Recent Advances in Laterally-Loaded Piles within Mechanically-Stabilized Earth Walls

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Abstract. Pile foundations have been increasingly installed within mechanically-stabilized earth walls (MSE) on rocks or compressible soils to support structural loads. Integral abutment bridges, sound walls, and traffic signs are common examples of the structures supported by pile foundations installed within or behind MSE walls. These structures are often subjected to lateral loads resulting from earthquakes, traffic loads, wind loads, and/or thermal expansion and contraction of bridge girders. Typical approaches available to design MSE walls are limited to MSE walls without pile foundations present within reinforced fill. To minimize the interaction between piles and the MSE wall, designers often suggest to place the piles at a distance of six to eight times the pile diameter and/or isolate the piles from the MSE wall by using corrugated pipes. These suggested designs lead to increasing the cost of projects by increasing the length of bridge spans or the diameter of piles and requiring pile embedment. Recently, several studies have been conducted to understand the interaction between piles and MSE walls when the piles are constructed within and close to wall facing. This paper provides a literature review on full-scale tests, reduced-scale tests, and numerical studies of piles constructed within or behind MSE walls. The review will focus on the effects of three key influence factors on lateral capacities of laterally-loaded piles and facing deflections of MSE walls including the pile location behind the wall facing, the ratio of the reinforcement length to the wall height, and the stiffness of the reinforcement layer. This paper will also discuss the available approaches to estimate the forces in the reinforcement layers and the lateral earth pressures behind the MSE wall facing due to the laterally-loaded piles.

1. Introduction

Pile foundations are often subjected to lateral loads in geotechnical applications. For design purposes, analyzing the responses of laterally loaded piles is required to estimate the ultimate lateral load capacities and displacements of the piles. Several methods are available in the literature to estimate the ultimate lateral load capacity and the displacement of a pile in soil. Among these methods are Prescription Value methods [1,2], Limit Equilibrium (LE) methods [3,4,5,6], and Elasticity Linear and Nonlinear methods [5,6,7,8,9,10]. However, all the analytical solutions in these methods were derived...
for piles in a homogenous medium or in layered soils without the presence of MSE wall facing close to the piles. Robertson et al. [11] observed the displacements induced by the laterally loaded pile within the range of six to eight times the pile diameter (D) and any structure within this range could affect the lateral capacity of piles and be also influenced by the piles. Figure 1 shows an example of a laterally-loaded pile within an MSE wall.

Figure 1. Integral abutment bridge (after Arenas, 2010)

To minimize the interaction between the piles and the MSE walls, designers suggested using a corrugated pipe (sleeve) around the pile to isolate the effect of the pile from the MSE wall. Ng and Chung [12] developed a three-dimensional numerical model to investigate the effect of sleeving on load transfer from a laterally loaded pile onto wall displacements, lateral earth pressures behind the wall, and the factors of safety of the wall against sliding and overturning. The numerical results showed that the lateral earth pressures induced by an unsleeved pile were higher than those by a sleeved pile. For example, at the lateral load of 5000 kN, the lateral earth pressures from the unsleeved pile at the shallow depths were between $K_p$ and $3K_p$ ($K_p$ is the Rankine passive earth pressure coefficient) multiplied by the vertical stresses with a maximum lateral pressure of 145 kPa at the depth of 2.5 m below the ground surface. After placing a sleeve around the pile, the maximum lateral earth pressure dropped to approximately 90 kPa. Khodair and Hassiotis [13] also developed a three-dimensional model of an integral bridge abutment to investigate the thermal loading effect on the pile as well as the soil surrounding the pile. The numerical model was verified with the results of a fully instrumented abutment and then a parametric study was conducted to investigate the influence of the diameter of the sleeve surrounding the pile. Their results revealed that the axial stresses in the pile decreased with increasing the sleeve diameter and the earth pressures at the perimeter of the sleeve were almost zero regardless the size of the sleeve. Another numerical study conducted by Arenas [14] to evaluate the benefit of the corrugated steel pipes around the abutment piles showed that the use of steel pipe sleeves had not reduced shear forces and moments of the piles. Even though the use of sleeve might significantly reduce the stresses from the piles, the overall cost will increase due to the increase of their diameters and embedded lengths to provide enough lateral resistance against the lateral forces on the piles.

