Use of discrete vertical reinforcement in active zone to improve the lateral response of the sheet pile wall

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In many earth-retaining problems, it is necessary to consider additional earth pressures produced by strip loads acting on the soil surface behind the wall. Therefore, this paper consists of a set of experiments on a small-scale model of a sheet pile wall adjacent to strip footing in sand. The effectiveness of discrete vertical reinforcement (model piles) inclusions in the active zone to reduce lateral wall deflection was studied. The investigations were carried out by varying the distance between sheet pile wall and strip footing, pile length, pile spacing and pile diameter. Also, the position of the pile row relative to the strip footing and the length of excavation in front of the sheet pile wall are considered. Test results indicate that this type of reinforcement significantly increases the stiffness of the soil and decreases the lateral deflection of the sheet pile wall produced by the pressure of strip load. A series of finite element analyses were performed using three-dimensional model. Bending moment graphs and lateral deflection of the sheet pile wall were presented and discussed.

يتناول هذا البحث دراسة معملية و نظرية لسلوك الستائر اللوحية المدفونة في تربة رملية بحيث تم زيادة مقاومتها الجانبية بعناصر تسليح رأسية (أسياخ معدنية ملساء) مدفونة في المنطقة الفعالة و تتعرض هذه الستائر اللوحية إلي ضغوط جانبية من قاعدة شريطية مجاورة . وتم عمل مقارنة بين السلوك الجانبي للستائر اللوحية قبل و بعد استخدام تسليح التربة. أيضا تم دراسة أهم العوامل المؤثرة علي السلوك الجانبي للستائر اللوحية وهي المسافة بين القاعدة الشريطية و الستائر اللوحية و طول التسليح الرأسي و المسافة بين أسياخ التسليح الرأسية و قطر سيخ التسليح و مكان التسليح و كذلك عمق الحفر المسنود بواسطة الستائر اللوحية. بالإضافة إلي عمل نموذج نظري ثلاثي الأبعاد باستخدام طريقة العناصر المحددة لدراسة تأثير العوامل المختلفة ومقارنتها مع النتائج المعملية التي تم الحصول عليها. وقد تم عرض ومناقشة نتائج التجارب المعملية و النظرية في صورة جداول ومنحنيات و تلخيص تأثير العوامل المختلفة.

Keywords: Sheet pile wall, Strip footing, Reinforced sand, Lateral deflection

1. Introduction

In many practical situations, loads due to roadways and other influences resting on the surface in the vicinity of the wall increase the lateral pressures on the wall. This increase in the lateral earth pressure will affect the behavior of the wall. Therefore, for earth retaining, it is necessary to consider additional earth pressure produced by the surcharge strip load acting on the soil surface behind the wall. Some of the methods that are currently used in the determination of the strip load generating lateral earth pressures are the elastic analysis, the simple "45^o load distribution", the conventional Coulomb earth pressure analysis, and the method proposed in Beton Kalender [5]. The distributions of earth pressure obtained from these methods differ significantly from each other and may lead to either very conservative or unsafe solutions.

Several investigators have studied using vertical elements as soil reinforcement to resist the lateral earth pressure. This method of reinforcement is meritorious and superior, when compared with other methods for different reasons such as: increasing the bearing capacity of the subgrade by confining the soil, decreasing the lateral pressure transmitted from foundations, easily used adjacent to existing foundations without any impediments, constructed by using small machine without any effects on the adjacent structures, and vertical reinforcement can be constructed inside the structures.

Bassett and Last [4], and Verma and Char [20] reported the possibility of using vertical reinforcement for increasing the bearing capacity of the subgrade soil. Mahmoud and

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Abdrabbo [15] studied the behavior of strip footings supported on sand reinforced by utilizing vertical reinforcing elements made of aluminum strips. It was reported that this type of reinforcement increases the bearing capacity of the subgrade and modifies the load-displacement behavior of the footing.

Abdrabbo and El-Hansy [1] investigated the methodology used in strengthening the loaded footings. In this research they studied the plate loading tests on sand to investigate the effect of the length of vertical reinforcing elements, distance between reinforcing elements and the edges of the footing, number of reinforcing elements, and the characteristics of sand. It was found that the length of the element below foundation level should be equal to twice the footing width. The element should be placed as close as possible to the footing with an adequate number of reinforcing elements.

Georgiadis and Anagnostopoulos [11] used a model sheet pile wall embedded in sand to investigate the effect of surcharge strip loads on wall behavior. The results of an experimental program were compared with different methods of computing lateral earth pressure. From the results, the bending moments along the sheet pile wall increase with the increase of the surcharge load and the decrease of the strip load distance to the excavation.

In the conventional design of retaining walls and bridge abutments, the lateral earth pressure due to live load surcharge is estimated by replacing the actual highway loads with a layer of backfill. According to John and Richard [13] based on the elastic theory to determine soil pressures within a soil mass due to loads on the surface, values of equivalent height of soil h_{eq} are not constant for all wall heights. Shorter walls must have a larger h_{eq} than higher walls. The values for h_{eq} recommended by a previous study were given and applied on for both retaining walls and abutments without distinction.

Timothy et al. [19] presented the results of finite element analyses of shear strain localization that occurred in non-cohesive soils supported by a geo-synthetically reinforced retaining wall. Results of the analysis suggest that strain localization develops from the toe of the wall to the ground surface, forming a curved failure surface. The results demonstrated the potential of the enhanced finite element method for capturing a collapse mechanism characterized by the presence of a failure surface through earthen materials.

El Sawwaf and Nazir [10] investigated the behavior of vertical anchor plates embedded in reinforced non-cohesive soil. Steel rods with different lengths and diameters placed vertically or inclined at different locations were used to reinforce the sand. The test results indicate that this type of reinforcement significantly increases the stiffness of the soil and the pullout resistance of shallow anchor plates.

The aim of this study is to gain more understanding about the behavior of the sheet pile wall embedded in non-cohesive soil reinforced by utilizing the vertical steel model pile in active zone adjacent to the strip footing.

2. Laboratory model tests

2.1 Model tank, footing and sheet pile wall

The experimental model consists of a tank, the footing, the sheet pile, a loading system, and a settlement-measuring device. The test tank, having inside dimensions of 1000 mm x 310 mm in plan and 600 mm in depth is made of steel with the front wall made of 20 mm thick glass and is supported directly on the steel base. The sides of the tank were braced with vertical and horizontal stiffeners so that no deflection occurs during the loading process. The glass side allows the sample to be seen during preparation. The inside walls of the tank are polished smoothly to reduce any friction with the sand as much as possible.

The rigid footing was made of a steel plate of 50 mm width, 20 mm thickness and 305 mm length. To over come the potential error due to friction on the sides of the tank, the length of the footing was made little smaller than the inside width of the tank to minimize any friction between the metal and the sides of the tank especially during the experimental operation.

The sheet pile wall consists of a flexible steel plate, which is 600 mm in length, and 305 mm in width and embedded 500 mm into the sand bed. The thickness of the sheet pile was 1.92 mm. Table 1 shows the details of the sheet pile section.

A rigid loading frame was used to apply the vertical load to the model strip footing through a hydraulic jack and a 4.5-kN proving ring. Two dial gauges were used to measure the settlement of the footing at each incremental load. Also, dial gauges 0.01 mm mounted in the center of the sheet pile wall at different elevations under the ground surface. These dial gauges were used to measure the lateral displacement of the model sheet pile wall at each increment of the load.

2.2. Backfill material and reinforcement

The sand used in this research is medium to coarse sand, dried and sorted by particle size. Three tests were carried out to determine the specific gravity of the soil particles and producing an average value of 2.657. The maximum and the minimum dry unit weight of the sand were found to be 19.35 and 15.97 kN/m^3 and the corresponding values of the minimum and maximum void ratios were 0.375 and 0.663, respectively. The particle size distribution was determined by using the dry sieving method and the results are shown in fig. 1. The effective size (D_{10}), the mean particle size (D_{50}), the uniformity coefficient (C_u), and the coefficient of the curvature (C_c) for the sand are 0.22 mm, 0.45 mm, 2.636 and 1.25, respectively. Using the Unified Soil Classification system, the sand was determined to be SP (poorly graded sand). The moisture content of the fill sand was about 2.31% during the testing period. In all experiments, the bulk density of the sand was maintained at 18.24 kN/m^3. The corresponding relative density of the sand was approximately 60 %. By using the direct shear test, the angle of the internal friction Ø of the sand estimated to be about 36.5°.

