



## Experimental Study on Anchored Sheet Pile Walls with Batter Piles in Sandy Soil under Combined Seepage and Cyclic Loading

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### ABSTRACT

In order to build flood barriers, erosion protection, cutoff walls, under dams, waterfront buildings, and excavation support systems, anchored sheet pile walls are used as either temporary or permanent constructions. In this study, An experimental investigation was conducted on a laterally anchored sheet pile wall installed in sandy soil subjected to combined seepage and cyclic load. The tests were performed with a Cyclic Load Ratio (CLR) of 40% for 100 cycles. Parameters investigated included anchor rod length ( $B= 4/3 H$ ), pile lengths of ( $L = 2/3H, H$  and  $4/3H$ ), and batter pile angles of  $15^\circ$ . In addition, a linear load of 5 kPa applied on ground surface near sheet pile wall and spacing between anchors of ( $S = 1/3 H, 2/3H$ , and  $H$ ) were considered. The batter piles were installed at a distance of 40 cm from the sheet pile wall. The test results showed that the increase of length of batter piles from  $2/3H$  to ( $H$  and  $4/3H$ ) leads to give good stability of the sheet pile wall by (12 - 84) % and (12 - 88) %, respectively. Strip footing tilting and total settlement near the sheet pile wall reduced as the length of batter pile. The anchored sheet pile wall system subjected to cyclic load was effective and safer when the length of batter pile 40 cm. The spacing between anchors  $S = 1/3H$  is the best compared to  $S = 2/3H$  and  $H$ . The spacing between anchors of  $S = 1/3H$  gives Stability to sheet pile wall anchored systems approximately (8-78%) and (38-82%) compared to spacing  $S = 2/3H$  and  $H$  respectively.

Keywords: Anchored sheet pile wall, Seepage, Sandy soil, Cyclic load, Batter piles.

### 1. Introduction

Anchored sheet pile walls are used as temporary or permanent structures to retaining soil and controlling water for the construction of cutting walls, barriers to flooding, erosion protection, under dams, waterfront constructions, and excavation support systems. Anchored sheet pile wall have been used to restrict excavation when it goes deeper than roughly 6 meters. To support the backfill material under horizontal pressure, the sheet pile is buried into the ground on the wall's other side. A sheet pile construction is made up of pile lengths that continuously connect. Numerical analysis of the sheet pile walls was performed using the GEO5 finite element analysis software. According to the findings, the ideal anchor angle is  $25^\circ$  in order to reduce the maximum bending moment and horizontal displacement at the top of the wall. The maximum displacement and internal pressures decrease as the angle of friction increases. The maximum bending moment, shear force, and wall displacement are all decreased by increasing soil cohesiveness. Increasing the number of anchor points increases the maximum shear force while decreasing the maximum bending moment and wall displacement, [1]. The sheet pile walls are supported by the stiffness of the material components and the passive pressure balancing of the soil. Pressure variations beneath the walls brought by an external load, such as construction activities or moving objects, increase the lateral force that is applied to the sheet-piled walls. This action may contribute to deflections and settlement, two factors that are crucial in evaluating the stability of sheet pile walls. On the field, surcharges of all types are common, surcharges that are near the excavation site and supported by the retaining wall's structure are receiving very little attention. These surcharges put additional pressure on the sheet pile, which may change its behavior and result in more displacement and an additional settlement, [2]. The distance between the model footing and the excavation face is one of the main parameters that determine the performance



of the sheet pile wall. When the footing is placed 200 mm from the excavated face, ground settlement makes up around 18% of the maximum excavation depth; when the footing is placed 800 mm from the excavation face, it only makes up 2.7%. The associated deflections of the sheet pile wall are approximately 19% and 30% of the maximum excavation depth.

Another study by [3] investigated the impact of cyclic loads on batter-anchored pile groups in sandy soil using three different types of piles: conventional piles, a single-helix and two helices piles. Screw piles with two helices provide greater resistance to the lateral cyclic load than single and conventional piles, as indicated by a pile with two helices and a pile without helices, [4]. A study by [5] on the lateral support of inclined pile groups on sandy soil with inclination angles of 5°, 10°, and 15° showed that the group piles of pattern (1x2) performed better than those of pattern (2x1) in resistance to cyclic loads. Another study, [6] focuses the importance of the distance between the excavation face and nearby foundations, showing that ground movement reached approximately 18% of the excavation depth when the footing was located 200 mm away, compared to only 2.7% at a distance of 800 mm. Seismic effects on braced excavations supported by sheet pile walls have been investigated in a numerical study. It has been found that the excavation systems can move laterally as a block during earthquakes, especially in soft silty clay, which could cause damage to adjacent water lines, [7]. A study by [8], found in comparison to vertical and positive batter pile, negative batter piles have been found to provide more lateral resistance. The downward migration of slip surfaces, which raises soil resistance, is the primary cause of this increased resistance in negative batter piles. On the other hand, when positive batter piles are subjected to lateral loads, the slip surfaces have a pattern to rise, which reduces the resistance of the soil and, as a result, decreases the pile's ability to support lateral loads. Under lateral load pressure, negative batter pilings perform better than both vertical and positive batter piles. The connection point with the pile cap or decks is usually where batter pilings fail most frequently.

