Interaction Between Strip Footings and Sheet pile Walls

M. Jao¹, F. Ahmed¹, G. Sudani¹, T. T. M. Nguyen²*, and M. C. Wang³

¹Department of Civil and Environmental Engineering
Lamar University, P.O. Box-10024, Beaumont, TX 77710
e-mail: jaomu@lamar.edu

²Department of Chemistry and Biochemistry
Lamar University, P.O. Box-10022, Beaumont, TX 77710
e-mail: ttnguyen15@lamar.edu

³Department of Civil and Environmental Engineering,
The Pennsylvania State University, 212 Sackett Building, University Park,
PA 16802; e-mail: mcw@psu.edu

ABSTRACT

When shallow foundations are in the backfill and near earth retaining structures, they may interact and adversely affect their stability. This study investigated the interaction between reinforced concrete sheetpile walls and reinforced concrete strip footings situated in the backfill and parallel to the walls. The investigation was made using the method of finite element analysis based on the theory of elasto-plasticity. The analysis was made for a range of conditions including footing location, loading intensities, wall thickness and soil type. Based on the results of the analysis, footing settlements and lateral displacement, wall deflection, lateral earth pressure on the wall, soil plastic yielding, and ultimate bearing capacity of footings were related to the conditions analyzed.


INTRODUCTION

Earth retaining structures, such as retaining walls and sheetpile walls are often used to enhance the utility of open space by eliminating ground slopes. After the slopes are removed and the ground behind the retaining structures is leveled, buildings are constructed on the backfill. When the buildings are not far behind the walls, the foundations and walls may interact resulting in an adverse effect on the stability of either the foundation or the wall or both. For example, the foundation-induced forces on the wall may cause excessive lateral wall deflection or displacement or even wall failure. It may also cause excessive foundation settlement or bearing capacity failure adversely affecting foundation stability. The problem of foundation and wall interaction has received little attention although there are studies on problems concerning lateral earth pressures induced by surcharge pressures atop the backfill. Some notable studies are Misra [1], Jarquio [2], and Motta [3].
These studies adopt either the limiting equilibrium approach or the theory of elasticity with assumptions of linear stress-strain behavior of backfill soil and wall. The results of these studies may be useful for the determination of wall stability under the effect of surcharge pressures induced by adjacent foundations atop the backfill. However, the potential effect of the wall on foundation stability cannot be determined.

A reasonable approach is to analyze the foundation and wall together with due considerations of the stress-strain and strength behaviors of foundation soil and wall. A very recent study performed by Sudani et al. [4] uses finite element analysis to study the stability of footings adjacent to pile walls.

Based on this approach, we report the analysis of the interaction between reinforced concrete sheetpile walls and reinforced concrete strip footings situated in the backfill and parallel to the walls. The analysis was made using the finite element method based on the theory of elasto-plasticity under various field conditions including footing location, loading intensity, wall thickness, and soil type. The response variables analyzed were the vertical settlement and lateral displacement of footing, the lateral deflection of the wall, the lateral earth pressure on the wall, the plastic yielding of backfill soil, and the ultimate bearing capacity of the footing. Each response variable is graphically related with the various field conditions analyzed to elucidate the interaction behavior between strip footings and sheetpile walls. Meanwhile, the engineering significance of the findings in terms of practical applications to the design and analysis of such a footing-wall system is discussed in details.

CURRENT STATE OF KNOWLEDGE

The problem of interaction between sheet-pile walls and strip footings on the backfill has received very little attention. However, there are numerous related studies that suggest it is an area worth investigating. These studies primarily focused on retaining walls with surcharge loading on top of the backfill. Notable studies include Misra [1], Jarquio [2], Steenfelt and Hansen [5], Motta [3], Georgiadis and Anagnostopoulos [6], Sudani et al. [4], among others. Of these studies, Misra [1] performed a theoretical analysis of lateral earth pressure distribution on retaining walls with different types of backfill subjected to wheel loading. He also compared the results with that obtained from Boussinesq’s solution, and reported, among other things, that a lower density backfill induces less lateral earth pressure on the wall than a denser backfill.

Using the modified forms of Boussinesq equation, Jarquio [2] derived a mathematical solution for lateral earth pressure against a retaining wall caused by a strip load. He also developed simplified expressions for locating the centroid of the lateral pressure diagram as well as the point of maximum unit lateral pressure. Steenfelt and Hansen [5] investigated the effect of strip loading on sheet-pile wall design. They demonstrated that the ratio of strip loading to unit weight of backfill soil, and the location of strip loading, have significant influence on the design load. They also provided an analytical solution for computing the lateral earth pressure induced by strip loading.