To avoid the use of sleeving pipes, a series of full-scale and reduced-scale tests as well as numerical analyses were conducted to investigate the interactions between the piles and the MSE walls and the influence factors on the lateral load capacity of piles and the performance of MSE walls. Pierson [15] conducted the first field load testing of laterally-loaded single and group drilled shafts
within the reinforced zone of a modular-block MSE wall. In his test, two types of uniaxial geogrid were used to reinforce the backfill material and the shaft length was equal to the wall height. This full-scale test was followed by a series of reduced-scale tests with similar test conditions in terms of wall type, reinforcement type, and pile toe depth (i.e., at the base of the MSE wall). Mohammed [16] and Mohammed and Han [17] investigated the factors influencing the performance of laterally loaded piles within MSE walls by conducting 18 reduced-scale models. These factors included pile offset, wall height, reinforcement length and spacing, and geogrid-wall facing connection. Jawad [18] conducted seven reduced-scale model tests and investigated four influence factors: (1) the offset distance of the pile within the MSE wall, (2) the effect of group piles, and (3) the effect of loading type, and (4) the effect of boundary condition. Based on the test results, a simplified additional lateral earth pressure distribution behind an MSE wall facing due to pile loading was proposed. Another series of full-scale tests of piles behind MSE walls have been conducted to study the effect of pile offset from the back face of the MSE wall on both the lateral resistance of the piles and the force resisting inextensible reinforcement [19,20,21,22,23]. These tests consisted of the concrete panel walls and the piles extended to the depth of 15 m below the base of the MSE wall to provide lateral support to the piles.

Additionally, several three-dimensional numerical studies were carried out to simulate the response of the piles behind the MSE wall and investigate the influence of the pile offset, the length of reinforcement (L) to the wall height (H), the reinforcement stiffness, the embedded length of pile, and the backfill properties [14,24,25,26,27,28].

After a literature review of the past studies about the laterally loaded piles within MSE walls, this paper will discuss the effects of the pile location behind the wall, the ratio of the reinforcement length to the wall height, and the stiffness of the reinforcement layer. This paper will also discuss the available approaches to estimate the forces in the reinforcement layers and the lateral earth pressures behind the MSE wall due to the laterally-loaded piles.

2. Lateral load capacity

2.1. Pile offset distance behind wall facing

Berg et al. [29] suggested a minimum offset from the back of the wall facing and the front of the pile as 0.5 m (driven piles) and 1.0 m (drilled shafts) to provide necessary space to achieve proper compaction of backfill material. However, placing the piles within this range might significantly reduce the lateral capacity of the piles. Therefore, several studies have been conducted to examine the effect of pile location behind the wall facing on its lateral capacity. Pierson [15] tested eight drilled shafts within the reinforced zone of a 42 m long, 6 m high MSE wall. The lengths and diameters of the shafts were 6.0 and 0.9 m, respectively, and the spacing between the shafts was 4.6 m. The single shafts were placed at the offset distances of one, two, three, and four times the shaft diameter (i.e., 1D, 2D, 3D, and 4D, D is the shaft diameter) from the center of the shafts to the back of the wall facing, while the group shafts were placed at 2D offset behind the wall facing. In this study, uniaxial geogrids were used as reinforcement. The measured load-displacement curves showed that the lateral load capacity of the shaft located at the 2D offset decreased by 50% as compared with that located at the 4D offset. Also, the individual shaft in the group test showed 20% reduction in the lateral load capacity of the shaft as compared with the shaft in the single shaft test [24].

