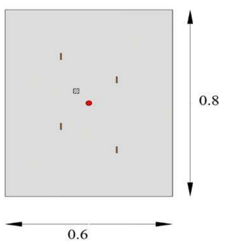

(a)

(b)

*Figure 2. (a) Shaking table along with perspex box used for the study, (b) Experimental setup*




(a)




(b)

$A_0$, $A_1$, $A_2$ & A3 are accelerometers

$P_1$ & $P_2$ are pore pressure transducers

- All dimensions are in meters and not to scale

*Figure 3. (a) schematic view of the test setup (b) plan*

## 2.4 Input Ground Motion

Before the start of the test, four accelerometers were installed to measure the acceleration of both the soil mass and the shake table during vibration. Among those four accelerometers three were kept inside the box (Bottom, middle, and top) and one was attached to the base plate of shake table. A constant input ground motion was applied to the base of the shaking table. A constant input ground motion was applied at the base of the shaking table. The same acceleration amplitude, frequency, and number of cycles were used for all three cases: without drains, with PVDs, and with CVDs. The test matrix is shown in Table 2. All ground motions were composed of 15 cycles of sinusoidal motions at a frequency of 2 Hz. Typically, 15 cycles of motion are linked with a Magnitude 7.5 earthquake (Seed, 1975), which is frequently regarded as the base magnitude for liquefaction investigations. The above sinusoidal motion was applied to the setup in terms of amplitude instead of acceleration, the conversion formula for acceleration to amplitude is given below.

$$D\ (mm) = \frac{ag}{2\pi^2 f^2} \qquad (1)$$

a= Acceleration in m/s$^2$
g= Acceleration due to gravity in m/s$^2$
f= Frequency in Hz

*Table 2. Test matrix for the study*

| Case | Relative density | Input acceleration | Frequency | No. of cycles |
|---|---|---|---|---|
| Without drains | 50% | 0.1g, 0.2g, 0.3g | 2Hz | 15 |
| PVD | | | | |
| CVD | | | | |

# 3 RESULTS AND DISCUSSIONS

## 3.1 Effect of input acceleration on excess pore pressure generation

Figure 4 elucidates the variation of pore pressure ratio with height the height of soil for different accelerations. Input acceleration (PGA) plays a dominant role in governing excess pore water pressure generation and the onset of liquefaction in saturated sandy soils. The present results clearly indicate that excess pore pressure ratio ($R_u$) increases systematically with increasing PGA at all depths and for all soil improvement conditions. The excess pore pressure ratio ($R_u$) was calculated as shown in Eq (2).

$$R_u = \frac{\Delta u}{\sigma'_{vo}} \qquad (2)$$

where Δu is the measured excess pore pressure and $\sigma'_{v0}$ is the initial vertical effective stress at the transducer depth prior to shaking.

At a low input acceleration of 0.1 g, $R_u$ values remain well below unity for soil-alone, PVD, and CVD cases, indicating stable soil response with limited cyclic strain accumulation. This behavior is consistent with earlier observations that low-amplitude shaking induces insufficient cyclic shear stress to cause significant contractive volumetric response in loose sands (Seed and Idriss, 1971).

With an increase in PGA to 0.2 g, a substantial rise in $R_u$ is observed, particularly in the soil-alone case, where $R_u$ approaches unity at intermediate depths. This reflects the enhanced cyclic shear stress ratio imposed by stronger shaking, leading to accelerated buildup of excess pore pressure. Similar acceleration-dependent pore pressure evolution has been reported in shaking table and centrifuge studies by Finn et al. (1971) and Ishihara (1996), who showed that liquefaction susceptibility increases markedly once a threshold cyclic stress level is exceeded.

At the highest input acceleration of 0.3 g, the soil-alone condition exhibits $R_u \geq 1$, confirming full liquefaction. Even in the presence of conventional PVDs, $R_u$ approaches or slightly exceeds unity, indicating that drainage measures become less effective under intense shaking. This reduction in efficiency at high PGA has also been noted by Yeung et al. (2014), who reported that the rate of pore pressure generation may exceed the dissipation capacity of vertical drains during strong seismic excitation.

