

Review Article

# Recent Advances in the Seismic Performance of Waterfront Sheet Pile Walls. A Review

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**Abstract** - This paper presents the latest advances in the study of waterfront, earthquake-prone sheet piles. The review sums up recent findings on how waterfront sheet-pile walls behave in earthquakes that cause soil liquefaction. It is necessary to know this to protect coastal structures. The seismic dangers to these walls are increasing. This review considers five aspects in the field of seismic performance of sheet pile walls: seismic lateral displacement, the effects of liquefaction, bending moments, settlements, and tilting. The research methodology depends on reviewing recent studies conducted between 2020 and 2026. The systematic literature review process was based on searching peer-reviewed articles in major scientific databases like Scopus, Web of Science, Google Scholar, and Science Direct. The results of the review indicate significant findings. The walls move toward the water side and rotate when liquefaction occurs during seismic loading. Also, anchorage can reduce the seismic effects and prevent the sheet pile from rotating during seismic loading. Excess pore water pressure increases in the backfill during the seismic loading and is greatly influenced by the interaction between the soil and the sheet pile wall. The review also showed that Cantilever sheet pile results in the highest settlement, while installing anchors to support sheet piles reduces these settlements. Moreover, double-anchored sheet piles could minimize the rotation of the sheet pile by 75%-78% compared to cantilever sheet piles. Recent studies could predict Bending Moments of sheet pile walls in seismic conditions, although these studies were based on numerical simulations without validating the predictions based on experimental findings. This study contributes to identifying the latest advances in studying the seismic behavior of sheet pile walls and discovering gaps that have not yet been taken into account in order to improve the seismic design of waterfront sheet piles.

**Keywords** - Earthquake, Seismic, Sheet piles, Performance, Quay walls.

## 1. Introduction

Waterfront sheet-pile structures are significantly utilized as retaining walls in water areas. The seismic behavior of this type of retaining structure is specifically subjected to soil liquefaction under seismic motion, which can result in high movements of both the backfill and the sheet pile itself. Waterfront sheet-piles have a benefit compared to gravity structures since they are lightweight, which results in reducing the seismic forces during seismic excitations [1].

Nevertheless, previous seismic motions, such as the Kobe earthquake that happened in 1995, and the 1983 Nihonkai Chubu earthquake in Japan [2], caused serious damage to these walls. The damage caused by these events to these structures is presented by lateral displacements that can adversely influence nearby shallow or pile footings.

Numerous research studies have been conducted to gain knowledge of the seismic behavior of waterfront sheet-pile structures in liquefied soil during seismic motion. These researchers utilized experimental works [1], 1-g shake table

experiments [3, 4], centrifuge modeling [5–7], and numerous simulations [8]. A basic aim in this research is to study seismic lateral displacement of these sheet piles placed at several water levels. Scholars and authors have addressed liquefaction using numerous techniques, such as recorded earthquake motions, synthetic shaking, and blasting. They have addressed cases where the foundation of the wall is fixed [6, 7] or floating [3–5, 8]. The findings illustrate that the lateral displacement of sheet-pile structures moves towards the water barrier, and these results were noted in both flexible [3–6] and rigid [7, 8] sheet piles.

The failure that happens due to soil liquefaction mainly takes place in cohesionless soils. To avoid this failure, numerous studies have conducted several simulations to study how sheet piles and cohesionless soil interact during seismic motion. These researchers have developed a system that assists in gaining knowledge of how weak, liquefiable soil layers influence the structure. These works have introduced significant information required to enhance ground improvement techniques [9–13]. As a result, several methods to avoid and prevent soil failure by liquefaction have been



conducted around the world, specifically in the United States and Japan [14–16]. Numerous studies have concentrated on utilizing sheet pile structures and grouting techniques to control the Excess Pore Water Pressure (EXPW), which is a major reason for liquefaction during seismic excitations.

The sheet pile structures act to prevent the flow of groundwater. This assists in controlling the water table level and stops lateral movement of soil, which leads to shear failure mitigation [17–19]. One big benefit of this method is that it can reduce both sideways ground movement and the loss of soil strength [20].

Also, sheet piles are more commonly used on flat ground, but can be applied on slopes too. For reinforcing slopes, studies show that a combined system using sheet piles along with other piles usually works better to reduce settlement and foundation damage caused by liquefaction than using sheet piles alone [21–23].

Several studies show a key gap in bending moment estimations and how Excess Pore Water Pressure (EPWP) generates [24–26]. Also, there is uncertainty about the efficiency of constitutive soil models, such as PM4Sand [27] and Manzari-Dafalias [28], to predict lateral sheet pile wall movements fairly well. Nevertheless, they have an issue in predicting bending moments accurately because of a lack of experimental data in this regard [9, 10]. Additionally, most studies addressed the sheet pile as a rigid body without considering the flexibility of sheet pile walls, in addition to neglecting to consider the soil-wall interaction influences on seismic behavior of sheet pile walls in terms of [29, 30].

Moreover, many studies depend only on numerical results with no consideration of experimental data or utilize simplified periodic loading instead of using real earthquake data records. This limits how well the results apply to real seismic events [12].

Due to the limited literature review on the latest developments in the seismic behaviour of waterfront sheet pile walls and the uncertainty surrounding progress and gaps in this field, this paper aims to cover, using a comprehensive literature review, the recent progress in evaluating how waterfront sheet pile structures perform during earthquakes. It focuses on five main areas: Seismic displacements, liquefaction, bending moments, settlements, and rotations.

This paper explores recent advances in these three fields illustrating the recent progress in these fields, gaps haven't addressed, mitigation techniques and research gaps haven't been addressed. The paper points out specific gaps that need attention—such as the missing validation for soil models and the need for bending moment measurements—to guide future research and improve seismic design standards for safe and reliable waterfront structures in earthquake zones.

## 2. Research Aim and Significance

The significance of this research is to explore recent advances in sheet pile quay walls' performance during earthquakes in liquefied soils. The aim of this research is to detect the latest developments in this field and identify the gaps and limitations that have not been studied and addressed yet. The study attempts to address five areas in seismic behavior of waterfront sheet piles: seismic movements, liquefaction phenomenon, bending moments, settlements, and rotations.

This study aims to focus on the factors and parameters that are affecting the seismic performance of sheet pile structures during seismic excitation, such as sheet pile flexibility, embedded depth, density, etc., and recent techniques to mitigate the seismic effects in sheet pile behavior in water areas. This paper review provides beneficial contributions for geotechnical researchers and Academics to serve as a base for more research in seismic design of sheet piles.

## 3. Research Methodology

The methodology of this paper utilizes a systematic literature review approach to summarize the latest progress on the seismic behavior of quay sheet pile structures. The systematic literature review process was based on searching peer-reviewed articles in major scientific databases like Scopus, Web of Science, Google Scholar, and ScienceDirect. It was concentrated on publications from 2020 to 2026 to shed light on the recent developments. The search approach utilized combinations of keywords. Major keywords included "sheet pile", "quay sheet pile", and "waterfront sheet pile". Minor keywords were "seismic behavior", "strong motion," and "seismic load." Also, other keywords comprised "liquefaction conditions" and "excess pore water pressure."

More terms were "bending moment" and "lateral movements." The search had been limited to publications such as journal articles, conference papers, and reports. Research was selected if it met these points: published between 2020 and 2026; concentrated on the seismic performance of sheet pile walls in liquefaction conditions; methods and techniques used, findings and results, mitigation measures of seismic behavior, and research gaps. It had excluded results, mitigation studies that only looked at dry or unsaturated soils without considering liquefaction, or concentrated only on static conditions. For each study reviewed, it had been collected data on experimental work details (soil type, density, seismic conditions applied, boundary conditions, sheet pile type), performance behavior (lateral displacements, excess pore water pressure ratios, bending moment) were collected.

Also, the review comprised numerical modelling and the software used, constitutive models used as PM4Sand and Manzari-Dafalias, and the seismic loading applied. The data

were grouped into five main topics matching the review’s focus: seismic displacements, liquefaction comprising excess pore water pressure generation and dissipation, bending moments, settlements, and rotations.

This approach assisted in systematically finding the latest progress and clearly determining research gaps that require future research.

### 4. Literature Review

#### 4.1. Seismic Displacements of Waterfront Sheet Pilings

In the field of investigating seismic displacements of waterfront quay walls under dynamic excitation, several studies have addressed this issue. Karkush et al. [31] used a plane-strain numerical model to examine the seismic performance of an anchored sheet pile quay wall. The main goals were to check the wall’s stability during an earthquake and to test how well adding an extra section to the structure (model 2), as illustrated in Figure 1.

