Influence of Soil Reinforcement on Horizontal Displacement of MSE Wall

Golam Kibria, S.M.ASCE[1]; MD. Sahadat Hossain, P.E., M.ASCE[2]; and Mohammad Sadik Khan, S.M.ASCE[3]

Abstract: Mechanically stabilized earth (MSE) walls offer simple construction techniques, pleasing aesthetics, and cost-effective solutions as an alternative to conventional gravity walls. However, design and construction should be carefully evaluated to achieve satisfactory performance of the wall. A case study is presented on a MSE wall located on State Highway 342 in Lancaster, Texas. The horizontal movement of the MSE wall was between 300 and 450 mm within 5 years of construction. A forensic investigation was performed to determine the causes of the excessive movement. It was identified that inadequate reinforcement length was one of the contributing factors that caused horizontal displacement of the MSE wall. The objective of this study was to determine the effects of soil reinforcement on excessive movement of the MSE wall. As a part of the forensic investigation, two inclinometers were installed at the site to monitor any additional movement of the MSE wall. The inclinometer results suggested that the wall continued to move at an average rate of 4.5 mm/month during the investigation period. A finite-element (FE) program was used to simulate horizontal displacement and stability of the MSE wall. It was observed that the numerical modeling results were in good agreement with inclinometer results. A parametric study was conducted to identify the effects of soil reinforcement on horizontal movement at varied wall heights and backfill conditions. Numerical analyses results indicated that the effect of reinforcement stiffness was not significant at a wall height of 4 m compared with 8 and 12 m. The wall movement varied from 74 to 29 mm for an increase in reinforcement stiffness from 250 to 42,000 kN/m at $1.0H$ reinforcement length. The variations in displacement with reinforcement lengths suggested that substantial reduction in displacement occurred for an increase in length-height (L/H) ratio from 0.5 to 0.7. FE modeling results were used for sensitivity analysis employing a statistical analysis program. Based on the analyses, reinforcement length and stiffness were identified as influential factors for the horizontal displacement of MSE walls at a specific height. **DOI:** 10.1061/(ASCE)GM.1943-5622.0000297.

Author keywords: MSE wall; Inclinometer; Finite-element modeling; Horizontal displacement; Sensitivity.

Introduction

A mechanically stabilized earth (MSE) wall is a composite system consisting of soil reinforcement, backfill material, a facing element, and a foundation (Elias et al. 2001). In the construction of a MSE wall, reinforcements are placed in layers in the backfill soil, and this reinforced mass resists the earth pressure caused by the retained soil using the relative motion between reinforcement and soil. Therefore, the performance of a MSE wall depends on the interaction among its components, particularly between soil and reinforcement (Desai and El-Hoseiny 2005). In addition, the earth pressure caused by the retained soil should be considered in the design with importance (Elias et al. 2001).

In current design practices, the recommended length of soil reinforcement is $0.7H$ (H = height of wall) or not less than 2.4 m, according to Federal Highway Administration (FHWA) (Elias et al. 2001) and AASHTO (2002). However, the National Concrete Masonry Association (Collin 2002) specified a minimum reinforcement length of $0.6H$. The use of recommended reinforcement length may be restricted where natural rock formations, human-made shoring systems, or another retaining walls are observed behind a MSE wall (Leshchinsky et al. 2004). In these cases, issues related to stability and excessive horizontal displacement can occur.

In addition to reinforcement length, the selection of backfill soil is important because Soong and Koerner (1999) reported 20 case histories on geosynthetic-reinforced wall failures resulting from the poor performance of marginal backfill. Backfill should be free-draining material and should not contain organic and deleterious substances (Elias et al. 2001). Furthermore, the earth pressure coming from the retained fill is resisted by the reinforced soil mass. Therefore, the effect of retained fill should be considered with importance during design.

Inadequate length of soil reinforcement may cause excessive horizontal displacement or even failure of a MSE wall. As a result, horizontal displacement poses significant concern when space behind a wall is limited (Bilgin and Kim 2010). This study was conducted on a MSE wall located at State Highway 342 in Lancaster, Texas. The horizontal movement of the MSE wall was between 300 and 450 mm within 5 years of construction. An extensive forensic investigation was performed using conventional soil test borings, geophysical testing (resistivity imaging), installation of inclinometers, and numerical modeling. Details on the geotechnical and geophysical testing can be found in the study conducted by Hossain et al. (2012).

The objective of this study was to determine the effects of soil reinforcement on excessive movement of a MSE wall. The computer

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program *PLAXIS 2D* (Plaxis 2010a, b) was used to develop a finite-element (FE) model for the prediction of MSE wall movement. A parametric study was conducted to identify the effects of various structural components of a MSE wall on horizontal displacement. Based on the numerical modeling results, statistical analysis was performed using *SAS 9.2* to identify the parameters that influence movement.

Background

Numerical Modeling of MSE wall

Mechanically stabilized earth (MSE) walls have gained significant acceptance since the 1970s because of their economic benefits compared with conventional gravity retaining wall (Elias et al. 2001; Bilgin 2009). MSE walls offer simple construction techniques, pleasing aesthetics, reliability, and a cost-effective solution (Mitchell and Zornberg 1995; Leshchinsky and Han 2004). However, design and construction should be carefully evaluated to achieve satisfactory performance of the wall (Elias et al. 2001). Performance data on MSE walls are required in many cases and can be obtained by field instrumentation, centrifuge tests, and full-scale physical modeling. Nevertheless, field monitoring and experimental tests are costly and time-consuming (Bergado and Teerawattanasuk 2008; Desai and El-Hoseiny 2005; Abdelouhab et al. 2011). As an alternative, computer-based numerical modeling can be used for the design, parametric studies, and forensic investigation of MSE walls (Karpurapu and Bathurst 1995; Hossain et al. 2012). According to Collin (1986), the computer program adopted for the design and analysis of MSE walls should be able to model structural components, construction sequence, soil behavior, and interface elements.

Limit-equilibrium, finite-difference, and FE methods are commonly used in the design and analysis of MSE walls. In the limit-equilibrium method, analysis is carried out either in a force-equilibrium or strain-compatibility approach. A properly adopted limit-equilibrium method can be used for determination of the factor of safety, but identification of progressive failure, deformation, and stress distribution in MSE walls may not be possible with this method (Han and Leshchinsky 2004; Ho and Rowe 1994).

The finite-difference method (FDM) was used by many researchers for numerical modeling of MSE walls (Lindquist 2008; Leshchinsky et al. 2004; Reddy and Navarrete 2008; Pierson et al. 2011; Youwai and Bergado 2004; Bergado and Teerawattanasuk 2008; Abdelouhab et al. 2011). Hatami et al. (2001) presented a numerical study on the potential use of reinforcements in different configurations of MSE walls. A total of 21 wrap-faced walls with different reinforcement layouts and stiffness values were modeled using the finite-difference program *FLAC*. It was assumed that the modeled walls were structurally stable and reinforcement pullout or yielding did not occur. The study results indicated that the reinforcement layers with small spacing and stiffness values provided reduced lateral displacement of facings, whereas shortening reinforcement length by 50% at every alternative layer was reported as a cost-effective method for the design of MSE walls.

Finite-element modeling of MSE walls can be performed using discrete and composite approaches. In discrete modeling, soil and reinforcements are considered separately, and various elements of the reinforced soil mass are modeled using different material properties (Ling 2003). Extensive information on stress concentration and interface behavior between soil and reinforcement can be obtained using a discrete approach. In contrast, the reinforced soil is considered as a homogeneous composite structure in the composite modeling method (Desai and El-Hoseiny 2005).