This percentage of the reduction in the lateral capacity of piles in uniaxial geogrid-reinforced MSE walls decreased in the reduced-scale models. For example, in the reduced-scale model test conducted by Mohammed [16], at the pile head displacement equal to 20% the pile diameter, the lateral capacities of the piles located at the 2D offset behind the wall facing decreased by 10% and 26% as compared with those located at the pile offsets of 4D and 6D, respectively. While in the reduced-scale model test conducted by Jawad et al. [30], the reduction in the lateral capacity of the pile located at the 2D offset was 28% as compared with that at the 4D offset.
In the full-scale tests of piles behind the facing of the concrete-panel MSE wall with steel reinforcement (i.e., steel rib and welded wire grid), the lateral capacity of piles increased with increasing the pile offset behind the wall facing. Price [19] tested five piles in two different sites to study the effect of pile offset from the back face of the MSE wall on both the lateral resistance of the piles and the forces resisted by the MSE steel reinforcement. Two hollow steel pipe piles of 0.32 m in diameter were tested in the first site. These pipe piles were placed at the offsets of 3.75 D and 7.5 D within a 6-m high MSE wall and extended to the depth of 15 m below the base of the wall to reach the hard layer. The other three piles used in the second site were hollow steel pipes of 0.4 m in diameter and were driven approximately 18 m below the base of the wall. One of the piles was located at the offset of 2.9 D behind the MSE wall face, while the other two piles were located at the offsets of 1.6 D and 5.2 D behind the MSE wall wing. Welded wire grid reinforcements were used in both sites with the reinforcement to wall height ratios (L/H) of 1.6 in the first site and 1.1 and 1.7 in the second site. The test results showed that the piles located at 7.5 and 3.8 times pile diameter from the wall facing had identical load-displacement curves. This result was attributed to the longer reinforcement length of 1.6H (H is the wall height), the locations of the piles relatively far from the wall face, and the reinforcement overlap for the pile due to the geometry of the wall near the corner. However, the other test result in Site 2 showed that the lateral load capacity of the pile decreased with the reduction of the offset distance from the back face of the MSE wall to the center of the pile. This result is consistent with that of Piersson [15].

Nelson [20] performed lateral loading tests similar to those conducted by Price [19] but with ribbed strip reinforcement. These tests were carried out on four piles located at 1.3D, 2.7D, 6.3D, and 7.7D offsets behind the facing of a 6.8-m high concrete-panel MSE wall. The test results showed that the final lateral load capacities of the piles located at the offsets of 1.3D and 2.7D decreased by 60% and 30% as compared with that located at 6.3D. Although the piles used in this test were similar to those in the Price [19] test, the pile lateral load capacities were much lower than those in the Price [19] test. For example, at the pile head displacement of 60 mm, the lateral load capacities of the piles located at the 2.9D offset in the Price [19] test and 2.7D in this test were 200 and 75 kN, respectively. The main reasons for this difference in the lateral load capacity are attributed to the different type of the wall and the different reinforcement used in these two tests.

Hatch [21] tested four steel pipe piles of 0.32 m in diameter as placed at the offsets of 1.9D, 3.2D, 4.3D, and 5.3D behind the MSE wall face. The test results showed that the lateral load capacities of the piles located at the offsets of 4.3D and 3.2D were almost similar. Hatch [21] attributed this result to the special location of the pile with the 4.3D offset (i.e., in front of the joint in the wall), while the pile with 3.2D was in front of the panel center. The test results also showed that the behavior of the pile with the 5.3D offset was similar to the reaction pile up to the pile head displacement of 44.5 mm, indicating that the wall had no effect on the lateral load capacity of the pile with the 5.3D offset. The load-displacement curves for the piles located at the offsets of 3.2D, 4.3D, and 5.3D showed a hyperbolic shape, indicating the progressive failure of the surrounding soil with increasing the lateral load. On the other hand, the load-displacement curve for the pile with the 1.9D offset was almost linear, indicating that the soil had a limited contribution in resisting the lateral load and the majority of the load was carried by the pile itself.

Han [22] carried out a series of tests similar to those conducted by Nelson [20] in terms of the pile size, the type of reinforcement, the embedded length of pile, and the type of soil. The piles were placed at the offsets of 1.7D, 2.8D, 3.1D, and 3.9D behind the facing of the 4.5-m high MSE wall. The ratio of the reinforcement length to the wall height was 0.9 in the test. The comparison between the lateral load capacities of piles at the 25 mm pile head displacement showed 50% and 20% reduction in the lateral load capacities of piles located at the offsets of 1.7D and 2.8D, respectively, relative to those of the piles located at the offset of 3.1D or 3.9D.

Besendorfer [23] tested four piles, which were located behind the wall face at the offsets of 1.7D, 2.8D, 2.9D, and 3.9D and extended to 4.5 m below the base of the wall. The reinforcement length to wall height ratio of 0.72 was used in this study, which was close to the typical ratio of 0.7 used in
walls that are subjected to static loading. The test results showed approximately equal lateral load capacities of the piles located at the offsets of 2.8D, 2.9D, and 3.9D behind the wall face and approximately 40% reduction in the lateral load capacity of the pile located at the offset of 1.7D as compared with those piles at other offsets. Besendorfer [23] pointed out some reasons that might contribute to this slight difference between the lateral load capacities of the piles located at the offsets of 2.8D and 3.9D behind the wall face. One of the reasons was related to the rainfall that occurred one day before testing the piles with 2.8D and 2.9D offsets, which might add some apparent cohesion to the soil and increased the unit weight of the soil. The other reasons were related to the panel configuration and compaction effort around the piles. Besendorfer [23] also developed a p-multiplier curve as a function of a normalized distance using the LPILE program including his own results and those from Price [19], Nelson [20], Hatch [21], and Han [22] as shown in Figure 2. The regression line showed that the piles with a normalized distance greater than four were not affected by the presence of the wall. Table 1 summarizes the field and laboratory tests available in the literature.