Motta [3] presented a closed form solution for computing the active earth pressure coefficient for retaining walls with surcharge pressures on the backfill located at varying distances from the wall. Seismic effects were also taken into account when using the pseudostatic approach. Good agreement was shown between the closed-form solution and the solution obtained using the Coulomb graphical approach for various conditions of surcharge and earthquake loadings. In their study of the effect of strip surcharge loading on the behavior of cantilever sheet-pile walls, Georgiadis and Anagnostopoulos [6] conducted model tests as well as finite element analyses using the computer program PLAXIS. They focused on the effect of lateral wall movement on the surcharge loading-induced lateral earth pressure, and reported that even small lateral wall yielding will drastically reduce lateral earth pressure and bending moments in the wall.
The preceding review shows that the available studies focused mainly on the effect of surcharge loading on the behavior of retaining walls. Although the surcharge loading on the backfill bears some resemblance to the footing induced loading, the effect of footing on wall performance should not be analyzed without the presence of footing. Another important aspect that requires consideration is the potential effect of a wall on footing performance. Thus, possible interaction between the wall and footing should be analyzed. A recent study performed by Sudani et al. [4] used a commercial finite element computer software ANSYS to analyze the behavior of footings adjacent to pile walls. They mainly focused on the displacement and stability of the footings without investigating the mechanistic behavior of a wall influenced by the adjacent footings. In a thorough analysis, the wall, soil, and footing need to be treated together as a system. More importantly, the analysis should take into consideration both elastic and plastic behaviors of the backfill soil. With all of these factors in mind, this study investigated wall-footing interaction using the theory of elasto-plasticity which is described below.

**METHOD OF ANALYSIS**

The wall-footing interaction behavior was analyzed using a two-dimensional plane-strain elastoplastic finite element computer program. In the analysis, both the backfill soil and reinforced concrete were treated as elastic-perfectly plastic materials. Before yielding, i.e. within the elastic range, the concrete behaved linearly, whereas the soil behaved nonlinearly following the hyperbolic stress-strain law of Duncan and Chang [6]. Beyond the elastic range, the plastic behavior of both materials obeyed the yield criterion of Drucker and Prager [7]. Meanwhile, Hooke’s law and the incremental stress-strain relation of Reyes [8] were employed to derive the constitutive relation of the backfill soil. In the derivation, the following elastic and plastic strain rates were used:

\[
\dot{e}_{ij}^e = \frac{1+\nu}{E} \dot{\sigma}_{ij} - \frac{\nu}{E} \dot{\sigma}_{kk} \delta_{ij} \tag{1}
\]

\[
\dot{e}_{ij}^p = \lambda \left( -\alpha \delta_{ij} + \frac{S_{ij}}{2\sqrt{J_2}} \right) \tag{2}
\]

in which \(\dot{e}_{ij}^e\) = elastic strain rate, \(\dot{\sigma}_{ij}\) = stress rate, \(\delta_{ij}\) = Kronecker’s delta, \(\nu\) = Poisson’s ratio, \(E\) = Young’s modulus, \(\dot{e}_{ij}^p\) = Plastic strain rate, \(\lambda\) = a scalar positive function of stress and strain, \(S_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \delta_{ij}\), \(\alpha = 2 \sin \phi / [\sqrt{3} (3 - \sin \phi)]\), \(\phi\) = internal friction angle, and \(J_2\) = second invariant of the stress deviator tensor. The details and validation of the computer program have been documented by Jao and Wang [10].

**CONDITIONS ANALYZED**

The strip footing analyzed was a 3 ft (0.91 m) wide reinforced concrete footing embedded to a depth of 3 ft (0.91 m). The reinforced concrete cantilever sheet-pile wall had a height (H) of 25 ft (7.62 m) with a penetration depth (D) of 28 ft (8.53 m). Of these four values, the footing size, embedment depth, and wall height were chosen based on the conditions commonly encountered in the field; the penetration depth of the wall was determined with a safety factor based on the free-earth support method to maintain wall stability. Variables considered in the analysis were five levels of wall thickness (t), four levels of footing location (b) behind the wall, and two types of backfill soil. The five wall thicknesses analyzed were 1 in. (25.4 mm), 2 in. (50.8 mm), 4 in. (101.6 in), 6 in.
(152.4 mm) and 3 ft (914.6 mm); and four footing locations were 3 ft (0.91m), 9 ft (2.74 m), 15 ft (4.57 m) and infinity. In the analysis, a uniformly distributed footing pressure \( p \) was used. A schematic view of the footing wall system together with the symbols used is presented in Figure 1.