Another study by [9] investigated effect of a pile group's angle of inclination on lateral resistance. In comparison to a pile inclined at 5°, a single helix pile inclined at angles of 10° and 15° presents about 9% and 18% more lateral tension, respectively. A work by [10] founded the rotation is the most important aspect in this investigation. The spin was constant for frequencies between 5 and 10 Hz. However, rotation gradually increased at 15 Hz until stabilizing at 200%, suggesting extremely hazardous conditions at this frequency. The study was carried out at one distance (H) from the sheet pile. It is highly advised to avoid operating at this frequency at the specified distance because the results suggested that 15 Hz is the most severe and dangerous frequency. In another study by [11] indicated when it comes to earthquake attraction, batter pilings are better than vertical piles. Smaller lateral and vertical displacements are seen as the batter angle increases. Furthermore, batter heaps have moment values that are roughly 42%, 43%, and 28% less than the similar vertical pile groups for edge, corner, and center piles, respectively. A work by [12] computed in comparison to higher load ratios, the impact of embedded lengths and pile spacing is small at a cyclic load ratio of 20%, and the condition is typically regarded as safe from failure. Displacement values range from 6% to 8.5% of the shaft diameter after 100 load cycles. On the other hand, significant lateral displacement is observed at cyclic load ratios of 50% and 80%, leading to quick increases with the number of cycles, making these kinds of conditions dangerous.

A study by [13] showed that the sheet piles were positioned beneath the hydraulic structural cover on heterogeneous soil. In addition to the piles above and below the system of hydraulics, intermediate piles have been utilized. The discharge, uplift pressure, and exit gradient were measured at the base of the hydraulic structure. The final results were tested using an artificial neural network, or ANN. At the validation, there had been good agreement, [14]. Many studies used anchor piles in problematic soils for compressive and pullout resistance as depicted in a studies by [15, 16, and 17]. The sheet pile wall used under concrete dam to reduce seepage and for support excavation as mentioned in studies, [18, and 19]. In sandy soil, anchored sheet pile walls under cyclic pressure were investigated experimentally. The anchor rod was 40 cm long, the pile was 30 cm long, and the anchors were spaced 10 cm apart. The impact of batter pile tilt (10°, 15°, and 25°) was assessed. The best results were obtained at 25°, and the results shown that raising the angle considerably decreased lateral displacement, settlement, and footing tilting, [20].

Limited studies have addressed the behavior of anchored sheet pile walls under combined cyclic loading and seepage conditions. Therefore, this study aims to investigate the effects of combined lateral cyclic loading and seepage on the lateral displacement of sheet pile walls, as well as on the vertical displacement and tilting of adjacent strip footings.

## 2. Methodology

### 2.1 Soil used

As seen in Figure 1, this sample of sandy soil was collected from the Karbala Governorate. As seen in Figure 2, the soil particle size distribution was calculated in accordance with ASTM D422-63. As indicated in Table 1, the National Centre for Construction Laboratories and Research (NCCLR) examined the sandy soil's chemical characteristics in accordance with British Standard BS 1377 (1990), Part 3. Table 2 shows the soil characteristics.

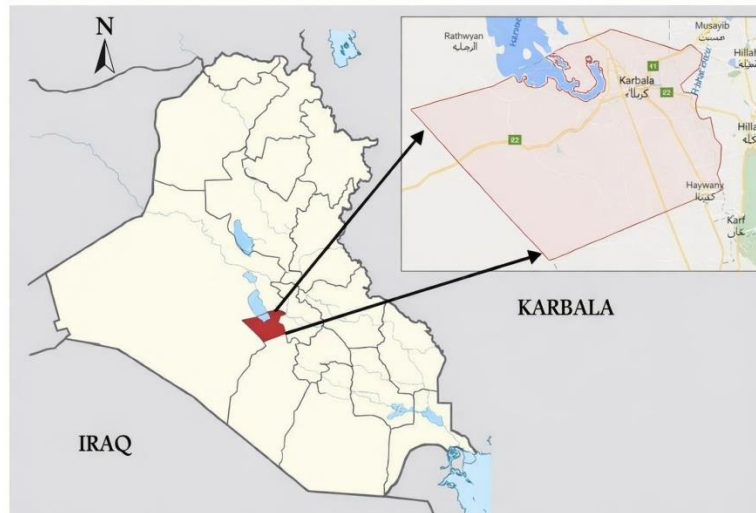


Figure 1. A Site from Which the Sample Was Taken, [5].

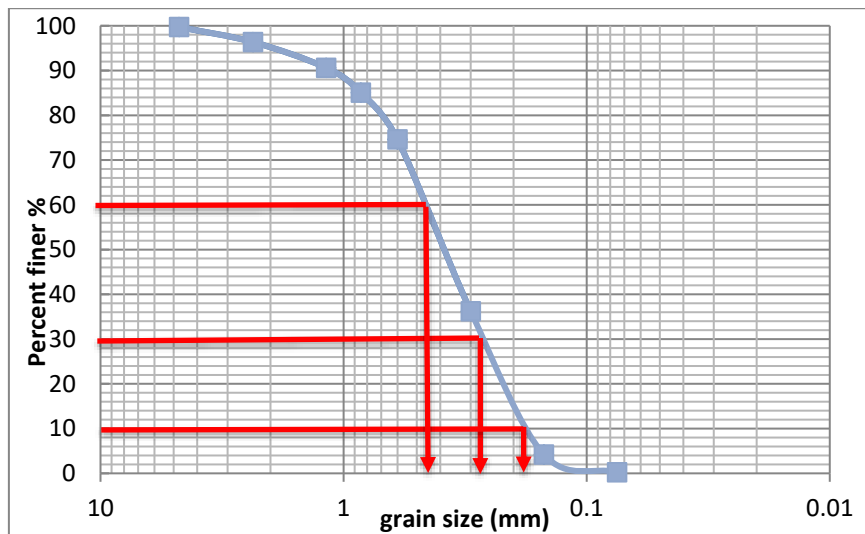


Figure 2. Distribution of Grain Size in the Sandy Soil.