![Figure 2. p-multiplier curves (after Besendorfer, 2015)](image-url)

**Table 1. A summary of field and laboratory tests**

| Test type | Wall and reinforcement | Pile | Key findings | References |
|-----------|------------------------|------|--------------|------------|
| Field     | H = 6 m, modular block MSE wall, uniaxial geogrid | 8 concrete drilled shafts, h = 6.0 m, D = 0.9 m, x = 1D, 2D, 3D, and 4D | The test results showed that the lateral capacity of the shaft located at x = 2D was 50% lower than that of the shaft at x = 4D. The results also showed a 20% reduction of the lateral capacity of each shaft in the three shaft group as compared with that of the single shaft. | Pierson [15] |
| Field     | H = 6 m high, concrete panel MSE wall, welded wire | Five hollow steel pipe piles, h = 21 m to a hard layer, D = 0.32 | The test results showed that the piles at x = 7.5D and 3.8D had identical load-displacement curves. This result was attributed to large L = 1.6H and large x | Price [19] |
2.2. Reinforcement stiffness

Several studies have been conducted to examine the effect of reinforcement stiffness on the performance of MSE walls. Leshchinsky and Han [31] investigated the effect of reinforcement...
stiffness on the global stability of geosynthetic-reinforced multitiered walls by conducting a two-dimensional numerical analysis. The results showed a negligible difference in the computed factor of safety by increasing the reinforcement stiffness from 1000 kN/m to 100000 kN/m. Zheng and Fox [32] investigated four different values of reinforcement stiffness \( J = 500, 1000, 1500, \) and 2000 kN/m and found that the use of reinforcement with the stiffness of 2000 kN/m had approximately 45% reduction in the maximum wall displacement as compared with that with 500 kN/m.

The aforementioned studies investigated the effect of reinforcement stiffness on the wall facing deflection without any presence of laterally-loaded piles within the reinforced zone of the MSE wall. Pierson [24], by conducting a three-dimensional numerical analysis, investigated the effect of reinforcement stiffness in the weak and strong directions on the response of laterally-loaded piles and the performance of the MSE wall. His results revealed that the increase of the stiffness in both directions increased the pile lateral load capacity and reduced the facing deflection. The numerical study conducted by Jawad and Han [33] investigated the effect of reinforcement stiffness on the lateral load capacities of various pile diameters. In his study, the piles were placed at the offset distance equal to two times the pile diameter behind the wall facing. The numerical results showed that the increase of the reinforcement stiffness from 1000 to 3000 kN/m increased the ultimate lateral load capacities of the piles of 0.5 m in diameter and 0.7 m in diameter by 57% and reduced the wall facing deflections at the top by 5.5% to 11%.

2.3. Length of reinforcement

To prevent the pullout failure of the reinforcement layer from the soil and minimize the MSE wall deformation, the required minimum reinforcement length (L) to wall height (H) ratio is typically 0.7 under static loading and 0.9 under seismic loading [29]. For construction purposes, however, designers sometimes use a reinforcement length to wall height ratio (L/H) more than one, for example, 1.6 in Price [19] and 1.2 in Nelson [20] and Hatch [21] at the time of their tests. An increase of the reinforcement length leads to increase the interaction area between the soil and the reinforcement, resulting in an increase in the lateral capacity of piles and reduce the wall facing displacement. Price [19], after conducting full-scale tests, found that the piles located at the offsets of 3.8 and 7.5 times pile diameter had almost the same lateral capacity. One of the reasons for this result was the longer reinforcement length of 1.6H used in the test. Mohammed [16] investigated three different reinforcement length to wall height ratios (i.e., 0.7, 1.0, and 1.3) by conducting reduced-scale model tests of piles behind the MSE wall facing. The test results showed that the lateral load capacity of the pile increased and the wall facing displacement decreased as the reinforcement length to wall height ratio increased, maybe due to the reduced model tests with lower stress levels. However, some studies showed that an increase of the reinforcement length to wall height ratio more than one had an insignificant effect on the lateral load capacity of the pile and the wall facing displacement. Jawad et al. [30] conducted a three-dimensional numerical analysis and investigated the effect of the reinforcement length to wall height ratio (e.g., 0.7, 1.0, and 1.3) on the lateral load capacity of the pile, the wall facing displacement, and the lateral earth pressure behind the wall facing. Their numerical results showed that the load-displacement curves, the wall facing displacements, and the lateral earth pressures behind the wall facing for the piles with the reinforcement length to wall height ratios of 1.0 and 1.3 were almost the same, indicating that the increase of the reinforcement length to wall height ratio more than 1.0 had an insignificant effect on the lateral load capacity of the piles placed at the 2D offset.