![Figure 1: Schematic view of the strip footing / sheet pile wall system](image)

**MATERIAL PROPERTIES**

Two different backfill soils were analyzed: a kaolin and a silty clay. The kaolin was commercially available under the name Edger Plastic Kaolin (EPK). The EPK had a median grain size of \( D_{50} \approx 0.001 \text{ mm} \) and a clay size fraction \(< 0.002 \text{ mm} \) of about 78%. It had a liquid limit of 58%, a plasticity index of 22, and a specific gravity of 2.60. The soil was classified as MH per the Unified Classification Systems. The EPK was compacted to 95% compaction of the standard Proctor compaction.

The silty clay was locally available in the area of State College, Pennsylvania. It contained about 10% (by weight) sand, 55% silt, and 35% clay-size, and had 37% liquid limit, 18 plasticity index, 2.67 specific gravity, and a classification of CL per the Unified Classification System.

The soil properties used in the computer analysis are summarized in Table 1. Also, included in the table are the properties of reinforced concrete obtained from the literature [11].
**Table 1: Material Properties of Soil and Concrete**

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial modulus in compression (psi)</th>
<th>Poisson’s Ratio</th>
<th>Dry unit weight (pci) (kN/m³)</th>
<th>Cohesion (psi) (kN/m²)</th>
<th>Internal Friction Angle (degrees)</th>
<th>Soil Constant (Rf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty Clay</td>
<td>677 (4670)</td>
<td>0.28</td>
<td>0.058 (15.7)</td>
<td>9.5 (65.5)</td>
<td>13.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Kaolin</td>
<td>2880 (19,843)</td>
<td>0.39</td>
<td>0.052 (14.1)</td>
<td>23.0 (158.5)</td>
<td>8.0</td>
<td>0.77</td>
</tr>
<tr>
<td>Concrete</td>
<td>3.3X10⁶ (2.27x10⁶)</td>
<td>0.30</td>
<td>0.090 (24.4)</td>
<td>810 (5,581)</td>
<td>39.6</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The stress-strain and strength properties of the test soils in compression were determined from the conventional triaxial compression test. The modulus of deformation in compression was computed from the following equation developed by Duncan and Chang [7]:

\[
E_c = E_i \left[1 - \frac{R_f (1 - \sin \phi)(\sigma_1 - \sigma_3)}{2(c \cos \phi + \sigma_3 \sin \phi)} \right]^2
\]

\[
E_i = K_h p_a (\sigma_3/p_a)^n
\]

In which \( E_c \) = tangential modulus of deformation in compression, \( E_i \) = initial modulus, \( c \) = cohesion, \( \phi \) = internal friction angle, \( R_f \) = ultimate stress to failure stress ratio, \( K_h \) and \( n \) = materials parameters, and \( p_a \) = atmospheric pressure.

The tensile stress-strain and strength properties of the soils were determined using the indirect tension test. Poisson’s ratio was computed from the bulk modulus, which was determined from the bulk compression test. The Young’s modulus needed in the computation of Poisson’s ratio was determined separately from the unconfined compression test.

**RESULTS OF ANALYSIS**

Results of computer analysis provided footing and wall responses including footing settlement and horizontal displacement, lateral deflection of wall, lateral earth pressure against the wall, ultimate bearing capacity of footing, and plastic yielding of backfill soil. These response variables were related with wall thickness and footing location for each backfill soil. The relations were used to evaluate and discuss wall-footing interaction behavior.