Table 1. Sand Soil's Chemical Composition.

Chemical properties	Values	Standards
Organic Matters Content, (%)	0.034	(BS 1377: 1990 part 3)

Gypsum Content, (%)	0.12
Total Soluble Salts Content, (%)	0.39
Sulphate Content (SO <sub>3</sub> ), (%)	0.05
Chlorides, (%)	0.192
pH	8.34

Table 2. Sandy Soil's Geotechnical Characteristics.

Characteristics	Values	Standards
D <sub>10</sub> in mm	0.19	ASTM D 422 and ASTM D 2487 (2006)
D <sub>30</sub> in mm	0.28	
D <sub>50</sub> in mm	0.38	
D <sub>60</sub> in mm	0.46	
Coefficient of uniformity (Cu)	2.66	
Coefficient of curvature (Cc)	0.82	
Classification (USCS)	SP	
Specific Gravity, G <sub>s</sub>	2.65	ASTM D 854 (2006)
Angle of Internal Friction (Ø)	36	ASTM D3040-04(2006)
$\gamma_d$ (min.) (kN /m <sup>3</sup> )	14.98	ASTM D 4253 - (2006)
$\gamma_d$ (max.) (kN /m <sup>3</sup> )	18.36	ASTM D 4254 - (2006)
$e_{max}$	0.8	.....
$e_{min}$	0.52	.....
$e_{field}, e_o$	0.612	.....
$\gamma_d$ (kN/m <sup>3</sup> )	17.03	.....
Relative density, Dr.%	67	.....

## 2.2 Test container

For this study, a locally produced steel rectangular container with dimensions of 1000 mm in length, 500 mm in width, and 660 mm in height was utilized. To allow for easy container transportation, two pieces of steel plate measuring 40 x 500 mm and 4 mm thick were positioned along each side of the container. The test container had three layers of anti-corrosion coating for reduce a friction between soil and container. A 900 × 550 mm piece of solidified anti-breaking glass was put on the front side of the container to make the examination easier. A drain pipe was installed both inside and outside the container to allow water to enter and moister the sample from below. Another drain was installed on the top side of the container to add water from above for the seepage process, as shown in figure 3.



Figure 3. Container of Test

### 2.3 Anchored Sheet Pile Wall

The dimensions of the anchored sheet pile model are 500 mm in length, 495 mm in width, and 5 mm in thickness, as seen in figure (4). A plate measuring 490 mm in length, 200 mm in width, and 2 mm in thickness is placed along the sheet pile wall and applies a cyclic load laterally.



Figure 4. Anchored Sheet Pile Wall with Wale.

### 2.4 Batter piles and rods

Two piles of 10 mm diameter with lengths of ( $L = 2/3H$ ,  $H$  and  $4/3H$ ) were used in this test, as shown in Figure (5), along with two 5 mm diameter rods with a length of  $B = 4/3H$ . Three different spacing of ( $S = 1/3 H$ ,  $2/3H$ , and  $H$ ) were also used between the rods.



Figure 5. Batter Piles and Rods.

### 2.5 Wale and batter pile locks

Wales are horizontal structural members installed along the sheet piles, as shown in Figure (4). The wale used in this study had dimensions of 480 mm in length, 40 mm in width, and 6 mm in thickness, and was positioned beneath the loading plate to distribute lateral earth pressures from the sheet piles to the anchors. Proper connections between the anchor rods and batter piles are essential to ensure effective load transfer, system stability, and structural integrity, enabling efficient transmission of both lateral and vertical loads.

## 2.6 Laboratory Testing Devices

This study employed a variety of equipment, including the following:

1. The sand raining device seen in Figure 6.
2. The loading device included the following parts, as seen in Figure 7:

The electrical control unit.

- The Motor Gearbox System.
- Data logging device.
- Load cell
- Two dial gauges and a linear variation displacement transducer (LVDT), as seen in Figure (8).



Figure 6. Sand Raining Device Used, [5].



Figure 7. The loading Device Structure, [15].

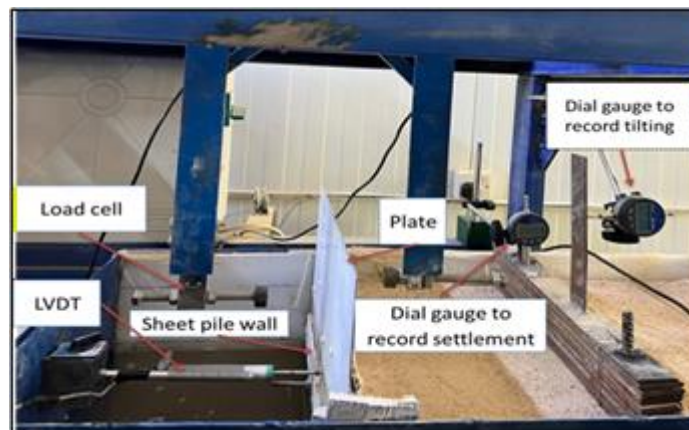


Figure 8. The Parts of the Loading Device's, [15].