In contrast, the CVD-treated soil maintains $R_u$ well below unity even at 0.3 g, demonstrating superior performance under high acceleration levels. This improved response can be attributed to the enhanced discharge capacity and structural stability of composite drains, which allow faster pore pressure dissipation during cyclic loading. Similar findings were reported by Rollins et al. (2004) and Madhav and Arlekar (2010), who emphasized that improved drainage efficiency significantly reduces acceleration-induced pore pressure buildup.

Overall, the results confirm that input acceleration not only controls the magnitude of excess pore pressure generation but also governs the effectiveness of liquefaction mitigation measures. While untreated soil rapidly liquefies under increasing PGA and PVDs offer limited resistance at high accelerations, CVDs remain effective even under strong shaking, highlighting their suitability for seismic ground improvement applications.

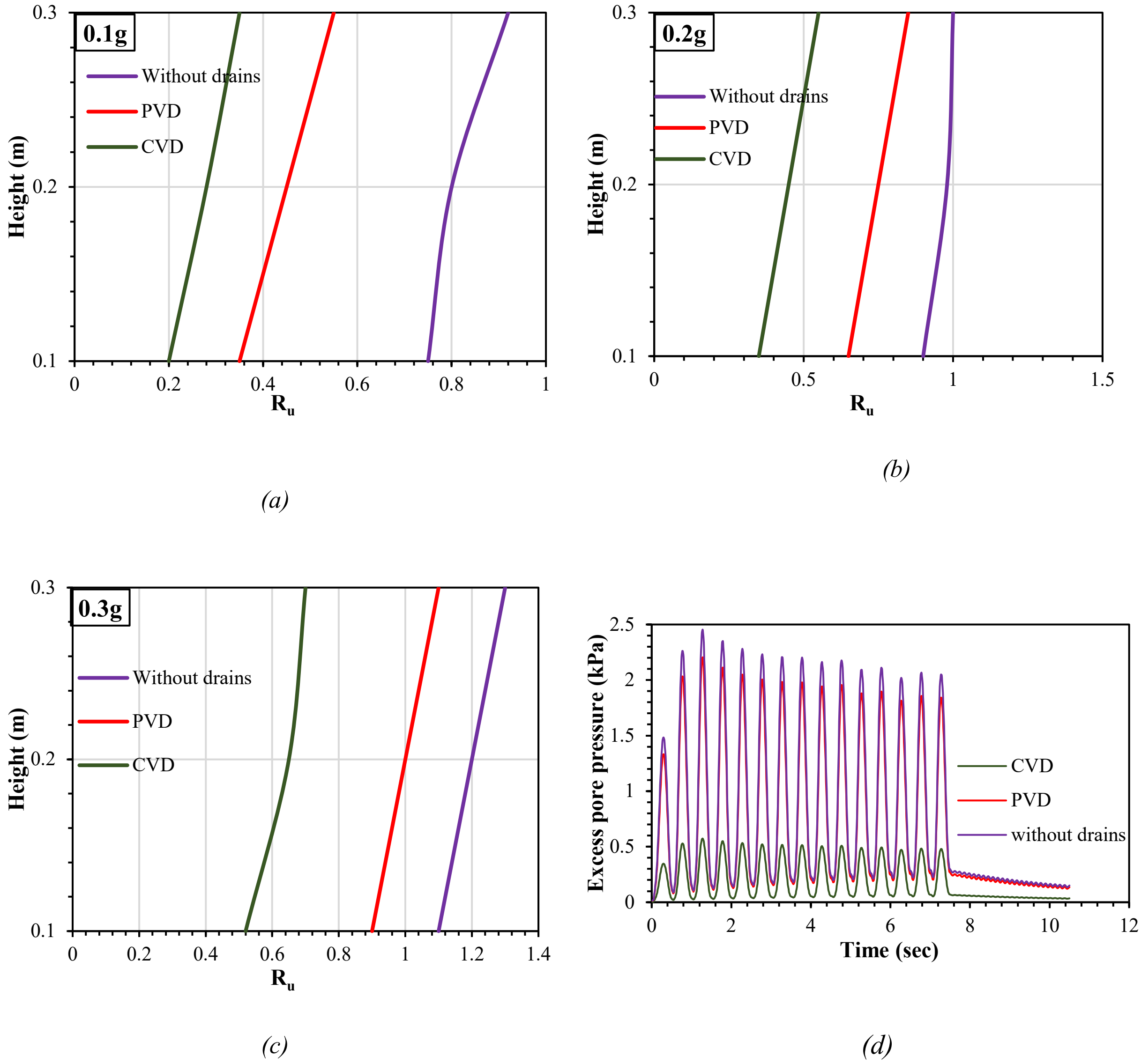


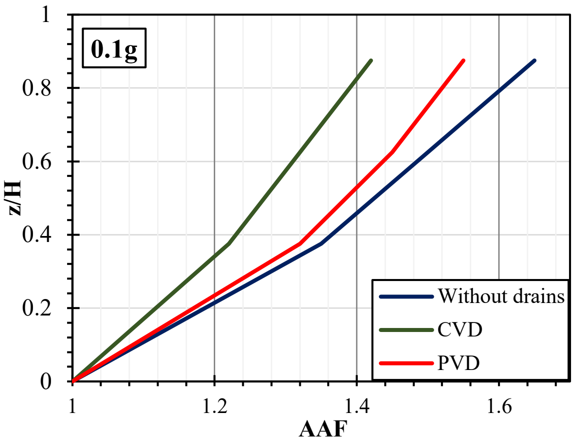

*Figure 4. Variation of pore pressure ratio with the height of soil for (a) 0.1g, (b) 0.2g (c) 0.3g and (d) pore pressure time history for 0.3g at 0.1m below the surface*