**INTERACTION BEHAVIOR**

1. **Footing Settlement**

Footing settlement vs. footing pressure relation varies with wall thickness and footing location as illustrated in Figure 2. More specifically, figure 2 graphically shows the relations for \( t = 2, 6, \) and 36 in. (50.8, 152.4 and 914.4 mm) with \( b/B = 1, 3, \) and \( \infty \) in the kaolin backfill. Note that the condition of \( b/B = \infty \) corresponds to the no-wall condition. Comparison of the curve of \( b/B = \infty \) with the other curves shows that under the same footing pressure conditions, a footing will undergo considerably greater settlement when located nearby a wall. This clearly indicates the adverse effect of a wall on footing settlement behavior.
Another view of the effect of a wall on footing settlement behavior is presented in Figure 3, in which footing settlement under two levels of footing pressure is plotted against wall thickness for three footing locations: b/B = 1, 3 and ∞. The two footing pressures equal 1/2 and 1/3 of the ultimate bearing capacity of footing, which is equal to 36,000 psf (1,724 kN/m²). These footing pressures correspond to the working pressures with safety factors of 2.0 and 3.0. Details on the determination of the ultimate bearing capacity are provided in a later section. As expected, the footing settlement decreases as the wall thickness increases, while the rate of settlement reduction diminishes with increasing wall thickness. Furthermore, the effect of wall thickness is more pronounced under a higher footing pressure.

Figure 3 also demonstrates that, under a constant footing pressure, footing settlement decreases with increasing footing location behind the wall. This can be attributed to the decreased footing-induced lateral earth pressure on the wall when the footing is located farther from the wall. A discussion on the footing-induced lateral pressure is provided in a later section.

For the silty clay backfill, the effect of the presence of a wall on footing settlement behavior resembles that for the kaolin backfill. Thus, no figures are presented for discussions here.
2. Horizontal Footing Displacement

Strip footings supported by a uniform and homogeneous backfill soil and subjected to a central vertical loading will undergo horizontal displacement only when their lateral supports are not equal on both sides. When a footing is nearby a wall, the lateral support provided by the wall may be smaller or greater than that on the other side depending on the footing location and wall stiffness. Figure 4 presents the effect of wall thickness on horizontal footing displacement for footings on kaolin with three levels of footing location (b/B =1, 3, and 5) and two levels of footing pressure (1/2 and 1/3 of the ultimate bearing capacity of the footing).

The data in Figure 4 show that the horizontal footing displacement decreases with increasing wall thickness. Note that the negative displacement denotes footing displacement toward the wall. The decreased displacement toward the wall with increasing wall thickness is primarily caused by the increased wall stiffness that provides a greater lateral support to the backfill.

The data also indicate that, for a constant wall thickness, the horizontal footing displacement increases as the footing is located closer to the wall. Furthermore, the higher footing pressure induces greater horizontal footing displacement as would be expected. The results of analysis show a similar effect of the wall on the horizontal displacement of footings supported by the silty clay backfill.
3. Lateral Wall Deflection

The lateral wall deflection profiles presented in Figure 5 are for kaolin backfill with footings subjected to 1/3 of the ultimate bearing capacity. The conditions involved are two wall thicknesses of 6 in. (152.4 mm) and 36 in. (914.4 mm), three footing locations of 3 ft (0.91 m), 9 ft (2.74 m), and 15 ft (4.57 m), and a no-footing condition.

Figure 4: Horizontal Displacement vs. Wall Thickness
The lateral wall deflection profiles show a maximum deflection at the pile head and gradually decrease to a minimum at the bottom of the piles. Figure 5 also shows that the magnitude of the wall deflection varies with wall thickness and footing location. A thicker wall deflects less due to its lower flexibility. The wall deflection also decreases when the wall is located farther from the wall because of lower footing-induced lateral pressure on the wall.

Below the dredge line, i.e. below 25 ft (7.62 m) depth, the deflection profiles also vary considerably with wall thickness and footing location. A comparison of the deflection profiles with and without-footing conditions for t = 6 in. (152.4 mm) shows the effect of footing on wall deflection. Without a footing, the wall deflects significantly less.

For the footings supported by the silty clay backfill and are also subjected to 1/3 of the ultimate bearing capacity, which is equal to 15,000 psf (718 kN/m²), the wall deflection pattern essentially resembles that of kaolin backfill although the magnitude of deflection differs as shown in Figure 6. The figure shows that under the condition of same wall thickness and footing location, the maximum wall deflection is considerably greater for silty clay than kaolin backfills.
4. Lateral Earth Pressure

The lateral earth pressure distribution for the kaolin backfill together with a 6 in. (152.4 mm) thick wall and a footing subjected to 1/3 of the ultimate bearing capacity is presented in Figure 7. Three footing locations, 3, 9 and 15 ft (0.9, 2.74, and 4.57 m) are shown, as well as, for comparison purposes the conditions for 36 in. (9144 mm) thick wall with 9 ft (2.74 m) location, and 6 in. (152.4 mm) wall without a footing.