Another important aspect of reinforced earth numerical modeling is the use of an appropriate constitutive model to predict soil behavior. The literature indicated a number of case studies in which MSE walls were modeled using the elastic-plastic Mohr-Coulomb constitutive model that yielded satisfactory results (Bergado and Teerawattanasuk 2008; Reddy and Navarrete 2008; Kim et al. 2010; Rowe and Ho 1998; Pierson et al. 2011; Leshchinsky and Vulova 2001). Huang et al. (2009) presented a study on segmental reinforced soil walls using modified Duncan-Chang, Lade, and Mohr-Coulomb constitutive models. According to the study, the predicted results were within the range of measured values under plane-strain conditions. It was also reported that the Mohr-Coulomb model provided satisfactory results when reinforced walls were simulated under working conditions.

Statistical Analysis in MSE Walls

It is evident from the literature that different statistical approaches can be used to evaluate the behavior of MSE walls. Chalermyanont and Benson (2004, 2005) described probabilistic methods for the internal and external design of MSE walls employing Monte Carlo simulations. Soil and reinforcement properties were randomly sampled from probability distributions, and safety factors were calculated using Elias-Christopher (external stability) and Bishop's simplified method (internal stability). Based on the study, reliability-based design (RBD) charts were developed at 0.01, 0.001, and 0.0001 probabilities of failure.

A multiple linear regression (MLR) analysis can be used to relate horizontal movement of MSE walls to reinforcement length, stiffness, backfill friction, and wall height. During development of the MLR analysis model, the assumptions should be determined based on the residual analysis. According to Kutner et al. (2005), residuals should be uncorrelated and normally distributed and have constant variance in the MLR analysis model. Transformations of the variables are recommended when MLR analysis assumptions are not satisfied. Generally, transformations in response and predictor variables are conducted using an inverse, logarithmic, square root, or power function. However, applicability of the function should be statistically evaluated before transformation.

Once the MLR analysis model assumptions are satisfied, stepwise regression can be performed to determine parameters of influence. This method is used to obtain potentially good models from backward elimination and forward selection algorithms. During the stepwise regression method, the parameter with the highest statistical significance is included in the model, and regression analysis is performed. After completion of the first analysis, another parameter is added to the preceding model, and the procedure is repeated. Typically, statistical significance tests (i.e., F-statistic) are used to select the parameters sequentially (Kutner et al. 2005).

Description of the MSE Wall

This study was conducted on a MSE wall located at State Highway 342 in Lancaster, Texas. The height of the wall was 7.6 m at Station 1 + 590, 8.1 m at Station 1 + 620, and 3.6 m at Station 1 + 790. The cross sections and variations in height of the wall are presented in Fig. 1. A storm sewer was located beneath the flume. The MSE wall was reinforced using steel wire mesh, and standard precast panels were used for the facing. Granular soil was proposed in the design of reinforced and retained fill.

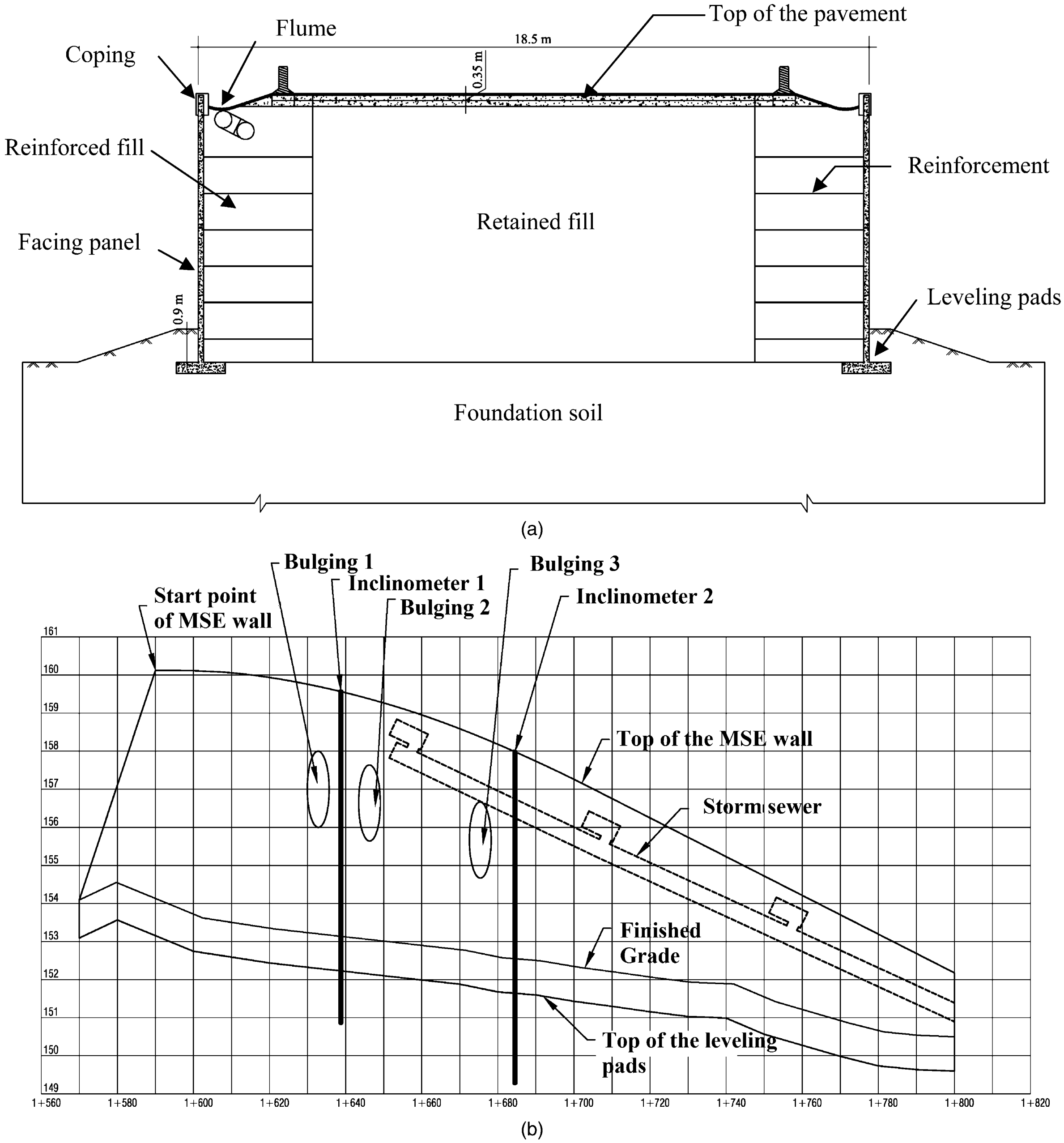

Fig. 1. (a) Cross section of MSE wall (qualitative); (b) variation in heights and locations of bulging

The set of plans indicated that the reinforcement length should be at least 2.4 m.

Significant horizontal movement was observed in the MSE wall within 5 years of construction. Extensive cracks were formed on the pavement as a result of excessive movement of the MSE wall. An investigation was performed to determine the possible causes of excessive movement that included geotechnical testing of the backfill soil and resistivity imaging (RI).

Based on the investigation, it was determined that excessive movement might occur as a result of the presence of perched water zones in the backfill-soil area. Laboratory investigation indicated that the percentages of fine fraction in the backfill soil ranged from 28.9 to 38.8%. Furthermore, inadequate soil reinforcement also might be responsible for the movement. Details of the geotechnical and geophysical investigation results can be found in the study conducted by Hossain et al. (2012).

Investigation Methodology

Inclinometer Installation

As a part of the investigation, two inclinometers were installed between Stations 1 + 630 and 1 + 640 and Stations 1 + 680 and 1 + 690, respectively (Fig. 2). The objective of the installation of inclinometers was to determine any additional movement of the MSE wall. Horizontal displacement of the wall was monitored from December 2009 to August 2011 on a biweekly basis.

