

FEM Analysis of Back-to-Back Geosynthetic-Reinforced Soil Retaining Walls

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Received: 2 April 2016 / Accepted: 11 August 2016
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Abstract Reinforced soil retaining walls with two opposite sides (back-to-back) are commonly used for embankments approaching bridges. This type of walls has complex geometry. The distance between two opposing walls is a key parameter used for determining the analysis methods in the federal highways administration guidelines. The objective of this research is to study under static conditions, the effect of the distance between the two back-to-back geosynthetic-reinforced soil retaining walls of embankment approaching bridges on the internal and external stability. Finite element method incorporated in the Plaxis software and analytical methods were used for this research. Parametric studies were carried out by varying the distance between side walls, to investigate their effects on the critical failure surface, the lateral earth pressure behind the reinforced zone, the wall displacement and on the required tensile strength of reinforcement.

Keywords Lateral earth pressures · Geosynthetics · Reinforced soil · Critical failure surface · Finite element analysis · Maximum tension · Wall displacement

Introduction

Due to their cost effectiveness and technical advantages, large numbers of reinforced soil walls are being designed and constructed throughout the world. For the past two decades, retaining structures in reinforced soils have

become very popular, especially the back-to-back reinforced soil for embankments approaching bridges to raise elevations.

Design of such walls, especially mechanically stabilized earth (MSE) walls, is considered as a special situation, which has a complex geometry in the FHWA Demonstration Project 82 [1].

In this FHWA design guideline, two cases are considered based on the distance of two back-to-back or opposing walls, D , as illustrated in Fig. 1.

When the distance, D , between the mechanically stabilized earth walls is greater than $H \tan(45 - \phi/2)$ where H is the height of the walls and ϕ is the friction angle of the backfill, full active thrust to the reinforced zone can be mobilized and the walls can be designed independently. For this case, the typical design method for MSE walls can be used. When D is equal to 0, two walls are still designed independently for internal stability but no active thrust to the reinforced zone is assumed from the backfill. In other words, no analysis for external stability is needed. However, Elias et al. [2] indicated that an overlap of $0.3H$ is required for no active thrust. Both guidelines indicate that when D is less than $H \tan(45 - \phi/2)$, the active thrust to the reinforced zone cannot be fully mobilized so that the active thrust should be reduced. Here D_i is defined as the interaction distance and expressed by

$$D_i = H \tan\left(45^\circ - \frac{\phi}{2}\right) \quad (1)$$

In the later FHWA report [3], for walls which are built back-to-back as shown in Fig. 2, a modified value of lateral pressure influences the external stability calculations. As indicated in Fig. 2, two cases can be considered and are discussed below.

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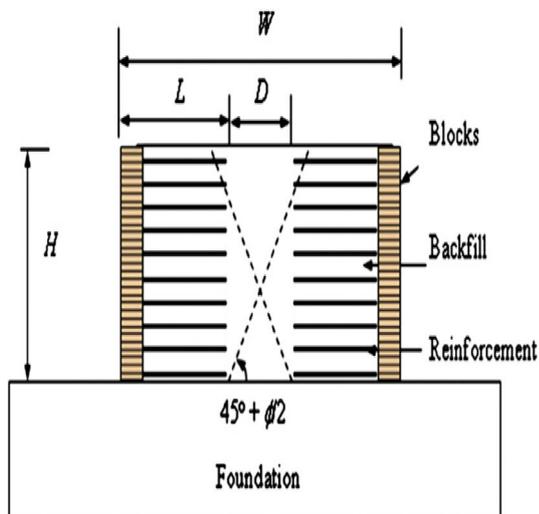


Fig. 1 The design of back-to-back MSE wall and definitions [1]

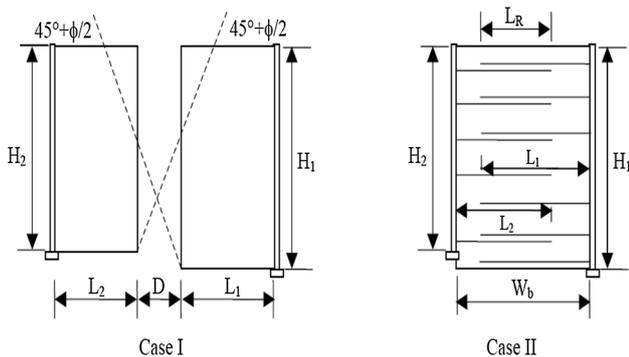


Fig. 2 The design of back-to-back MSE wall [3]