![Figure 6: Lateral Wall Deflection Profiles for Kaolin and Silty-Clay](image)
Figure 7: Lateral Earth Pressure Distribution for Kaolin

For the 6 in. (152.4 mm) thick wall with a footing pressure equal to 1/3 of the ultimate bearing capacity, the distribution curves below a depth of about 17 ft (5.18 m) are fairly close to each other and increase almost linearly with depth. Above 17 ft (5.18 m), the curves show close to zero lateral stress from pile head to a depth of 4, 5, and 5.5 ft (1.21, 1.52, and 1.67 m) respectively for the footing location b=3, 6, and 9 ft (0.91, 1.83, and 2.74 m). The lateral stress then sharply increases to a peak value at a depth of about 6, 9, and 10 ft (1.83, 2.74, and 3.05 m) respectively for the footing location b=3, 6, and 9 ft (0.91, 1.83, and 2.74 m); and drops to a value and then increases with depth and merges together at a depth of about 17 ft (5.18 m). The zero lateral stress at the top portion of the pile is due to the large wall deflection and separation of the wall with backfill soil. The occurrence of the peak values at different depths is because footing induced pressure on the wall reaches a maximum at some depth below the footing base per Boussineq’s pressure distribution. However, the magnitude of the peak values appears to be much less than the combination of the Boussineq’s pressure distribution and active state of geostatic stress due to the large wall deflection.

The lateral pressure on the 6 in. (152.4 mm) wall without a footing is essentially zero from the top to a depth of about 3 ft (0.91 m), then increases with depth due to the increased geostatic stress. Primarily because of the stronger support, the lateral pressure for the 36 in. (914.4 mm) thick wall is much greater than those for the 6 in. (152.4 mm) thick walls between depth of 10 ft (3.05 m) to the...
dredge line. The pattern of pressure distribution is more regular for the 36 in (914.4 mm) than those for 6 in. (152.4 mm) thick walls. However, it is very difficult to determine the magnitude of lateral pressure using the classical lateral earth pressure theory. The lateral earth pressure distribution curves for the 6 in. (152.4 mm) thick walls with and without a footing on the silty clay backfill are presented in Figure 8.

![Figure 8: Lateral Earth Pressure Distributions for Silty-Clay](image)

Although some similarities in the general curve shapes between Figures 7 and 8 are seen, the depth at which the lateral earth pressure increases from a near zero value is much greater for silty clay than for kaolin backfill. The larger depth for silty clay can be attributed to greater wall deflection when comparing with kaolin backfill. For the same reason, the peak values induced by the footing pressure on the wall appear to also be reduced. For the condition without footing pressure (p=0.0), the close to zero stress depth changes from 3 ft (0.91 m) to 9 ft (2.74 m) is due to the larger wall deflection in silty clay.

5. Ultimate Bearing Capacity

The ultimate bearing capacity of footing was determined using three different methods and the smallest value thus obtained was taken as the ultimate bearing capacity of the footing analyzed. The three different methods are:

(1) Determine the footing pressure at the distinct yield point in the footing pressure vs. footing settlement relation curve. This is a criterion proposed by Vesic [13].
(2) Determine the footing pressure at the intersection of tangents to the initial and ultimate portions of the pressure vs. settlement curve, if no distinct yield point is available.

(3) Determine the footing pressure at the point on the curve indicating an increase in the rate of soil element yielding. The curve relates the footing pressure to the area of yielded soil elements.

The analysis of the ultimate bearing capacity was made for various conditions including three different wall thicknesses, three different footing locations, and the condition of footing infinitely distant from the wall, i.e. no wall effect. To evaluate the effect of the wall on the ultimate bearing capacity, the ratio of bearing capacities between the footing near the wall and the footing very far from the wall is plotted against footing location for different wall thicknesses in Figure 9 for kaolin and in Figure 10 for silty clay backfills.