## 2.7 Preparation of Sandy Soil and Test Procedure

A container that was 50 cm in width, 100 cm long, and 66 cm high was used to prepare the sample. To ensure that water reached the soil layers, a 5 cm layer of gravel was applied. Additionally, a piece of permeable cloth was positioned to separate the sand and gravel layers, as seen in figure (9).



Figure 9. Gravel Layer.

A process of sedimentation was used to prepare the sandy soil sample, which produced 6 horizontal layers with a relative density of 67% that were each 10 cm thick. With a 30 cm excavation depth and a 15 cm backfilling depth, sheet pile walls were set up in the negative zone 30 cm from the container. Here,  $H$  appears for the free wall height, which is 30 cm.  $0.005H$  should be the passive failure. 10 cm below the soil's surface, two rods are attached to the piles. After that, the Container is pushed in the direction of the loading Device. By pumping water from below into the container, about 30 cm of the soil layers are saturated with water in order to remove air from the soil. It takes about 10 minutes to reach saturation. In order to prevent soil development, water is involved in the passive side while keeping the water pressure constant. The water level is maintained 15 cm above the soil surface for the purpose of seepage, as seen in figure (10) and figure (11).



Figure 10. Installation of Anchored Sheet Pile Wall, Seepage Process after Prepared Soil.

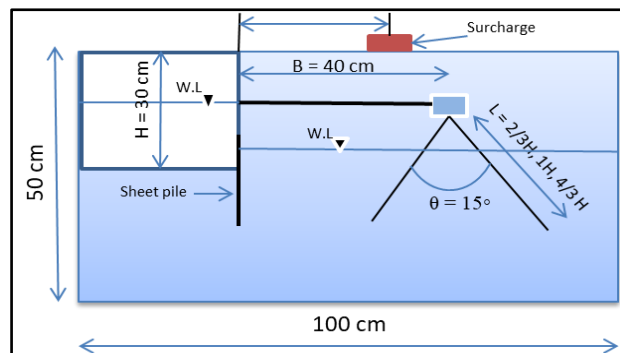


Figure 11. Cross Section of the Testing Container.

### 3. Results and Discussion

The lateral displacement of sheet piles is plotted with number of cycles for three lengths of batter piles and three spacing between anchors. A passive failure line is also located in each figure to determine the behavior of the

sheet pile wall during cyclic loading. Many parameters are investigated in this study, including batter pile length and anchor spacing.

Settlement and tilting of the strip footing on the ground surface near sheet pile wall are recorded during cyclic loading. The results of these studies are discussed in the following sections:

### 3.1 Effect of batter pile length

#### 3.1.1 Sheet pile wall lateral displacement

Figures (12-14) show the lateral displacement of sheet pile wall with number of cycle during the test period for three spacing between anchors ( $S = 1/3 H$ ,  $2/3H$ , and  $H$ ) respectively. It is obvious from these figures that the lateral displacement is reduced with increasing length of batter piles. For spacing  $S = 1/3 H$ , the greatest length of batter pile  $L/H = 4/3$  gives good stability to the sheet pile wall system and does not exceed passive failure (passive failure is defined by Dass (2011) equal to  $0.005 H$ ), [21] during the 100 cycles of test. Conversely, the length of batter piles  $L/H = 2/3$  exceeded passive failure at cycle numbers 12 and 16 respectively. This may be due to increased soil resistance and embedment effect, which increased with the increased length of the pile.

#### 3.1.2 Total settlement of strip footing

Figures (15 -17) show the total settlement of strip footing for different lengths and spacing when the angle between the batters piles equal to  $15^\circ$ . The increasing in length of batter piles leads to a reduced total settlement of strip footing. This is due to an increase in anchorage resistance for long piles compared to the movement of pile in short length. All models tested for lengths ( $L = 2/3H$ ,  $H$ , and  $4/3H$ ) for spacing ( $S = 1/3 H$ ) remained below allowable settlement, the allowable settlement equal to (10% of width of strip footing), where width of strip footing equal to 40 mm. The soil movement behind the sheet pile wall is slightly affected by cyclic load when the length of the batter pile is increased; therefore, the total settlement of strip footing is reduced.

#### 3.1.3 Tilting of Strip Footing

Figures (18-20) illustrate the tilting of strip footing with the number of cycles for different lengths of batter piles and spacing between anchors. It is clear that a shorter batter piles result in greater tilting of strip footing. The soil movement below the strip footing increases as a result of increased lateral displacement of the sheet pile wall at shorter batter piles.

In summary, the length of batter piles  $L = 4/3H$  gives the best stability of a sheet pile wall anchored system more than other lengths  $L = H$  and  $L = 2/3H$  by approximately 84 % and 88 %, respectively.

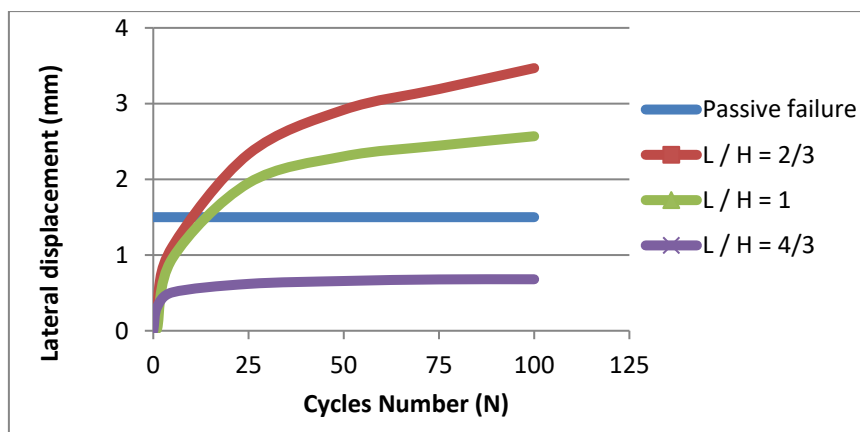


Figure 12. Lateral Displacement of Anchored Sheet Pile Wall for Angle ( $\theta = 15^\circ$ ), ( $S/H = 1/3$ ).