For Case I, the overall base width is large enough so that each wall behaves and can be designed independently. In particular, there is no overlapping of the reinforcements. Theoretically, if the distance, D , between the two walls is shorter than

$$D_i = H_1 \tan\left(45^\circ - \frac{\phi}{2}\right) \tag{2}$$

where H_1 is the taller of the parallel walls, then the active wedges at the back of each wall cannot fully spread out and the active thrust is reduced. However, for design it is assumed that for values of

$$D_i > H_1 \tan\left(45^\circ - \frac{\phi}{2}\right) \approx 0.5H_1 \tag{3}$$

then full active thrust is mobilized.

For Case II, there is an overlapping of the reinforcements such that the two walls interact. When the overlap, L_R , is greater than $0.3H_2$, where H_2 is the shorter of the parallel walls, no active earth thrust from the backfill needs to be considered for external stability calculations.

While, the FHWA guideline [1] did not provide any method on how to consider the reduction of the active thrust when $D < D_i$, Elias et al. [2] provided the following recommendation for this intermediate configuration “the active earth thrust may be linearly interpolated from the full active case to zero”, Ryan et al. [3] indicate that for intermediate geometries between Case I and Case II, the active earth thrust may be linearly interpolated from the full active case to zero. No justification was provided for this recommendation.

Both limit equilibrium and numerical methods have been successfully used to evaluate the stability of MSE walls [4–6] that yielded close results in terms of factors of safety and critical failure surfaces. Leshchinsky et al. [7] demonstrated through shaking table tests that geocell reinforced earth walls under seismic loading failed in a rotational or translational mode, which could be modeled using a limit equilibrium method. Anastasopoulos et al. [8] performed shaking tests on back-to-back retaining walls.

Using the difference finite and limit equilibrium methods, Han and Leshchinsky [9] investigated the effect of the distance, D , between walls (width to height ratio) on internal and external stability of MSE walls under static conditions. It shows that two back-to-back walls perform independently when they are far apart and interact with each other, when they are close.

A full-scale back-to-back geosynthetic-reinforced soil retaining walls (GRS) was constructed to evaluate the effect of the geosynthetic type on the internal deformation of the wall by Won and Kim [10]. Due to the large distance of $D (=0.88H)$, no interaction was observed from two sides of walls. However, no investigation was conducted to evaluate the effect of the distance D . Therefore, an analysis is needed to evaluate the internal and external stability of back-to-back GRS walls under static conditions.

In the present study, to evaluate the internal and external stability of back-to-back geosynthetic-reinforced soil retaining walls, the finite element method (FEM) incorporated in the Plaxis software is adopted to investigate the effect of the width to height ratio of the wall (W/H) on the critical failure surface, lateral earth pressure behind the reinforced zone, the wall displacement and the required tensile strength of reinforcement.

Numerical Modeling

Finite Element Method

In this study, Plaxis finite element program specifically intended for the analysis of geotechnical engineering problems is used. In this finite element program, a two-

dimensional plane strain model with six node triangular element was used. During the automatic generation of mesh, clusters are divided into triangular elements by the program. The element stiffness matrix is evaluated by numerical integration using a total three Gauss points (stress points). During the finite element calculation, displacements are calculated at the nodes and stresses are calculated at the stress points [11]. The finite element model used in the current research was validated for static conditions, through a series of comparison analysis with actual test data, and reported by Guler et al. [12, 13]. Therefore, in the present work, the finite element model was established using the same soil material model, reinforcement model and boundary properties used by Guler et al. [13].

Baseline Case

The geometry of the baseline model used in this study is shown in Fig. 3. In this baseline case, the back-to-back wall width (W) to height (H) ratio is equal to 2.0 and the distance at back of two walls, D is equal to 3.6 m, which is slightly greater than $H \tan (45 - \phi/2) = 3.2$ m. This baseline geometry is similar to that used by Han and Leshchinsky [9]. Based on the FHWA design guideline [3], a typical design method for a single wall can be adopted. The reinforcement length, $L = 4.2$ m, was selected, based on the typical reinforcement length/wall height ratio of 0.7 recommended by the FHWA design guideline. The height of back-to-back GRS walls is fixed at 6 m.