![Figure 9: Ultimate Bearing Capacity Ratio vs. b/B](image-url)
Both Figures 9 and 10 indicate, as would be expected, that for a given wall thickness, the ultimate bearing capacity decreases when the footing is located near the wall. In addition, for a given footing location, the ultimate bearing capacity decreases more for a thinner wall than for a thicker wall. The minimum distances at which the influence of the wall diminishes can be estimated for the various wall thicknesses. For the kaolin backfill, the minimum distances are approximately 9, 15, 16.5 ft (2.7, 4.5, and 5.0 m) for wall thicknesses of 6, 4, and 2 in. (152.4, 101.6, and 50.8 mm), respectively. For the silty clay backfill, the minimum distances are approximately 15 ft (4.5 m) for 6 in. (152.4 mm) thick wall, 18 ft (5.5 m) for 4 in. (101.6 mm) thick wall and much greater than 18 ft (5.5 m) for 2 in. (50.8 mm) thick wall.

The minimum distance between wall and footing stated above is considerably greater for the silty clay than the kaolin backfill. This can be attributed to the larger internal friction angle of silty clay (13.5) than kaolin (80). Based on Terzaghi’s bearing capacity theory for footings on the level ground, the maximum horizontal extent of sliding surface measured from the footing edge is approximately 7.75 ft (2.36 m) or 2.5B for kaolin and 9.35 ft (2.85 m) or 3.1B for silty clay assuming a smooth footing base. These two theoretical values are considerably smaller than the aforementioned

Figure 10: Ultimate Bearing Capacity Ratio vs. b/B
minimum distances between footing and wall, primarily because no interaction was considered in the theoretical analysis. According to the results of the analysis, it seems that a strip footing should be away from a thick wall of over 6 in. (152.4 mm) at least five times the footing width to avoid significant adverse effect of wall on the ultimate bearing capacity of the footing.

6. Soil Yielding Pattern

The soil around the footing and wall will begin to undergo plastic yielding when the combined shear and normal stresses in the soil reach a critical value. The location of initial yielding and the rate of growth depend on loading intensity, footing location, and wall thickness. The plastic soil yielding pattern of the kaolin backfill for a 2 in. (50.8 mm) thick wall with a strip footing located at 3 ft (0.91 m) behind the wall is illustrated in Figure 11.

![Soil yielding pattern](image)

**Figure 11**: Soil yielding pattern for a footing located at 3 ft from a 2-inch thick wall (Kaolin).

The figure shows that plastic yielding initiates at both sides of the footing then propagates sideward toward the wall as well as downward deeper into the backfill, and that the zone of yielding reaches the wall. When the footing is located farther away at 9 ft (2.74 m) behind the wall, the yielding pattern, demonstrated in Figure 12, also skews toward the wall but this time does not reach the wall.
Figure 12: Soil yielding pattern for a footing located at 9 ft from a 2-inch thick wall (Kaolin).

Figure 13: Soil yielding pattern for a footing located at 9 ft from a 6-inch thick wall (Kaolin).
The plastic yielding pattern of a 6 in. (152.4 mm) thick wall with kaolin backfill plus a footing located at 9 ft (2.74 m) behind the wall is presented in Figure 13. A comparison between Figures 12 and 13, both having the same footing location but different wall thicknesses, reveals only slight difference in the shape although plastic yielding for the 2 in. (50.8 mm) wall seems to be spreading a bit more toward the wall. The slight difference between the two indicates little effect of wall presence on soil plastic yielding because of the relatively large spacing between the wall and footing. It is interesting to note that, in Figures 11, 12, and 13, a small zone of soil immediately underneath the footing base remains unyielding, which substantiates Terzaghi’s [14] theory that an unyielding soil wedge exists beneath rough footing bases under ultimate loading.

For the same wall thickness of 6 in. (152.4 mm) and footing location at 9 ft (2.74 m) but with the silty clay backfill, the soil plastic yielding zone spreads to the wall as shown in Figure 14.

![Figure 14: Soil yielding for a footing located at 9 ft from a 6-inch thick wall (Silty-Clay).](image)

The difference in plastic yielding patterns between Figures 13 and 14 can be attributed to the different shear strength properties of the two soils. The more plastic yielding in the silty clay can be attributed to a much lower cohesion of silty clay. In addition, as previously stated, the silty clay has a larger internal friction angle and therefore, the sliding zone extends farther than that of kaolin backfill according to Terzaghi’s theory [14].

**DISCUSSIONS**

The results of the analysis presented above indicate that the interaction between footing and sheetpile wall will result in increases in wall deflection, lateral earth pressure on the wall and footing settlement as well as a decrease in the ultimate bearing capacity of the footing. In addition, the
interaction will induce lateral displacement of footing. Thus, it appears that the interaction may adversely influence the performance of both the wall and the footing. The degree of interaction depends on many factors such as footing location behind the wall, wall thickness, loading intensity on the footing, and backfill soil type, among others. We note that the conditions analyzed were associated with only one level each of wall height and footing width. Nevertheless, for different wall heights and footing widths, the general conclusion concerning the behavior of footing and wall interaction should hold although the numerical data may differ.