Development of FE Model

The MSE wall was modeled using the two-dimensional (2D) FE program *PLAXIS 2D* (Plaxis 2010a, b), which required an assumption that the strain in the direction perpendicular to the plane

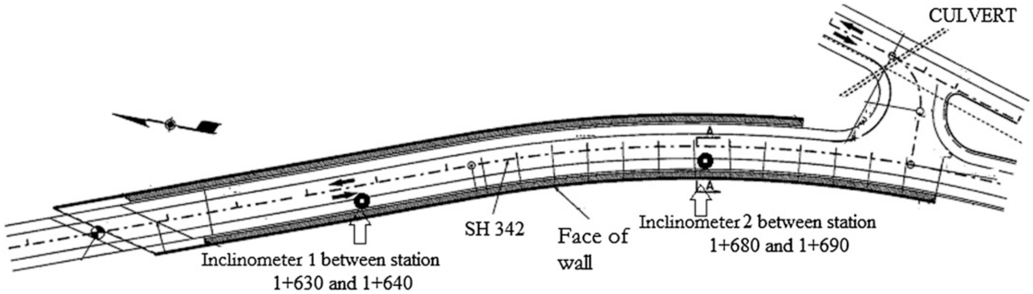

Fig. 2. Locations of inclinometers

was zero. Therefore, a plane-strain condition was considered in the analyses. The behavior of reinforced fill, retained fill, and foundation soil was simulated using an elastic–perfectly plastic Mohr-Coulomb yield function with a nonassociated flow rule.

The properties of backfill soil and structural elements in the model were in accordance with the proposed design. The presence of the water table was not observed during soil test borings, but a few perched water zones were identified in the backfill area from resistivity imaging. The perched water zones were simulated using saturated soil clusters. It should be mentioned that permanent loading was not observed within the MSE wall; therefore, a surcharge was not considered in the model (Elias et al. 2001).

Soil reinforcement was modeled using geogrid elements in *PLAXIS 2D* (Plaxis 2010a) that considered only axial stiffness. The reinforcement length-to-height (L/H) ratio was 0.32, which was specified by the set of plans. A storm sewer was located beneath the flume; therefore, the first reinforcement layer was placed 1.5 m below the top of the wall. The lift thickness of the reinforcement was not provided in the design; hence three vertical spacings of 0.6, 0.8, and 1.0 m were considered in the initial models.

Beam elements were used to simulate facing and leveling pads, where both axial and bending stiffness was considered. The thicknesses of the concrete facing and leveling pads were 0.15 and 0.6 m, respectively. Standard fixities were used in the current model, which allowed full fixity at the base of the geometry and roller conditions at the vertical sides.

A previous study indicated that the variation in displacement was negligible for the reduction in interface angle from 1.0 to 0.67 of reinforced-fill friction (Rowe and Ho 1998). Therefore, interface friction between soil and reinforcement was considered to be 0.67 of the friction angle of reinforced backfill. During the modeling, the behavior of the interface was characterized by Mohr-Coulomb yield criteria. The properties of the interface were calculated by multiplying the interface friction factor (0.67) with the strength properties of the associated soil layers. It was assumed that the relative movement of the interface would occur in both perpendicular and parallel directions. The displacements were determined from the ratio of induced stress and stiffness perpendicular and parallel to the interface. It should be mentioned that interfaces were composed of five pairs of nodes and five Newton-Cotes stress-integration points for stiffness matrix calculation and connected with the soil elements.

A robust triangulation process was used to generate a 15-noded unstructured mesh. The horizontal displacement of the MSE wall was determined using a global stiffness matrix procedure after mesh generation. It is recommended to use a global stiffness matrix when a linear relationship exists in the elastic domain of the material model (Mohr-Coulomb) (Plaxis 2010b). Elastoplastic deformation analysis was performed to determine the horizontal displacement. In addition, the overall stability of the MSE wall was determined using the phi-c reduction procedure. The geometry and mesh configuration of the model are presented in Fig. 3. Material data-set parameters used in the current model are presented in Tables 1 and 2 (Hossain et al. 2012).

Results

Inclinometers

Construction of the MSE wall was completed in 2004. It was reported that the MSE wall moved as much as 300 to 450 mm during the years 2004–2009. The horizontal movement of MSE wall was monitored from December 2009 to August 2011. Inclinometer results indicated that the movement of the MSE wall was not significant from December 2009 to May 2010; however, an additional 38 mm of horizontal movement was recorded in the following 15 months. The rate of movement ranged from 2.5 to 12.7 mm/month during this period. The average rate of movement from December 2009 to August 2011 was 4.5 mm/month. A summary of the movement of the MSE wall is presented in Table 3.

Numerical Modeling

Numerical modeling results of the MSE wall for three different lift thicknesses suggested that the maximum horizontal displacements were 263, 277, and 287 mm for 0.6-, 0.8-, and 1.0-m vertical spacing of the reinforcement, respectively. The field monitoring results indicated a total displacement of 344 mm. Therefore, predicted horizontal displacement with a vertical spacing of 1.0 m was close to the results obtained from the inclinometers. Horizontal displacement of the MSE wall with 1.0-m lift thickness is presented in Fig. 4.

Overall stability of the MSE wall was determined using the phi-c reduction method in *PLAXIS 2D* (Plaxis 2010a). During the analyses, the soil strength parameters were successively reduced until the overall factor of safety reached a minimum value. The overall factor of safety did not change significantly for the variation in lift thickness. It was identified that the factor of safety was approximately 1.2. The failure surface extended 10 m beyond the reinforced zone, which indicated that the reinforcement length might not be adequate. In addition, variations in factor of safety for the three lift thicknesses might not occur because reinforcement length was identified as the dominant factor in the stability analyses. The observed failure surface from the numerical analysis is presented in Fig. 5.

It should be mentioned that reinforcement was not provided at the top 1.5 m because of the presence of a storm sewer at that location. This lack of reinforcement also might be responsible for the excessive displacement at the top of the wall.

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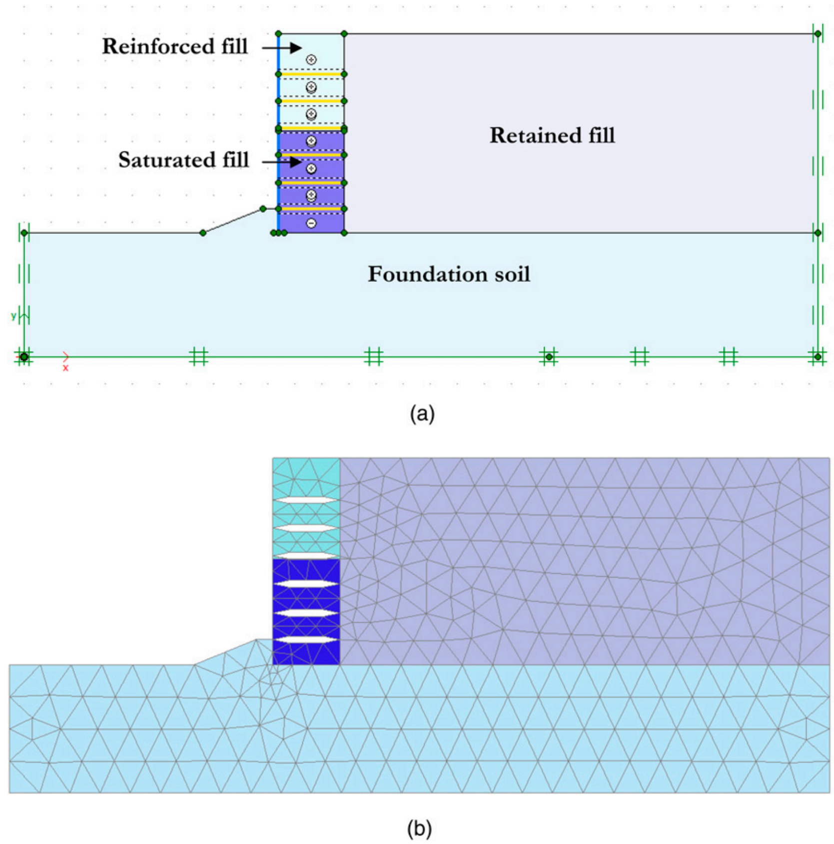

Fig. 3. (a) Geometry of MSE wall; (b) mesh connectivity

Table 1. Soil Parameters Used in the Model (Hossain et al. 2012, © ASCE)