In liquefaction studies, $R_u$=1 corresponds to zero effective stress. The slight exceedance of above unity observed during peak shaking is attributed to transient dynamic effects and minor uncertainty in estimating the initial effective stress. It does not indicate sustained negative effective stress in the soil.

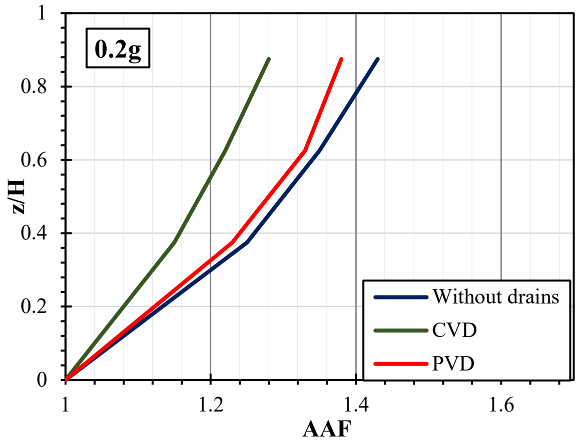
## 3.2 Effect of input acceleration on acceleration amplification factor (AAF)

Figure 5 shows the Variation of AAF with height for different accelerations. The acceleration amplification factor (AAF) increases with height for all base acceleration levels due to the reduction in confining pressure toward the ground surface, which results in lower small-strain stiffness in the shallow soil layers. Similar height-dependent amplification trends have been widely reported in site response studies (Seed and Idriss, 1970).

At a low base acceleration of 0.1g, the soil response remains largely linear, with minimal shear strain development. Under such conditions, soil stiffness is preserved and material damping remains low, leading to higher amplification and a steep increase in AAF toward the ground surface. This behavior is consistent with the linear site response observed in sandy soils under weak ground motions (Kramer, 1996).