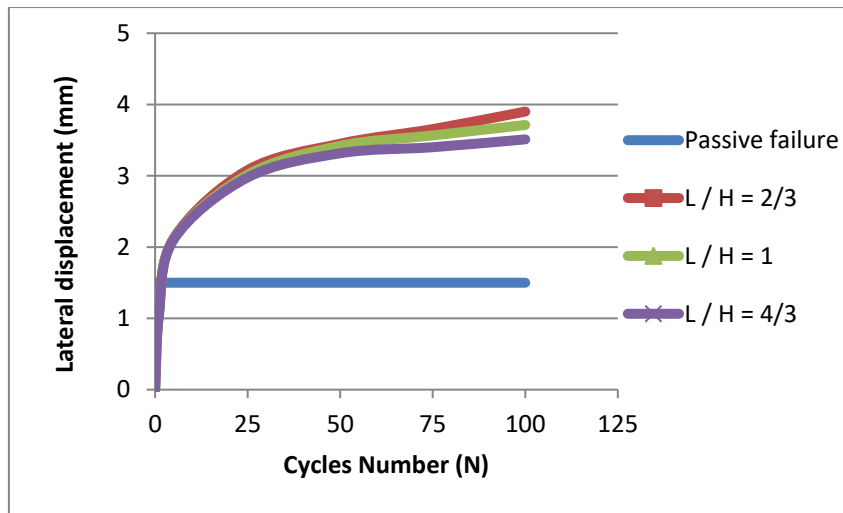


Figure 13. Lateral Displacement of Anchored Sheet Pile Wall for Angle ( $\theta = 15^\circ$ ), ( $S/H = 2/3$ ).

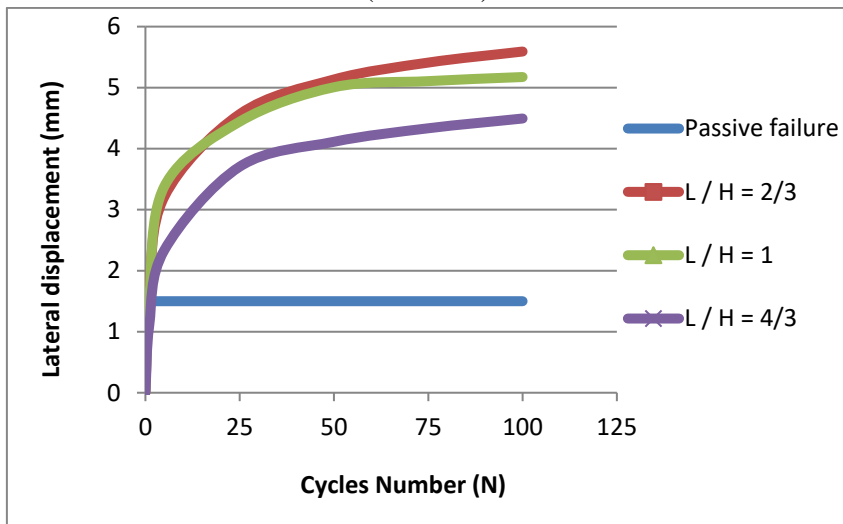


Figure 14. Lateral Displacement of Anchored Sheet Pile Wall for Angle ( $\theta = 15^\circ$ ), ( $S/H = 1$ ).

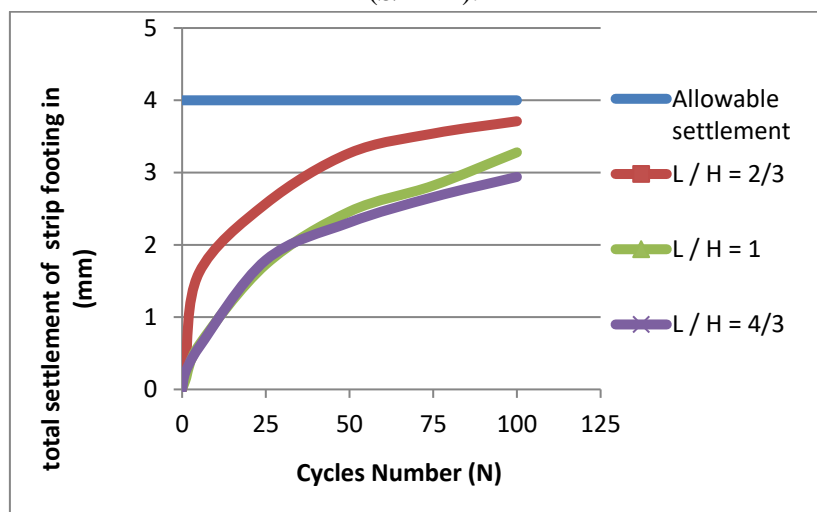


Figure 15. The Total Settlement for Strip Footing near Anchored Sheet Pile Wall ( $\theta = 15^\circ$ ), ( $S/H = 1/3$ ).