Parameters	Select backfill	Random backfill	Foundation soil
γ (unsaturated) (kN/m^2)	18.8	18.8	16
γ (saturated) (kN/m^2)	22	22	16
Φ (angle of friction) (degree)	34	30	27
C (cohesion) (kN/m^2)	1	1	8.45
ψ (dilatancy angle) (degree)	4	0	0
E (modulus of elasticity) (kN/m^2)	12,500	10,000	5,500
Poisson's ratio	0.32	0.3	0.3

Table 2. Structural-Element Parameters Used in the Model (Hossain et al. 2012, © ASCE)

Structural element	Axial stiffness (kN/m)	Bending stiffness ($kN{\cdot}m^2/m$)
Facing panel	4,017	3.08×10^6
Soil reinforcement	150	—

Comparison of Predicted Movement with Inclinometer Results

Numerical modeling and inclinometer results showed that the maximum movement occurred at the top of the wall. A rotational failure pattern was identified from the analyses that was in good agreement with the inclinometer results. A comparison of the horizontal displacement predicted by *PLAXIS 2D* (Plaxis 2010a, b) with the total field movement during the years 2004–2011 is presented in Fig. 6.

Table 3. Wall-Movement Summary

Time period	Total movement (mm)	Movement/month (mm)
May 2004–October 2009	300–450	4.5–7
December 2009–May 2010	1–2	<1
June 2010–July 2010	5–8	2.5–4
August 2010–May 2011	16–24	1.27–1.9
June 2011–August 2011	24–38	8–12.7

A total movement of 344 mm was observed in the field, whereas the numerical modeling results provided a maximum movement of 287 mm. Therefore, the field movement was 19.9% greater than the predicted movement. This variation might occur as a result of infiltration of surface water through the cracks in the pavement. Fig. 6 suggests that the measured horizontal displacements at different depths of the wall match fairly well with the predicted results.

Parametric Studies

Investigation of the MSE wall indicated that inadequate reinforcement length might be one of the factors that caused excessive movement. Therefore, a parametric study was conducted to determine the effect of reinforcement length and stiffness on horizontal displacement at varied wall heights and reinforced- and retained-fill conditions. The material properties of the facing panels and leveling pads were similar to those in the MSE wall. However, a vertical spacing of 0.8 m was used based on the maximum spacing design criteria of the FHWA (Elias et al. 2001).

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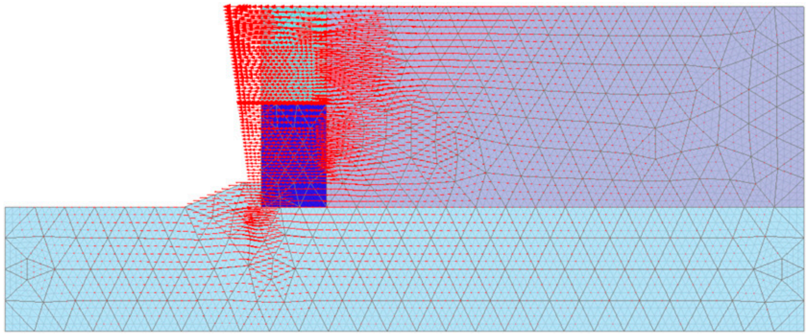

Fig. 4. Maximum horizontal displacement 287 mm (arrows indicate direction of movement of MSE wall)

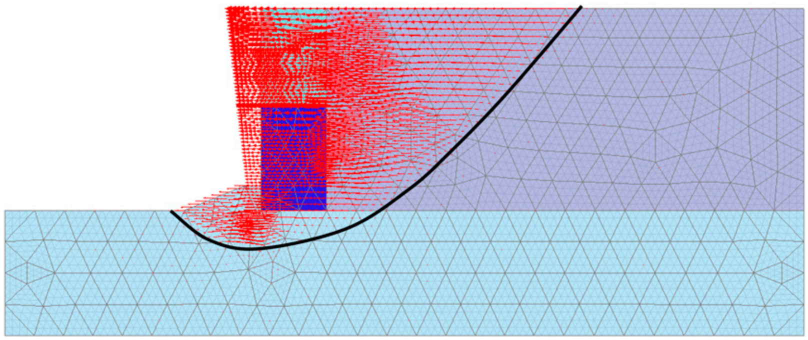

Fig. 5. Overall factor of safety of 1.2 (arrows indicate direction of movement of MSE wall)

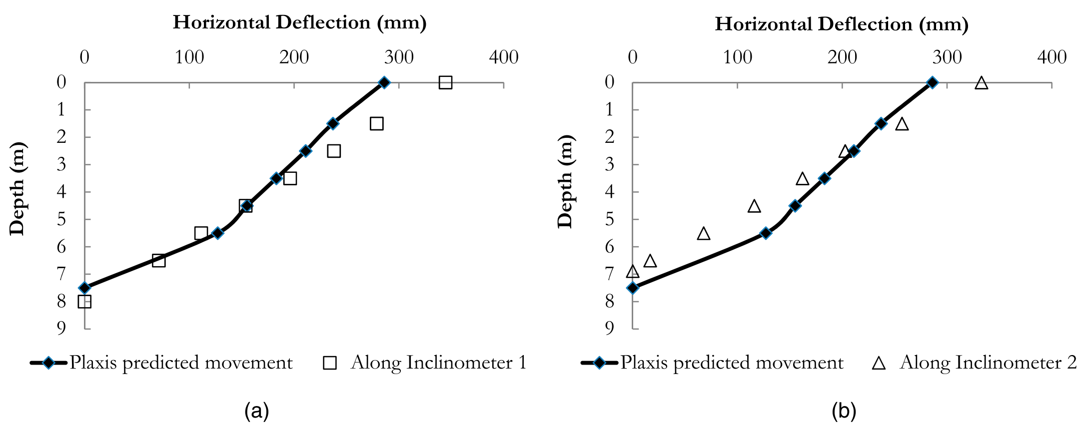

Fig. 6. Comparison of total horizontal movement with numerical modeling: (a) Inclinometer 1; (b) Inclinometer 2

Parametric studies were performed at varied MSE wall heights of 4, 8, and 12 m. The length and stiffness of the soil reinforcement ranged from $0.3H$ to $1.0H$ and 150 to 42,000 kN/m, respectively. It was observed that MSE walls with a height of 12 m were not stable at low L/H ratios and stiffnesses. Therefore, the numerical results presented in this paper were applicable only to stable MSE walls (factor of safety > 1.0). The friction angles in the model for the reinforced and retained fill were 26, 30, 34, 38, and 42° and 26, 30, and 34°, respectively. During the analyses, it was assumed that the friction angle of the reinforced fill was higher than the friction angle of the retained fill. The ranges of structural properties in the parametric studies of MSE are summarized in Table 4.

