Parametric study on performance of laterally loaded drilled shafts in an MSE wall

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Abstract

Drilled shafts are sometimes built in an MSE wall to support superstructures subjected to lateral loads. However, current design methodology isolates the interaction between drilled shafts and MSE walls, and the designs are independent. This design practice results in inappropriately designed drilled shafts and MSE walls. A three-dimensional numerical model of drilled shafts within an MSE wall was developed using FLAC3D and was calibrated with published data of a full-scale field study. Then the calibrated model was used for a parametric study to investigate the influence of various parameters on the synergistic performance of the drilled shafts and the MSE wall. The performance was assessed in terms of lateral displacement of the drilled shaft and MSE wall, the induced lateral earth pressure, and the induced strain in the geogrid. The investigated parameters in this study included the backfill material properties, the geogrid tensile stiffness and length, the distance between the drilled shaft and the MSE wall, and the length of the drilled shaft. An elastoplastic soil constitutive model, able to consider the compression and shear hardening, was used for the backfill material. The facing of the MSE wall was simulated as an assembly of discrete blocks which interacted with each other through interfaces. It was found that the properties of the backfill material, the distance between the drilled shaft and MSE wall, and the length of the drilled shaft had influence on the deflections, lateral earth pressure and strain in the geogrid. The extent of the influence varied and depended on the loads. The geogrid tensile stiffness and length did not show salient influence.

Keywords: MSE wall; Drilled shaft; Lateral displacement; Geosynthetic

1. Introduction

As infrastructure keeps expanding, newly constructed structures sometimes invade into the footprints of the existing structures. For instance, drilled shafts have been increasingly constructed within the reinforced zones of MSE walls to support various superstructures, such as wind walls, noise barriers, traffic signs, transmission towers, and bridge decks (for example, Anderson, 2005; Anderson and Brabant, 2005). These superstructures are subjected to considerable amount of lateral loads, such as wind loads, lateral pressure induced by soil movements, and/or seismic inertial forces (Pierson, 2007; Rollins et al., 2009). Due to the close association between the drilled shaft and MSE wall, any lateral load on the drilled shaft is expected to have some consequences on the performance of the MSE wall. However, the current design methodology isolates the interaction between drilled shafts and MSE walls, namely, the designs consider two independent structures and ignore the synergistic effect (Pierson et al., 2008). This design practice has resulted in inappropriately designed drilled shafts

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and MSE walls. Without considering the lateral support from the MSE wall, the drilled shafts are unduly embedded into the foundation soil/rock or increased to a larger diameter to obtain its lateral capacity (Pierson, 2007). For the test section where a drilled shaft (diameter=0.9 m) was located 1.8 m back from the MSE wall, the drilled shaft deflected about 50 mm under a lateral force of 250 kN (Pierson, 2007). However, if the support of the MSE wall is ignored, the drilled shaft has to embed into the bedrock and the diameter has to increase to 1.3 m to limit the deflection to 50 mm under a load of 250 kN. On contrary, the laterally loaded drilled shafts induce additional lateral pressures on the MSE wall and sometimes cause distress to the MSE wall, such as, dislocating the facing panels, undesirable lateral displacement of the wall, and rupture or pullout of the reinforcements. The research on the behavior of laterally drilled shafts within MSE walls is still at an infancy stage and the reported studies are scarce. Pierson et al. (2008) completed a full-scale field study on the behavior of laterally loaded drilled shafts within an MSE wall. Multiple drilled shafts of different lengths and/or different distances from the MSE wall were built and tested. Unlike the current practice, the drilled shafts were not embedded into the foundation rock in that study. It was found from the study that the MSE wall could provide considerable lateral support for the drilled shafts. After reporting dislocation of the facing panels, Berg et al. (2009) suggested that the induced earth pressure could be significant and should be studied further. Huang et al. (2011, 2013) performed a numerical analysis on one of the drilled shafts tested by Pierson et al. (2008) to further investigate the behavior of the drilled shaft and MSE wall.

This paper presents a numerical parametric study which investigated the influence of various parameters, such as the backfill material properties, geogrid tensile stiffness and length, distance between the drilled shaft and the MSE wall, and the length of the drilled shaft, on the displacement of the MSE wall and drilled shaft, the induced lateral earth pressure, and the induced strain in the geogrid reinforcement.