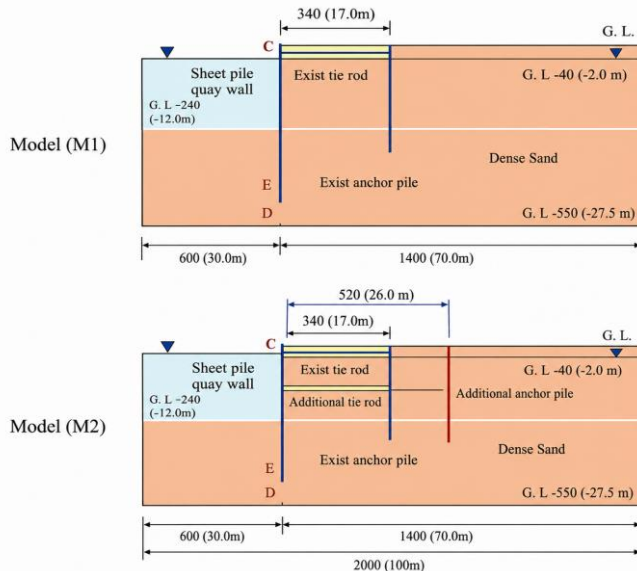
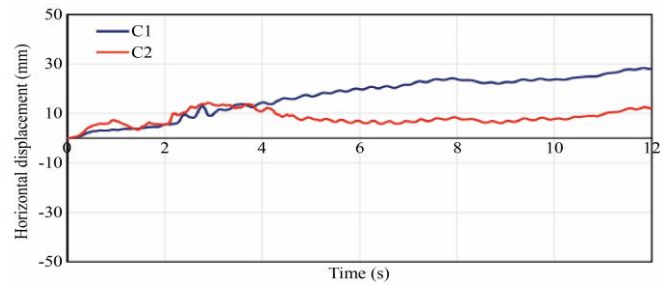


Fig. 1 Waterfront sheet pile with and without strengthening [31]

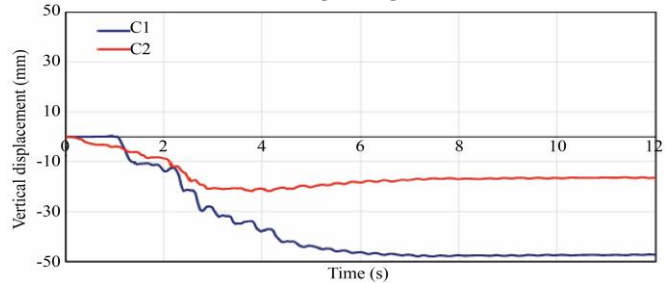
The model’s configuration was from both the foundation and backfill made of sandy soil. Using PLAXIS-2D software for energetic analysis, it obtained results like displacement and acceleration curves. The findings showed that seismic forces greatly impact the quay wall’s behavior.

The results show that using a tie rod anchor system greatly reduces the earthquake effects on sheet pile quay walls. This method cut horizontal and vertical movements caused by seismic forces by 49.5% and 46.5%, respectively, where Figure 2 shows horizontal displacement at the top point C of the sheet pile wall before and after adding an extra section, while Figure. Figure 2 shows vertical displacement at the top point C of the sheet pile wall before and after adding an extra section, in which C1 indicates displacement before strengthening and C2 indicates displacement after

strengthening. However, this study should do more earthquake tests on anchored sheet pile walls with different setups for more research in this field.



(a) Time History Horizontal Displacement before and after strengthening



(b) Time History vertical Displacement before and after strengthening  
Fig. 2 Time history seismic response of sheet pile [31]

Based on an experimental test, Korre et al. [32] addressed in their study the seismic performance of a waterfront sheet-pile structure retaining a liquefied medium-dense sand. The study required developing two identical experimental models (RPI10-2020 and RPI\_REP-2020) applying seismic excitation with 0.23 g. The model setup included a smooth, rigid aluminum sheet-pile wall embedded 0.5m into a dense sand layer ( $D_r = 90\%$ ), supporting a 4m-thick backfill of Ottawa F-65 sand ( $D_r = 65\%$ ). The model used is illustrated in Figure 3.

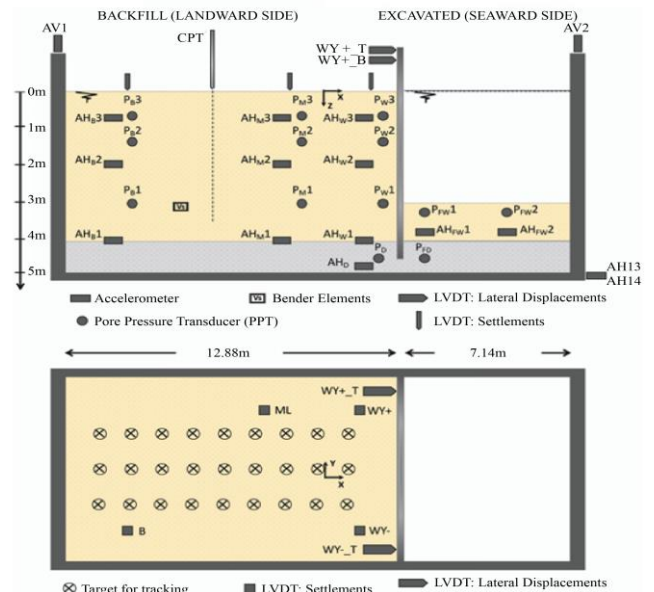


Fig. 3 Model Configuration [32]

The models were shaken with a single destructive, ramped sinusoidal motion (0.15g, 1 Hz, 5 cycles). The tools utilized comprised accelerometers, EXPW sensors, Linear Variable Differential Transformers (LVDTs), a high-speed camera, and pressure sensors on the sheet pile. The research did not vary design factors but concentrated on checking the repeatability of centrifuge tests and the interaction between soil and wall. The main findings about seismic displacement and settlement showed that the sheet-pile wall moved considerably and consistently seaward and rotated. The top of the wall shifted about 0.73m and rotated around 6.5°, causing a permanent sideways movement at the ground surface of about 0.47m, where the seismic time history lateral displacement is illustrated in Figure 4. Settlement was mostly even across the backfill surface about 0.08m, but there was much larger settlement about 0.20m right next to the wall because it moved outward.

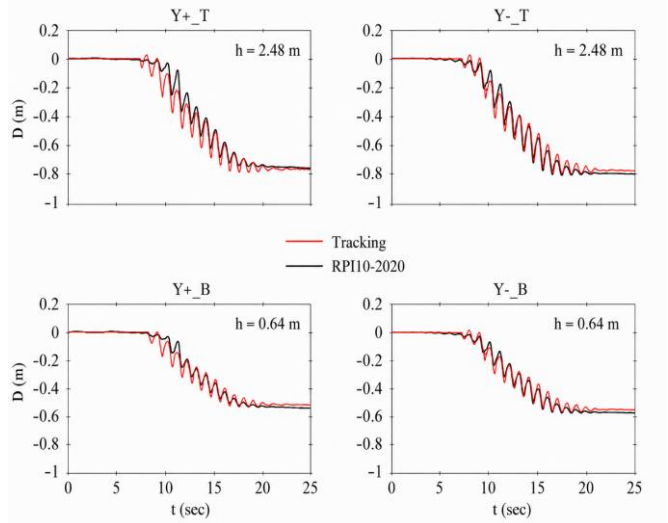


Fig. 4 Time History Lateral Displacement Based on Vertical Distance from The LVDT To the Soil Surface (H) [32]

While Korre et al. [32] addressed the interaction between soil and sheet pile wall in liquefied soil, some limitations had been noted where the study addressed only rigid walls and seismic excitation with certain acceleration; it did not detect the seismic performance of flexible anchored sheet-pile walls subjected to several seismic conditions.