Table 4. Summary of MSE Wall Properties Used in the Parametric Studies

Parameter	Analysis performed
MSE wall height	4, 8, and 12 m
Ratio of reinforcement length to wall height	0.3–1.0
Reinforcement stiffness	150–42,000 kN/m
Friction angle of reinforced fill	26, 30, 34, 38, and 42°
Friction angle of retained fill	26, 30, and 34°

Effect of Reinforcement Stiffness

The variations in horizontal displacement with reinforcement stiffness were identified for three different wall heights (4, 8, and 12 m),

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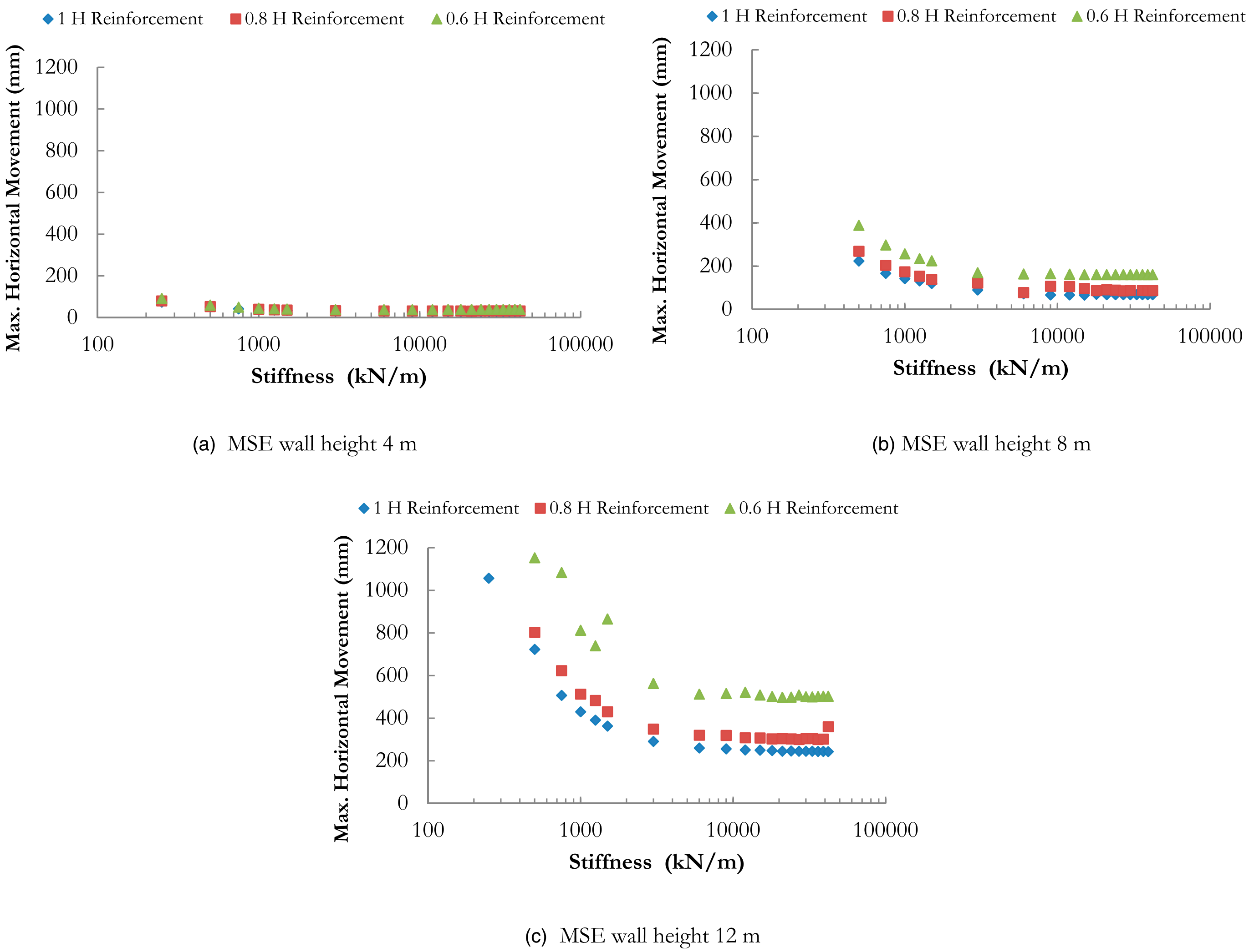

Fig. 7. Effect of stiffness on horizontal displacement of MSE wall

as shown in Fig. 7. The illustrated results corresponded to reinforced- and retained-fill friction angles of 34 and 30°, respectively. Reinforcement stiffness values were presented in logarithmic scale for ease of visualization (Rowe and Ho 1998; Siddiquee and Alam 2005). Fig. 7 indicates that horizontal displacement decreased with an increase in reinforcement stiffness at each reinforcement length.

It was observed that the effect of stiffness was not significant at a wall height of 4 m. The range of movement decreased from 74 to 29 mm for an increase in stiffness from 250 to 42,000 kN/m at 1.0H reinforcement length. However, the horizontal movement was 389 mm at a reinforcement stiffness and length of 250 kN/m and 0.6H for an 8-m wall. Movement of the wall decreased to 66 mm when reinforcement stiffness and length were 42,000 kN/m and 1.0H, respectively. In addition, the observed reduction in displacement ranged from 57 to 66% for an increase in reinforcement length of 0.6H to 1.0H at this wall height.

Based on the numerical analyses, horizontal deformation of the wall increased significantly at a stiffness lower than 1,000 kN/m, but a substantial change in horizontal displacement had not occurred at higher stiffnesses. A similar trend was observed in the study conducted by Youwai and Bergado (2004), in which the observed horizontal displacement was significant at low reinforcement stiffness.

The variation in horizontal deformation with reinforcement stiffness can be explained by the study conducted by Rowe and Ho (1998). According to that study, a reinforced soil system provides resisting force to maintain equilibrium condition in the MSE wall. Strain development in the reinforced soil is restricted considering that strain compatibility exists between the reinforcement and the soil. Therefore, a reduction in strain in the reinforced soil occurs with an increase in stiffness. In the current numerical analysis, horizontal strains were measured at a point in the reinforced soil for the 12-m wall (4.9 m below the top surface and 2.9 m from the facing). The variation in horizontal strain with reinforcement stiffness is illustrated in Fig. 8. It was shown that the strain decreased with an increase in reinforcement stiffness.

Effect of Reinforcement Length

The effect of reinforcement length on horizontal displacement of a MSE wall is presented in Fig. 9. A large stiffness of 30,000 kN/m was considered to identify the effect of reinforcement length because the variations in displacement with stiffness were insignificant at this condition. The illustrated results corresponded to reinforced- and retained-fill friction angles of 34 and 30°, respectively. Fig. 9 indicates that a significant reduction in horizontal movement occurred for an increase in L/H ratio from 0.5 to 0.7. For a 12-m wall, an increase in

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L/H ratio from 0.5 to 1.0 reduced horizontal movement from 816 to 245 mm. Therefore, a twofold increase in reinforcement length caused a 70% reduction in displacement. Moreover, horizontal displacement reduced 72.5 and 44.2% for an increase in L/H ratio from 0.5 to 1.0 in a 8- and 4-m MSE wall, respectively.

The study conducted by Chew et al. (1991) indicated that an increase in L/H ratio from 0.5 to 0.7 caused a 50% reduction in displacement. In this study, the percent reductions were 50.7, 53.8, and 42.3% for the 12-, 8-, and 4-m MSE walls, respectively. Therefore, the results obtained were in good agreement with the study conducted by Chew et al. (1991).

The effect of reinforcement length on horizontal movement can be explained by the location of the Rankine failure plane. A reduction in the horizontal displacement occurred when the length of the reinforcement extended beyond the Rankine failure plane.

Effect of Reinforced and Retained Soil

Numerical analyses indicated that the horizontal displacement of the MSE wall was influenced by reinforcement stiffness and length. Therefore, the variations in horizontal movement with reinforced- and retained-soil friction angles were discussed at fixed reinforcement stiffness and length, respectively.

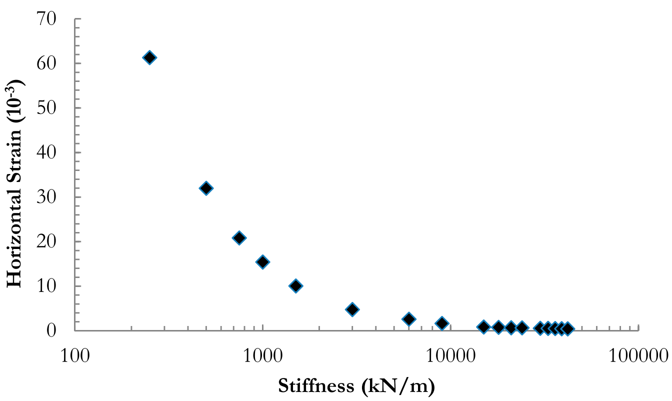

Fig. 8. Variation in horizontal strain at a point inside reinforced fill (for 12-m wall)

At Fixed Reinforcement Stiffness

The variations in displacement with reinforced-fill friction angle for three wall heights are presented in Fig. 10. It should be noted that the variations presented were at a retained-fill friction and reinforcement stiffness of 30° and 30,000 kN/m, respectively.