2. Study scheme

This study encompasses calibrating a three dimensional (3D) numerical model and then performing a parametric study. The geometry of the numerical model was adapted from the test sections reported by Pierson et al. (2009a, 2009b) as a prototype and the cross-section of the model is presented in Fig. 1. The material properties of retained soil, foundation rock, and MSE wall facing blocks and were adopted from Pierson (2007). The geogrid layers started from 0.2 m above the leveling pad elevation. The MSE wall used 10 layers of punch-drawn uniaxial geogrid among which the bottom four layers were UX 1500 (Geogrid A) and the top six layers were UX 1400 (Geogrid B). All of the geogrid layers were 4.2 m in length, which is the required minimum reinforcement length (i.e., 0.7 H) according to FHWA specifications (Berg et al. 2009). The geogrid layers started from 0.2 m above the leveling pad and were spaced 0.6 m vertically thereafter and were connected to the MESA\textsuperscript{©} facing blocks by connectors. A clean poorly graded crushed limestone aggregate was used as the backfill material, which had a maximum particle size of 20 mm, and \( D_{10}, D_{30} \) and \( D_{60} \) of 3, 6, and 15 mm, respectively.

Fig. 1. Numerical model (unit in m) (modified from Huang et al., 2013).

3. Field study of Pierson et al. (2008)

The study conducted by Pierson (2007) and Pierson et al. (2008) has been so far the most comprehensive field study on the behavior of laterally loaded drilled shafts built within an MSE wall. The study provided field monitoring data to calibrate the numerical model. A test MSE wall (6 m high and 43 m long) was built inside the southwest clover of the I-435/Leavenworth interchange in Kansas, USA. The layout of the MSE wall and the drilled shafts is shown in Fig. 2(a) and the cross-sections of the test wall are similar to what is shown in Fig. 1. The field study included testing eight drilled shafts (i.e., A, B, C, D, BS, BG1, BG2 and BG3) with an equal diameter of 0.9 m. The MSE wall, founded on a weathered limestone layer with a rock quality designation (RQD) 70%, had six test sections and one control section, and two wing wall sections at the ends. The six test sections included five 4.5 m wide test sections (i.e., Sections A, B, C, D, and BS) for single shaft testing, one 13.5 m wide test section (i.e., BG) for group shaft testing, and one 6 m wide control section as shown in Fig. 2(a). To reduce the influence from the adjacent test sections, the MSE wall facing blocks and geogrid reinforcements were discontinued at the boundaries of the test section.

For each of the single shaft test sections, only one drilled shaft was constructed. Shafts A, B, C, and D were located at 0.9, 1.8, 2.7, and 3.6 m from the back of the MSE wall facing, respectively and all of them penetrated the full height of the MSE wall. Shaft BS, located at 1.8 m away from the MSE wall, was relatively shorter and its tip was situated 1.25 m above the leveling pad elevation. The MSE wall used 10 layers of punch-drawn uniaxial geogrid among which the bottom four layers were UX 1500 (Geogrid A) and the top six layers were UX 1400 (Geogrid B). All of the geogrid layers were 4.2 m in length, which is the required minimum reinforcement length (i.e., 0.7 H) according to FHWA specifications (Berg et al. 2009). The geogrid layers started from 0.2 m above the leveling pad and were spaced 0.6 m vertically thereafter and were connected to the MESA\textsuperscript{©} facing blocks by connectors. A clean poorly graded crushed limestone aggregate was used as the backfill material, which had a maximum particle size of 20 mm, and \( D_{10}, D_{30} \) and \( D_{60} \) of 3, 6, and 15 mm, respectively.
The MSE wall and the drilled shafts were instrumented with slope inclinometers, LVDTs, tell-tales, earth pressure cells, strain gauges, and photogrammetry targets. This technology was used to monitor the deflections of the drilled shafts and the MSE wall, the lateral earth pressure, and the geogrid strains (Pierson et al., 2008, 2009a, 2009b). The instrumentation plan is shown in Fig. 2(b).

