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Numerical Investigations on the Behavior of Back-to-Back Mechanically Stabilized Earth Walls: Effect of Structural Components

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ABSTRACT

Over the years, the behavior of Mechanically Stabilized Earth Walls (MSEWs) has been intensively studied, where several design guidelines are now available. However, for Back-to-Back Mechanically Stabilized Earth Walls (BBMSEWs), widely encountered in road construction projects, a survey of the literature shows that a little attention has been paid to the behavior of this type of walls. The existing design manuals and the few numerical investigations do not provide a clear answer on the seismic response of BBMSEWs. Given their importance in transportation systems, understanding the dynamic behavior of BBMSEWs becomes a necessity. For this purpose, this paper reports results from numerical analysis that was carried out to evaluate the influence of numerous parameters of structural components, such as backfill type, wall facing type, reinforcement stiffness and distance between opposing walls, on the static response and dynamic response of an idealized 6 m high BBMSEW with 12-m width. The length of reinforcement is 4.2 m, so the distance between opposing walls is 3.6 m. In this study, geotechnical Finite Element software PLAXIS 2D was adopted, while wall displacement and tensile load in reinforcement were selected as criteria of stability. Based on the findings, it was shown that using stiffer reinforcement leads to a significant decrease in horizontal wall displacement and involves a less reduction of maximum tensile loads in reinforcement. When flexible reinforcements were used, the type of facing wall should have a significant effect on the BBMSEW behavior. Under self-weight, the theoretical solutions overestimate tensile load in the reinforcements. By decreasing the distance between opposing walls to zero, the reinforcements from both sides would meet in the middle and the magnitude of the displacement has been significantly reduced. In this case, designers might be tempted to use single layers of reinforcement that are connected to both wall facings. In this special arrangement of reinforcement, it was revealed that connecting two opposing walls reduces only the maximum horizontal displacement, while the effect of axial rigidity of reinforcement was found to be negligible.

KEYWORDS: Back-to-back walls, Tensile load, Reinforced soil, Seismic load, Wall displacement.

INTRODUCTION

In the design of traditional retaining wall systems, the most important component is the determination of active and passive lateral earth pressure coefficients, particularly under seismic load and many studies were conducted and summarized (e.g. Al-Zoubi, 2015; Hazirbaba et al., 2019). As a result of the variability of structural components (backfill soil, reinforcement, …etc.), the design of Mechanically Stabilized Earth Walls (MSEWs) becomes more complex than traditional walls. On the other hand, MSEW structures allow, less construction time and lower cost over their conventional retaining walls such as gravity and cantilever retaining walls.

Although the basic principles of these composite structures have been used throughout history, MSEWs were developed in their current form in 1960s. Today, a variety of Mechanically Stabilized Earth Walls, widely used in the road projects, has been extensively built all over the world. The increasing use and acceptance of

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MSEW has been triggered according to a number of technical advantages including better seismic performance and the ability to tolerate large total and differential settlements without structural distress. The design and dynamic response of MSEWs have been based on the results from both model tests and numerical analysis and their stability must be justified for several criteria, such as lateral earth pressure, tensile load in the reinforcement, … etc. Therefore, the influence of component properties, such as reinforcement type, vertical spacing of the reinforcement, facing type and backfill material of the reinforced soil zone, has been demonstrated on the stability of the walls.

Since 1980, geosynthetics has been increasingly used in geotechnical and environmental engineering applications in most parts of the world (Souliman and Zapata, 2011). In the early 20th century, geosynthetic reinforcement products, such as geotextile and geogrid reinforcements, have gradually gained recognition as a viable alternative to metallic strips/mats as tensile reinforcements as they can offer many distinct advantages over metallic inclusion. Therefore, geosynthetic products have been extensively used as protection and isolation in several infrastructures and industrial projects, such as buried pipes and foundations (Nanda et al., 2017; Kou and Shukla, 2019). As well, geosynthetic products have been used in several newly developed geotechnical engineering techniques, such as geosynthetic-encased stone columns (Muzammil et al., 2018). Recently, these products have helped designers and contractors solve several types of engineering problems in the form of a wide variety of structures and wall types, such as low-volume roads, bridge abutments and geosynthetic-reinforced soil having full-height rigid facing (Keller, 2016; Ghaderi et al., 2017; Tatsuoka et al., 2019).