Fig. 10 shows that the horizontal displacement decreased with an increase in reinforced-fill friction angle from 30 to 42°. A significant reduction in displacement was not found in the MSE wall with a height of 4 m. However, a displacement of 161 mm was observed at a L/H ratio of 0.6 and a reinforced-fill friction angle of 30° in an 8-m wall. The displacement reduced to 64 mm with a reinforced-fill friction angle of 42° under similar condition. Table 5 presents a summary of the maximum and minimum movement for the increase in reinforced-fill friction angle from 30 to 42°.

Numerical analyses indicate that the displacements were large at a L/H ratio of 0.6 and reinforced-fill friction angles of 30 and 26°. The variations observed in horizontal displacement with reinforced fill at different L/H ratios can be explained by the study conducted by Rowe and Ho (1998). According to these authors, a zero-force line exists behind the Rankine failure plane. The lateral displacement is not significant when reinforced soil intercepts a substantial area between the vertical wall and the zero-force line. Area of reinforced fill, Rankine failure plane, and the zero-force line for the 12-m wall with a reinforced-fill friction angle of 30° is illustrated in Fig. 11. A significant area between the wall and the zero-force line was not covered by reinforced fill at this condition. It should be mentioned that the horizontal movement was as much as 729 mm in the 12-m wall with reinforced- and retained-fill friction angles of 30 and 26°, respectively. In addition, mobilization of tensile force as a result of the relative movement at the interface depends on the reinforced-fill friction angle and contact area between the soil and reinforcement. Therefore, both the reinforced soil coverage area and the mobilization of tensile force might cause the observed variations.

At Fixed Reinforcement Length

The variations in horizontal displacement for the increase in reinforced-fill friction angle from 30 to 42° are presented in Fig. 12. The results presented corresponded to 0.7H reinforced length and 30° of retained-fill friction angle. It was observed that the reduction in horizontal movement with the increase in reinforced-fill friction angle was not significant in the 4-m wall. However, movement

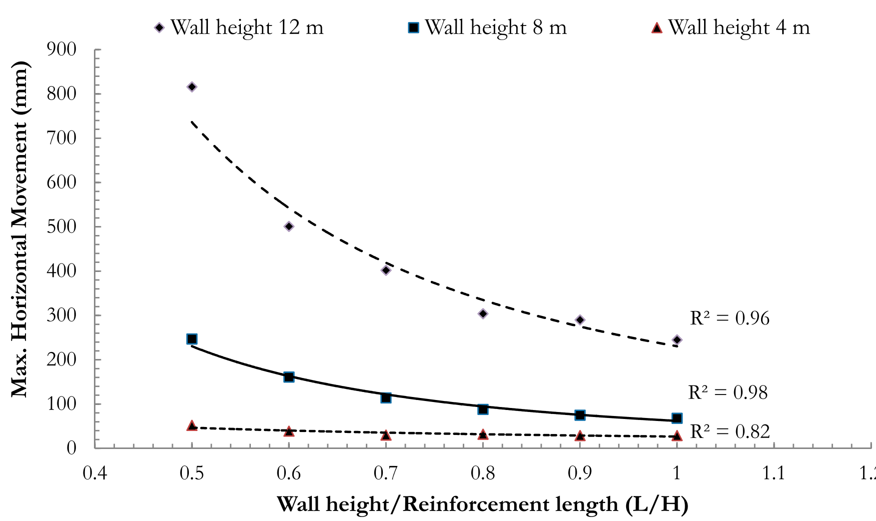

Fig. 9. Effect of reinforcement length on horizontal displacement of MSE wall

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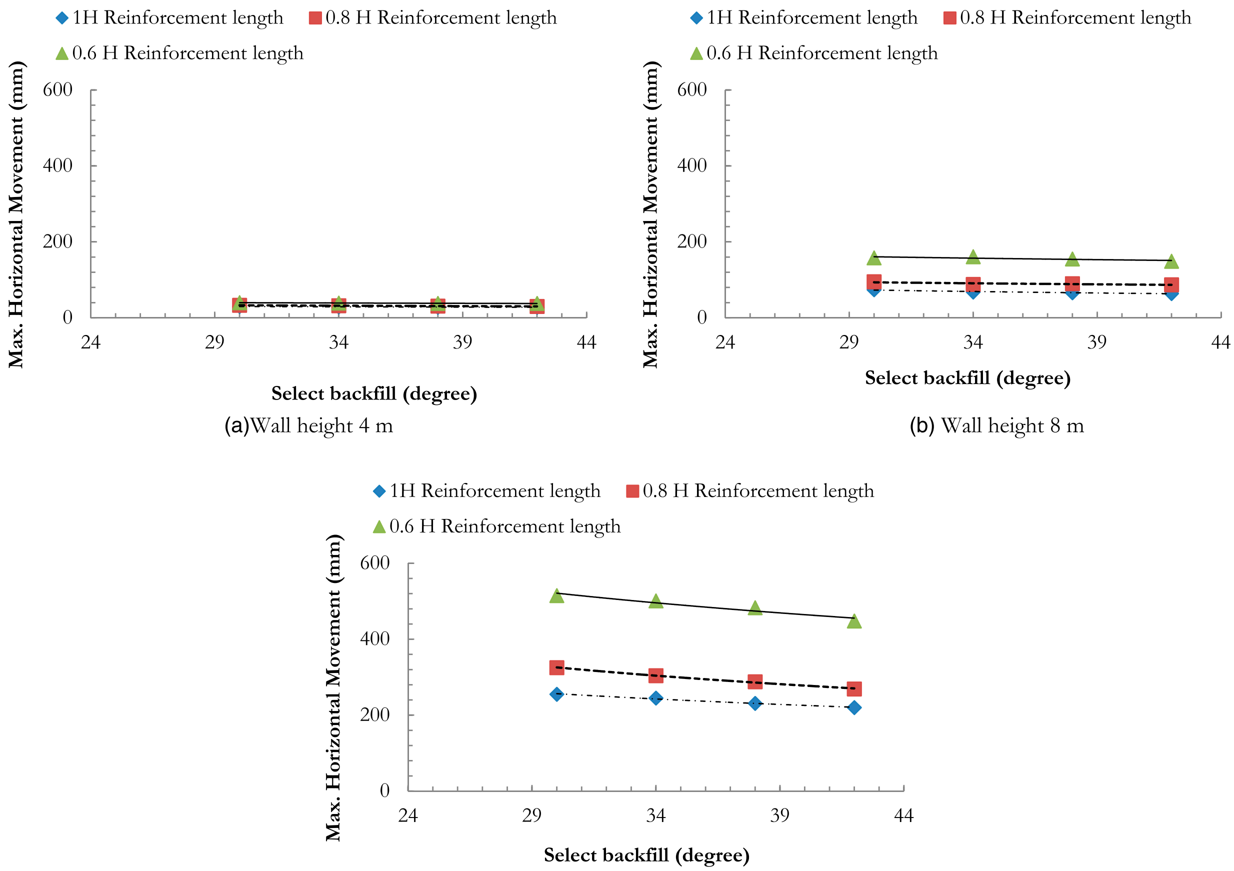

(a) Wall height 4 m

(b) Wall height 8 m

(c) Wall height 12 m

Fig. 10. Variation in displacement with reinforced fill at 30,000 kN/m reinforcement stiffness and retained-fill friction angle of 30°

Table 5. Maximum and Minimum Movement for Two Retained Fills (Stiffness = 30,000 kN/m)

		Retained fill 30°		Retained fill 26°	
Wall height (m)	L/H ratio	Minimum displacement (mm)	Maximum displacement (mm)	Minimum displacement (mm)	Maximum displacement (mm)
4	1	28	30	32	35
	0.8	30	33	36	41
	0.6	38	40	48	56
8	1	64	74	74	96
	0.8	87	95	100	125
	0.6	149	161	191	227
12	1	220	255	255	320
	0.8	269	325	333	420
	0.6	448	515	599	729

reduced from 268 to 150 mm for the 8-m wall. This variation was determined at a reinforcement stiffness of 1,000 kN/m. In addition, horizontal displacement decreased as much as 38% in the MSE wall with a height of 12 m. A summary of maximum and minimum horizontal movement for the increase in reinforced-fill friction angle from 30 to 42° is presented in Table 6.