4. Numerical model

4.1. Constitutive models

Geogrid, drilled shaft and MSE wall facing blocks were considered as elastic materials. Geogrid was simulated by plane triangular elements that can sustain tension only. The retained soil, grade soil, and foundation rock/soil were considered as linearly-elastic perfectly-plastic materials with Mohr–Coulomb failure criteria. The backfill material was simulated by an elastoplastic model (called Cap-Yield model in FLAC3D (Itasca Consulting Group, 2009)), which can consider both compression and shear yielding. The compression yield surface, formulated in Eq. (1), is a curved surface perpendicular to the mean stress axis in the principal stress space, while the shear yield surface, formulated in Eq. (2), is a rotary surface symmetric to the mean stress axis in the principal stress space.

\[ f^c = \frac{q^2}{\alpha^2} + p^2 - p_r^2 \]  \hspace{1cm} (1)

\[ f^s = M p' - q \]  \hspace{1cm} (2)

Fig. 2. Test sections (unit in m): (a) layout of test section; and (b) instrumentation plan (modified from Pierson, 2007).
shape of the elliptical cap yield surface; $p_c$ is the cap pressure, which defines the size of the compression yield surface and is formulated in the following equation:

$$p_c = p_{ref} \left[ 1 + R k_{ref} \frac{\varepsilon^p}{p_{ref}} \right]^2$$

where $p_{ref}$ is the reference mean stress; $k_{ref}$ is bulk modulus at the reference pressure, $p_{ref}$; $\varepsilon^p$ is the plastic volumetric strain; $R$ is a constant.

Eq. (2) is different from the yield function of Modified Cam–Clay (MCC) model in that $M$ is a function of the mobilized friction angle, $\phi_m$ but not the ultimate friction angle, $\phi_f$. In Cap–Yield model, the friction angle, called mobilized friction angle ($\phi_m$), is not a constant but is a function of the accumulative plastic shear strain, $\gamma'$. The relationship between $\phi_m$ and $\gamma'$ is shown in Eq. (4). When the soil reaches limit state, the friction angle becomes ultimate friction angle, $\phi_f$.

$$\gamma' = \frac{p_{ref} \sin \phi_f}{G_{ref}} \left[ \frac{1}{1 - \sin \phi_f \sin \phi_m} - \frac{H_f}{R_f} \right]$$

where $G_{ref}$ is the shear modulus at the reference pressure; $\phi_f$ is the ultimate friction angle; and $R_f$, the failure ratio, is a constant less than 1. $R_f$ defines the ratio between the deviator stress at failure and the ultimate deviator stress (Duncan et al. 1980).

The reference bulk modulus, $K_{ref}$, was calculated according to the hyperbolic function as shown in Eq. (5), and then $K_{ref}$ was used to calculate $G_{ref}$. The determination of the parameters of the hyperbolic function was discussed thoroughly in Huang et al. (2013).

$$K_{ref} = K_c \left( \frac{p_{ref}}{p_0} \right)^n \text{ (unit : MPa)}$$

where $K_c$ is bulk modulus constant; $n$ is exponential constant. $K_c$ and $n$ were determined to be 45 MPa and 0.65, respectively (Huang et al., 2013).

During the modeling, the bulk modulus was kept updating as function of the mean principal stress, $p'$, as shown in the following equation:

$$K = (1 + R)k_{ref} \left( \frac{p'}{p_{ref}} \right)^{0.5} \text{ (unit : MPa)}$$

The compression yielding follows the associated flow, while the shear yielding follows the non-associated flow which is indicated in the following equation:

$$g = \sigma_1' - \sigma_3'$$

where $\sigma_1'$ and $\sigma_3'$ are the effective major and minor principal stresses, respectively.

### 4.2. Material properties

The properties of the materials are listed in Table 1. More details of the material properties should be referred to Pierson (2007), Pierson et al. (2008) and Huang et al. (2013).

### 4.3. Interface models

The contacts between dissimilar materials were simulated by interface models, which included the interfaces between the adjacent MSE blocks, the interfaces between the drilled shaft and foundation rock, and the interfaces between geogrid and backfill materials. The interface properties are listed in Table 2. The interfaces between the facing blocks were simulated by linearly-elastic perfectly-plastic springs with the Mohr–Coulomb failure criterion. The upper and lower surfaces (i.e., horizontal surface) of the blocks were rough and the friction angle, cohesion, shear stiffness were based on the direct shear tests conducted by Huang et al. (2009). The side surfaces (i.e., vertical surface) were relatively smooth and the reported friction angle and cohesion Ling et al. (2004) were used in this study. The interfaces between the drilled shaft and the limestone were simulated by the same interface model as blocks. The friction angle and cohesion between concrete and limestone were reported to be of 51° and 290 kPa, respectively (Kishen and Saouma, 2004) and these values were used with a reduction factor of 0.8 in this study. The bond strength of the
weathered limestone–concrete interface (i.e., cementation strength) was assumed to be the minimum value of the tensile strength of weathered limestone, tensile strength of the concrete, and bond strength of the interface between the intact limestone and concrete. The details on how to determine the bond strength can be found in Huang et al. (2013). The geogrid was modeled as an elastic material and the friction angle between the backfill material and geogrid was assumed the same as the friction angle of the backfill material. Huang et al. (2011) derived the shear stiffness of the interfaces between the backfill material and geogrid from the published pullout test data, which was adopted in this study.