Nowadays, geosynhentic products have been increasingly used in MSEWs as well as for roadway, bridge approaches and railway construction. The role of these structures with metallic or geosynthetic reinforcements in supporting the self-weight of the backfill soil, roadway structure and traffic loads is indisputable.

Based on observations in seismically active zones, these structures have demonstrated higher resistance to seismic loading than rigid concrete structures (e.g. Ling et al., 2001; Koseki and Shibuya, 2004). Therefore, extensive numerical and laboratory investigations were carried out to show high stability of MSEWs under earthquake conditions (e.g. Huang and Wu, 2009; Sabemahani et al., 2009).

Although the behavior of simple MSEWs is extensively reported in the literature, structures with more complex geometries with large external loads are rarely discussed. In the Federal Highway Administration (FHWA) document, reinforced soil structures with special geometries, including: bridge abutments with MSE walls, superimposed (tiered) MSEWs, MSEWs with uneven length reinforcements (trapezoidal walls), shored MSEWs, stable feature MSEWs and back-to-back MSEWs (BBMSEWs, are reported and discussed (Berg et al., 2009).

Often encountered in the construction of bridge approaching embankments and highway ramps, the distance, *D*, between opposing walls is the key parameter for determining the stability of BBMSEWs under static conditions (Berg et al., 2009). For BBMSEWs, it is always difficult to separate internal stability from external stability given that the most critical slip-failure surface may pass through both reinforced and unreinforced sections of the structure (Berg et al., 2009). Hence, a global stability analysis is generally required for this type of structure, in which the best method to use is the numerical method.

Therefore, the work reported in the current paper was divided into two separate parts. Firstly, it presented an overview of the literature that refers to the numerical investigations related to BBMSEWs. Secondly, numerical investigations were carried out using the finite element method showing the influence of primary component properties on BBMSEW response to static and dynamic loads.

LITERATURE REVIEW ON THE NUMERICAL BBMSEW ANALYSIS

Numerous studies have focused on MSEWs in simple configuration and extensive research has been successfully carried out using the numerical method to investigate the static response and seismic response of this type of structure.

Consequently, by the use of the Finite Element Method (FEM) incorporated in PLAXIS code, the effects of several parameters, such as backfill type, facing type, reinforcement stiffness and peak ground acceleration, on the cyclic response of MSEWs were investigated (Güler et al., 2012). They showed that the deformations and reinforcement tensile loads increased during cyclic load application and using stiffer reinforcement resulted in reduced wall displacements and increased tensile loads in the reinforcement.

Despite the importance of BBMSEWs as a major component of the transportation system, a survey of the literature shows that little attention has been paid to the static behavior and seismic behavior of BBMSEWs. Carefully conceived, numerical investigations offer the possibility to improve understanding that referred of BBMSEW behavior. To our knowledge, the first research refer to this type of retaining walls was presented by Han and Leshchinsky (2010). They have used the Difference Element incorporated in FLAC code to show the effect of the distance between walls. It was concluded that two walls perform independently when they are far apart and interact when they are close to each other. Still under static conditions, FEM analyses and limit equilibrium methods were formulated to study the effect of the distance, *D*, between the two opposing walls on the internal and external stability of BBMSEWs. At first, Benmebarek et al. (2016) and Djabri and Benmebarek (2016) have shown that two walls act independently when they are far apart and interact when they are close to each other. Later, Benmebarek and Djabri (2017) investigated the effect of the overlap length of reinforcement (*LR*) on the performance of close BBMSEWs under self-weight and pointed out that decreasing *LR* leads to increasing the lateral movements and decreasing the safety factor.

Under dynamic conditions, the American FHWA design guidelines based on the equilibrium method limit did not give a clear and justified answer to how internal and external stability changes with respect to the distance between opposing walls and provided only some recommendations for seismically active areas (Berg et al., 2009). Since experimental tests referring to BBMSEWs are not given in the literature, numerical methods remain the best solution to recognize the behavior of this type of retaining walls. Recently, Benmebarek and Djabri (2018) presented a numerical study that focused on the effects of the distance between walls and harmonic motion characteristics; namely, peak ground acceleration and frequency, on the stability of BBMSEWs. The results suggest that both maximum displacement of walls and tensile load in the reinforcement are strongly affected by the reduction in the distance between opposing walls. In addition, peak ground acceleration and frequency have strong influences on internal and external stability of such structures.