3. Wall facing displacement

Since the wall facing is one visible part of the structure, the deformation of the wall facing should be within an allowable range so that it does not affect the aesthetics of the MSE wall. Berg et al. [29] suggested that the allowable lateral displacement for MSE walls under extreme events be in the range of 50 to 100 mm. Pierson [15] measured the lateral displacement of the modular-block MSE wall,
which was induced by laterally-loaded piles located at different offset distances behind the wall facing. The vertical profile of the wall facing displacement showed the maximum displacement occurring at the top of the wall, and then the displacement decreased with the depth toward the base of the wall. However, the wall facing displacement profile in the horizontal direction showed that the wall moved more along the wall centerline, and the movement decreased with an increase of the distance from the wall centerline as shown in Figure 3. This figure also shows an increase in the maximum wall displacement and a decrease of the influenced width with a decrease of the pile offset behind the MSE wall facing.

![Figure 3. Horizontal profiles of wall facing displacements (after Jawad, 2019)](image)

Price [19] measured the displacements of a concrete-panel MSE wall using three different ways: (1) Linear Variable Differential Transformers (LVDTs), (2) Shape Arrays (SA), and (3) String Potentiometers (SP). Similar to the Pierson [15] test, the pile closer to the wall facing induced more wall deformation with the maximum displacement at the top of the wall. The results of these three measurement methods showed that the wall displacements in front of the pile measured by the Shape Arrays method were larger than those measured by the LVDTs or the String Potentiometers. The reason was that the plastic pipes used in the Shape Arrays method were placed in a relatively uncompacted soil behind the wall. Hatch [21] used the Digital Image Correlation (DIC) system beside SA and SP to measure the wall facing displacements. The results from the SA were not accurate; however, they were used to check the results from DIC and SP. The data from the DIC system showed that the maximum wall displacement occurred at the top of the wall in the middle of the joint. The results from Hatch [21] also showed that the wall facing displacement was limited to one wall panel on either side of the pile and to 1.5 wall panels down from the top. Han [22] showed the displacement results of four different wall configurations induced by the piles located at the offset distances of 1.7D, 2.8D, 3.1D, and 3.9D behind the wall facing. The comparison exhibited that the wall facing displacement induced by the pile located at the offset of 2.8D was larger than others. This phenomenon happened because there was only one reinforcement layer supporting the top panel. Jawad et al. [30], after conducting reduced-scale model tests, found a relationship between the pile
head displacement and the maximum wall facing displacement by including the test results from Pierson [15]. The reason for selecting these field tests instead of other tests mentioned before is that these tests had similar test conditions to the model tests in terms of wall type, pile stiffness, reinforcement type, and pile toe depth (i.e., at the base of the MSE wall). From the suggested relationship, the maximum wall displacement can be estimated based on the pile displacement, the pile offset, and the pile diameter.