4.4. Model calibration

The above-described numerical model was used to simulate the test sections of the field study of Pierson (2007) for verification purpose. The modeling was undertaken sequentially by initializing the foundation stress field, constructing the MSE wall by lifts, and then laterally loading the drilled shaft with equal force increments, i.e., in a “load-control” mode. The compaction effect during backfilling was simulated by initializing additional lateral earth pressure (Huang et al., 2013). To ensure the adequacy of the numerical model, the numerical model was used to simulate the test sections of A, B, D, and BS of Pierson et al.’s study. Test Section C was not simulated since this section was bounded by a sloped wing wall at one side and the details of the wing wall were unknown. The results for the numerical analyses were compared with field test data in terms of drilled shaft and MSE wall displacements and the comparison showed good agreement between numerical results and field test data (Figs. 3–5). Fig. 5 shows the horizontal displacements profiles of the MSE walls when the drilled shafts were displaced by 50 mm. The displacements presented are of the MSE wall facing at 5.4 m above the leveling pad. Due to the symmetric nature, only half of each profile is presented. The numerical analyses accurately captured the field test data.

5. Parametric study

On the basis of the model calibration, a parametric study was performed. The investigated parameters and their variation ranges are presented in Table 3. The material properties reported by Pierson (2007) and Huang et al. (2013) as presented in Table 1 are used for the baseline case. The model geometry is shown in Fig. 1 and for the baseline case the drilled shaft was located at 1.8 m from the MSE wall. Each time, one parameter was deviated from the baseline case to investigate its influence on the performance of the drilled shaft and the MSE wall. The modulus of the backfill is not a constant but depends on the stresses as shown in Eqs. (5) and (6). The modulus, \( K_c \), is proportional to the modulus constant, \( K_u \), which consequently can be considered as a modulus or stiffness indicator. In this parametric study, the influence of the
modulus was investigated by varying the modulus constant, $K_c$.

6. Results and discussions

The performance of the drilled shaft and MSE wall was evaluated in terms of the displacements of the drilled shaft and the MSE wall as well as the lateral earth pressure and geogrid strain induced by the laterally loaded drilled shaft.

6.1. Drilled shaft displacement

Fig. 6 presents the influence of the friction angle of the backfill material on the shaft displacement under different loads. The influence of the friction angle is negligible when the loads are low, such as 100 and 200 kN. As the load increases, the effect of the friction angle becomes salient, namely, the higher friction angle results in less shaft displacement. The effect of the friction angle on the shaft displacement is approximately linear when the load is less than 300 kN, and becomes non-linear when the load is 400 kN. The non-linear effect under 400 kN can be approximated by a power law curve. The variation of the effect of the friction angle with the load level is explainable. When the backfill is still predominantly in an elastic state, the influence of the friction angle is negligible. With the increase of the load, the backfill starts to yield gradually. As a result, the effect of the friction angle becomes appreciable and the non-linearity appears. Considering an allowable displacement of 50 mm, the influence of the friction angle is moderate.

Fig. 7 presents the effect of the backfill modulus constant, $K_c$, on the shaft displacement. The modulus constant shows a more significant influence on the shaft deflection than the friction angle. The increased modulus, i.e., stiffer material, leads to a reduced shaft displacement. The effect of the modulus on the displacement shows non-linearity starting from an earlier stage compared with the starting stage of the nonlinearity as shown in Fig. 6 (friction angle). The non-linear

![Fig. 6. Influence of the friction angle on shaft displacement.](image)

![Fig. 7. Influence of the backfill material modulus on shaft displacement.](image)

Table 3

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Variation range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backfill material</td>
<td>Modulus constant (MPa)</td>
</tr>
<tr>
<td>Friction angle (deg.)</td>
<td></td>
</tr>
<tr>
<td>Geogrid</td>
<td>Length (m)</td>
</tr>
<tr>
<td></td>
<td>Tensile stiffness (kN/m)</td>
</tr>
<tr>
<td>Distance between MSE wall and drilled shaft (m)</td>
<td></td>
</tr>
<tr>
<td>Length of drilled shaft (m)</td>
<td>0.9, 1.8°, 3.6</td>
</tr>
<tr>
<td></td>
<td>10, 15, 20°</td>
</tr>
</tbody>
</table>

The values used in the baseline case.
The effect of the modulus on displacement can be approximated by power law curves and is attributable to the dependence of the modulus on the stress.