More recently, Sravanam et al. (2009, 2020) presented two numerical studies using Difference Element FLAC software. It was demonstrated that connecting two opposing walls to each other does not significantly modify the pressure distribution. On the other hand, connected walls can be designed in the same way as that of unconnected walls without any other modifications in the design parameters.

The survey of literature shows that most of the studies about BBMSEWs have primarily concentrated on the effect of the distance between walls and the seismic load components on the stability of BBMSEWs. Unfortunately, the very limited number of numerical studies identified above illustrate that the current understanding of BBMESW behavior is incomplete. For all these reasons, Finite Element Method incorporated in PLAXIS 2D, version 8 (Brinkgreve, 1998) was selected and extended numerical analysis was performed to evaluate the influence of several important structural design components on the static behavior and dynamic behavior of BBMSEWs.

PARAMETRIC STUDY

In the current paper, parametric studies using FE Method incorporated in PLAXIS code were carried out. The effects of the chosen structural components such as: (1) facing wall, (2) reinforcement type, (3) backfill soil and (4) distance between walls on the performance of BBMSEWs are presented. The results were assessed in terms of horizontal wall displacements and tensile loads on the reinforcement.

Geometry of the Investigated Model

The Finite Element PLAXIS 2D software program adopted in the current research was perfectly used in many recent studies under both self-weight and seismic condition loads (Djabri and Benmebarek, 2016; Benmebarek et al., 2016; Benmebarek and Djabri, 2017; Benmebarek and Djabri, 2018). For this purpose, a series of finite element models were performed using the same material model for soils, reinforcement, boundary properties, … etc. as reported in previous studies (Güler et al., 2012; Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017; Benmebarek and Djabri, 2018). The current study deals with the influence of several parameters on the behavior of BBMSEWs, widely encountered in road projects, under static and seismic conditions.

According to geometrical and geotechnical practices, an *H*=6 m BBMSEW height was selected for a reference model of walls. The width of the walls is *W*=12 m, which corresponds to a ratio *W/H*=2.0 and the distance between the opposing walls is *D*= 3.6 m. The length of reinforcement is *L*=4.2 m corresponding to 0.7*H*, which is appropriate to the FHWA design guidelines (Berg et al., 2009) as shown with all geometrical BBMSEW parameters in Figure (1). The wall is embedded at a depth of 0.02 m with a 0.04 m wide leveling pad. Based on this configuration, the two opposing walls perform interaction (Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017). In this case, numerous parameters are selected, such as backfill material of reinforced soil, facing panels and elastic stiffness of reinforcement, to investigate their influence on internal and external stability of BBMSEWs under static and cyclic conditions. In addition, the effect of decreasing the distance between opposing walls to 0 m is evaluated. For this distance, connecting the reinforcement in the middle is discussed.

Material Proprieties for Parametric Study

The soil is divided into two different zones: reinforced, natural backfill and base soil foundation. Mohr-Coulomb failure criterion is used to represent the soil in the physical model and a stiff soil is chosen as the base soil to minimize its influence on the behavior of reinforced soil. As arranged in Table 1, material proprieties of soils chosen to simulate selected granular and cohesive reinforced fill were identical to those reported from many previous studies (Güler et al., 2012; Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017; Benmebarek and Djabri, 2018). Square concrete panels are modeled using plates of 1.50 m side and 0.15 m thickness. Two layers of reinforcement are attached to each panel corresponding to vertical reinforcement layers with a spacing of 0.75 m (Figure 1.b).

The connection between facing elements is modeled by simple hinges and the compressibility that develops between them is neglected (Brinkgreve, 1998). For comparison purpose, the modular block facing elements have a width of 0.5 m and a height of 0.25 m corresponding to two levels of reinforcement for every three blocks (Figure 1.c). The concrete panels and modular blocks follow elastic and Mohr–Coulomb criteria, respectively, with material proprieties summarized in Tables (2 and 3) which have also been used in previous numerical investigations (Güler et al., 2012; Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017; Benmebarek and Djabri, 2018).