Important parameter, the back-to-back wall width to height ratio (W/H), is selected in this study to investigate his influence on the critical failure surface, the wall displacement, the active thrust to the reinforced zone, the required tensile strength of reinforcements, the lateral earth pressure and the maximum tension in reinforcements. In addition to $W/H = 2.0$ for the baseline case, two other W/H

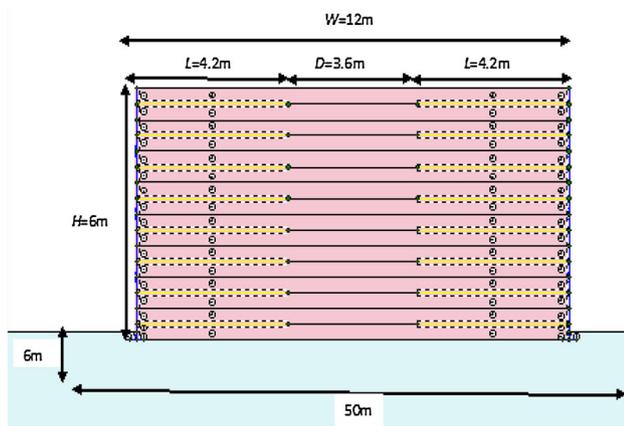


Fig. 3 Dimensions of the GRS walls baseline case

ratios (1.4 and 3.0) were used in the parametric study. To test FEM numerical method, the same models were used for analytical analysis, based on the Rankine theory and Meyerhof theory in the NF P94-270 French guidelines [14], available for walls with one side.

Soil Properties

The linear elastic perfectly-plastic Mohr–Coulomb Model (MCM) model was used to define the soil (reinforced and natural backfill). The following six parameters were required as an input: Elasticity modulus (E), Poisson ratio (ν), cohesion (C), internal friction angle (ϕ), dilatancy angle (ψ), and shear modulus (G). High-strength parameters were assumed for the foundation soil to prevent any possible failure. In Table 1 all soil properties, used in many previous studies [13], are summarized.

Reinforcement and Facing Properties

The reinforcing elements used to define geosynthetic could only sustain tensile forces and have no bending stiffness. These elements are used to model soil reinforcement as geosynthetic (woven fabric). The material property of reinforcement is the elastic axial stiffness (EA), the values of EA for geosynthetic are chosen as 2000 kN/m. The reinforcement layers were placed at 0.75 m vertical spacing. In our parametric analysis, concrete panels facing were modeled using plates of 1.50 m of width and height, a panel thickness of 0.15 m is widely used.

Therefore, the elastic stiffness of 4.5×10^6 kN/m is chosen to represent the concrete panels. A Poisson ratio (ν) of 0.1 and a weight of 3.6 kN/m²/m were specified. The weight of the panel was obtained by multiplying the unit weight of the concrete panel (24 kN/m³) by the thickness of the plate. The connection between facing panels is modeled by some researchers by simple hinges and the compressibility that develops between them due to the presence of pads is neglected. Since deformations are the main outcome of this study, instead of hinges rubber bearing pads were modeled using the same type of elements that were used for the facing panels. At indicate, these parameters of geosynthetic reinforcement and concrete panels are also used in many previous studies [13].

Interface Properties and Boundary Conditions

Modeling the interfaces within reinforced soil wall components has been always a challenge [15]. In the current model, interface elements were placed between concrete panels and backfill soil, and between the backfill soil and reinforcement. The roughness of the interaction was modeled by choosing a suitable value for the strength

Table 1 Soil index properties of investigated model [13]

	Foundation soil Mohr–Coulomb	Backfill soil (reinforced and natural backfill) Mohr–Coulomb
Unit weight (γ_{dry}) [kN/m ³]	22	18
Elasticity modulus (E) [kN/m ²]	200,000	30,000
Poisson ratio (ν)	0.1	0.3
Internal friction angle (ϕ) [°]	30	35
Cohesion (C) [kN/m ²]	100	5
Dilatancy angle (ψ) [°]	0	0
Shear modulus (G) [kN/m ²]	90.909	11.540

reduction factor R_{int} in the interface. The strength properties of interfaces are linked to the strength properties of the soil layer by Eqs. (4) and (5).

$$C_i = R_{\text{int}} C_{\text{soil}} \quad (4)$$

$$\tan \phi_i = R_{\text{int}} \tan \phi_{\text{soil}} \quad (5)$$

where ϕ_{soil} and C_{soil} are the friction and the cohesion of the soil, respectively, and ϕ_i and C_i are the friction and the cohesion of the interface, respectively. To facilitate calculations, strength reduction factors were taken as 0.67. In the finite element model, side's boundaries have only horizontal fixity and the bottom boundary has both horizontal and vertical fixities.