4. Lateral earth pressure behind the wall
Lateral earth pressure distribution behind the wall facing is one of the key information that can be used for designing MSE or other type of walls. Therefore, several full-scale tests, reduced-scale tests, and numerical analyses have been conducted to estimate the lateral earth pressures behind the MSE wall facing induced by laterally-loaded piles. Pierson [15] and Huang et al. [26] found that the maximum lateral earth pressure, due to the lateral shaft movement, was located within the lower part of the MSE wall, not within the upper part while the FHWA NHI-10-024 guideline [29]. suggested that the lateral pressure distribution from the pile foundation on the MSE wall face decreases linearly or nonlinearly with the wall depth. Jawad et al. [30] measured the additional lateral earth pressure along the back face of the wall using earth pressure cells. The test results from Jawad et al. [30] showed that the additional lateral earth pressure distribution with the wall elevation was non-linear. The maximum lateral earth pressure was located at an elevation of 80% the wall height, while the minimum lateral pressures were observed at the bottom and top of the wall. Based on the measured lateral earth pressures, Jawad [18] proposed a simplified method to design an MSE wall supporting a pile foundation within its reinforced zone. The additional lateral earth pressure calculated in the proposed design method corresponds to that induced by a laterally loaded pile at the pile head displacement of 20% of its diameter. The distribution of the additional lateral earth pressures behind the wall facing was assumed to have a three-dimensional shape and the maximum lateral pressure was assumed to be a percentage of the passive earth pressure, which mainly depended on the pile location within the MSE wall. Jawad [18] also developed an equation to estimate the maximum additional lateral earth pressure based on the proposed shape of pressure distribution.

5. Force in the reinforcement layer
Another key parameter for designing the MSE wall is the force generated in the reinforcement layer during lateral pile loading. Pierson [15] monitored the strains in the uniaxial geogrid layers placed at different elevations to estimate the forces generated by the shaft movement. The test results from Pierson [15] showed that the maximum strain happened near the pile location. Price [19] investigated the relationship between the maximum force in the reinforcement (i.e., welded grid) induced by pile movement and the normalized distance (lateral distance from the center of the pile to the center of a grid divided by the distance from the back face of the wall to the center of the pile). This relationship showed that the induced force in the reinforcement decreased with an increase of the normalized offset distance. Nelson [20] plotted the normalized force (the maximum induced force in the reinforcement divided by the lateral load on the pile) in the strip against the normalized offset distance. The test results from Nelson [20] showed significant scatter of the data about the best-fit curve; therefore, a tentative envelope was plotted to provide a conservative estimate of the additional force in the reinforcement induced by the laterally loaded pile. Hatch [21] also developed a plot of the normalized load versus normalized offset distance including the data, the best-fit line, and the envelope from Price [19], who also used welded wire grids. The induced forces in the reinforcement layers were higher than those on the Price [19] envelope, showing the data from Price [19] were not adequate for design. Similar to Hatch [21], Han [22] developed a plot of the normalized induced force in the reinforcement versus the normalized offset distance by including the data, the best fit line, and the envelope from Nelson [20] (2013), who also used ribbed steel strips. The induced forces were also higher than the
design envelope proposed by Nelson [20]. After conducting a statistical analysis on the data from his own test and Nelson’s test, Besendorf [23] created two different regression models to predict the induced forces in the reinforcement layers. In one model, the depth below the ground surface was used as a variable while in the other model the vertical stress was the variable. Jawad [18] calculated the maximum induced tensile forces in the geogrid rib (i.e., the one beside the pile) at the pile head displacement of 20% of its diameter using the proposed additional lateral earth pressure distribution behind the wall facing. The calculated tensile forces from the proposed method showed reasonable match with those measured from the model tests based on the measured strains in the geogrid.

6. Conclusions
Laterally-loaded piles within the reinforced zone of MSE walls are a complicated geotechnical problem due to the interaction between the piles and the MSE walls. Understanding such a problem requires the investigation of the key influencing factors on both the piles and the MSE walls. Therefore, this study summarizes these key factors that affect the response of the pile and the performance of the MSE wall. Based on the field tests, lab tests, and numerical analyses, the following conclusions can be drawn:

1. When the pile offset distance within the MSE wall (i.e., modular blocks or concrete panels) decreased from 4D to 2D, the maximum reduction in the lateral pile capacity was approximately 50%.
2. The location of the maximum induced force in the reinforcement (inextensible and extensible) by the pile movement was within the upper portion of the wall close to the pile location.
3. In the concrete-panel MSE wall, the maximum wall displacement was in the upper concrete panel at the joint, and the wall deformation was limited to one wall panel on either side of the pile and to 1.5 wall panels down. While in the modular-block MSE wall, the maximum wall displacement was also within the upper part of the wall and the influenced width of the wall increased with the increase of the pile offset behind the MSE wall facing.
4. Based on the numerical analysis, an increase of the reinforcement stiffness had a significant effect on the increase of the lateral load capacities of the piles and less effect on the decrease of the wall displacements.
5. When the reinforcement length to wall height ratio (L/H) was more than 1.0, the reinforcement length had an insignificant effect on the lateral load resistance of the piles and the facing displacement of the wall.

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