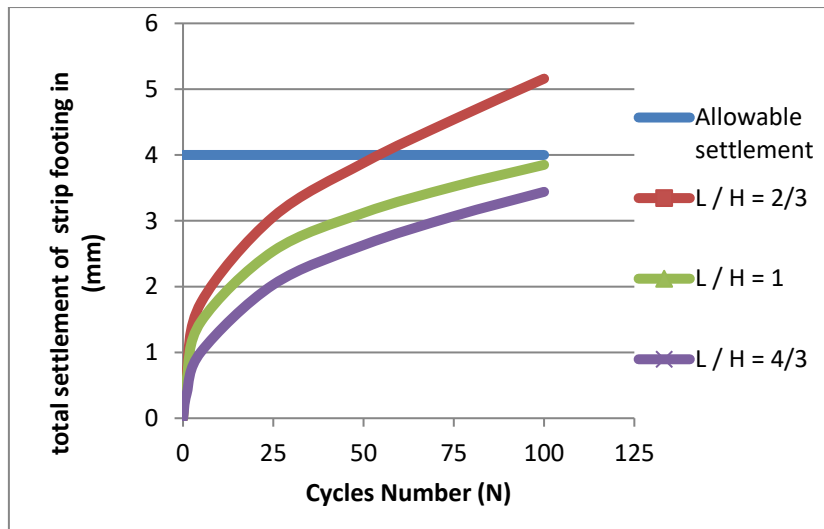


Figure 16. The Total Settlement for Strip Footing near Anchored Sheet Pile Wall ( $\theta = 15^\circ$ ), ( $S/H = 2/3$ ).

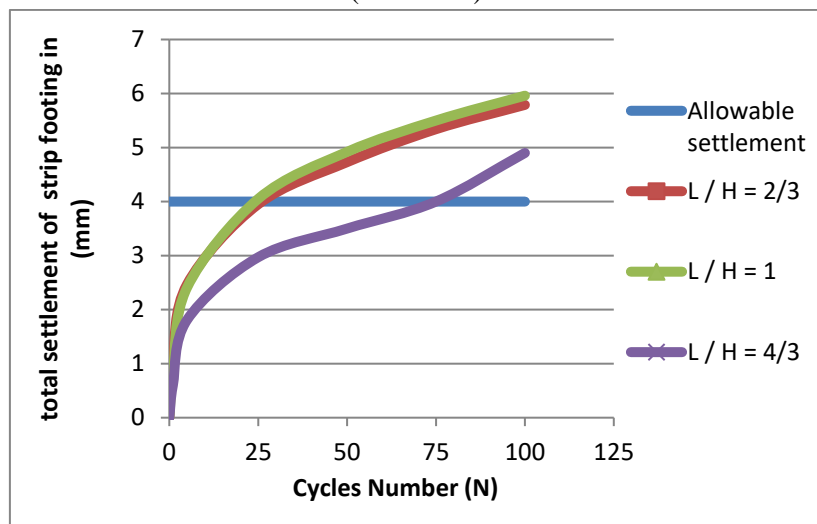


Figure 17. The Total Settlement for Strip Footing near Anchored Sheet Pile Wall ( $\theta = 15^\circ$ ), ( $S/H = 1$ ).

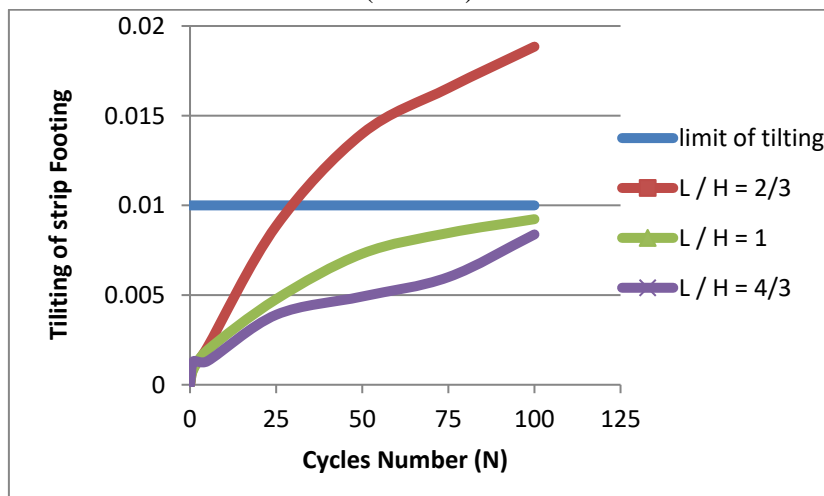


Figure 18. Tilting of Strip Footing near Anchored Sheet Pile Wall for ( $\theta = 15^\circ$ ), ( $S = 1/3 H$ ).