In this investigation, the reinforcement was used in a vertical form of soil reinforcement. The type of this reinforcement technique was the vertical steel model piles. A smooth steel model pile, with a diameter of 6, 9, 12 mm and a total length of 50, 100, 150, and 200 mm was placed in a position between the strip footing and the sheet pile wall to model the vertical reinforcement.

2.3. Experimental setup and test program

The procedures for the preparation of the experimental model are quite similar to those of Selvadurai and Gnanendran [17]. The model sheet pile wall was installed vertically using a special guide system, which holds the sheet pile wall vertically during the installation. A sand layer with thickness equals to 50 mm was placed and observed through the front glass wall up to a height of 500 mm. The unit weight of the sand and its required relative density was controlled by pouring a pre-determined weight of sand into the testing tank to fill each layer, and then the sand surface was leveled and compacted. Special wooden plates and reference markers on the front glass wall were used to form the required sand level. The model footing was then placed at a specific position on the surface of the compacted sand. The model steel piles were installed vertically between the footing and the sheet pile wall by using a special guide system, which held the piles vertically during the installation.

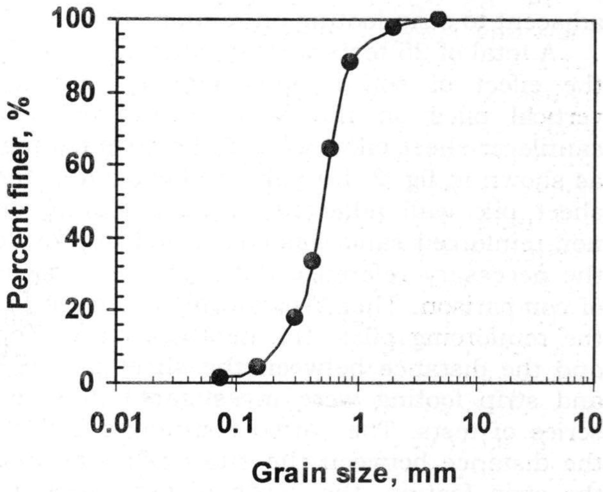

Fig. 1. Grain size distribution curve of the sand used in the tests.

Table 1
Details of the sheet pile section

Type of S.P.W. section	E_{steel} kN/m²	Steel yield strength kN/m²	Section area cm²/m	Moment of inertia, I_{zz} cm⁴/m	EA kN/m	EI kN. m²/m
Steel	210×10^6	430×10^3	19.20	0.059	40.32×10^4	0.124

The guide system was initially clamped in the tank edges and then the piles were pushed by hand to the designed place and spacing through holes with diameters made almost equal to the pile diameter. No visible movement in the sand surface was observed during the installation process. The difference in the relative density of the sand, which occurred during the pile installation due to the difference in the pile lengths or pile spacing, was considered small and thus was neglected. Finally, the sand in front of the sheet pile wall was carefully excavated by using suction of 50 mm steps down to the required depth.

The dial gauges were placed in position at the footing center and along the sheet pile wall. The load was applied incrementally. Each load increment was maintained constant till the vertical displacement of the strip footing stabilized. Fig. 2 shows a typical configuration of the model sheet pile wall adjacent to strip footing on reinforced sand.

A total of 25 tests were conducted to study the effect of soil improvement by utilizing vertical piles on the behavior of both the cantilever sheet pile wall and the strip footing, as shown in fig. 2. Initially the behavior of the sheet pile wall adjacent to strip footing on non-reinforced sand was conducted to provide the necessary reference data for the purpose of comparison. Then, several arrangements of the reinforcing piles, the depth of excavation and the distance between the sheet pile wall and strip footing were investigated in seven series of tests. The varied conditions include the distance between the sheet pile wall and the strip footing, the depth of excavation H, the pile length L, the pile spacing S, the pile diameter D and the distance between the pile row and the strip footing X. The sand relative density D_r = 60%, was kept constant through the research. Table 2 summaries all the tests program with both the constant and the varied parameters illustrated.

3. Results and discussion

Load-settlement curves were obtained for the test model. The ultimate lateral capacity of the sheet pile for non-reinforced and reinforced sand (*q_U non-reinforced*) and (*q_U reinforced*) was obtained from the load-lateral deflection curves. The behavior of the sheet pile due to reinforced soil is represented by using a non-dimensional factor called the Sheet Pile Capacity Ratio (*SPCR*) to assist in comparing the test results. This factor is defined as the ratio of the ultimate lateral capacity of the sheet pile with soil reinforcement (*q_U reinforced*) to the ultimate lateral capacity of the sheet pile in tests without soil reinforcement (*q_U non-reinforced*).

$$SPCR = q_U \text{ reinforced} \, / \, q_U \text{ non-reinforced}. \quad (1)$$

At the same time and from dial gauge readings along the sheet pile wall, the lateral deflections (S_H) were measured. Another factor to consider is the efficiency of the reinforcement on the lateral deflection characteristics of the sheet pile wall. The Lateral Deflection Reduction Factor at ground surface (*LDRF*) is used and defined as:

$$LDRF = (S_H) \text{ reinforced} \, / \, (S_H) \text{ non-reinforced}. \quad (2)$$

The results of the model tests for each parameter are given in tables 3-4 and discussed in the following sections.

Table 2
Model test program

Series	Constant parameters	Variable parameters
I	tests on non-reinforced sand, H/B=5.0	a/B=2, 4, 6
1	H/B=5, a/B=4, S/B=1, L/B=2, D/B=0.18	X/B=0.5,1, 2, 3
2	H/B=5, a/B=6, S/B=1, L/B=2, D/B=0.18	X/B=0.5,1, 2, 3
3	H/B=5, a/B=4, S/B=1, X/B=2, D/B=0.18	L/B=1, 2, 3,4
4	H/B=5, a/B=4, L/B=2, X/B=1, D/B=0.18	S/B=0.5, 1, 1.67, 2.5
5	H/B=5, a/B=4, L/B=2, X/B=2, D/B=0.18	S/B=0.5, 1, 1.67, 2.5
6	H/B=5, a/B=4, L/B=2, X/B=2, S/B=1.0	D/B=0.12, 0.18, 0.24
7	D/B=0.18, a/B=4, L/B=2, X/B=2, S/B=1.0	H/B=3, 4, 5, 6

Note: see fig. 2 for definition of variables
Footing width (B) is kept constant = 50mm.

Table 3
Summary of model test results for non-reinforced sand (series I)

Series	H/B	a/B	q_u (kN/m^2)	S_H (mm)
I	5	2	25.20	3.81
		4	27.90	3.26
		6	34.40	2.23

Distance between S.P.W. and strip footing: a/B = 2, 4, 6.

Depth of excavation: H/B = 3, 4, 5, 6.

Pile length: L/B = 1, 2, 3, 4.

Pile spacing: S/B = 0.5, 1.0, 1.67, 2.5.

Pile diameter: D/B = 0.12, 0.18, 0.24.

Distance between pile row and strip footing: X/B = 0.5,1,2, 3.