Geosynthetic reinforcements, such as geotextiles, geogrids and metallic strips, could only sustain tensile forces and have no bending stiffness. In this analysis, the behavior of the geosynthetic reinforcements is simulated using geogrid element incorporated in PLAXIS 2D (line element with two translational degrees of freedom at each node). The only material property required for the reinforcement is tensile stiffness (*EA*). The values of stiffness reinforcement were chosen as 2000, 10000 and 69000 kN/m representing geotextiles, geogrids and metallic reinforcements, respectively. These stiffness reinforcement values have been also used in many previous studies (Bathurst and Hatami, 1998; Güler et al., 2012; Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017; Benmebarek and Djabri, 2018).

Construction Stages

Back-to-back mechanically stabilized earth walls were built in stages simulating the actual and real construction process of these structures in accordance with previous studies (Benmebarek et al., 2016; Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017; Benmebarek and Djabri, 2018). 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. At the end of construction that only considered the weight of the backfill, static condition was achieved so that the model was ready for the application of cyclic load.

After reseating displacement to zero, the model was subjected to harmonic cyclic excitation at the structure base. It is important to note that the soil compaction was not taken into consideration, while the facing walls are slightly embedded in the foundation soil, which decreases the value of maximum tensile load in the first reinforcement layer.

Interface and Boundary Conditions

Soil–reinforcement interaction is the most important factor which governs the design, modeling and stability of earth structures, like reinforced soil walls. Many laboratory experiments have been carried out and revealed that the interaction mechanism depends reinforcement characteristics, soil model parameters and on the interrelationship between these materials (e.g. Hedge and Roy, 2018).

In the current study, interface elements were placed between facing panels and backfill soil and between the backfill soil and the reinforcement (Figure 1). For the Mohr-Coulomb model, the strength reduction factor R_{inter} is the main interface parameter (Brinkgreve, 1998).

In general, for real soil-structure interaction, the interface is weaker and more flexible than the soil and in the absence of detailed information, it may be assumed that R_{inter} is of the order of 0.67 (Brinkgreve, 1998), which is the value taken in the present research.

Under self-weight, boundaries have only horizontal fixity and the bottom boundary has both horizontal and vertical fixities (Djabri and Benmebarek, 2016; Benmebarek and Djabri, 2017).

In addition, in order to avoid spurious reflection during dynamic analysis, absorbent boundaries were specified.