Modeling of Construction in the Finite Element Model (Stage Construction)

In accordance with the FHWA 2009 Guidelines [3], the back-to-back reinforced soil retaining walls are built in stages. The backfill is placed in layers and the reinforcement and facing elements are placed sequentially. In the present study, the analyses simulated the actual construction process. This means that reinforcement layers and facing elements were placed in sequence with the placement of the backfill layers. For each layer this process was repeated until the entire structure was built to a height of 6 m. The stage construction process enables an accurate and realistic simulation of construction of the wall. Soil compaction was not modeled during stage construction because it is known that compaction effects usually diminish by the overburden stress toward the end of stage construction [16].

Results

Critical failure surfaces, walls displacements, lateral earth pressure and the tensile loads in the reinforcement were used as the criteria to evaluate the results from the parametric study. The horizontal wall displacements were taken

from the nodes on the walls facing at the same elevations as the reinforcements. The reinforcement tensile loads reported were maximum tensile loads observed along the reinforcement during the analyses.

Critical Failure Surfaces

The locations and shapes of critical failure surfaces of the back-to-back walls at different wall width to height ratios (W/H) determined based on the contours of shear strain rates in the numerical analysis are presented in Figs. 4, 5 and 6.

Figure 4 shows that the critical failure surfaces in two opposing walls do not intercept each other, therefore, they behave independently. This conclusion is consistent with that from the previous studies conducted by the authors [5, 9]. Since the analytical method cannot analyze two side walls, which become important when the distance between the walls gets closer, the results presented below are based on the numerical analysis unless noted.

The interaction distance, D_i , based on the FHWA design guideline can be determined using Eq. (2). For the backfill with the friction angle of 35°, the interaction distances are $0.53H$. In other words, when the wall width to height ratio, $W/H > 1.93$, the two back-to-back walls should perform