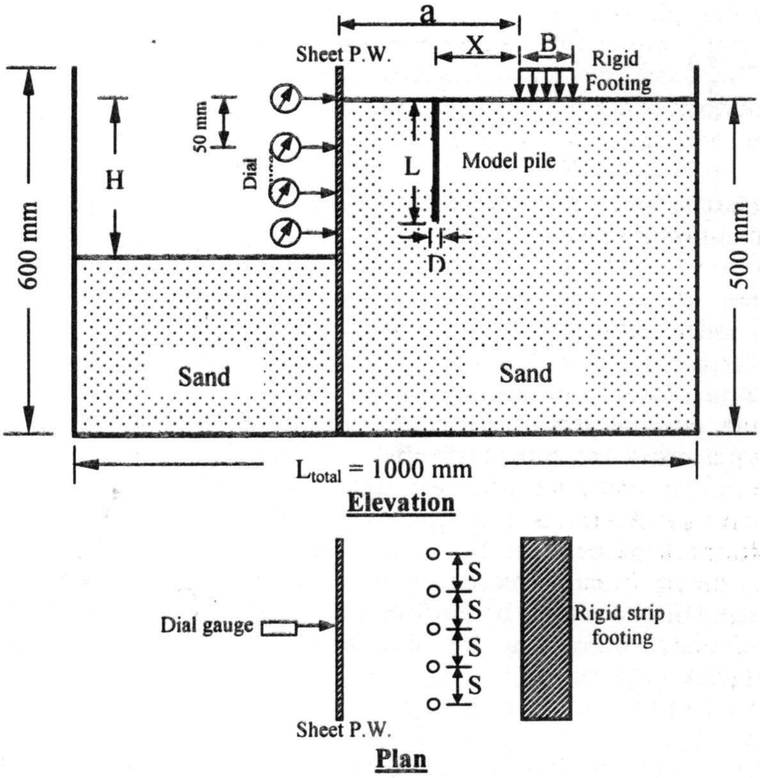

Fig. 2. Schematic diagram of the model test configuration.

Table 4
Summary of model test results for reinforced sand (series 1-7)

Series	H/B	a/B	S/B	L/B	D/B	X/B	q_u (kN/m²)	S_H (mm)	SPCR	LDRF
1	5.0	4.0	1.0	2.0	0.18	0.5	34.82	2.89	1.25	0.886
	5.0	4.0	1.0	2.0	0.18	1.0	36.05	2.47	1.29	0.759
	5.0	4.0	1.0	2.0	0.18	2.0	39.28	2.17	1.41	0.666
	5.0	4.0	1.0	2.0	0.18	3.0	42.88	1.99	1.54	0.611
2	5.0	6.0	1.0	2.0	0.18	0.5	43.42	1.89	1.26	0.851
	5.0	6.0	1.0	2.0	0.18	1.0	46.68	1.53	1.36	0.688
	5.0	6.0	1.0	2.0	0.18	2.0	53.15	1.42	1.55	0.638
	5.0	6.0	1.0	2.0	0.18	3.0	65.08	1.21	1.89	0.545
3	5.0	4.0	1.0	1.0	0.18	2.0	31.84	2.50	1.14	0.768
	5.0	4.0	1.0	2.0	0.18	2.0	39.28	2.17	1.41	0.666
	5.0	4.0	1.0	3.0	0.18	2.0	45.10	1.77	1.62	0.544
	5.0	4.0	1.0	4.0	0.18	2.0	47.40	1.60	1.70	0.492
4	5.0	4.0	0.5	2.0	0.18	1.0	44.71	1.99	1.60	0.610
	5.0	4.0	1.0	2.0	0.18	1.0	36.05	2.47	1.29	0.758
	5.0	4.0	1.67	2.0	0.18	1.0	33.26	2.56	1.19	0.785
	5.0	4.0	2.5	2.0	0.18	1.0	31.95	2.63	1.15	0.807
5	5.0	4.0	0.5	2.0	0.18	2.0	47.80	1.77	1.71	0.543
	5.0	4.0	1.0	2.0	0.18	2.0	39.28	2.17	1.41	0.666
	5.0	4.0	1.67	2.0	0.18	2.0	35.20	2.49	1.26	0.763
	5.0	4.0	2.5	2.0	0.18	2.0	32.80	2.56	1.18	0.785
6	5.0	4.0	1.0	2.0	0.12	2.0	36.60	2.41	1.31	0.740
	5.0	4.0	1.0	2.0	0.18	2.0	39.28	2.17	1.41	0.666
	5.0	4.0	1.0	2.0	0.24	2.0	40.80	1.82	1.46	0.558
7	3.0	4.0	1.0	2.0	0.18	2.0	55.32	1.53	------	------
	4.0	4.0	1.0	2.0	0.18	2.0	48.88	1.85	------	------
	5.0	4.0	1.0	2.0	0.18	2.0	39.28	2.17	1.41	0.666
	6.0	4.0	1.0	2.0	0.18	2.0	33.21	2.73	------	------

3.1. Behavior of the sheet pile wall embedded in non-reinforced sand

From the results of the experimental model strip footing tests on non-reinforced sand adjacent to a sheet pile wall, the variations of the horizontal displacement of wall with vertical stress of strip footing (q) for different footing locations are shown in fig. 3 (series I). The above-mentioned figure shows that at the same vertical stress q, increasing the distance (a) between the sheet pile wall and a strip load decreases the lateral movement of the wall. In addition, the sheet pile capacity increases by increasing the distance (a).

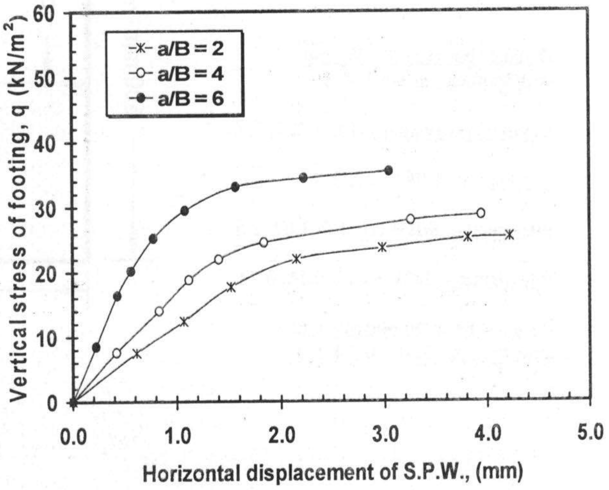

Fig. 3. Vertical stress versus horizontal displacement at different a/B ratios (series I)

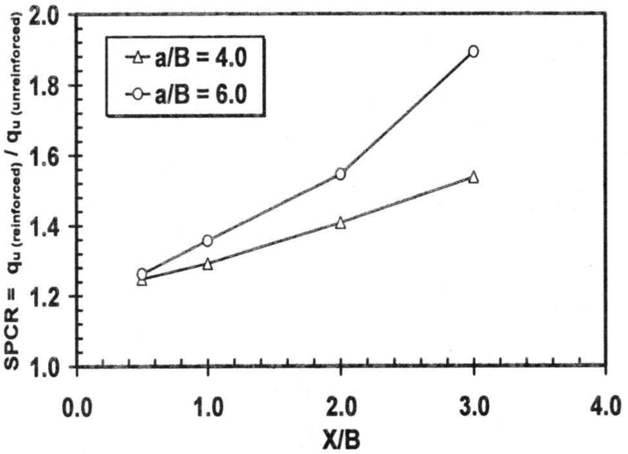

Fig. 4. Variation of SPCR with X/B (series 1-2).

3.2. *The influence of the pile row location on the strip footing*

Two series (1-2) of tests were conducted to study the influence of pile row location between the model strip footing and the sheet pile wall. All variables were kept constant except distance X was varied.

From the results of table 4, it is obvious that the inclusion of vertical reinforcement (model piles) would improve the performance of the sheet pile wall by increasing the ultimate capacity and reducing the movement of the system. The variation of the *SPCR* and the lateral deflection reduction factor *LDRF* with X/B are shown in figs. 4 and 5, respectively. It should be mentioned that increasing the X/B ratio will increase the sheet pile capacity and decreases the lateral deflection of the wall. Fig. 4 shows that installing the row of piles at a distance of X/B ≤ 1.0 has a slight effect on the sheet pile response. Although the curves do not show a peak point which can be considered the optimal location of piles, it can be concluded that the greatest benefit can be obtained by placing the row of piles as close as possible to the sheet pile wall. However, for practical reasons, the pile row located at (a/2) is considered the best location that gives the maximum gain in the sheet pile capacity. There is no room for doubt, as shown in fig. 5, that the closeness of the pile rows to the sheet pile decreases the lateral deflection of the wall. This can explained by the fact that these vertical piles resist the lateral displacement and increase the lateral confinement of soil particles behind the wall. Therefore, installing the pile rows closer to the sheet pile leads to a greater soil mobilized lateral resistance behind the wall and hence, a greater wall lateral movement resistance.