Fig. 8 shows the effect of the length of the shaft on the shaft displacement. Intuitively, under a given load, the displacement of the shaft can be decreased by increasing the length of the shaft. Fig. 8 shows by increasing the shaft length the shaft displacement can be reduced exponentially. This finding implies that increasing the shaft length is very effective at increasing the shaft capacity or decreasing the shaft deflection.

Fig. 9 shows the effect of the distance between the drilled shaft and the MSE wall on the shaft displacement. In Fig. 9, the distance is presented as a ratio of the distance between the shaft and the MSE wall (D) to the length of the reinforcement (L). In this study, the reinforcement length is 4.2 m, which is 0.7 of the MSE wall height (6 m). Since the reinforcement length defines the range of the reinforcement zone, the distance presented as a ratio of the distance to the reinforcement length can be deemed an indicator of the shaft location in the reinforcement zone. Clearly, the distance between the shaft and the MSE wall has a significant influence on the shaft displacement. The displacement of the shaft increases greatly, when it is located closer to the MSE wall. As shown in Fig. 9, under the load of 50 kN, the displacements for the shafts located at 0.43 and 0.86 are nearly the same, while the displacement for the shaft located at 0.21 is much greater. When the drilled shaft is located close to the MSE wall, the drilled shaft relies largely on the support provided by the MSE wall facing and the support from the backfill soil is negligible.

The tensile stiffness and the length of the reinforcement have negligible influence on the shaft displacement unless the shaft is loaded to a very large deformation (i.e., > 150 mm). The negligible influence of the geogrid tensile stiffness and length can be attributed to the fact that the effect of the geogrid was localized. Pierson et al. (2011) reported that the laterally loaded shaft only caused additional tension in the geogrid closely surrounding the shaft. This phenomenon can be explained as the uniaxial geogrid has a weak strength in the cross machine direction (CMD), which prevents the tension being transmitted a larger area.

6.2. MSE wall displacement

Fig. 10 shows the effect of the backfill material friction angle on the MSE wall displacement. The friction angle shows a moderate effect on the MSE wall displacement when the lateral load is no greater than 200 kN. However, as the load increased to 300 kN, the effect of the friction angle becomes significant and non-linear.

Fig. 11 shows the effect of the backfill material modulus. The higher modulus constant causes less displacement of the MSE wall. This phenomenon is consistent with the fact that the drilled shaft displaces less with a higher backfill material
modulus. The curves for 200 and 300 kN can be fitted with logarithmic curves.

Fig. 12 illustrates the effect of the shaft length on the MSE wall displacement. The shaft length has a significant influence on the MSE wall displacement. The increase of the shaft length decreases the MSE wall significantly when subjected to the same load. Unlike the effect of the shaft length on the shaft displacement, the effect of the shaft length on the MSE wall displacement is approximately linear.

Fig. 13 shows the influence of the distance between the drilled shaft and the MSE wall on the MSE wall displacement. The influence of the distance is significant at all load levels investigated. The MSE wall deflection shows significant non-linear increase as the drilled shaft is constructed closer to the MSE wall.

Similar with their influence on the shaft deflection, the geogrid tensile stiffness and length have negligible influence on the MSE wall displacement.

6.3. Induced lateral earth pressure

The laterally loaded shaft causes a lateral earth pressure increase at the MSE wall. This additional pressure induced by the laterally loaded shaft may result in distress on the MSE wall. Thus, this paper only presents the maximum lateral earth pressure induced by the laterally loaded shaft, which excludes the lateral earth pressure developed before the load is applied. The effect of the friction angle on the lateral earth pressure is shown in Fig. 14. Generally, the higher friction angle leads to a lower lateral earth pressure increase. The effect of the friction angle on the lateral earth pressure is consistent with the effect of the friction angle on the shaft and MSE wall displacement. At the low load level, the soil behavior is predominantly elastic, and the effect of the friction angle is moderate. When the soil enters the plastic state, the backfill soil with a higher friction angle can provide more support which reduces the shaft and MSE wall displacements and alleviates the lateral earth pressure on the MSE wall.