Using a combined method of numerical simulation and lab testing, Libb and Manzari [33] suggested a simpler way to estimate how sheet-pile walls behave during earthquakes in liquefiable soil. They focused on lateral movement and rotation. The study used a hybrid approach: first, a Type-C Finite Element (FE) simulation was run with OpenSEES to model a specific LEAP-2022 centrifuge test (RPI1) (Figure 5). This FE model represented a rigid sheet-pile wall set in Ottawa F65 sand (Figure 5(b)), with a liquefiable backfill layer ( $D_r = 59%$ ) above a dense base layer ( $D_r = 90%$ ). The setup experienced a base shaking with a PGA of 0.254  $m/s^2$ . The FE analysis, calibrated with advanced soil models (Manzari-

Dafalias, PM4Sand), helped get the critical shear stress time-history near the wall's embedded tip. The main part of the study then moved this complex problem to a smaller scale. The stress path found was recreated in Cyclic Direct Simple Shear (CDSS) tests on sand samples prepared at the same density (about 90%) and initial stress.

The method is tested only for a single, rigid wall with a specific embedment in dense soil. It has not been checked for flexible anchored walls or walls in different soil layers (like fully liquefiable layers). The method also assumes the rotation shift point is known beforehand and that the wall moves as a rigid body, which might not apply to all wall types or severe damage. Also, the method does not cover backfill settlements, which are important for seismic performance.

Lastly, using the equivalent linear method for stress paths may reduce accuracy in cases with strong nonlinear behavior or large strains.

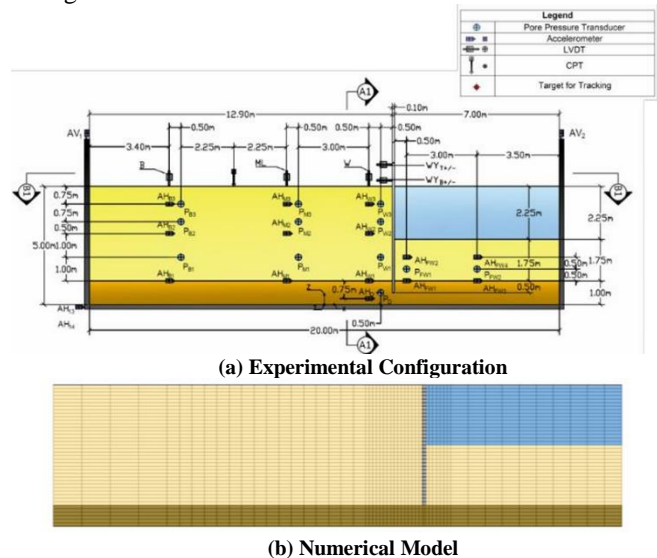


Fig. 5 Experimental and Numerical Model developed by [33]

Based on a series of 1-g shaking table model tests, Yoon et al. [34] compared how well the sheet pile method and the grouting method reduce liquefaction-induced settlement for existing structures. They built physical models at a 1:50 scale using a similitude law for strain-softening soils. The model ground was made of Jumunjin standard sand with a 150 mm thick liquefiable layer (relative density  $D_r = 45%$ ) over a non-liquefiable layer ( $D_r = 85%$ ). This supported a model two-story building. The models were shaken with a sinusoidal input motion (0.6g, 10 Hz) to cause liquefaction. A key part of the study was a parametric analysis: for the sheet pile method, the main variable was the embedded depth ratio (0.55 to 1.0), which is the pile length divided by the liquefiable layer depth.

According to the grout technique, the major parameter was the cement mixing ratio, which was varied from 0.4 to

0.55. The major result affirmed that both techniques significantly minimized vertical displacement in comparison to soil with no treatment, but they act differently. For sheet pile walls, the optimum embedded depth ratio was 0.75 to reduce settlement by approximately 79% in comparison to untreated soil. The sheet pile wall acted as a barrier, which limited the lateral movement of soil and prevented the pore water pressure from rising initially. However, it also slowed pore pressure release after liquefaction, which resulted in vertical displacement. Compared to methods, the grouting technique was generally superior at reducing vertical displacement and wall rotation. Nevertheless, the sheet pile wall was more effective at minimizing the pore water pressure during seismic excitation. The study found that the selection of the technique is based on soil conditions: sheet pile structures perform better for liquefiable soils at deep layers and high-water levels, while the grouting technique is superior for upper layers and local strengthening.

A study developed by Pakzad & Arduino [35] utilized an experimental work and numerical simulations on cyclic direct simple shear tests on Ottawa-F65 sand to simulate the Manzari-Dafalias (MD) and PM4Sand models. A 2D finite element model was created in OpenSees assuming plain-strain conditions. The model included parameters like cyclic stress ratio, initial shear stress, relative density, and motion characteristics such as PGA, Arias intensity, and number of cycles. The main findings show that both models captured general trends in wall displacement and settlement behind the wall. However, PM4Sand often overestimated displacements, while MD matched the experiments more closely, as illustrated in Figure 6. Both models had difficulties when initial shear stress was present. The study also pointed out some gaps: no modeling of changing permeability, a simple soil-structure interaction that ignores separation and impact, limited testing under high-cycle loading, and limited study of scale effects.

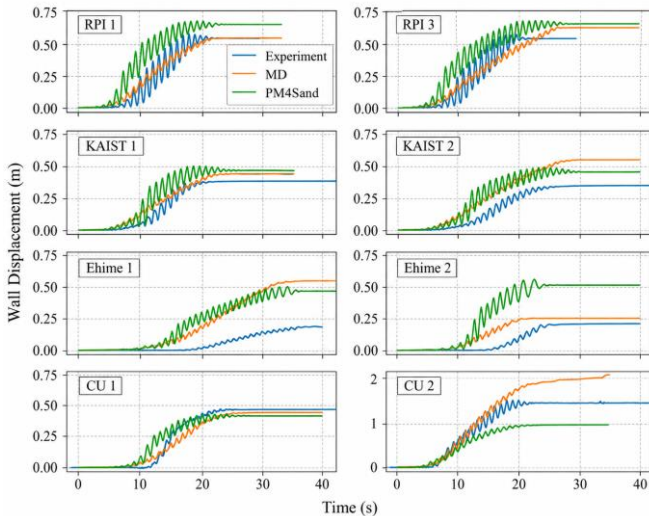


Fig. 6 Time history of wall displacement corresponds to different centrifuge tests [35]

Basu et al. [36] used the numerical software FLAC 8.0 with the PM4Sand model to simulate 11 LEAP 2020 centrifuge tests. These tests involved a sheet-pile wall holding back saturated Ottawa F-65 sand. The 2D finite difference model had a 0.5 m mesh and unbonded soil-wall interfaces. It recreated the spin-up, shaking, and post-shaking phases. Important factors studied included Relative Density (DR), which was estimated by mass-based and CPT-based methods, soil permeability (constant versus increasing during liquefaction), model setup, interface properties, mesh size, and time step. The model setup is illustrated in Figure 7.

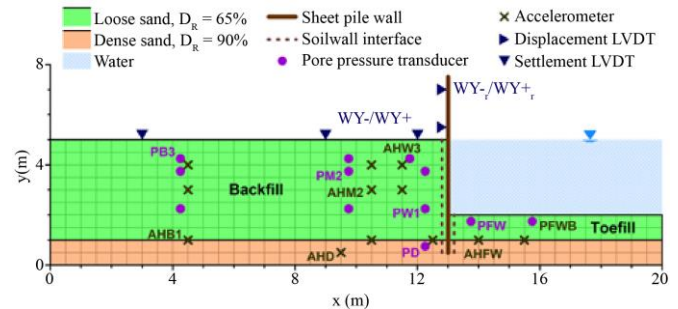


Fig. 7 Model set up [36]

The Major result was that relative density greatly affects the permanent sheet pile displacement. Some limitations in the study had been observed, such as the friction between the soil and the sheet pile. In addition, there is a limitation in addressing the high-frequency seismic excitation and the lack of use of real earthquake data records.