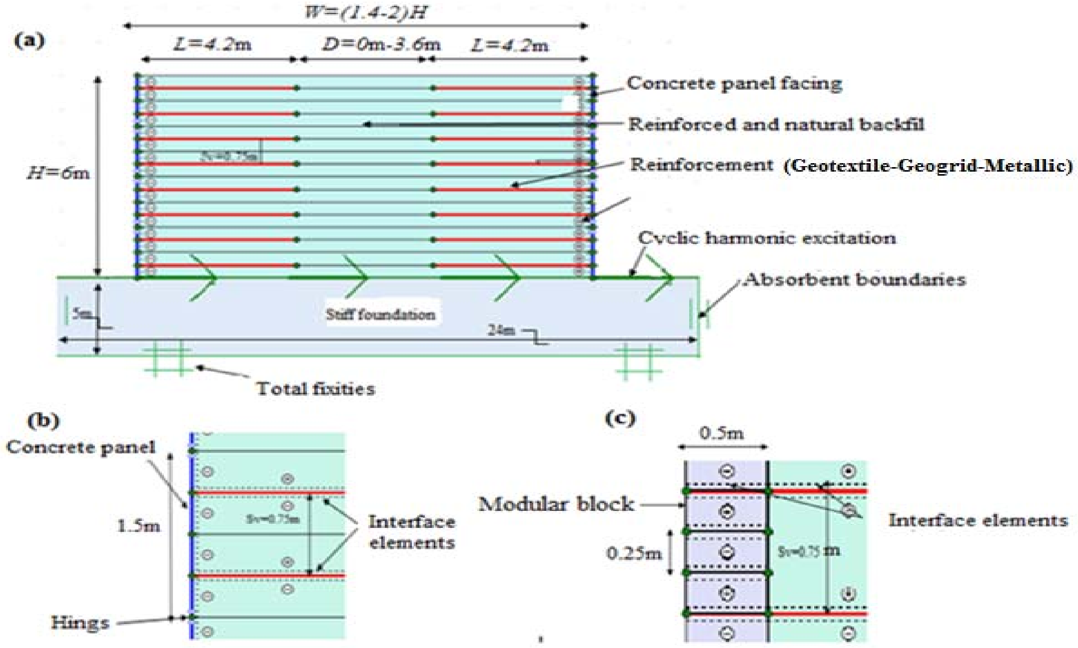


Figure (1): The geometry of investigated BBMSEW models subject to cyclic harmonic excitation: (a) BBMSEW dimensions, (b) details of concrete panels and (c) details of modular blocks

Table 1. Material properties of soil layers of investigated models (Benmebarek and Djabri, 2018)

Parameters of soils	Cohesive backfill	Granular backfill	Base soil
Unit weight, γ_{dry} (kN/m³)	18	18	22
Elasticity modulus, E (kN/m²)	30000	30000	200000
Poisson's ratio, v	0.3	0.3	0.1
Internal friction angle, ϕ (°)	5	35	30
Cohesion, C (kN/m²)	50	5	100
Dilatancy angle, ψ (°)	0	0	0

Table 2. Concrete panel proprieties (Benmebarek and Djabri, 2018)

Material model	Elastic stiffness, *EA* (kN/m)	Flexural rigidity, *EI* (kN/m^2/m)	Unit weight, γ_c (kN/m^3)	Weight of panel, W_c (kN/m^2/m)	Poisson's ratio, *v*
Elastic	4.5×10^6	8.438	24	3.6	0.1

Table 3. Modular block element proprieties (Güler et al., 2012)

Material model	Unit weight, γ_{dry} (kN/m^3)	Elasticity modulus, *E* (kN/m^2)	Poisson's ratio, *v*	Cohesion, *C* (kN/m^2)	Internal friction angle (°)
Mohr-Coulomb	20	30000	0.1	200	35

Simulation of Cyclic Harmonic Loading

The accelogram selected in this study has both increasing and decreasing peak acceleration portions and is expressed by the following Equation:

$$\ddot{U}(t) = \sqrt{\beta \cdot e^{-\alpha t}} \cdot t^{\xi} \cdot \sin(2 \cdot \pi \cdot f \cdot t) \quad (1)$$

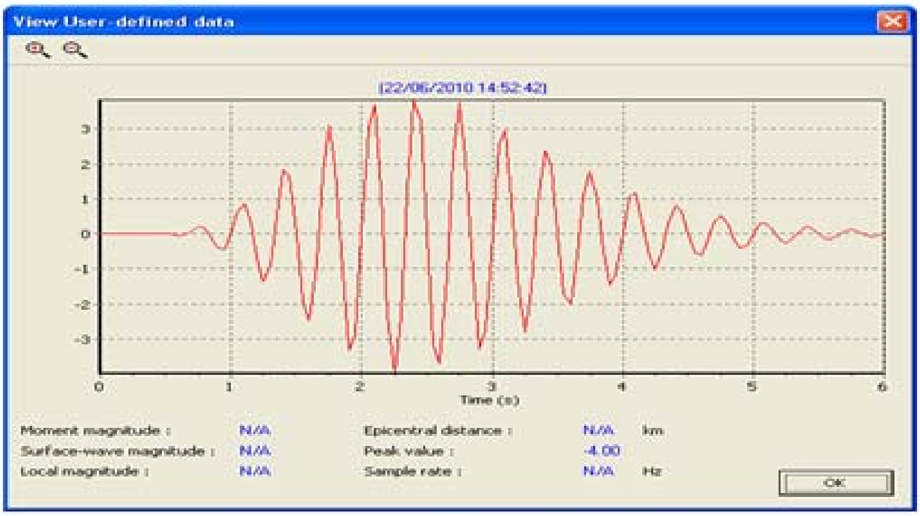
where α=5.5, β=55 and ξ=12 are constant coefficients *f* is frequency and *t* is time.

This accelogram was also used by many authors (Bathurst and Hatami, 1998; Güler et al., 2012; Benmebarek and Djabri, 2018) and has been accepted as a good representation of commonly encountered accelerograms.