3.3. *The influence of the pile length*

One series of tests were carried out on a sheet pile wall with H/B = 5.0, a/B = 4.0, S/B = 1.0, and X/B = 2.0 to study the effect of the pile length on the improvement of the behavior of the wall adjacent to the surcharge strip load. In order to appreciate the effect of the pile length, the sheet pile capacity ratio SPCR, is plotted in fig. 6 for different pile lengths. The figure clearly demonstrates the significant effect of the pile length on improving the sheet pile capacity. The sheet pile capacity increases when increasing the pile length. It is clear that there is an optimum pile length to the footing width ratio L/B of about 3.0. When L/B > 3.0, the performance of the pile length becomes rather minimal and appears that the pile length has no appreciable effect on the sheet pile capacity. This can be explained by that increasing the pile length leading to more stability for the pile and greater resistance for the lateral movement of the soil particles behind the sheet pile wall. For a pile length ratio higher than 3.0, L/B > 3.0, there is no appreciable effect on the sheet pile capacity as the complete confinement condition of soil particles was achieved.

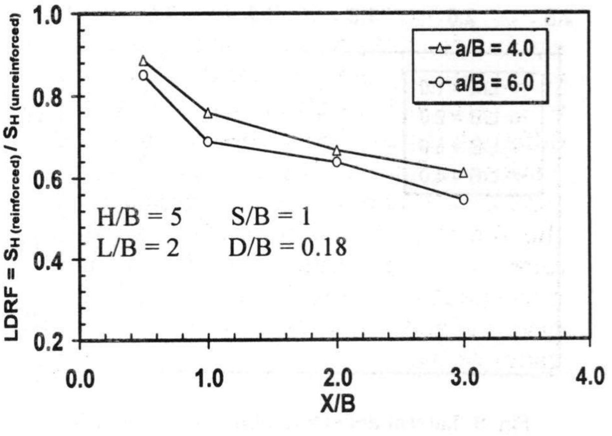

Fig. 5. Variation of LDRF with X/B (series 1-2).

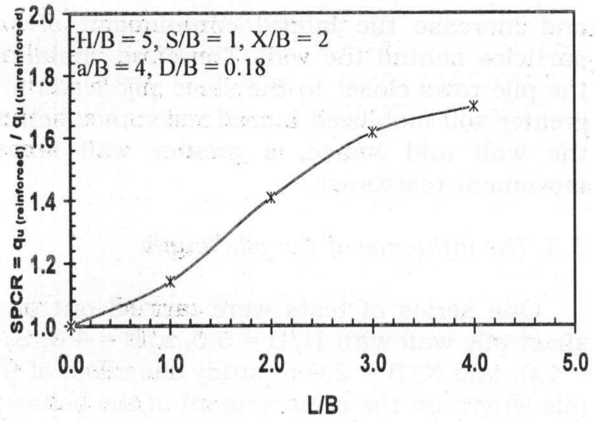

Fig. 6. Variation SPCR with normalized pile length LB (series 3).

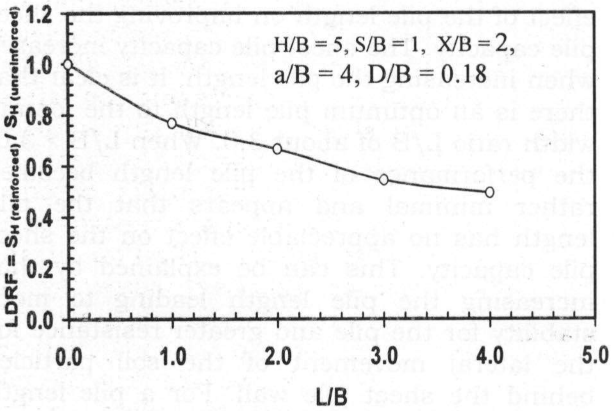

Fig. 7. Variation of LDRF with normalized pile length L/B (series 3).

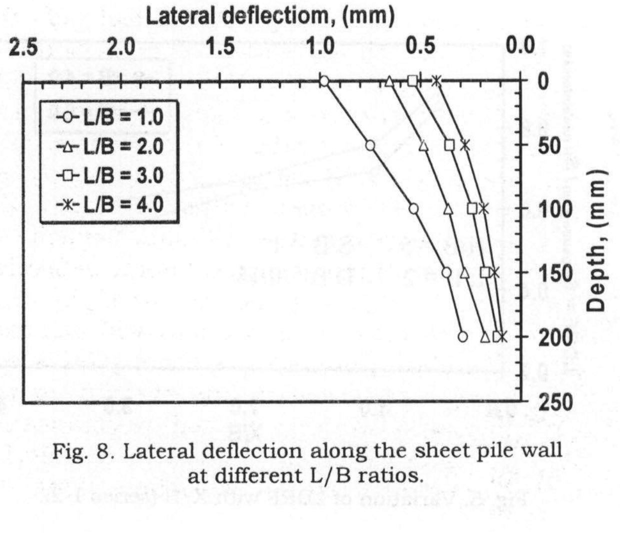

Fig. 8. Lateral deflection along the sheet pile wall at different L/B ratios.

In the same way, fig. 7 shows the variation of the lateral deflection reduction factor LDRF with the pile length. It is obvious that using the vertical pile with L/B = 1.0, the maximum lateral deflection of the sheet pile wall at ground surface is reduced by about 23% with respect to the case of no reinforcement. For a pile length ratio higher than 3.0, L/B > 3.0, the performance of the pile length becomes rather minimal on the lateral deflection of the sheet pile wall.

From the dial gauge reading along the free length of the sheet pile wall, fig. 8 shows the lateral deflection along the sheet pile due to a surcharge strip load that equals 23.60 kN/m^2 at different L/B ratios. The figure also demonstrates that increasing the pile length not only decreases the maximum lateral deflection at ground surface but also decreases the lateral deflection along the length of the sheet pile wall.

3.4. *The influence of pile spacing*

To investigate the effect of pile spacing, tests were conducted for a sheet pile wall adjacent to a surcharge strip load with a/B=4.0, H/B= 5.0, L/B = 2.0, and D/B=0.18. For each pile spacing ratio S/B, the vertical piles were placed at two different distances from the footing edge X/B = 1.0 and 2.0.

The variation of *SPCR* and LDRF with normalized pile spacing S/B for different X/B distances is shown in figs. 9-10 respectively. The results clearly indicate that decreasing the pile spacing leads to a significant improvement in the behavior of the sheet pile wall. By decreasing the pile spacing, the clear distances between them becomes smaller leading to a greater confinement condition for soil particles behind the wall. As the pile spacing decreases, the piles become more like a continuous barrier and the influence of soil arching becomes more pronounced, so the soil does not reach the limit state until the soil is deformed greatly. Therefore, as shown in Fig. 9, decreasing the S/B ratio increases the sheet pile capacity ratio. The same trend can be observed for the pile position X/B = 1.0 and 2.0. This increase in the sheet pile capacity is pronounced for pile spacing ratios less than 2.0 (S/B < 2.0). At (S/B) > 2.0 the improvement in the sheet pile capacity is not appreciable.

Fig. 10 shows the variation of the lateral deflection reduction factor with pile spacing S/B. It is clear that there is a great effect of pile spacing on the lateral deflection of the sheet pile. So; the maximum lateral deflection for the sheet pile wall decreases as the distance between piles becomes closer. This can be explained by the fact that closer pile spacing leads to a higher initial stiffness for granular soil and a greater pile resistance for the lateral displacement by the arching effect, as reported by Chen and Martin [8].

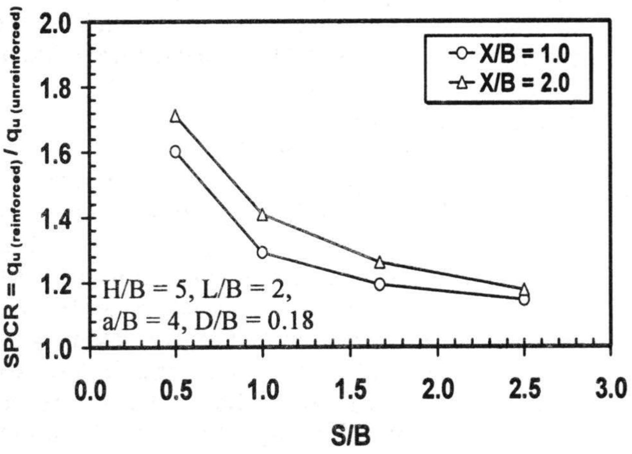

Fig. 9. Variation of SPCR with normalized pile spacing S/B (series 4-5).