Of the two different backfill soils investigated, the silty clay has a larger internal friction angle compared to kaolin and therefore has a greater lateral extent of slip surface under the ultimate loading. Consequently, to avoid interaction, the minimum spacing between wall and footing is greater for the silty clay than for the kaolin soil. Meanwhile, for a given footing location within the minimum spacing, the reduction in ultimate bearing capacity due to the interaction is greater for the silty clay than for the kaolin. Thus, the effect of the interaction on the ultimate bearing capacity of the footing should be analyzed for each backfill soil type to determine the critical footing location as well as the percent of reduction in ultimate bearing capacity.

![Figure 15: Comparison of Lateral Earth Pressure Distributions Induced by Surface Loading for Kaolin.](image)

The lateral earth pressure on the wall induced by a strip surface loading excluding geostatic pressure is determined using three different methods (Bowles, Jarquio, FEM Analysis) and compared in Figure 15. Note that the strip surface loading has a width of 3 ft (0.91 m) and is located at 9 ft (2.73 m) behind the wall that retains the kaolin backfill. Such a loading is equivalent to the condition of 3 ft (0.91 m) surface footing located at $b/B = 3$. The footing is subjected to a pressure of 12,000 psf (575 kN/m²), which is equivalent to 1/3 of the ultimate bearing capacity of the footing. The figure shows that the curves of Bowles [15] and Jarquio [2] have essentially the same shape although the magnitude differs considerably. The shape of the curve obtained from the finite element analysis varies from the other two curves, in that the compressive pressure below the dredge line increases almost linearly with depth as opposed to decreasing with depth. Such a disparity may be attributed to
the fact that the Bowles and Jarquio methods use elastic theory without a consideration of wall-footing interaction and that these solutions assume that the wall is rigid and stationary. In fact, the wall will deflect in response to the lateral pressure, and the wall deflection will in turn cause readjustment of lateral earth pressure. The non-existent lateral pressure atop the wall is primarily caused by the wall deflection away from the backfill as illustrated in Figure 5. Therefore, lateral earth pressure cannot be accurately determined without a consideration of wall-footing interaction.

When a strip footing on the backfill is nearby a sheetpile wall, the interaction between the wall and footing may cause lateral footing displacement as well as considerable footing settlement exceeding either the maximum allowable total settlement or the differential settlement or both. Thus, the structural design for buildings supported by such a footing/sheetpile wall system requires special attentions. These should focus on minimizing potential structural damage due to lateral footing displacement and the differential settlement between two adjacent footings. Measures for minimizing potential structural damage include reducing the footing load, stiffening the structural frame, moving the footing farther away from the wall, and possibly others.

**SUMMARY AND CONCLUSIONS**

The interaction behavior between reinforced concrete strip footings and cantilever sheetpile walls was investigated using finite element analysis. The footings were located on the backfill and parallel with the walls. The strip footing analyzed was 3 ft (0.91 m) wide with the base embedded at 3 ft (0.91 m) below the backfill surface. The reinforced concrete sheetpile wall had a height of 25 ft (7.62 m) with a penetration depth of 28 ft (8.53 m). The analysis was made with different loading intensities, five levels of wall thickness, four levels of footing location behind the wall, and two types of backfill soils. The response variables analyzed included footing settlement, horizontal footing displacement, lateral wall deflection, lateral earth pressure on the wall, plastic yielding of soil, and ultimate bearing capacity of footing. Results of the analysis indicate that the degree of interaction depends greatly on footing location and wall thickness. This interaction affects the performance of both wall and footing in such a way that the vertical settlement and horizontal displacement of the footing, the lateral wall deflection, and the lateral earth pressure increase, while soil plastic yielding intensifies, and the ultimate bearing capacity of the footing decreases.

Based on the analysis, a minimum distance between the wall and footing exists, beyond which the interaction becomes minimal. When the footing is near the wall, the interaction may cause structural damage to both the wall and the building supported by the footing. Possible measures for minimizing potential structural damage include moving the footing farther away from the wall, reducing the footing load, and stiffening the structural frame of the building.

**REFERENCES**