The effect of the backfill modulus on the lateral earth pressure is shown in Fig. 15. The higher modulus constant results in less lateral earth pressure increase. Under different loads, the lateral earth pressure decreases linearly with the increase of the modulus constant. This phenomenon is consistent with the fact that the MSE wall displacement decreases linearly with the increase of the backfill modulus constant as shown in Fig. 11.

Fig. 16 presents the effect of shaft length on the induced lateral earth pressure. The longer shaft reduces the induced lateral earth pressure since the longer shaft can distribute the force to a larger area. The increase of the influenced area leads to less induced lateral earth pressure for a given load. As a
result, the vertical influence range of the drilled shaft is a function of the shaft length.

Fig. 17 shows the effect of the distance between the MSE wall and the shaft. As the distance from the MSE wall increases, the lateral earth pressure increase is lessened. When the shaft is located further from the MSE wall, the width of influence becomes greater (Pierson et al., 2011). The force is projected into a larger area and, consequently, the induced lateral earth pressure is less for a given load. The effect of the distance on the lateral earth pressure is significant even at low load level and the effect is more pronounced with an increase in the load. The effect at different loads approximately follows a power law as illustrated in Fig. 17.

The effects of the geogrid tensile stiffness and length are negligible unless the shaft is loaded to a very large displacement, i.e., \( > 150 \text{ mm} \).

6.4. Induced additional strain in geogrid

When the shaft is loaded with lateral forces, the geogrid layers are tensioned. The movement of the shaft only leads to a strain increase in the geogrid which is in the vicinity of the drilled shaft (Pierson et al. 2011). The geogrid located at the back and on two sides of the shaft experiences noticeable strain increase; however, the increase vanishes rapidly with the distance from the shaft. The geogrid located in front of the drilled shaft experiences strain reduction, since the material located between the shaft and the MSE wall is compressed. The strain increase, though limited to a small area, is significant and should not be neglected. This paper only presents the strain induced by the laterally loaded shaft, which excludes the strain developed before loading.

Figs. 18–21 presents the influence of the friction angle, the modulus, the shaft length and the distance between the shaft and the MSE wall on geogrid strain increase. The effects of
these factors on the geogrid strain are consistent with the effects of these parameters on shaft displacement. When the drilled shaft is displaced, the geogrid is stretched; thus, the drilled shaft displacement is somewhat an indicator of the elongation of the geogrid.

The effect of the geogrid tensile stiffness and length on the geogrid strain is negligible, which is consistent with the negligible effect of the geogrid tensile stiffness and length on the shaft displacement.

7. Conclusions

Based on the completed parametric study, the following conclusions are presented:

- The friction angle and modulus of the backfill material, the length of the drilled shaft, and the distance between the shaft and the MSE wall have noticeable influence on the displacements of the shaft and MSE wall, the induced additional lateral earth pressure, and the induced additional strain in geogrid. With the parameter variation range of this study, the geogrid tensile stiffness and length have insignificant influence on the behaviors of the shaft and MSE wall at low lateral loads.

- The increases of the backfill material friction angle and modulus, the shaft length, and the distance between the shaft and MSE wall result in decreases on the displacements of the shaft and MSE wall, the induced lateral earth pressure, and the induced strain. The effect of the friction angle on the behaviors of the drilled shaft and MSE wall is not significant until the backfill enters the plastic states, while the backfill modulus, the shaft length and the distance between the shaft and the MSE wall always show significant influence on the behaviors of the shaft and MSE wall.

- The shaft length shows an exponential influence on the shaft displacement and the induced strain in geogrid. The distance between the shaft and MSE wall shows a power law influence on the MSE wall displacement and the induced lateral earth pressure.

- Designers who look to improve the strength of their MSE wall and laterally loaded shaft systems should use longer shafts, higher quality backfill, and avoid placing shafts closer to the back of the wall facing than 45% of the reinforcement length.

- Additional research needs to be conducted to evaluate shafts loaded as a group, smaller diameter shafts or piles, and strengthening the reinforcement directly around the shaft.

In summary, this study presents the influence of various factors on the performance of the drilled shaft and the MSE wall, and the empirical relationships between the factors and the performance. The results of this study can provide useful information to develop a design guideline.

References