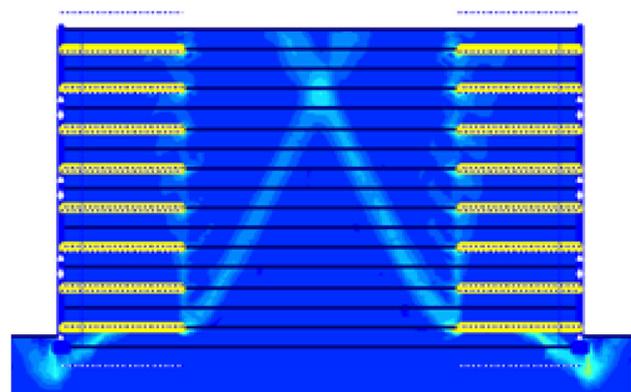


Fig. 4 Critical failure surfaces within walls at $W/H = 3.0$

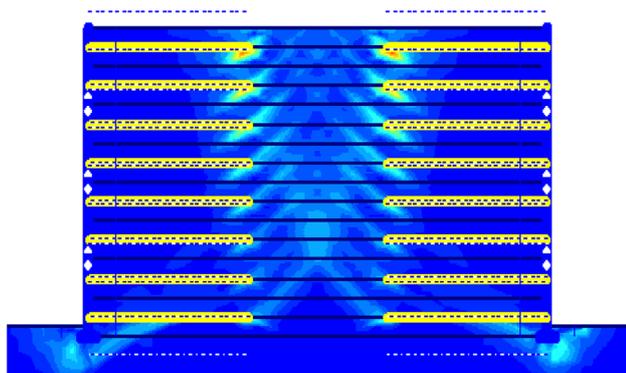


Fig. 5 Critical failure surfaces within walls at $W/H = 2.0$

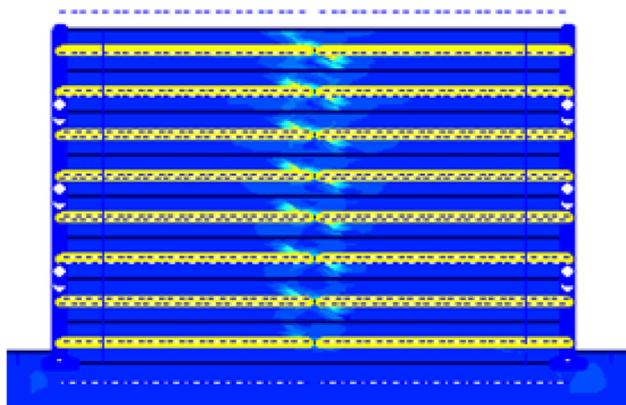


Fig. 6 Critical failure surfaces within walls at $W/H = 1.4$

independently. However, Fig. 5 shows that the back-to-back walls still interact each other when $W/H > 2.0 > 1.93$ and friction angle of the fill is equal to 35° . So, the FEM results confirmed the numerical results obtained in the previous study [5]. Apparently, assumption in the FHWA design guideline is not supported by the numerical result. However, the FHWA assumption leads to more conservative results. So, studies with other W/H ratios between 2.0 and 3.0 are required.

Figure 6 shows the critical failure surfaces developed within the back-to-back walls when there is no retained fill between these two walls (i.e., $D = 0$ m). In this case, reinforcement layers are not connected when they meet in the middle of the walls. Figure 6 shows that the critical failure surfaces in two opposing walls developed at the end of each reinforcement and do not intercept each other walls, therefore, they behave independently. This conclusion is consistent with that from the previous studies conducted by the authors [5, 9].

Lateral Earth Pressure Behind the Reinforced Zone

Based on the FHWA guideline [1, 2], the lateral earth pressure or active thrust behind the reinforced zone for the

external stability analysis should depend on the width to height ratio. Figure 7 presents the numerical results of the lateral earth pressure, Ph , behind the reinforced zone at a different elevation of the wall, hz .

It is clearly shown that the lateral earth pressure exists behind the reinforced zone, even for the width to height ratio of $W/H = 1.4$ (i.e., no retained fill). However, the FHWA guideline [1] suggested that the lateral earth pressure for external analysis should be ignored if $D = 0$ (i.e., $W/H = 1.4$). Obviously, this suggestion would yield an unsafe design. So, the later FHWA guidelines [3] indicate that the active thrust is reduced, which is confirmed by the FEM method.

Figure 7 also shows that the average lateral earth pressure behind the reinforced zone is close to the active Rankine lateral earth pressure when the width to height ratio is large (for example, $W/H = 3.0$ and 2.0). However, the lateral earth pressure decreases when the width to height ratio decreases.

The percent of the active lateral thrust behind the reinforced zone to the theoretical active Rankine lateral thrust, Ph , is presented in Fig. 8, which shows the influence of the width to height ratio on the mobilization of the lateral thrust. So, an increase of the width to height ratio from 1.4 to 3.0 increases the lateral thrust behind the reinforced zone.

The Maximum Horizontal Displacement

Figure 9 shows the maximum displacements calculated using the finite element method (FEM). The distribution of the maximum horizontal displacements is similar to those obtained by Guler et al. [13], the maximum displacement occurred at the crest of the walls at the end of the staged construction. Figure 9 shows that the maximum horizontal