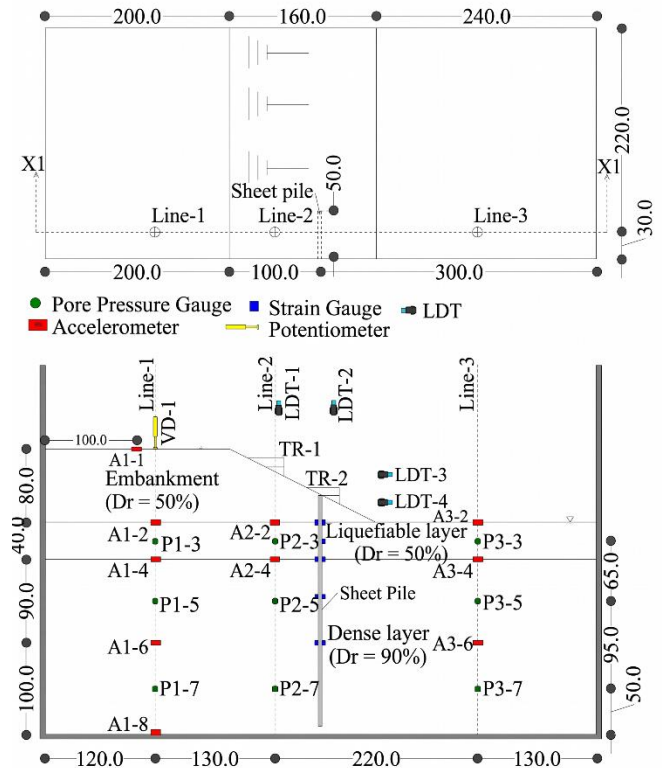


Fig. 8 Model Installation by [37]

Research by Saha et al. [37] utilized a series of centrifuge experiments at an acceleration of 0.5g to test the efficiency of sheet pile structures to minimize lateral spreading of liquefaction beneath embankments. The model illustrated in Figure 8 had a loose, liquefiable Toyoura sand layer on top of a dense sand layer, supporting a sloped embankment. The main factors studied were the thickness of the liquefiable layer (4 m and 8 m) and the width of the sheet pile (full width versus a limited 5 m width).

The research showed that installing sheet piles reduced lateral soil movement by 30–50% nearby. This worked similarly well for both thin and thick liquefiable soil layers.

Despite these findings, the study left out some important factors. These included the effects of the period of earthquakes and recording vertical displacement after liquefaction.

Sahare & Ueda [38] used a centrifuge experimental work utilizing a rigid box with a polymethyl methacrylate window, executing experiments on a cantilever sheet pile retaining structure wall retaining backfill from Ottawa F-65 sand soil.

The prototype was equipped with accelerometers, pore pressure transformers, laser sensors, strain gauges, and a high-speed camera to analyze the images, adopting the DIPP-MOTION program and MATLAB-based Biharmonic spline interpolation. The ground motion period lasted 20 seconds.

Sahare & Ueda [38] noted that excessive suction drops happened during sheet pile movement toward the backfill, but temporary release of these suction drops during the sheet pile rotation toward the seaside resulted in large soil softening and plasticization, leading to significant cumulation of lateral seismic displacements. The authors had not considered several aspects: inserting the sheet pile into different embedment depths. Additionally, there is a limitation in using real earthquake data records, as the study is based on a simple sinusoidal load. Moreover, the study had not addressed investigating the role of anchors to resist the seismic influences or the effect of the flexibility of the sheet pile on deformation mechanisms.

Mercado et al. [39] adopted a pressure-dependent multi-surface plasticity model (PDMY02) in OpenSees software to model 13 prototype-scale centrifuge experiments from the LEAP-2022 project. These experiments had been conducted at Cambridge University (CU), Ehime University (EU), KAIST, and Rensselaer Polytechnic Institute (RPI). The study procedures included: validating parameters of the model utilizing undrained cyclic triaxial test and cyclic direct shear test conducted on sandy soil with Relative Densities (DR) range from (55 -90) %, and numerical simulation with limit parameter modification after comparing the numerical results with the testing findings.

The numerical model used plane-strain, adopting a finite element type for soil (four-node quadrilateral element) while using an elastic beam element type for the sheet pile wall. A perfectly plastic material had been used for tangential interaction between the backfill and the sheet pile with a friction angle of 32°. The seismic lateral displacements using numerical modeling adopting OpenSees showed overestimation of sheet pile lateral movements in all tests conducted on saturated sand. Differences in lateral displacement predictions between experimental and numerical results varied from 31.4% for the CU testing to 169.7% for the RPI-1 tests. For instance, the RPI-1 tests predicted a displacement value of 0.475 m while the simulation estimation was 1.281 m. The EU-1 test gave a displacement value of 0.184 m, but the prediction was 0.735 with a difference of up to 298.6%. Nevertheless, the dry experimental tests (KAIST-3) illustrated extremely slight differences. This indicates that water and soil-sheet pile interaction subjected to liquefaction conditions basically lead to the overestimation, and to deal with these issues and to solve the problems in differences between experimental and numerical results, parameters of the liquefaction model in simulation have been controlled to fit the experimental findings. Despite significant efforts in addressing the seismic behavior of sheet pile in liquefaction conditions, the study did not look at how different sheet pile embedment depths or wall flexibilities change displacement patterns; there was no investigation of using anchors to enhance the seismic behavior of sheet piles or other strengthening techniques.

Hung et al. [40] executed numerous centrifuge experimental tests utilizing a beam-type centrifuge with a 3m platform radius and a maximum capacity of 100g-ton. The prototype was developed utilizing the pluviation technique with fine quartz sand ( $D_r=70\%$ ). These emulated sheet pile models of PZ 40 double kind. Four test configurations were executed: cantilever sheet pile, single anchor sheet pile, and double-anchor sheet pile. These models were subjected to seismic loading at 1Hz with 15 cycles and maximum accelerations applied at the base of the model of 0.16g, 0.33g, and 0.45g. The cantilever sheet pile illustrated a highest seismic lateral movement of 0.60m subjected to seismic acceleration 0.16g, and according to PIANC code [41], it can be said that the wall has failed according to the estimated seismic displacement value. The single-anchored sheet pile wall exposed seismic lateral displacement up to 0.23m, 1.70m, and 1.09m when subjected to ground motion with maximum accelerations of 0.16g, 0.33g, and 0.45g, respectively, and based on the PIANC code [41], the single-anchored wall failed at an acceleration value of 0.33g while the seismic performance of the double-anchored sheet pile was extremely good. This model configuration showed the least seismic lateral displacement values 0.04m, 0.48m, and 0.11m when exposing the model to different seismic acceleration value. Numerous significant points were not considered: the study was based on testing sandy soil with a relative density 70%,

so the impacts of relative density values on seismic lateral movement remain unknown. Also, the study did not address the effect of embedment depth ratios or sheet pile flexibilities, the effect of water level variation behind and in front of the sheet pile. Also, the study requires conducting numerical modelling to test soil models in the presence of water behind and in front of the wall, and considering liquefaction using advanced constitutive models such as PM4Sand and SANISAND-MSF.

Nguyen et al. [42] used the finite element technique with PLAXIS 2D software to investigate the seismic displacement of the waterfront sheet pile after improvement using soil reinforcement with Cement Deep Mixing (CDM). The numerical simulation comprised 15-node triangular plane strain elements. The backfill was modeled in liquefaction conditions using the UBC3D-PLM model, which is utilized to study liquefaction behavior. The authors adopted the use of real earthquake records. Results related to seismic displacement showed that the sheet pile achieved the highest horizontal displacement of 22.78 cm with no improvement using cement deep mixing. However, the quay sheet pile improved by cement soil mixing reduced the lateral movement to 17.17 cm. The parametric study illustrated that increasing the surface area of soil strengthened by CDM led to a reduction in the seismic lateral displacement from 22.78 to 17.17 cm.

Although this study addressed improving the sheet pile performance in seismic conditions, the research neglected validating the results with experimental tests.

Abuo Zenab et al. [43] carried out a study addressing how a rigid waterfront wall responds when a dense sand layer is retained. Abuo Zenab et al. [43] utilized the finite element method using PLAXIS 2D to simulate the model. The UBC3D-PLM constitutive model was used to simulate liquefaction conditions in the backfill. The study addressed the impact of ground motion amplitude increment on the seismic performance of the sheet pile by measuring lateral displacements. The findings demonstrate that increasing ground motion amplitudes results in increasing horizontal displacement of the sheet pile because of soil–sheet pile interaction.

The study conducted by Zeng and Taiebat [44] illustrated that the seismic lateral displacement of sheet-pile wall during strong ground motion in liquefiable cohesionless soil is affected by the seismic two different kinds of cyclic deformation—cyclic motion and residual deformation accumulation. The way these two behaviors spread and dominate is based significantly on the embedment depth of the sheet pile wall. Zeng and Taiebat [44] utilized the SANISAND-MSF model, which was modified utilizing 65 CDSS tests and investigated with 16 LEAP centrifuge experiments. The authors introduced an innovative measure

named the cumulative average shear modulus. This measure considers a credible stiffness-based indicator that isolates the two systems. Cumulative average shear modulus values that are close to zero refer to cyclic motion, while higher values that are higher than 2 MPa point to residual deformation development. A main result is that the lateral movement at the upper sheet-pile structure levels off when the embedment ratio reduces to a value less than 0.67. However, the study has some gaps: it did not cover anchored sheet pile walls often used in ports, and it used only smooth sinusoidal motions instead of real earthquake data. Despite these limitations, the research offers valuable insights for design based on performance.