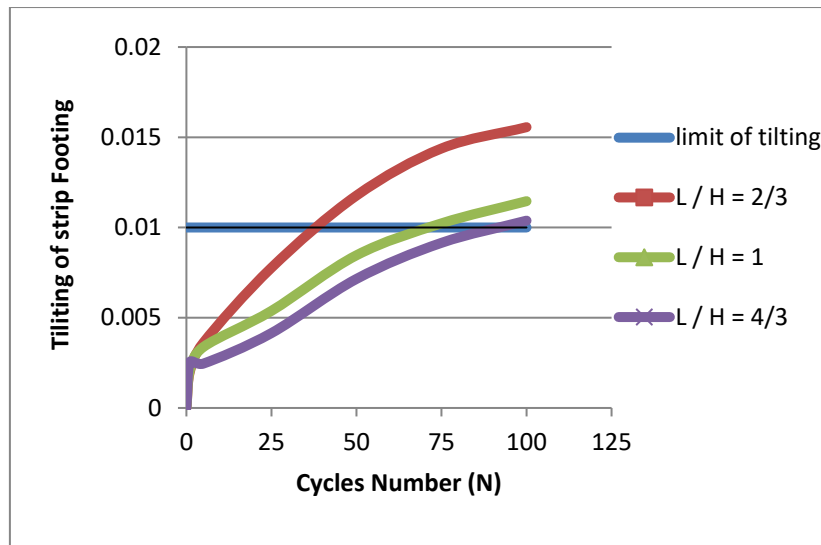


Figure 19. Tilting of Strip Footing near Anchored Sheet Pile Wall for ( $\theta = 15^\circ$ ), ( $S = 2/3 H$ ).

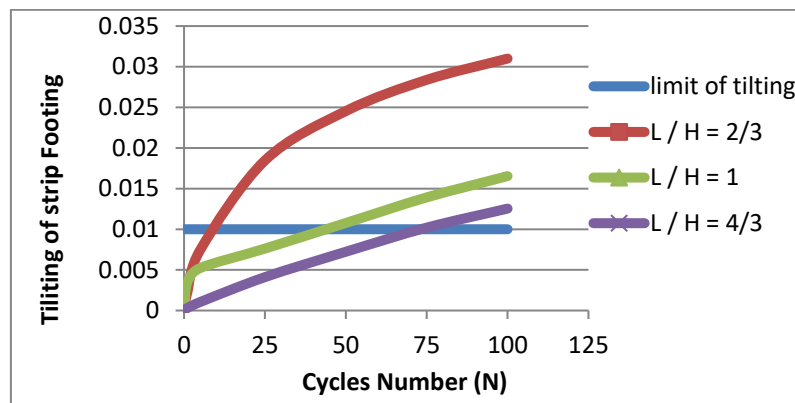


Figure 20. Tilting of Strip Footing near Anchored Sheet Pile Wall for ( $\theta = 15^\circ$ ), ( $S = H$ ).

### 3.2 Effect of spacing between anchors

#### 3.2.1 Lateral displacement of sheet pile wall

Figures (21 - 23) depict the relationship between the lateral displacement of the sheet pile wall and the cyclic number for spacing between anchors ( $S = 1/3 H$ ,  $2/3 H$ , and  $H$ ) for batter pile lengths ( $L = 2/3 H$ ,  $H$ , and  $4/3 H$ , respectively). Closer spacing result in reduced lateral displacement of the sheet pile wall. When the anchors are close together, they provide more resistance to cyclic load and seepage forces. Reduced spacing increases resistance to cyclic and seepage-induced forces, constrains soil movement behind the wall, and therefore limits wall deflection.

#### 3.2.2 Total Settlement of Strip Footing

Figures (15 - 17) show the number of cycles with total settlement of Strip footing for spacings ( $S = 1/3 H$ ,  $2/3 H$  and  $H$ ) and length of Batter Pile ( $L = 2/3 H$ ,  $H$  and  $4/3 H$ ) respectively. The increase in spacing between anchors caused an increase in total settlement of strip footing because the soil between anchors became unrestrained and lead to reduced stability of the Sheet Pile Wall.

#### 3.2.3 Tilting of Strip Footing

Tilting of  $S = 1/3 H$  gives tilting of Strip footing under allowable tilting, especially  $L = H$  and  $4/3 H$ . The tilting is increased and exceeded the tilting limit for spacings  $S = 2/3 H$  and  $H$ .

In Summary; The spacing between anchors  $S = 1/3 H$  is the preferable compared to  $S = 2/3 H$  and  $H$ . The spacing between anchors of  $S = 1/3 H$  gives Stability to sheet pile wall anchored systems approximately 78% 82% compared to spacing  $S = 2/3 H$  and  $H$  respectively.

The cyclic load caused an increase in pore water pressure, coinciding with seepage occurring below and behind the sheet pile wall. The interaction between cyclic load and seepage with soil give different behaviors of models

used in the study. In general, the case of model using length of batter pile ( $L = 4/3 H$ ) and anchor spacing ( $S = 1/3 H$ ) represents the better case for reducing lateral displacement of the sheet pile wall, total settlement, and tilting of the strip footing.

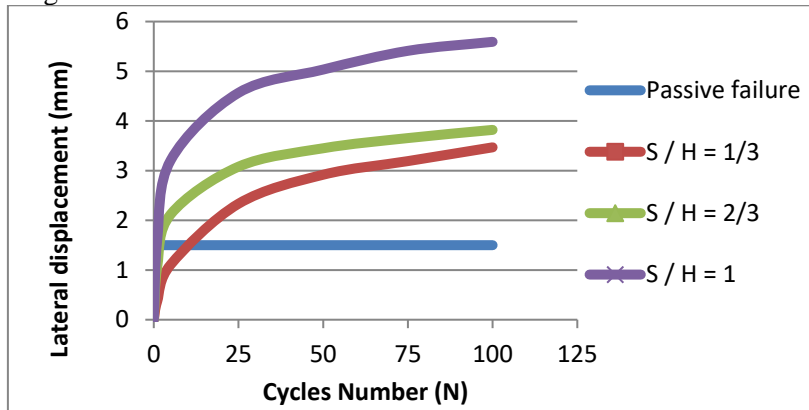


Figure 21. Lateral Displacement of Anchored Sheet Pile Wall with Batter Pile Angle ( $\theta = 15^\circ$ ), ( $L = 2/3H$ ).