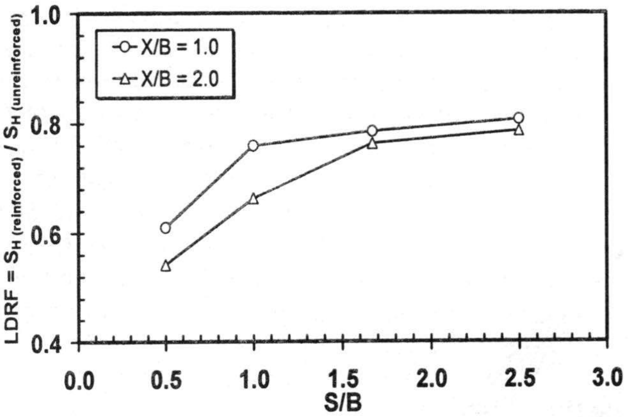

Fig. 10. Variation of LDRF with normalized pile spacing S/B (series 4-5)

Their results reveal that pile spacing is significant in the formation and shape of the arching zone for a row of piles embedded in granular soil under lateral active loading and lateral soil movement.

3.5. The influence of the pile diameter

The objective of these tests was to investigate the effect of the pile diameter on the improvement of the behavior of the sheet pile wall (series 6). Piles were placed at constant spacing equal to S/B = 1.0 and at a distance from the footing edge of X/B = 2.0. Pile diameters (D) of 6.0, 9.0, and 12.0 mm were used in the tests. The values of the sheet pile capacity ratio and the lateral deflection reduction factor obtained from these tests are shown in table 4. It can be noticed that the SPCR increases as the pile diameter increases. At the same time, increasing the pile diameter has a greater effect in decreasing the lateral deflection of the sheet pile wall. This is due to the fact that as the pile diameter increases its resistance to the lateral movement becomes greater and hence, the sheet pile capacity ratio increases and the lateral deflection of the sheet pile decreases. However, increasing the pile diameter leads to increasing the sheet pile capacity until a pile diameter ratio D/B= 0.18. At ratio (D/B > 0.18) it appears that the pile diameter has no appreciable effect on the sheet pile capacity.

3.6. The influence of excavation depth

In order to study the effect of the excavation depth H, series of tests with an excavation depth ratio of H/B of 3.0, 4.0, 5.0, and 6.0 were carried out using the same a/B ratio of 4.0, the S/B ratio of 1.0, the L/B ratio of 2.0 and the X/B ratio of 2.0 (series 7). As shown in table 4, it is clear that increasing the H/B ratio decreases the ultimate capacity of sheet pile and increases the lateral deflection of the wall. This can be explained by that increasing the excavation depth will decrease the embedded depth of the sheet pile in soil leading to a decrease in the stability of the sheet pile wall and in the small resistance for lateral movement. As shown in fig.11, measurements of lateral deflection along the sheet pile wall at a vertical footing stress q=23.60 kN/m^2 showed that with the increase of the excavation depth H, the lateral deflection along the sheet pile increases. Therefore, it was concluded that increasing the excavation depth affects the shape of the lateral deflection along the sheet pile wall and decreases the effect of vertical reinforcement. This may be explained by the fact that increasing the excavation depth decreases the passive resistance in front of the wall, which gives the stability for the sheet pile. Therefore, the contribution of vertical reinforcement in increasing the stability of wall becomes relatively less and hence, the improvement is not significant. This observation was consistent with that reported by Timothy et al. [19].

4. Numerical analysis

Numerical study using the Finite Element Method (FEM) was carried out to examine conditions, which have not been modeled experimentally. The FEM can be particularly useful for identifying the patterns of deformations and stress distribution in the soil at all loading stages. Three dimensional analysis using elasto-plastic soil models and the commercial software package COSMOS/M professional version 2.6 (2000) were carried out.

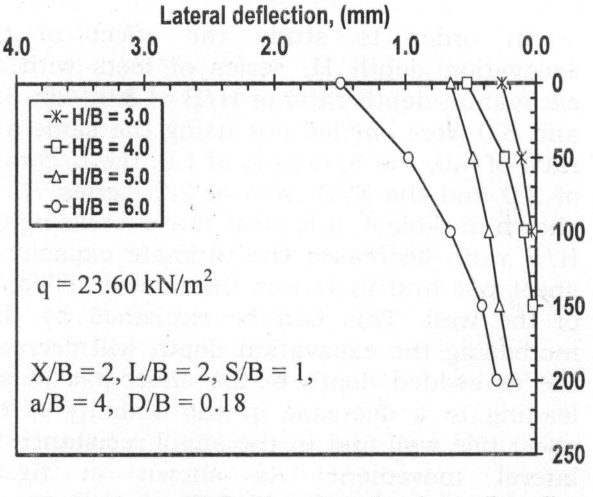

Fig. 11. Lateral deflection along the sheet pile wall at different H/B ratios (series 7).

All the finite element calculations were based on 8-node isoperimetric three-dimensional solid elements with three translation degrees of freedom. The total length, width, and height of the mesh were taken 1000, 310, and 500 mm respectively as modeled in the experimental work. The unequal-spaced nodes used in both the horizontal and vertical directions, did not affect the element output results as stated in the user's manual of the program.

The finite element mesh of reinforced sand with 6 discrete vertical piles is shown in fig.12. The mesh consists of 12870 brick elements with 15263 nodes. The upper plane of the mesh was left free, the other side boundaries and the bottom planes were fixed.

4.1. Material properties

Three dimensional 8-node isoparametric vertical solid elements have been used in the analyses to simulate the model piles and the sheet pile wall. The model pile and the sheet pile wall were assumed linear elastic, with elastic modulus (E_p = 210 x 10^6 kN/m^2) and Poisson's ratio (ν = 0.3). The sand was assumed to have associative characteristics, following Drucker-Prager's model [9] (elasto-plastic soil model) with an associative flow rule. The material parameters involved in the models can be easily determined from standard laboratory tests by using a well-defined procedure and many of these parameters have a broad database. In using this material model, small strains assumption is made as stated in the user's manual of the program. The dilatancy angle (ψ) of the sand was ($\psi=\phi-30^0$). The friction angle of the footing-soil interface was taken at δ= (0.50 to 0.75) ϕ, where (ϕ) is the angle of the internal friction of the sand. The friction coefficient between the pile and sand, (μ) used in defining the gap-friction elements, is $\mu=\tan\delta$. In the analyses, no-tension analysis was applied to the sand in which the minimum principal stresses were kept positive for each element. The iterative procedure was based on the modified Newton Raphson method.

Thin friction 3D brick elements were inserted between the footing and the sand, the sheet pile wall and the sand, the model pile