#### 4.2. Liquefaction Phenomenon

Research by Saha et al. [37] showed that sheet pile structures mitigate lateral displacement by 30–50%, but their impact on reducing vertical displacement was limited. This indicated that vertical displacement mainly happened because of compaction due to seismic loading. Significant gaps in their work comprised the impacts of cyclic degradation during strong seismic motion. However, Pakzad & Arduino [35] conducted a comparison between numerical findings using advanced soil models, such as the Manzari–Dafalias (MD) and PM4Sand, with experimental data. Both methods showed disagreement in the predictions of EPWP with experimental results. Nevertheless, MD often predicts pore pressure values higher than the experimental results and gives shear strain values lower than the experimental tests, whereas PM4Sand had issues with cases involving initial static shear stresses.

A Main result was that the models could not precisely estimate soil behavior under high initial shear stress. This indicates a main validation gap for excess pore pressure behavior during seismic loading. They also found that increasing cycling loading resulted in wrong predictions, showing a limitation in simulating cyclic degradation. To address this issue, Ning et al. [45] proposed a modified pseudo-static way that comprises an equivalent number of cycles and EPWP variations to predict the stability of the sheet pile wall. Their experimental tests illustrated that wall rotation initiated early during seismic loading and showed the formation of excess pore water pressure. Nevertheless, their approach addressed sheet pile behavior only at failure without considering the previous stages.

Korre et al. [32] provided an experimental work that addresses the behavior of the water front sheet-pile quay wall during seismic loading in liquefied sand. It concentrated on (EPWP) variations during an earthquake in liquefied soil. The findings illustrate that liquefaction basically happened in the backfill soil, where the excess pore water pressure ratio,  $r_u$  up to 1.0 as illustrated in Figure 9, which indicates full liquefaction, indicating that soil liquefaction happens during seismic excitation.

However, local zones beside the sheet-pile structure illustrated strong dilative behavior. It was shown that a rise in negative EPWP resulted from the interaction between soil and sheet pile when the sheet pile rotated outward. This fluctuation in excess pore pressure behavior affirms the importance of considering the interaction between soil and structure in either minimizing or increasing liquefaction impacts, besides rigid sheet pile structures. On the other hand, the research by Korre et al. [32] did not detect long-term influences of liquefaction after earthquake, such as sheet pile stability and the loss of soil resistance with time. These issues are significant for seismic design. Additionally, while the research utilized tactile sensors and high-quality cameras well to study the interaction between soil and sheet pile, there is a need to verify the findings using numerical simulations using Finite element methods and advanced software to validate the observed EPWP, settlement, and lateral displacements. This would help to enhance predictions of seismic sheet pile performance in liquefied soil.

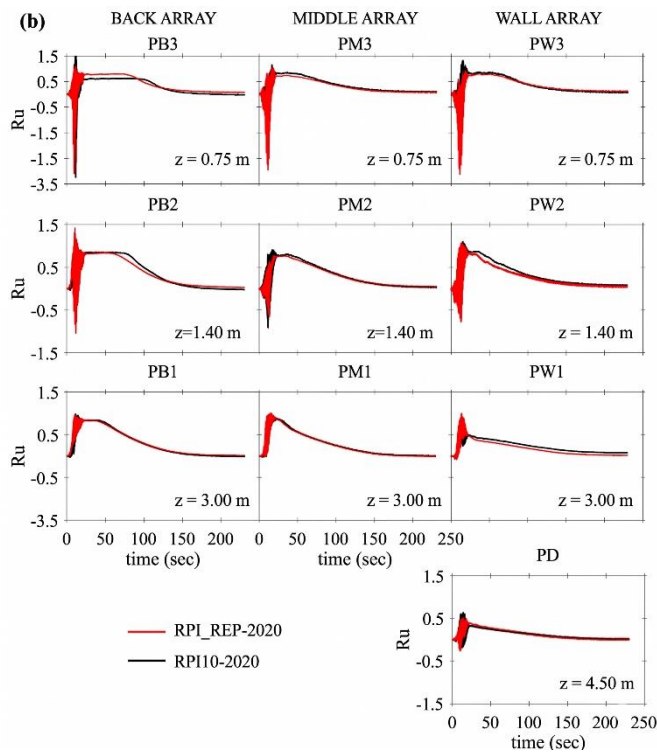


Fig. 9 Excess pore water pressure ratio [32]

According to the Research by Ning et al. [45], the seismic behavior of sheet-pile structures in liquefied soils is evaluated utilizing a modified pseudo-static method. This approach comprises the influences of (EPWP) within the limit equilibrium method. Ning et al. [45] proposed an analytical approach that integrates the Conti–Viggiani (C–V) [47] earth pressure distribution with a model for EPWP build-up. They utilize an equivalent number of cycles to transfer irregular periodic loads into a uniform periodic stress. Centrifuge tests illustrate that the generation of excess pore pressure in the backfill results in sheet pile rotation and consequently results

in an unstable sheet pile wall. Failure happens within the first few major loading cycles. The measured bending moments match well with the predictions from the proposed method.

This is especially true in showing how the maximum bending moment moves downward as passive pressure grows and EPWP rises. However, there is a gap in studying soil–sheet pile movement, which is not sufficiently addressed.

While this study provided a beneficial contribution to the seismic performance of sheet piles, it only addressed the initial failure. It had not been studied what occurs after shaking in liquefied soil, such as reconsolidation, deformation, or the displacement accumulated during cyclic loading. These factors are significant to study modern displacement-based design standards in the seismic design of waterfront sheet piles.

In the experimental study by Yoon et al. [34], the effectiveness of sheet-pile and grouting methods in reducing liquefaction damage is tested using 1-g shaking table experiments on a two-story building model. The results show that both methods greatly lower structural settlement compared to untreated ground. The grouting method reduces settlement by 85%, which is better than the sheet-pile method's 79% reduction. Nevertheless, the behavior of excess pore water pressure significantly differs between the two approaches. The sheet-pile technique reduces EPWP rise at the initial onset of seismic motion but works on slowing down EPWP dissipation after soil liquefaction, leading to increasing EPWP, which results in settlements. However, grouting leads to an increase in generating EPWP but assists in dissipating faster, probably because of better permeability and no hydraulic barrier.

A main limitation of the study is that pore pressure and deformation are not analyzed together. While vertical displacement and excess pore water pressure are observed separately, the correlation between excess pore water pressure and settlement has not been highlighted. Also, effective earth pressure variations in addition to soil-sheet pile movement are not addressed. Moreover, the experimental tests utilized simple cyclic loading and did not address real earthquake data records.

Sahare & Ueda [38] studied using a centrifuge test generating excess pore pressure in the backfill retained by a cantilever sheet pile wall. During the first stage of the seismic load, positive excess pore pressure developed in the sand; the backfill was negligible, with an EXWP ratio of less than 1.0, and consequently, the liquefaction in the backfill had not occurred. During the second stage of the seismic excitation, excessive negative excess pore pressures were generated at the sandy soil near the sheet pile during translation of the sheet pile wall toward the backfill. During the third stage of the seismic loading, the sheet pile became stable as the soil in the

passive zone in front of the sheet pile began regaining shear strength while reducing excess pore water pressure. It was noted that a significant gap was not considered: the lack of using real earthquake data records, and the effect of water level variation on excess pore water pressure generation. Additionally, it is necessary to conduct calibration to compare the excess pore water pressure generated while utilizing the centrifuge test with the numerical simulation adopting constitutive models such as PM4Sand or Manzari-Dafalias.

Zeng et al. [46] used a detailed numerical simulation method with the SANISAND-MSF plasticity model in OpenSees Software. The authors validated the simulation utilizing 56 Cyclic Direct Simple Shear (CDSS) experiments on Ottawa F-65 sand. The models had been simulated using the finite element method, adopting Two-dimensional plane-strain to simulate 13 prototype-scale centrifuge experiments from the LEAP-2022 project. These experiments comprised 8 saturated and 5 dry sandy soils. The input cyclic waves were controlled at 1 Hz with 5-10 cycles. The numerical modelling illustrated that all saturated centrifuge tests subjected to extensive cyclic liquefaction early during the cycling loading.