The interface friction between soil and reinforcement increases with an increase in reinforced-fill friction angle. An equilibrium condition in the reinforced mass occurs at a smaller force when the reinforced-fill friction angle is high (Rowe and Ho 1998). This might cause a reduction in displacement with an increase in reinforced-fill friction angle.

Furthermore, numerical analyses indicate that horizontal movement of the MSE wall was influenced by the retained-fill soil. It was observed that displacement of the MSE wall was high at 26° of retained-fill friction angle. Lateral earth pressure on the reinforced soil increases with the reduction in shear strength of retained fill. An increase in lateral earth pressure on the reinforced fill might cause the observed increase in displacement at retained-fill low friction angles.

Sensitivity Analysis

Stepwise Regression

The sensitivity of the horizontal displacements on structural components of MSE walls was determined using a stepwise regression method with *SAS*. To do this, multiple linear regression (MLR) analyses were conducted and diagnosed with respect to several statistical assumptions. It was found that the initial model was not able to satisfy the MLR analysis assumptions and required transformation of the parameters. The final form of the model after transformation is as follows:

$$\log(y) = 0.502 + 2.196\log(x_1) + \frac{0.398}{x_2} - 0.0095(x_3) - 0.0208(x_4) + \frac{8.481}{\sqrt{x_5}} \quad (1)$$

where y = horizontal displacement at the top of the facing (mm); x_1 = height of the MSE wall (m) from the ground surface;

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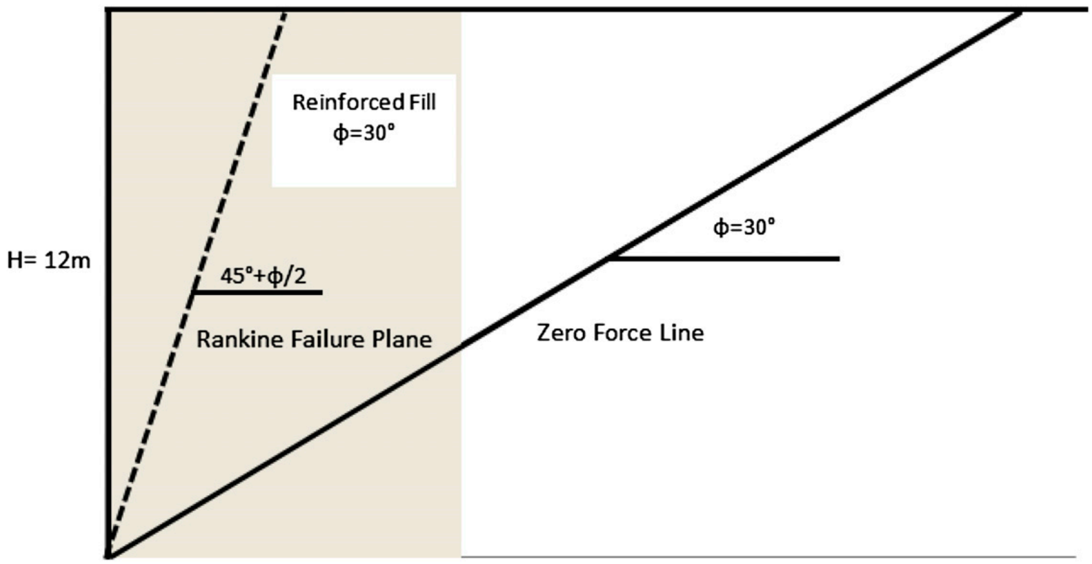

Fig. 11. Reinforced-fill, Rankine failure plane, and zero-force line for 12-m wall at reinforced-fill friction angle of 30°

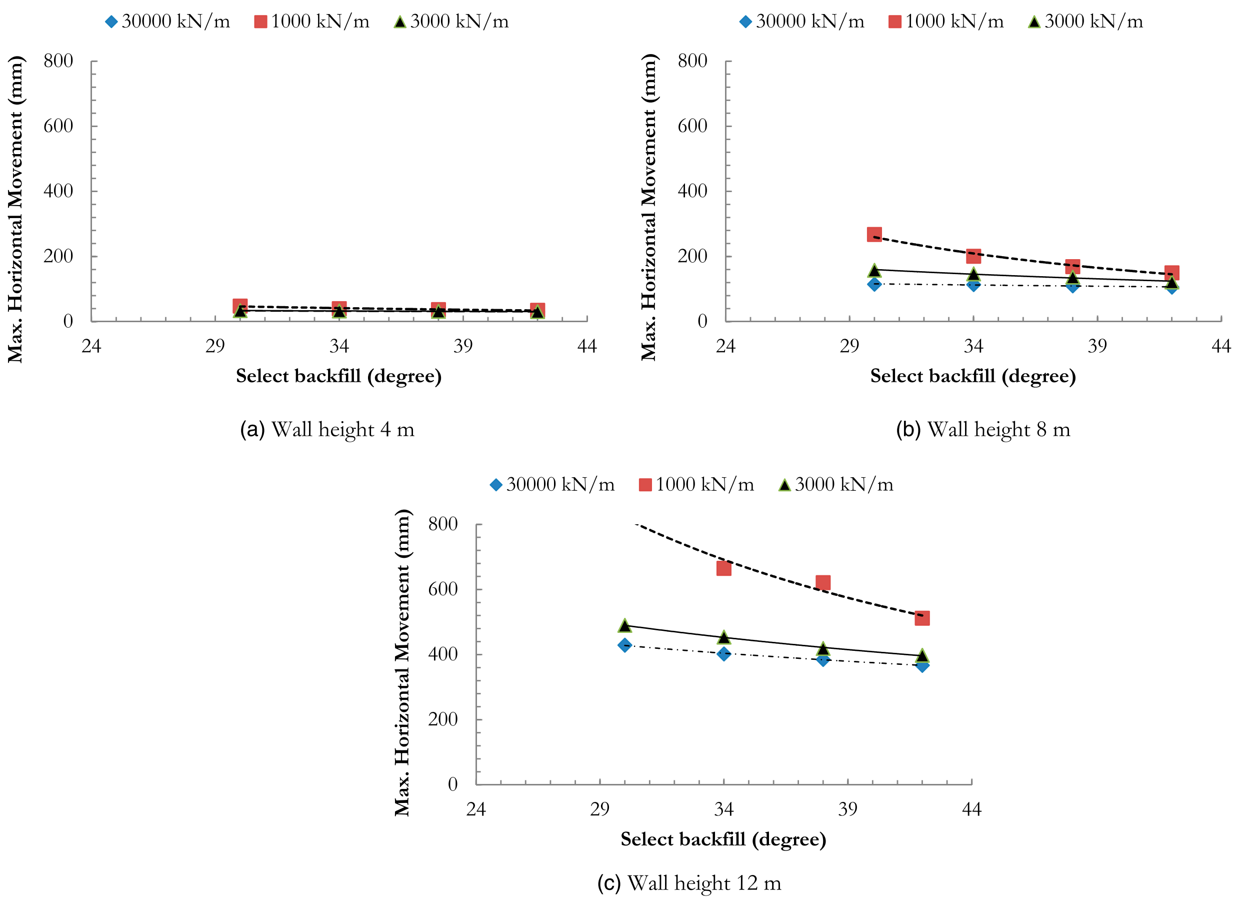

Fig. 12. Variation in displacement with reinforced fill at $0.7H$ reinforcement length and retained-fill friction angle of 30°

x_2 = reinforcement L/H ratio; x_3 = friction angle of reinforced fill (degrees); x_4 = friction angle of retained fill (degrees); and x_5 = stiffness of reinforcement (kN/m).