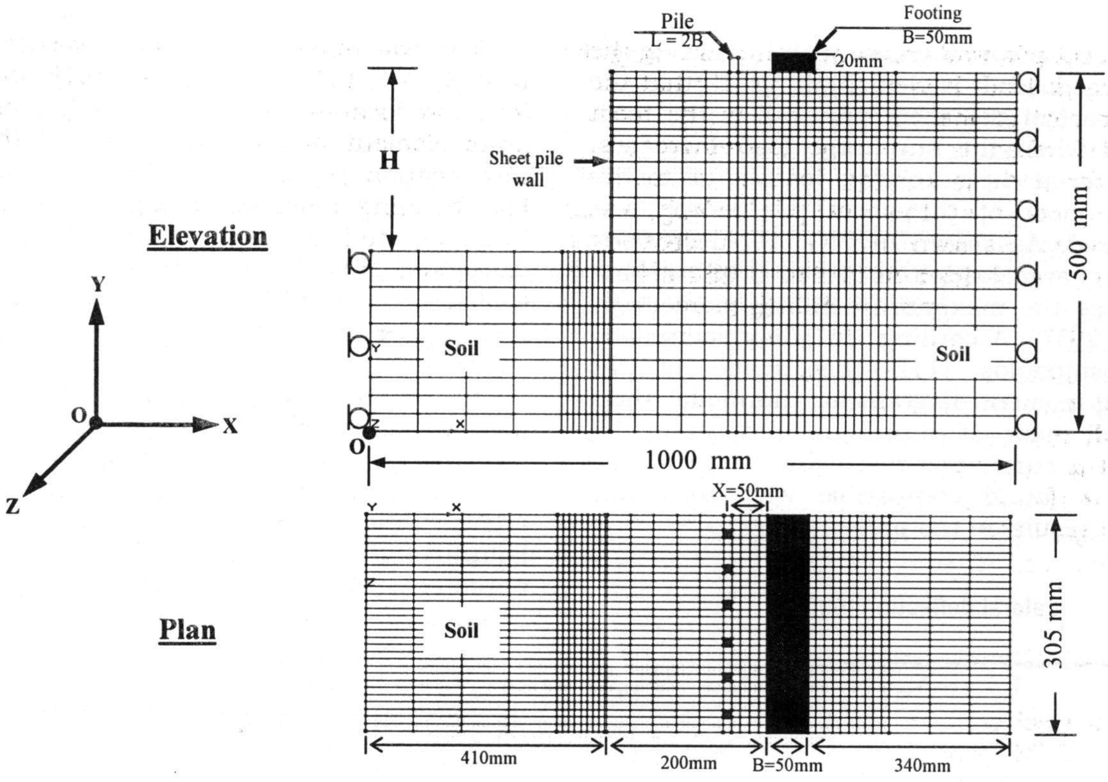

Fig. 12. Mesh used in finite element analysis for reinforced soil with 6 piles.

and the sand from all sides in order to consider slippage at the soil-structure interface. The frictional elements had the same material constants of those of the surrounding sand layer except for $\psi = 0^0$, where (ψ) is the angle of dilatancy.

4.2. Loading and output

Load increments are used in all the load stages applied in the tests. In general, 10 increments are given. The iterative procedure in the analysis was based on the modified Newton Raphson method. Closer intervals are used at higher loads to reflect the nonlinear response better. At each load step, the main outputs in FEM solution were the load-deformation behavior, stresses at nodal points, and the type of behavior at every node, whether elastic or plastic. Since the outputs are in the form of stresses, and as the sheet pile cross-section is considered, the bending moment along the sheet pile wall was calculated as:

$$M_{zz} = \sigma_{zz} I_z / x. \quad (3)$$

Where, M_{zz} is the bending moment about the Z-axis, σ_{zz} is the output stress from the solid element in the Z-direction, I_z is the sheet pile cross section moment of the inertia about the Z-axis, and x is half the thickness of sheet pile wall. Complete results of finite element solution for the effect of vertical reinforcement on the behavior of the sheet pile wall adjacent to the strip load for different cases is introduced in this part.

4.3. Results of numerical analysis

Results of the finite element analyses are shown in figs. 13 – 19. Figs. 13 and 14 show the effect of the surcharge load magnitude for non-reinforced soil on the lateral deflections and the bending moments along the sheet pile wall when placed at a distance of 200 mm from the edge of a 250 mm deep excavation respectively. As expected, both figures demonstrate that the lateral deflections (x-direction) and the bending moments along the sheet pile wall increase with increasing the surcharge load. It is clear from fig. 13 that the upper part of the sheet pile wall is the most affected when the surcharge load increases. Therefore, at the surcharge load equal to 40 kN/m², most of the sheet pile length was influenced. As shown in FIG. 14, decreasing the surcharge load from 40 to 26.67 kN/m² decreases the maximum bending moment by about 29%. According to Georgiadis and Anagnostopoulos [11], the shape of the bending moment diagram for the model sheet pile wall made of aluminum and set in dry sand at a surcharge load equal to 12 kN/m² which is found compatible with the finite element results of the present work.

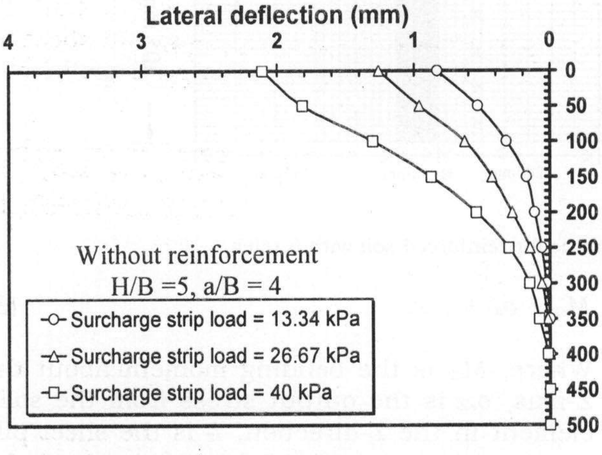

Fig. 13. Deflection along the sheet pile at different surcharge strip load.

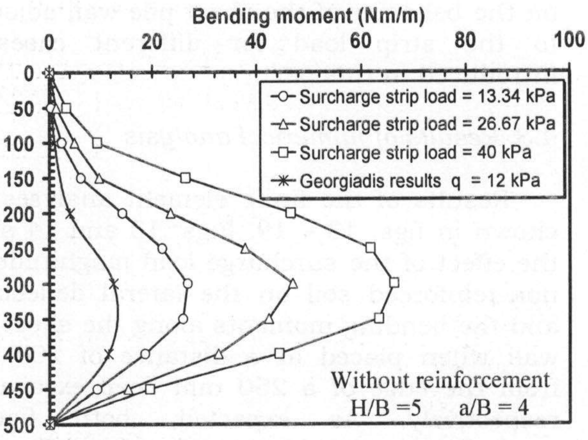

Fig. 14. Bending moment along the sheet pile at different surcharge strip load.

The soil reinforced by using vertical piles with S/B=1, L/B = 2.0, D/B = 0.18 and X/B (pile row location) was variable. By using the finite element method, the effect of the pile row location (X/B) on the lateral deflections and bending moments along the sheet pile wall was studied. The variation of the lateral deflections and bending moments along the wall are shown in Figs. 15 and 16 and that the surcharge strip load equals 26.67 kN/m² placed at a/B = 4.0 and H/B = 5.0.

It may be seen from these figures that the presence of vertical reinforcement reduces the lateral deflections and bending moments along the sheet pile wall. Since the lateral deflection and bending moment are the main causes of failure of the sheet pile wall, using vertical reinforcement has improved the overall behavior of the sheet pile wall.

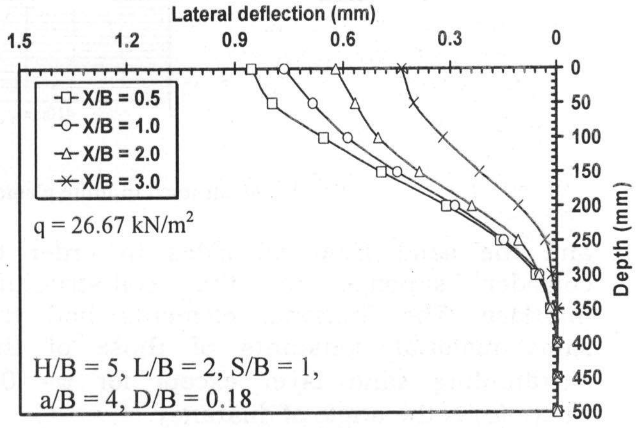

Fig. 15. Deflection along the sheet pile a different X/B ratios.

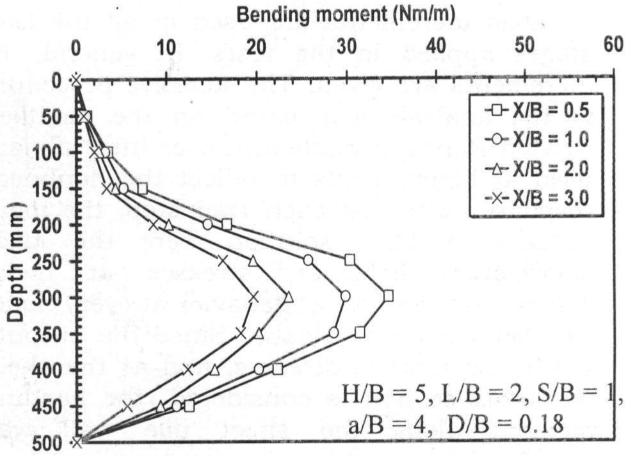

Fig. 16. Bending moment along the sheet pile at different X/B ratios.