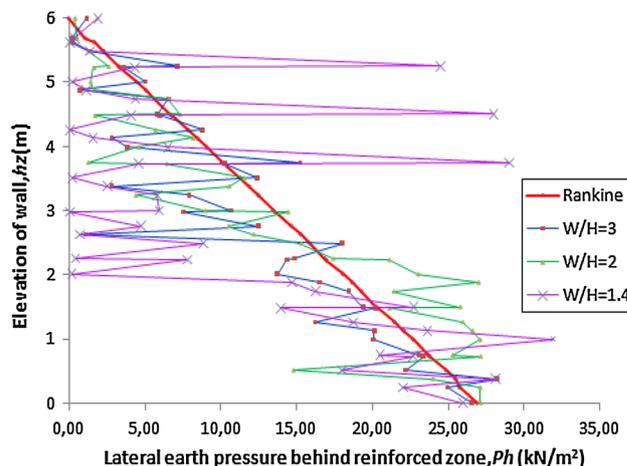


Fig. 7 Distribution of lateral earth pressure behind the reinforced zone

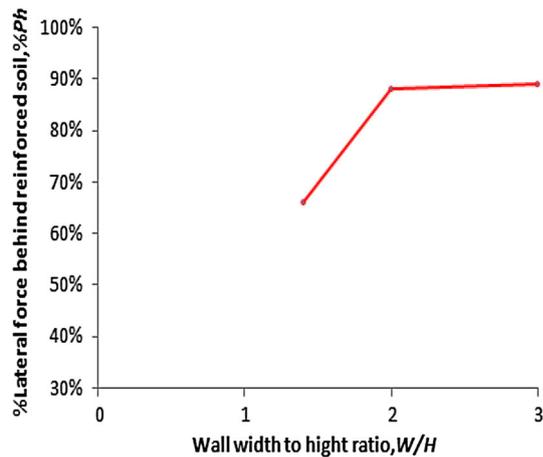


Fig. 8 Percent of lateral thrust behind the reinforced zone

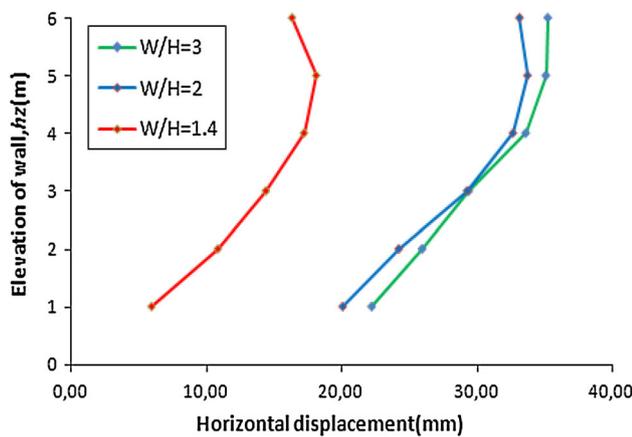


Fig. 9 Horizontal wall displacements

displacement is almost same for $W/H = 3.0$ and 2.0 . However an increase of the width to height ratio from 1.4 to 3.0 increases the maximum horizontal displacement. These results justified as the back-to-back walls do not interact each other, so, the two back-to-back walls should perform independently when $W/H > 2.0$.

Distribution of Maximum Tension with Height

The distribution of the maximum tension, T_{max} , on each reinforcement is plotted against the height of the reinforcement, h_z , in Fig. 10. These distributions are linear and similar to those obtained by Guler et al. [13] for the wall with one side. The width to height ratio of the back-to-back wall has a slight effect on the distribution of the maximum tension in the reinforcement at height, i.e., the overall maximum tension increases with the increase of the width to height ratio. This result implies that it is slightly conservative to ignore the influence of the width to height ratio on the overall maximum tension in the internal stability analysis of the back-to-back reinforced walls.

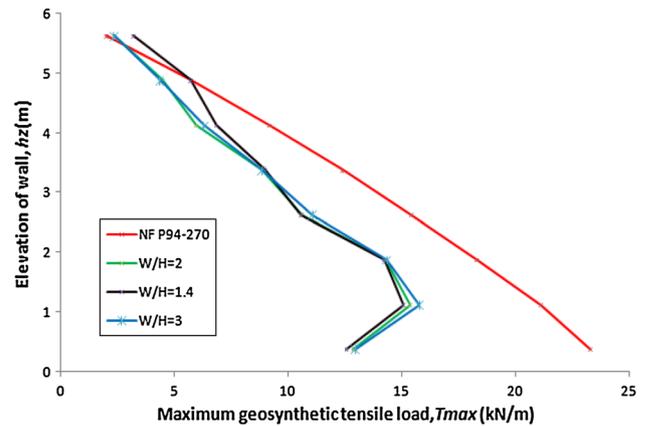


Fig. 10 Distribution of maximum tension in reinforcement

Required Tensile Strength

The required overall maximum tensile tension or strengths of reinforcements for all ratios W/H cases are presented in Fig. 11. The results calculated from the analytical method [14] were based on the analyses of one side wall, therefore, no interaction of two opposing walls was considered. In other words, the required tensile strengths do not change with the W/H ratios. Figure 11 clearly shows that a decrease of W/H ratio from 3.0 to 1.4 reduces the required maximum tensile strength of reinforcement. This result implies that the back-to-back walls for both backfill materials still interact at W/H ranging from 2.0 to 3.0. The FEM analysis without considering the interaction of the opposing walls would provide conservative design of back-to-back GRS walls. The difference in the maximum tensile strength of reinforcement with and without considering the interaction is within 6 %. The required maximum tensile