Numerous significant gaps have been noted. The simulation showed fast and widespread liquefaction in the backfill, while experiments predicted late and restricted liquefaction. To deal with this, the liquefaction parameters of the model had been controlled and mitigated. Also, the semi-fluidized state model overestimated post-liquefaction shear strains and sheet pile displacements, illustrating that the model lacks a technique to control post-liquefaction shear strains based on relative density immediately. Third, the authors did not consider that different wall embedment depths, wall flexibilities, or anchored versus cantilevered setups affect EPWP patterns. Fourth, actual earthquake data records had not been used. Lastly, the study did not compare the simulated EPWP patterns with other experimental data beyond LEAP-2022, nor did it compare the SANISAND-MSF model to other constitutive models like PM4Sand or PDMY03 for the same problems.

Mercado et al. [39] addressed Excess Pore Water Pressure (EPWP) development in the backfill behind the sheet pile, the PDMY02 model was validated and controlled utilizing contractive parameters and dilative parameters via comparing the results with numerical models to emulate (EPWP) behavior from undrained cyclic triaxial and experiments. The findings illustrated that the generation rate of EPWP was well observed by the numerical results via most sensors provided by experimental work. The agreements were satisfied at the lower and upper horizontal arrays of pore pressure transformers. Nevertheless, some errors appeared at the sensors beside the wall. Mercado et al. [39] explain these differences because of the lack of the model's ability to simulate drainage conditions at the soil-sheet pile interface accurately. Additionally, some numerical models illustrated

robust negative EPWP spikes not noted in centrifuge testing, particularly beside the bottom of the deposit. This indicated the simulation overestimated dilative behavior at low confining pressures. Mercado et al. [39] noticed that the multi-yield surface model causes swift dissipation and low post-liquefaction vertical displacements, and the low bulk modulus method assisted in dealing with this problem. Although the authors indicated that the model predicted much sharper liquefaction resistance curves than tests, this means numerical modeling was not sensitive enough to the cyclic stress ratio. For higher CSR levels, predictions needed more cycles to reach large deformations than experiments, while for lower CSR, estimations achieved large deformations with fewer cycles. The authors did not look at how different soil permeabilities influence EPWP dissipation ratios. The authors did not check how changing water table levels influences EPWP development. Lastly, the research did not conduct a comparison between the PDMY02 model performance with other constitutive models (like PM4Sand, SANISAND-MSF) for the same boundary value problems, leaving uncertainty about the models' relative strengths.

Nguyen et al. [42] calculated the excess pore water pressure ratio ( $r_u$ ) utilizing the UBC3D-PLM constitutive model to simulate liquefaction conditions in the backfill layer during cycling loading. The distribution of excess pore pressure had been studied at different times of the earthquake time history by calculating  $r_u$  for both quay sheet pile with and without CDM reinforcement. The findings showed that liquefaction basically happened far from the sheet pile structure and not directly behind the sheet pile, since the lateral movements of the wall toward the water barrier increased pore volume in the sand beside the wall, which prohibited EPWP from increasing. The surface of the soil was more likely to liquefy than deeper soil, in which the  $r_u$  up to 1.0, which means fully liquefaction near the soil surface in both cases. The EPWP around the anchor increased significantly due to the movement of these anchors during cyclic loading. The CDM technique increased the excess pore water pressure in the sand beside the sheet pile compared to the sheet pile with no CDM reinforcement, in which  $r_u$  reached 0.6 with CDM against a minimal increase with no CDM technique. This happened since the CDM technique led to a reduction in sheet pile displacement, which means lower pore volume increase beside the sheet pile, allowing EPWP to generate faster. The authors inferred that while the CDM technique has no benefit in minimizing, it actually increases the liquefaction potential in the soil directly behind the sheet pile.

#### **4.3. Bending Moment of waterfront Sheet pilings**

A study by Ning et al. [45] estimated d bending moment of sheet pile wall in liquefied soils during seismic loading, addressing some of the gaps of previous research. Analytical methods, such as the Mononobe-Okabe (M-O) and the Conti and Viggiani (C-V) approaches [47], had been formulated for

dry or cohesionless soils and ignored consideration of the pore water pressure generation, which can increase in cohesionless soil during seismic motion [47, 48]. Also, while some centrifuge studies looked at how soil and structures interact in wet conditions [49, 50], few concentrated on the internal forces, such as the Bending Moment estimation of sheet pile wall structures during seismic motion. Ning et al. [45] address this by suggesting a changed pseudo-static stability method that includes the excess pore pressure ratio ( $r_u$ ) and uses the equivalent number of cycles idea to turn irregular cyclic loading into regular cyclic loading. This helps calculate how bending moments change from normal conditions to failure, which was missing in earlier design methods. Their centrifuge tests confirmed the method works. They showed bending moments nearly doubled at failure from about 10 kN·m/m to about 20 kN·m/m, and the spot of highest bending moment moved down as  $r_u$  grew a detail that older methods missed.

The research also illustrated that water pressure in front of the wall reduced the Bending Moment approximately 7.7%, a detail often ignored in simple design rules. By combining pore pressure changes with mechanical balance, this research offers a better way to check sheet pile wall stability in coastal areas where liquefaction can happen. This helps meet the design needs based on actual performance during earthquakes and liquefaction.

Also, a numerical study by Basu et al. [36] offers useful insights into simulating bending moments in sheet-pile walls during seismic liquefaction. It takes into account the limitations of numerical and experimental studies. Numerous previous studies concentrated on movement and excess pore pressure behavior, but the study ignores predictions of bending moments because of gaps in experimental test data in studies [50, 51]. The study [37] dealt with this issue by numerical simulation, adopting FLAC, and the soil liquefaction was simulated using the PM4Sand model and estimated bending moments and shear forces in the sheet-pile structure during seismic motion, but these estimations could not be validated because no bending moment estimations were available from experimental data. On the other hand, the research illustrated that mesh size significantly impacted bending moment estimations.

Hung et al. [40] conducted an experimental study to estimate the bending moment along the sheet pile wall length using a strain gauge record connected to the sheet pile at several elevations, and the measurements were recorded every 5 seconds during cycling loading. The cantilever sheet pile achieved a maximum bending moment of 95.84 kN·m/m, while the single-anchored sheet pile exhibited greater bending moments compared to the cantilever type, with a maximum value of up to 169.23 kN·m/m during the seismic motion. It was inferred that the double-anchored sheet pile minimized the bending moment by 50% compared to the cantilever sheet pile, whereas the single-anchored sheet pile resulted in

bending moments almost twice those of the double-anchored sheet pile and cantilever sheet pile.

Nguyen et al. [42] studied the bending moment estimation along the sheet pile that was predicted using numerical modelling utilizing the finite element method, adopting PLAXIS 2D. The findings present a comparative study of quay sheet pile with and without CDM reinforcement during the real earthquake data record. The analysis illustrated that the sheet pile without CDM reinforcement achieved the highest positive and negative bending moments of 1,102.53 kNm and 615.62 kNm, respectively.

However, the sheet pile improved using the CDM technique significantly minimized both positive and negative bending moments to 986.73 kNm and 302.72 kNm. This presents approximately a 10% reduction in positive moment and a 51% reduction in negative moment. The parametric study illustrated that increasing the CDM surface area reduced the bending moment values. Although there have been great efforts to estimate bending moment along the sheet pile wall, there is a limitation to validate these bending moment estimations of the sheet pile with experimental testing, such as a centrifuge test.

#### **4.4. Rotational Response of Sheet Pile Walls**

Rotation of sheet pile structures is a significant failure patterns that impact the seismic behaviour and serviceability of waterfront sheet pile structures. Seismic rotation is generated during the seismic loading and directly impacts the strength of the sheet pile and the stabilization of the backfill.

Experimental tests and numerical studies have illustrated that sheet pile structures rotate toward the seaside during seismic loading. It was noted that there was a lack of and limitations in studies addressing the tilting and rotation as a failure mode of sheet pile quay walls, which requires more research efforts in this failure mode of seismic behaviour of sheet pile walls. It was noted that there was a lack of and limitations in studies addressing the tilting and rotation as a failure mode of sheet pile quay walls, which requires more research efforts in this failure mode of seismic behaviour of sheet pile walls. Korre et al. [32] illustrated that rigid sheet pile structures rotate towards the excavated side by approximately 6.5° when subjected to seismic acceleration of 0.15g. Hung et al. [40] studied reducing the seismic tilting of sheet pile quay walls using double-anchored sheet piles, which could minimize the rotation of the sheet pile by 75-78% compared to cantilever sheet piles.