It should be mentioned that the closeness of the pile row to the sheet pile wall (X/B increases) caused a significant decrease in the lateral deflections and bending moments along the sheet pile wall. The percentage decreases in the maximum lateral deflections and bending moments along the sheet pile wall of about 49% and 43% for X/B increased from 0.5 to 3.0 respectively.

As shown in fig. 17, a comparison between the theoretical and experimental results is made in the form of a variation of the maximum lateral deflection of the sheet pile wall at ground surface with X/B ratio. It is clear that increasing the (X/B) ratio will decrease the maximum lateral deflection on the sheet pile wall for theoretical and experimental results. The closeness of the pile row to the sheet pile wall (X/B increase), will improve the behavior of the sheet pile by reducing the lateral earth pressure from the soil and the additional earth pressure due to surcharge strip load. This can be attributed to that the pile row will resist the lateral earth pressure by a greater confinement condition for soil particles before it influences the sheet pile wall.

Theoretical investigation was performed to study the influence of the pile length on the lateral deflections and bending moments of the sheet pile wall at the surcharge strip load equal 26.67 kN/m^2. The length of the vertical piles was varied from L/B = 0.0 (no reinforcement) to L/B = 4.0. Fig. 18 shows the variation of maximum lateral deflection of the sheet pile wall with the L/B ratio. Not surprisingly, the figure indicates that the length of the vertical reinforcement has a major influence on the decrease in maximum lateral deflection.

It is obvious that the maximum reduction in lateral deflection is noticed at L/B varied from 1.0 to 3.0. When the L/B ratio is higher than 3.0, (L/B > 3), the maximum lateral deflection of the sheet pile wall decreases with minor value. This can be attributed to the maximum lateral surcharge pressure on the sheet pile wall by using an elastic solution observed at a depth of about B to 3B under ground level (Georgiadis and Anagnostopoulos [11]). The results of the theoretical study are in good agreement with the experimental results. In the same way, as shown in fig. 19, increasing the L/B ratio decreases the maximum bending moment along the sheet pile wall. It is obvious that using vertical pile reinforcement with the L/B equal to 2.0 is adequate to reduce the maximum bending moment drastically. At L/B = 2.0, the maximum bending moment reduces relative to the case of a non-reinforcement by about 36% to 58% with respect to the pile row location. The additional series of finite element analyses were conducted to examine the scaling effect and to give useful data pertaining to prototype scale. The size of the footing, fill's thickness, piles dimensions and mesh boundary dimensions were increased 20 times to simulate prototype scale behavior (i.e., footing width = 1.0 m, width of mesh = 20 m, depth of mesh = 10 m, and pile diameter = 0.2 m). The properties of the sand fill, piles, and sheet pile remain the same as in the original model scale studies.

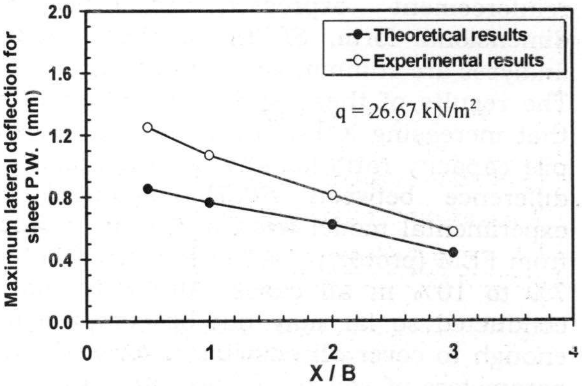

Fig. 17. Maximum lateral deflection versus X/B for experimental and theoretical results

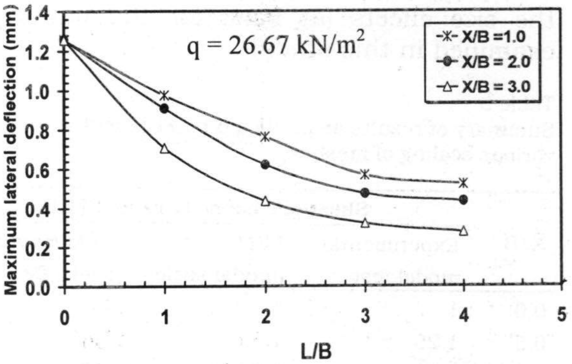

Fig. 18. Maximum lateral deflection versus L/B for different X/B ratios

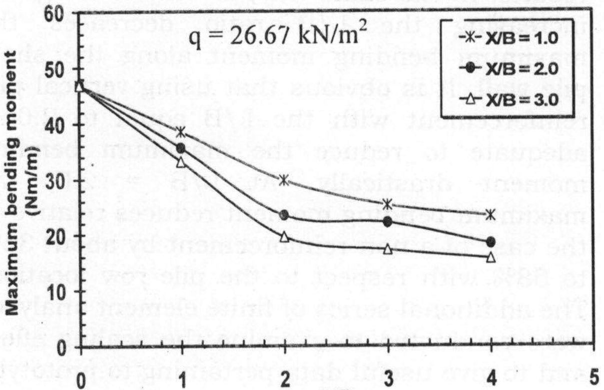

Fig. 19. Maximum bending moment versus L/B for different X/B ratios

The pile row location X/B was varied and the other parameters were kept constant at S/B = 1.0, D/B = 0.18, L/B = 2.0, H/B = 5.0, and a/B = 4.0. The results of ultimate lateral capacity of the sheet pile with soil reinforcement expressed in the non-dimensional form, *SPCR*, for these series of analyses are summarized in table 5.

The results of these series of tests exhibited that increasing X/B ratio increases the sheet pile capacity ratio for any scaling model. The difference between *SPCR* calculated from experimental model tests and that calculated from FEM (prototype scale) is ranged between 7% to 10% in all cases. Although analyses conducted so far may not be comprehensive enough to cover all possible ranges of scaling parameters of soil reinforcement with vertical piles, results from these limited numbers of finite element analyses seem to indicate that the predicted results are not too sensitive to the size effects (at least for the parameters examined in this study).

Table 5
Summary of results as predicted by FEM with various scaling of meshes

X/B	Sheet pile capacity ratio, SPCR		
	Experimental model test	FEM (model scale)	FEM (prototype scale, B=1.0 m)
0.0	1	1	1
0.5	1.25	1.32	1.36
1.0	1.29	1.34	1.38
2.0	1.41	1.50	1.55
3.0	1.54	1.61	1.69

5. Scale effects

As in all small-scale model tests, particularly in sand, scale effects need to be considered. There are several important factors that invalidate the use of small-scale models, which have been constructed in sand and tested at 1g. These include the highly exaggerated influence of dilatancy at low stress present in a small-scale model (Vesic [21]), side friction on the model container walls, boundary conditions, and the particle size of sand relative to footing width, model pile diameter which is referred to as the "Particle Size Effect".

At the beginning with respect to dilatancy angle, Bolton [6] stated that relative density of sand has a major effect on dilatancy angle. Here increasing the relative density will exhibit far greater dilatancy at low stress (small-scale model). Georgiadis and Anagnostopoulos [12] demonstrated that at relative density 60% and stress levels varying from 1.0 kN/m^2 to 5.0 kN/m^2 in the small-scale models, the dilatancy angle varied from 25° to 20° respectively. At the same time, the angle of dilatancy calculated as ($\psi = \varnothing - 30$) equal to 11.5°. Therefore, the stress level has a major effect on dilatancy angle of the sand particularly for comparison between small-scale model data and prototype scale chosen for numerical model with relatively dense sand with D_r = 60%. Thus, extreme caution is therefore urged in using data from small-scale mode.

The second factor is side friction developed on the model container walls, Bransby and Smith [7] pointed out that; with smooth side walls and relatively wide tank, side friction does not have a significant effect on the active earth pressure or the velocity field in the active state. In this research, the inside walls of the tank are polished smoothly to minimize friction with the sand domain as much as possible. According to Westergaard [22] the pressure isobars of a strip footing extend deeply five times the footing width. Azam et al. [2] conducted that the effect of the bedrock on the footing performance becomes negligible when the soil layer thickness approaches approximately six times the footing width. Therefore, for neglecting the effect of boundary conditions, the length of the container was taken 20 times the footing width and the soil layer thickness was taken ten times the footing width. Also the longer side in front of the tank was provided with removable glass plate because of its relatively high modulus of deformation, and low coefficient of friction (Balachandran [3]).