*(a)*

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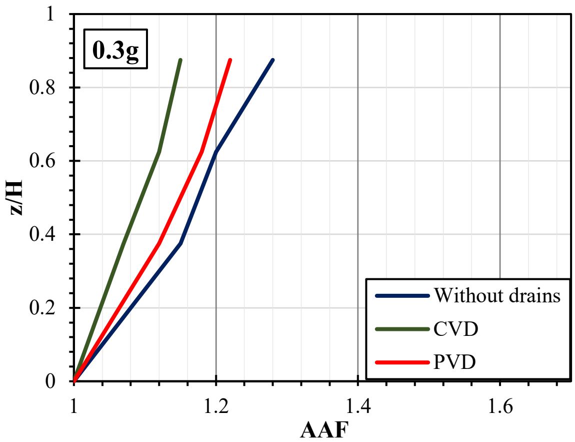


*(c)*

*Figure 5. Variation of AAF with height for three cases at different accelerations (a) 0.1g, (b) 0.2g and (c) 0.3g*

As the base acceleration increases to 0.2g and 0.3g, nonlinear soil behavior becomes dominant. The increase in cyclic shear strain leads to shear modulus degradation and enhanced hysteretic damping, which promotes greater seismic energy dissipation within the soil mass. Consequently, both the magnitude of AAF and its rate of increase with height are reduced. Similar suppression of amplification under strong shaking has been reported by Ishihara (1996) and Vucetic and Dobry (1991), who demonstrated that increased damping at large strain levels significantly limits acceleration amplification.

The inclusion of Composite Vertical Drains (CVDs) results in a moderate reduction in AAF relative to the soil-alone condition, with surface reductions of approximately 6–8%, 2–3%, and 2–3% for base accelerations of 0.1 g, 0.2 g, and 0.3 g, respectively. This reduction is attributed to the additional damping and limited energy absorption provided by the geofoam-based composite core of the CVDs. Similar damping-induced reductions in acceleration response due to compressible inclusions have been reported by Alcala-Ochoa, (2023) and Madhav and Arlekar (2010). However, the relatively low volume fraction of geofoam in the CVD system limits its contribution to mass reduction and energy dissipation, resulting in only moderate attenuation of AAF. Hence, CVDs act primarily as localized damping elements rather than providing full seismic isolation.

For prefabricated vertical drains (PVDs), the reduction in AAF is smaller, approximately 3–4%, 1–2%, and 1–2% for base accelerations of 0.1 g, 0.2 g, and 0.3 g, respectively. The influence of PVDs on acceleration response is indirect and is mainly associated with their ability to dissipate excess pore water pressure during shaking, thereby limiting soil softening and stiffness degradation. This behavior is consistent with findings by Rollins et al. (2004) and Yeung et al. (2014), who noted that improved drainage reduces nonlinearity-induced amplification under cyclic loading.

Overall, the results confirm that higher input acceleration suppresses acceleration amplification throughout the soil column, and that both CVDs and PVDs improve seismic response compared to untreated soil. Among the two, CVDs exhibit slightly superior performance due to their combined drainage and damping characteristics. Nevertheless, the limited geofoam content restricts the maximum achievable reduction in AAF, emphasizing the critical role of material composition and volume fraction in seismic energy mitigation.

## 4 CONCLUSIONS

This study investigates the effectiveness of Prefabricated Vertical Drains (PVDs) and Composite Vertical Drains (CVDs) in mitigating liquefaction-induced pore pressure generation and acceleration amplification under different seismic input levels.

a. Excess pore water pressure increased with input acceleration and depth, with the untreated soil reaching liquefaction ($R_u \approx 1$) at higher acceleration levels.
b. PVDs reduced pore pressure buildup and delayed liquefaction through enhanced drainage; however, their effectiveness decreased under strong shaking due to rapid pore pressure generation.
c. CVDs consistently exhibited lower $R_u$ values and improved seismic response compared to PVDs and soil-alone cases, owing to the combined effects of drainage and additional damping.
d. Acceleration amplification increased toward the ground surface but reduced with increasing input acceleration; both PVDs and CVDs lowered amplification, with CVDs providing marginally superior performance.

## ACKNOWLEDGEMENTS

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