The Key gaps in studies reviewed are that there are no standard rotation measurements; there are no efforts on sheet pile flexibility impacts; there is no research on using, and no analytical approaches or empirical formula to predict rotation. Future research efforts should emphasize making standard metrics, addressing flexible sheet piles, and investigating anchor effects.

#### 4.5. Settlements of Sheet Pile Walls

The settlement of sheet pile structures and the backfill soil behind the wall is one of the most significant criteria to check how the sheet pile quay wall behaves during seismic motion.

Numerous tests and numerical studies have investigated how sheet pile structures settle due to earthquakes. Korre et al. [32] executed centrifuge experiments on a rigid waterfront sheet pile structure that retains medium-dense sand in liquefaction conditions. They utilized cyclic motion with a peak acceleration of 0.15g. Their findings illustrated that vertical displacements were mostly even across the surface of the backfill soil, approximately 0.08m in prototype scale.

However, settlement in the backfill directly behind the wall was approximately 0.20m, since the sheet pile moved toward the seaside. The research illustrated that approximately 78% of the total settlement occurred during the cyclic loading, and the rest occurred after seismic loading during reconsolidation. Korre et al. [32] indicated that the sheet pile assisted in slowing down the quick rise in pore water pressure early during seismic loading, but made the pressure take longer to go away after liquefaction. This could result in more vertical displacements later. Likewise, Hung et al. [40] carried out centrifuge testing on an anchorage sheet pile structure with different anchor configurations. They illustrated that sheet pile without anchors achieved the highest settlements, approximately 0.33m. However, sheet pile with single or double anchors reduced the settlements.

Yoon et al. [34] ran 1-g shaking table experiments in order to compare sheet pile and grouting techniques to minimize liquefaction damage. They illustrated that the sheet pile technique with an optimum embedment depth ratio of 0.75 minimized the vertical displacements by approximately 79%, reducing them from 162mm to 33mm. However, grouting performed better, minimizing vertical displacements by 85% with a cement mixing ratio of 0.45.

Saah et al. [37] addressed how sheet pile structures minimized liquefaction-induced lateral movement under embankments utilizing centrifuge testing with liquefiable strata. They illustrated that sheet piles reduce lateral displacement by 30-50% beside the sheet piles, but did not significantly minimize vertical displacement of the embankment. This illustrates a main restriction of sheet pile support, which is considered effective to reduce lateral movement; they don't prevent the backfill from getting denser and settling vertically after seismic loading.

Basu et al. [36] addressed the effects of relative density estimation on vertical displacements of sheet pile structures. The study also demonstrated that settlements that occur before applying seismic load during centrifuge operation were greatly influenced by how the model was constructed.

Although several studies have been conducted to estimate settlements, there are still significant gaps. It was noted that a main conflict among the studies reviewed was about the efficiency of sheet piles to minimize settlement. Yoon et al. [34] illustrated clearly that sheet piles prevent drainage after liquefaction, which can result in minor settlement.

However, other researchers either neglect this or do not address its long-term impacts. The dissipation of pore water pressure is slow, and the settlement that is linked to reconsolidation is rarely observed beyond the first second after cyclic loading. Consequently, there is an obvious question about how much vertical displacement accumulates after cyclic loading because of reconsolidation.

Pakzad and Arduino [35] also indicated that constitutive models, such as PM4Sand and Manzari-Dafalias, cannot precisely estimate findings when there is initial shear stress in the backfill soil. Additionally, the differences in settlement estimations increase with increasing cycles since the models do not deal with cyclic degradation well.

## 5. Results and Discussion

According to the displacement of sheet pile walls in seismic conditions, the studies reviewed in this research illustrated that sheet-pile quay structures move significantly toward the water barrier during seismic excitation in soil that is liquefied, regardless of the flexibility of the wall. Karkush et al. [31] showed that anchored sheet piles could mitigate seismic lateral displacements and settlements of sheet piles by about 49.5% and 46.5%, respectively.

This confirms the efficiency of anchors to reduce seismic effects. However, their study was based only on numerical models and was not tested under different seismic conditions. Korre et al. [32] introduced strong experimental data from centrifuge models. The data obtained is a movement of 0.73 m at a point located at the top of the wall toward the sea and a rotation of 6.5°.

Vertical displacements increased beside the sheet pile because of this movement away from the backfill. Their experimental tests concentrated only on one rigid wall design and certain seismic conditions. Their study ignored the behavior of walls under different seismic accelerations.

Libb and Manzari [33] estimated seismic displacements accurately but proposed that the sheet pile rotates as a rigid wall around a known point; these findings may not be achieved for flexible or seriously damaged sheet piles. In general, these studies show that displacement and settlements are accurately predicted for specific cases, but there is a need for more efforts to conduct more research considering wall flexibility, embedment depth, anchor type, and real seismic records. The paper reviewed showed significant points of

bending moment estimation for structural design. Ning et al. [45] provided a significant contribution by proposing a modified pseudo-static technique that comprises EPWP and an equivalent number of cycles.

Their experimental tests illustrated that bending moments approximately double at failure, from 10 to about 20 kN·m/m. Additionally, they noted that the point location of the maximum bending moment value moved downward by increasing pore pressure.

This behavior cannot be captured by traditional analytical solutions, such as Mononobe-Okabe. They also recorded a 7.7% reduction in bending moment as a result of hydrodynamic pressure in front of the sheet pile, which is neglected in seismic design. Basu et al. [36] supported this finding with a numerical simulation study, illustrating that bending moments and shear forces can be estimated by numerical simulations, but the predictions were sensitive to the mesh size in the finite element method.

Saha et al. [37] showed that the cyclic loads are responsible for generating (20–40) % of the total internal forces during seismic excitation. This emphasizes that pseudo-static methods, such as Mononobe-Okabe, that neglect periodic loading, can't provide reliable predictions. A popular theme in this research is the lack of experimental validation of bending moment values. Most experimental tests do not estimate bending moments, so they are based on predictions by numerical methods.

One of the most significant results from studies reviewed is that EPWP changes across several locations and is greatly related to soil-structure interaction. Saha et al. [37] and Korre et al. [32] noted that full soil liquefaction, which  $r_u$  is 1 usually occurs in the backfill during seismic loading. Meanwhile, soil beside a rigid sheet pile illustrates dilative behavior with negative EPWP spikes during outward rotation.

This illustrates that soil-wall interaction can either decrease or increase soil liquefaction locally, which is almost ignored in standard free-field liquefaction research. Yoon et al. [34] compared several reduction techniques and illustrated that sheet pile structures mitigate the initial increase in excess pore pressure and also reduce its later dissipation, which can lead to settlements.

Nevertheless, a major issue noted by Pakzad & Arduino [35] and Ning et al. [45] is that advanced soil models such as PM4Sand and Manzari-Dafalias do not precisely predict soil response subjected to high initial static shear stress. These soil models are in disagreement with experimental estimation validation trouble, along with using cyclic motions instead of real seismic excitation data records, which limits how well numerical simulations can predict soil behavior subjected to seismic loads.

Regarding the settlement failure mode of sheet piling, the reviewed research affirms that sheet pile structures are exposed to significant settlements during cyclic loading. Korre et al. [32] illustrated that approximately 78% of vertical displacement occurs during an earthquake. Hung et al. [40] found that cantilever sheet pile results in the highest settlement, while installing anchors to support sheet piles reduces these settlements.

Interestingly, Yoon et al. [34] found that sheet pile structures with an optimum embedment depth ratio of 0.75 reduced settlements by 79%, but this ratio should be investigated. Saha et al. [37] indicated a key limitation of sheet pile reinforcement is that while sheet pile structures minimize lateral displacement by 30-50%, they do not significantly minimize vertical displacement in thin liquefiable strata. This is due to vertical displacement mainly coming from seismic compaction, not lateral movement.

Basu et al. [36] added that the constitutive soil models utilized in numerical simulations, such as PM4Sand and Manzari-Dafalias, are mostly calibrated with simple shear tests concentrating on shear strain accumulation. These tests pay less attention to volume compression; therefore, settlement estimations differ more than lateral displacement estimations.

About the tilting mode of sheet piling in seismic conditions, reviewed studies affirmed that rotation toward the seaside is a major failure mode during seismic liquefaction. Korre et al. [32] illustrated that rigid sheet pile structures rotate towards the excavated side by approximately  $6.5^\circ$  when subjected to seismic acceleration of 0.15g.