The third factor, one of the most important effective factors in the test results, is the "Particle size effect" of sand relative to footing width (Ovesen [16]; Tatsuoka et al. [18]). The ratio of the mean particle size to the footing width, D_{50}/B, which decreases with an increase in the footing width could affect the bearing capacities. Kusakab [14] summarized test data and indicated that the particle size effect on the bearing capacity becomes less marked for a D_{50}/B ratio smaller than 1/100. This suggests that the particle size effect in this study should be small, since the ratio for the model used was ($D_{50}/B = 0.009$). In the present tests, the 6, 9, 12-mm diameters for model piles were 13.34, 20, and 26.67 times grater than the mean particle size (D_{50}) for the sand of 0.45-mm, which satisfies the criterion proposed by Ovesen [16], who recommended ratios in excess of (15 – 30) to avoid scale effects.

6. Conclusions

A series of experimental tests and numerical analyses on the model cantilever sheet pile walls subjected to the surcharge strip loads were carried out to investigate the effect of discrete vertical reinforcement in active zone on the behavior of the sheet pile wall embedded in granular soil. The following conclusions can be derived from the test results and their analysis:

1- The results of the model tests and numerical analyses have shown that the provision of the soil reinforcement (row of vertical piles) behind the sheet pile wall has a significant effect in increasing the ultimate lateral capacity of the sheet pile embedded in granular soil. The sheet pile capacity improvement significantly depends on the location of the pile row relative to the sheet pile, pile's length, pile's spacing, pile's diameter and the excavation depth in front of the wall.

2- The closeness of the pile rows to the sheet pile wall decreases the lateral movement and increases the ultimate lateral capacity of the wall. The sheet pile capacity improvement becomes negligible when the piles row is placed at a large distance away from the wall ($X/B \leq 1.0$) where X is the distance between the piles row and the strip footing and B is footing's width. For practical reasons, piles row located in the middle, between the footing and the sheet pile could be considered the best location for a maximum gain in sheet pile capacity.

3- A significant increase in the sheet pile capacity ratio is gained when the pile length is increased. The optimum pile length to the footing width ratio (L/B) is about 3.0. When $L/B > 3.0$, the performance of the pile length in improving the sheet pile becomes rather minimal and it appears that pile length has no appreciable effect on the ultimate capacity and lateral movement of the sheet pile wall.

4- As the pile spacing decreases, piles behave more like a continuous barrier and the influence of soil arching becomes more pronounced. Decreasing the pile spacing/footing width ratio (S/B) leads to an increase in the sheet pile wall capacity and to a decrease in the lateral deflection of the wall. Increasing the sheet pile capacity is pronounced for a pile spacing ratio less than 2.0 ($S/B < 2.0$), for ratio ($S/B > 2.0$) the improvement in the sheet pile capacity is not appreciable.

5- Increasing pile diameter improves the ultimate capacity of the sheet pile wall and at the same time decreases the lateral deflection of the wall.

6- Soil reinforcement by utilizing model piles behind the sheet pile wall is significant in improving the response of the wall when the excavation depth (H) is less than or equal to half of the sheet pile length.

7- The finite element method helped in better understanding of failure patterns, of the deflection along the sheet pile and bending moments along the wall for both non-reinforced and reinforced sand. The analyses show better agreement with the experimental results in that the vertical reinforcement between the wall and the footing had a considerable effect on the behavior of sheet pile wall.

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References

[1] F.M. Abdrabbo and R.M. El-Hansy, "Strengthening of Loaded Footing-Soil System", Alexandria Engineering Journal, Vol. 32 (4), pp. 193-198 (1993).

[2] G. Azam, C.W. Hsieh and M.C. Wang, "Performance of Strip Footing on Stratified Soil Deposit with Void", Journal of Soil Mechanics and Foundations, ASCE, Vol. 117, SM5, pp. 753-772 (1991).

[3] S.B. Balachandran, "Modelling of Geosynthetic Reinforced Soil Walls," PhD Thesis, the University of Cambridge (1996).

[4] R.H. Bassett and N.C. Last, "Reinforcing Earth Below Footings and Embankments", Proc. Symp. On Earth Reinforcement (1978).

[5] Beton Kalender, Verlag von Wilhelm Ernst and Sohn, Munich, Germany (1983).

[6] M.D. Bolton, "The Strength and Dilatancy of Sands", Geotechnique, Vol. 36 (1), pp. 65-78 (1986).

[7] P.L. Bransby and I.A.A. Smith, "Side Friction in Model Retaining Wall Experiments", Journal of Geotechnical Engineering, ASCE, GT7, pp. 615-632 (1975).

[8] C. Chen and G. Martin, "Soil-Structure Interaction for Landslide Stabilizing Piles", Computers and Geotechnics, Vol. 29 (2002).

[9] D.C. Drucker and W. Prager, "Soil Mechanics and Plastic Analysis of Limit Design", Q. Appl. Math., Vol. 10, pp.157-164 (1952).

[10] M. El Sawwaf and A. Nazir, "The Effect of Soil Reinforcement on Pullout Resistance of an Existing Vertical Anchor Plate in Sand", Computers and Geotechnics, Vol. 33, pp. 167-176 (2006).

[11] M. Georgiadis and C. Anagnostopoulos, "Lateral Pressure on Sheet Pile Walls Due to Strip Load", Journal of Geotechnical and Geoenvironmental Engineering, January, pp. 95-98 (1998).

[12] M. Georgiadis and C. Anagnostopoulos, "Displacement of Structures Adjacent to Cantilever Sheet Pile Walls", Soil and Foundations, Vol. 39 (2), April, pp. 99-104 (1999).

[13] S.K. John and M.B. Richard, "Effect of Live Load Surcharge on Retaining Walls and Abutments," Journal of Geotechnical and Geoenvironmental Engineering, October. Vol. 128 (10), pp. 803-813 (2002).

[14] O. Kusakabe, "Foundations, Chapter 6 of Geotechnical Centrifuge Technology, (ed. by Taylor, R.N.)", Blackie Academic and Professional, London (1995).

[15] M.A. Mahmoud and F.M. Abdrabbo, "Bearing Capacity Tests on Strip Footing on Reinforced Sand Subgrade", Can. Geotechnical Journal, Vol. 26 (1) (1989).

[16] N.K. Ovesen, "The Scaling Low Relationship- Panel Discussion", Procedure 7th European Regional Conference on SMFE, pp. 319-323 (1979).

[17] A.P.S. Selvadurai and C.T. Gnanendran, "An Experimental Study of a Footing Located on a Slope Fill: Influence of a Soil Reinforcement Layer", Can. Geotechnical Journal, Vol. 26, pp. 467-473 (1989).

[18] F. Tatsuoka, M. Okahara, T. Tanaka, K. Tani, T. Morimoto and M.S.A. Siddiquee, "Progressive Failure and Particle Size Effect in Bearing Capacity of a Footing on Sand", Procedure of Geotechnical Engineering Congress, ASCE, Geotechnical Special Publication, pp.788-802(1991).

[19] Y.L. Timothy, I.B. Ronaldo, G.D. Blaise and L.M. Richard, "Capturing Strain Localization Behind A Geosynthetic-Reinforced Soil Wall", International

Journal for Numerical and Analytical methods in Geomechanics, Vol. 27, pp. 425-451 (2003).

[20] B.P. Verma and A.N. Char, "Bearing Capacity Tests on Reinforced Sand Subgrades", Journal of Geotechnical Engineering Div., Vol. 112 (1986).

[21] A.S. Vesic, "Analysis of Ultimate Loads of Shallow Foundations", Journal of Soil Mechanics and Foundations, ASCE, Vol. 99 (1), pp. 45-71 (1973).

[22] H.M. Westergaard, "A Problem of Elasticity Suggested by a Problem in Soil Mechanics: Soft Material Reinforced by Numerous Strong Horizontal Sheets, in Contributions to the Mechanics of Soils," Stephen Timoshenko 60th Anniversary Volume, New York (1938).

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