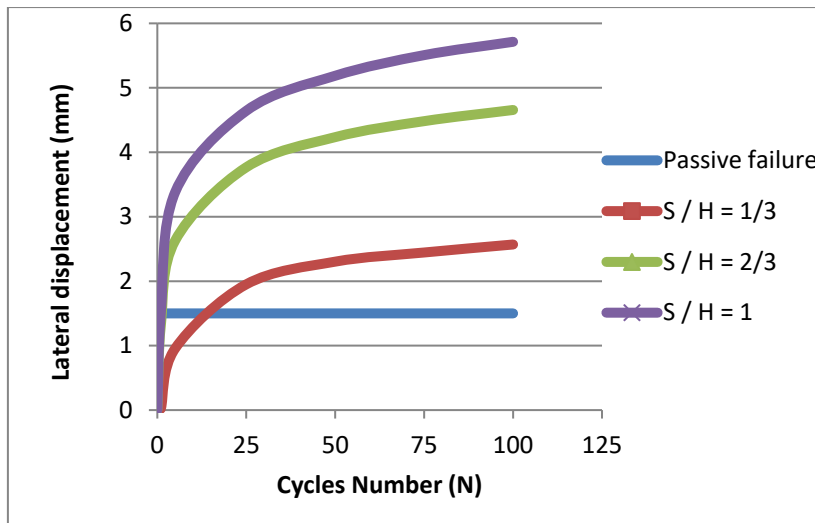


Figure 22. Lateral Displacement of Anchored Sheet Pile Wall with Batter Pile Angle ( $\theta = 15^\circ$ ), ( $L = H$ ).

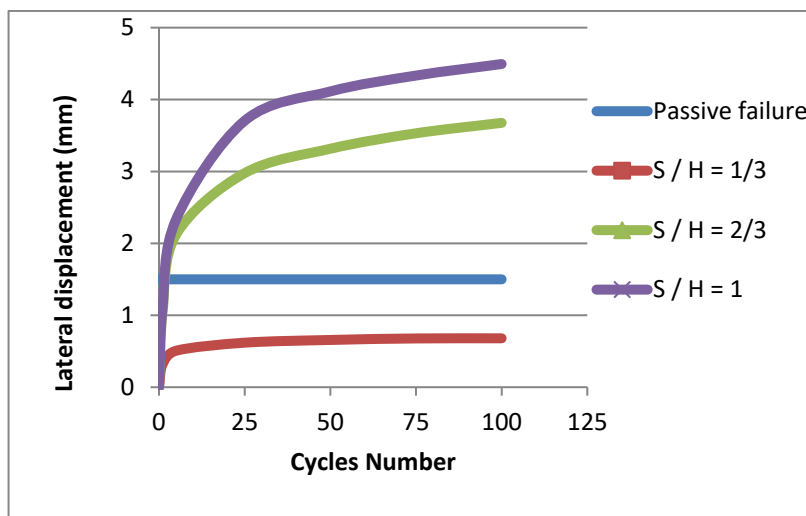


Figure 23. Lateral Displacement of Anchored Sheet Pile Wall with Batter Pile Angle ( $\theta = 15^\circ$ ), ( $L = 4/3 H$ ).

#### 4. Conclusion

The following main points are drawn from this study:

1. The length of batter piles and the spacing between anchors have a significant influence on stability of anchored system under the effect of coupled cyclic load and seepage conditions .
2. The increasing of length of batter piles ( $L = 2/3 H$ ,  $H$  and  $4/3H$ ) lead to decrease in the horizontal displacement of sheet pile wall. Longer batter piles improvement the performance of the sheet pile wall because they provided deeper anchorage into the soil, which increases the resistance against lateral displacement. When the pile length increases, more skin friction between soil and pile. Also, longer piles transfer the applied loads to deeper and more stable soil layers, which reduces displacement and increases overall stability of the system.
3. The length of batter pile ( $L = 4/3 H$ ) gives the best stability of a sheet pile wall anchored system more than other lengths ( $L = H$ ) and ( $L = 2/3 H$ ) by approximately 84 % and 88 %, respectively.
4. The increased in length of batter piles leads to a reduced total settlement of strip footing and close spacing leads to small displacement of the sheet pile wall.
5. Reduced length of batter piles leads to increased tilting of strip footing. The soil movement below the strip footing increases as a result of increased lateral displacement of the sheet pile wall at low lengths of batter piles.
6. The spacing between anchors affects how the load has been distributed along the wall. When anchors have been properly spaced, The forces are distributed evenly and there is no concentration of stress in one place. The spacing between anchors of  $S = 1/3H$  gives stability to sheet pile wall anchored systems approximately (8-78%) and (38-82%) compared to spacing  $S = 2/3H$  and 1 respectively.
7. Cyclic loading has a significant impact on soil behaviour because it causes repeated loading and unloading, which leads to gradual accumulation of deformation. In sandy soil, cyclic loading can cause rearrangement of particles and reduction in stiffness over time.

#### Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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#### Author Contributions

All authors contributed to the conception and design of the research problem. Shaimaa Ahmed Abdulhadi collected and organized recent related works. Hassan Obaid Abbas verified the recommendations in the proposed framework. All authors contributed to the design and formulation of the proposed approach. All authors provided detailed discussions and critical analysis of the proposed design. All authors participated in reviewing the results and approved the final version of the manuscript.

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