Hung et al. [40] studied reducing the seismic rotation of sheet pile quay walls using double-anchored sheet piles, which could minimize rotation of the sheet pile by 75-78% compared to cantilever sheet piles.

Although recent advances in addressing the seismic performance of sheet pile quay walls, main knowledge gaps remain. There is no standard method to measure failure modes of sheet piles across the studies reviewed; sheet pile flexibility impacts on seismic performance are not studied, and there are no validated analytical methods for seismic behavior prediction.

Figure 10 illustrates the scope of coverage of topics related to the seismic behavior of sheet pile walls, which was reviewed through recent studies between 2020 and 2026. Figure 10 shows that the largest number of published research papers on the seismic behavior of sheet pile quay walls in ports address lateral displacement, followed by liquefaction. Fewer studies examine the distribution of bending moments along the sheet pile and subsidence, while studies addressing sheet pile quay walls' tilting are limited.

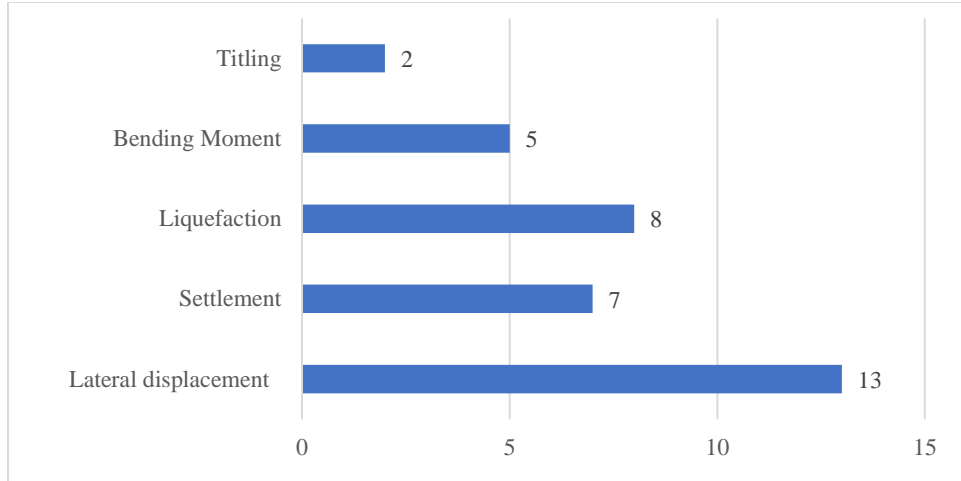


Fig. 10 Number of Studies Covering Modes of Seismic Behavior of Sheet Pile Walls

Table 1 summarizes the recent advances and the knowledge gaps in the field of seismic performance of sheet pile quay walls. Table 1 could be a basis for future research in this field.

Table 1. Recent Advances and Knowledge Gaps in the Field of Seismic Performance of Sheet Pile Quay Walls

Seismic Behavior	Recent Advances	Knowledge Gaps	References
<b>Lateral Displacement, Settlements, and Rotations</b>	<ul style="list-style-type: none"> <li>• Double-anchored sheet piles placed close together minimize lateral shift by 91% compared to cantilever sheet piles.</li> <li>• Strengthening sheet piles using CDM minimizes the lateral shift by approximately 25%</li> <li>• Cantilever sheet pile results in the highest settlement, while installing anchors to support sheet piles reduces these settlements.</li> <li>• Double-anchored sheet piles could minimize the rotation of the sheet pile by 75-78% compared to cantilever sheet piles.</li> </ul>	<ul style="list-style-type: none"> <li>• The impact of sheet pile flexibility on lateral shift.</li> <li>• Lack of experimental tests to be calibrated with numerical simulations to validate lateral displacement results.</li> <li>• Lack of using real data of earthquake time history to predict seismic displacement.</li> <li>• Lack of investigation of several parameters related to anchorage sheet pilings, such as anchor spacing, anchor length, and anchor rigidity</li> </ul>	[31-43].
<b>Bending Moment</b>	<ul style="list-style-type: none"> <li>• Developing a modified pseudo-static method including the excess pore pressure ratio (<math>r_u</math>) and an equivalent number of cycles.</li> <li>• Traditional methods like Mononobe-Okabe do not capture this behavior.</li> <li>• The hydrodynamic water pressure reduces the bending moment of sheet pile walls by approximately 7.7%.</li> <li>• double-anchored sheet piling minimized bending moments by 50% compared to cantilever sheet piles.</li> <li>• Cement Deep Mixing (CDM) minimizes the bending moment by approximately by 51%</li> </ul>	<ul style="list-style-type: none"> <li>• Bending moment estimations using Numerical simulation are in need of calibration with experimental testing, such as centrifuge or shaking tables.</li> <li>• The correlation between EPWP generation and bending moment developed during seismic loading is not well investigated.</li> <li>• The impact of sheet pile flexibility on bending moment estimation is not investigated.</li> </ul> <p>The effect of anchor configuration on minimizing bending moments has not been addressed.</p>	[36, 37, 40, 41, 44].

<p><b>Liquefaction</b></p>	<ul style="list-style-type: none"> <li>• Soil-sheet pile interaction has a significant role in liquefaction modes</li> <li>• Liquefaction occurs in the backfill soil when (<math>r_u</math>) up to 1</li> <li>• Excess pore water pressure increases in the backfill soil while increasing cycling loading.</li> <li>• The PDMY02 model proved that the increased EPWP ratio was well matched by numerical results.</li> <li>• EPWP around anchors increases greatly due to anchor mobilization during seismic loading.</li> </ul>	<ul style="list-style-type: none"> <li>• No calibration studies have compared excess pore water pressure from centrifuge tests with results from numerical simulations using models like PM4Sand or Manzari-Dafalias.</li> <li>• The effects of different wall embedment depths, wall flexibility, or anchored versus cantilevered setups on EPWP patterns have not been explored.</li> <li>• There is a lack of use of actual data records of earthquake time history to investigate liquefaction potential.</li> <li>• Constitutive soil models to predict soil liquefaction potential in the backfill require more investigation.</li> </ul>	<p>[32, 34, 35, 37, 38, 39, 41, 45].</p>
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Source: by authors

## 6. Conclusion and Future Scope

This paper comprises a comprehensive literature review of recent progress in how sheet pile quay walls behave during seismic motions that was conducted between 2020 and 2026. It concentrates on five behavior modes: seismic displacements, liquefaction potential, settlements, rotations, and bending moments. The findings illustrate that during liquefaction conditions, sheet pile walls usually move toward the seaside and are exposed to tilting. The findings showed that single-and double-anchored sheet piles significantly minimize these displacements compared to cantilever sheet piles. Nevertheless, there is still a knowledge gap in how sheet pile flexibility, embedment depth, and anchor configuration impact shift modes. It was noted that most research reviewed utilized periodic loads instead of real earthquake time history data records. Regarding liquefaction, Advanced constitutive soil models like PM4Sand, Manzari-Dafalias, and SANISAND-MSF usually fail to predict excess pore water pressure generation because of the need to control accurately liquefaction parameters related to these constitutive models.

For bending moments estimations, an enhanced pseudo-static approach that takes into account ( $r_u$ ) and equivalent cycle numbers seem promising. Still, most researchers estimated that the bending moment depends on numerical simulation, which lacks validation with experimental results to validate bending moment estimations. Settlement and tilting are considered the main failure modes. The review showed that cantilever sheet piles result in the highest

settlement, while installing anchors to support sheet piles reduces these settlements. Also, double-anchored sheet piles could minimize the rotation of the sheet pile by 75-78% compared to cantilever sheet piles.

This study strongly recommends directing future research efforts to validate the results of seismic performance of sheet pile structures using numerical simulation with experimental testing, such as shaking table tests or centrifuge tests. These experimental tests should also estimate bending moments and vertical displacements to validate numerical simulation results. Constitutive soil models that address liquefaction potential, such as PM4Sand and Manzari-Dafalias, require accurate validation and control of liquefaction parameters of the constitutive models during seismic loading. Future efforts should also utilize real earthquake time history data records, addressing sheet pile flexibility, embedment depth, and spacing between anchors, anchor properties, and develop standard approaches to predict rotation and settlement after liquefaction in seismic conditions. Future studies should search for innovative techniques to improve waterfront sheet pile structures under seismic conditions. Also, future research should develop reliable seismic design regulations to ensure safe and high-performance sheet pile quay structures in seismic zones.

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All authors contributed equally to this work.

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