After development of the MLR analysis model, stepwise regression was used to identify parameters of influence on displacement. It was observed that horizontal displacement was highly sensitive to the height of the wall. Reinforcement stiffness also was identified as a significant parameter for horizontal movement. A model with two parameters, i.e., stiffness and height, explained as much as 86% of the variation in displacement. Furthermore, addition of the L/H ratio into the model increased the coefficient of regression R^2 from 86 to 92%. The sequential increase in coefficient of regression at different iterations is presented in Table 7.

Interaction Surface

The coupled interaction between the influential parameters and horizontal movement was investigated for a 12-m MSE wall, as presented in Fig. 13. A series of interaction equations was developed considering two independent variables, whereas reference values were used for the remaining parameters. Based on FHWA (Elias et al. 2001) recommendations and observed results, reference values were selected. The reference values of L/H ratio, reinforced-fill and retained-fill friction angles, and reinforcement stiffness were 0.7, 34 and 30°, and 30,000 kN/m, respectively.

Fig. 13(a) indicates that a significant increase in displacement did not occur with a L/H ratio of 0.7 and a reinforced-fill friction angle of 34°. In addition, the interaction surface was fairly parallel with the horizontal plane beyond a L/H ratio of 0.7 and a retained-fill friction angle of 30°, respectively [Fig. 13(b)]. However, substantial reductions in horizontal movement were observed with the increase of reinforcement stiffness and L/H ratio. According to Fig. 13(c), horizontal displacement was more than 500 mm at a L/H ratio of 0.6 and reinforcement stiffness of 500 kN/m. Similar trends were observed for displacement-stiffness–reinforced-fill friction angle and displacement-stiffness–retained-fill friction angle surfaces. Based on the illustrations of interaction surfaces, the reinforcement stiffness and L/H ratio were identified as two important parameters affecting horizontal displacement of a MSE wall at a specific height.

Table 6. Maximum and Minimum Movement at Two Retained Fills (Reinforcement Length = $0.7H$)

		Retained fill 30°		Retained fill 26°	
Wall height (m)	Stiffness (kN/m)	Minimum displacement (mm)	Maximum displacement (mm)	Minimum displacement (mm)	Maximum displacement (mm)
4	1,000	35	48	41	70
	3,000	31	34	37	45
	30,000	30	33	36	41
8	1,000	150	268	189	396
	3,000	122	158	159	218
	30,000	30	42	129	155
12	1,000	512	828	638	1,162
	3,000	398	490	493	679
	30,000	367	429	449	547

Table 7. Summary of Stepwise Regression Analysis

Iteration	Sequential addition	R^2
1	x_1	78%
2	x_1, x_5	86%
3	x_1, x_5, x_4	92%
4	x_1, x_5, x_2, x_4	95%
5	x_1, x_5, x_2, x_4, x_5	96%

Note: x_1 = height; $x_2 = L/H$ ratio; x_3 = reinforced-fill friction angle; x_4 = retained-fill friction angle; x_5 = reinforcement stiffness; R^2 = coefficient of regression.

Conclusions

The objective of this study was to determine the effect of soil reinforcement on excessive movement of a MSE wall. A case study was presented on a MSE wall located at State Highway 342 in Lancaster, Texas. It was reported that the movement of the wall ranged between 300 and 450 mm during the years 2004–2009. Two inclinometers were installed to monitor any additional movement of the MSE wall. It was observed that the wall continued to move at an average rate of 4.5 mm/month during the investigation period. The FE program *PLAXIS 2D* (Plaxis 2010a, b) was used to model the MSE wall. Based on the investigation, it was identified that inadequate reinforcement length might be one of the factors affecting the stability of the wall. A parametric study was conducted to identify the influence of soil

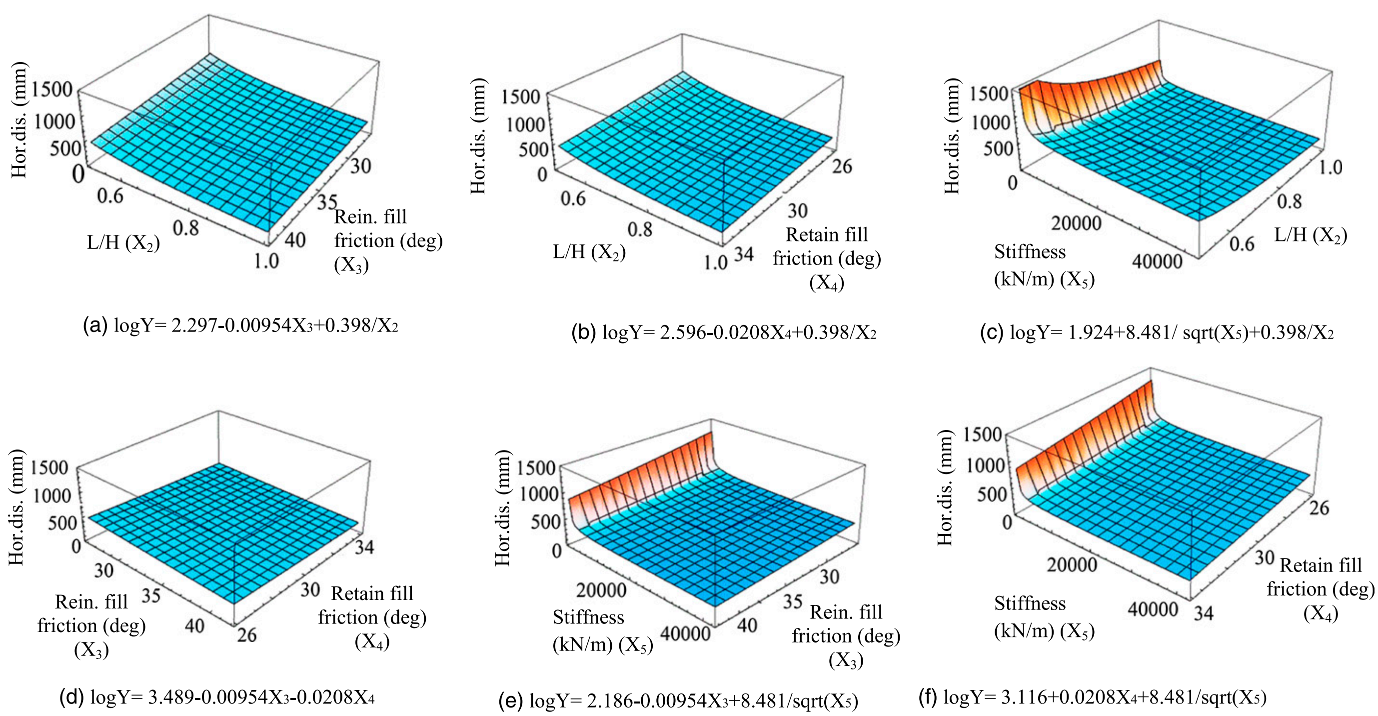

Fig. 13. Interaction surfaces of horizontal movement

reinforcement at varied wall heights and backfill conditions. Numerical modeling results indicated that horizontal displacement decreased with an increase in reinforcement stiffness, length, and backfill soil friction angle at a fixed wall height. It was observed that the effect of reinforcement stiffness was not significant at a wall height of 4 m. However, horizontal movement increased to 389 mm at a reinforcement stiffness and length of $250\,\mathrm{kN/m}$ and $0.6H$, respectively, for an 8-m wall height. The variations in displacement with reinforcement length suggested that a substantial decrease in displacement occurred for an increase in L/H ratio from 0.5 to 0.7.

Based on the numerical analysis results, statistical analysis was conducted to predict the influence of backfill and reinforcement on horizontal movement using stepwise regression and a coupled interaction surface. According to the results, reinforcement stiffness and length were identified as influential parameters affecting the horizontal movement at a specific MSE wall height.

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