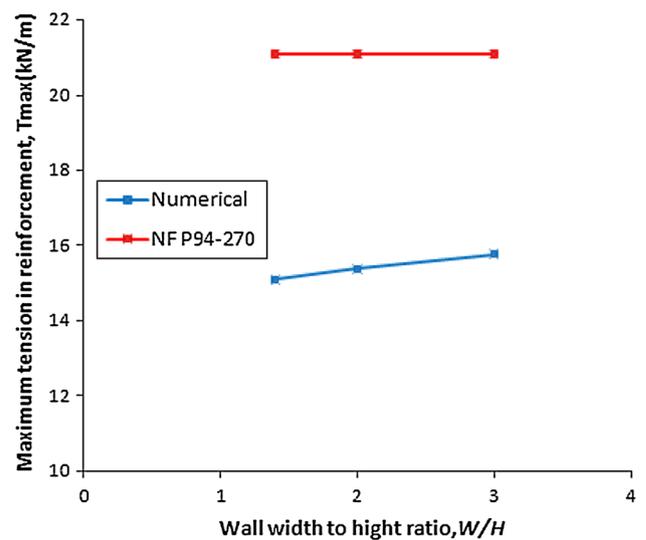


Fig. 11 Required maximum tensile strength of reinforcement

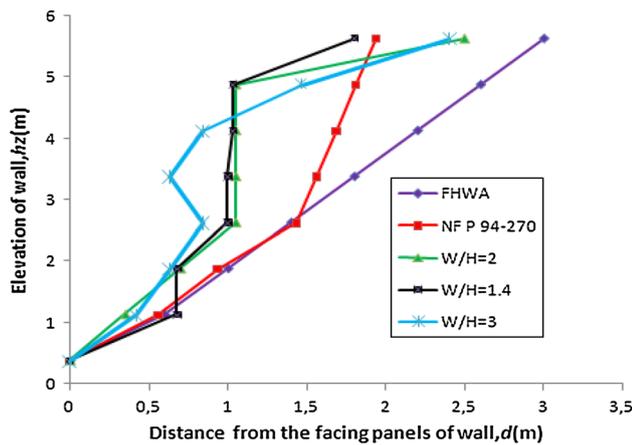


Fig. 12 The maximal tension line of the reinforcement

strengths can be used for the selection of reinforcements as in the back-to-back reinforced retaining walls.

The Maximal Tension Line of the Reinforcement

The maximal tension line of the reinforcement (distance of the maximal tension in reinforcements from the side of wall, d) obtained under static conditions is shown in Fig. 12. It can be seen that the geometry (i.e., different W/H ratio) of the back-to-back geosynthetic-reinforced soil retaining walls has no influence on the lines of maximum traction obtained numerically, and these lines were found closer to NF P94-270 guidelines from those in FHWA. The results of the tension lines calculated from the analytical method [3, 14] were based on the analyses of one side wall, therefore, no interaction of two opposing walls was considered, and so, the analytical results of one side wall may be used for back-to-back walls.

Conclusions

Investigations, under static conditions, for the behavior of two back-to-back geosynthetic-reinforced soil retaining 6.0 m high walls, were made using a finite elements program Plaxis and analytical methods.

Studies show that two back-to-back geosynthetic-reinforced soil walls perform independently when they are far apart and interact with each other when they are close. This interaction will change the location and shape of critical failure surface. Maximum tension in geosynthetic was nearly independent of the distance between the back-to-back walls.

However, the FHWA assumption leads to more conservative results. Ignoring the external lateral earth

pressure on the reinforced zone, when the distance of the back-to-back walls, D , equals to 0; results in an unsafe design for external stability.

When the distance of the two back-to-back walls gets closer; the required maximum tensile strength of reinforcement slightly decreases. Ignoring the effect of the width to height ratio on the overall maximum tensile strength of reinforcement, results in a slightly conservative design for internal stability.

Since the analytical methods cannot analyze two side walls, it is shown that the finite element method can be used perfectly for analysis of the back-to-back reinforced soil walls under static conditions.

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