A global damping Rayleigh term that was proportional to the mass and the stiffness of the system was used. Global damping was applied to the model using Rayleigh coefficients α and β. The Rayleigh coefficient α is related to the influence of the mass on damping and the coefficient β is related to the influence of the stiffness on the damping of the system. This means that as α value increases, lower frequencies are damped more and as β value increases, higher frequencies are damped more (Brinkgreve, 1998). Bathurst and Hatami (1998) have used a viscous damping ratio of 5% for conventional reinforced concrete cantilever wall-backfill systems less than 10 m in height subject to similar situation of seismic excitation. Hence, a conservative damping ratio of 5% given after adjusting both Rayleigh coefficients was chosen for the parametric analysis reported in the current study.

Peak ground of input acceleration (PGA) as 0.4 g and a constant frequency as 1.5 Hz are selected as components for cyclic harmonic load that was horizontally applied at the base of the models.

Besides harmonic loading, there is also the possibility to read data from an ASCII or SMC format file with a digitized load signal. Benmebarek and Dajbri (2018) have created an ASCII file with world pad Microsoft program to input cyclic harmonic load applied at equal time intervals of 6s. Hence, the accelogram obtained by Equation (1) and given by input ASCII file PLAXIS 2D displayed in Figure 2 was adopted for the current numerical investigation.



Moment magnitude : N/A
Surface-wave magnitude : N/A
Local magnitude : N/A
Epicentral distance : N/A km
Peak value : -4.00
Sample rate : N/A Hz

Figure (2): Accelerogram of cyclic loading used in the analysis (Benmebarek and Djabri, 2018)

RESULTS AND DISCUSSION

Horizontal wall displacement and maximum tensile loads in the reinforcement were used as the criteria to evaluate the results from the parametric study. The wall displacement curves are plotted at the junction points of concrete panel facing and at the reinforcement level of modular blocks. Each maximum load value for a reinforcement layer corresponds to the maximum tensile load recorded along the entire length of that layer. Analytical calculation (NF P 94-270, 2009) and numerical analysis (Güler et al., 2012) for walls with simple geometry are selected to verify the accuracy of results obtained from this FEM analysis. The results under static condition (only under self-weight) for walls with concrete panels, granular backfill and geotextile reinforcement were reported from Djabri and Benmebarek (2016). Before applying base excitation, the displacements were readjusted to zero, so that the given results of displacements in dynamic loading were only caused by cyclic harmonic load effects.

A numerical simulation run was carried out on eleven models in order to highlight the influence of the primary BBMSEW components, such as backfill properties, facing type and reinforcement stiffness. This investigation was extended to the effect of the distance between oppising walls. Finally, the case of connecting reinforcement at the middle was discussed.

The Influence of Wall Facing and Stiffness Reinforcement

For concrete panel facing and according to the results obtained by Djabri and Benmebarek (2016), the maximum horizontal wall displacement for modular blocks occurred at 1 m (0.17*H*) from the crest of the wall at the end of the construction (Figures 3.a and 3.c).

After the application of cyclic loading, the maximum displacement shifted to the bottom according to previous FEM analysis (Güler et al., 2012; Benmebarek and Djabri, 2018) (Figures 3.b and 3.d). Under cyclic load, the maximum wall displacement for modular block facing is lower when compared to walls with concrete panel facing (Figures 3.b and 3.d).

Regardless of wall facing, the maximum lateral displacement had been always the greatest for geotextiles. At the same time, increasing the reinforcement stiffness highly diminished the wall displacement, particularly under seismic condition. In the static case, the numerical results showed that the maximum displacements for both metallic and geotextile reinforcements were quite close to each other despite the fact that the axial rigidity of metallic reinforcement is much higher than that of geotextile reinforcement (Figures 3.a and 3.c).

The distribution of the maximum tension load along the height of the wall for both walls facing with granular soil is shown in Figure (4). In all cases, the values of the maximum reinforcement loads were larger under dynamic loading than the calculated loads for the end-of-construction (i.e., self-weight). Moreover, the reinforcement load increased in any layer with increasing reinforcement stiffness, while it was unaffected by wall facing type.

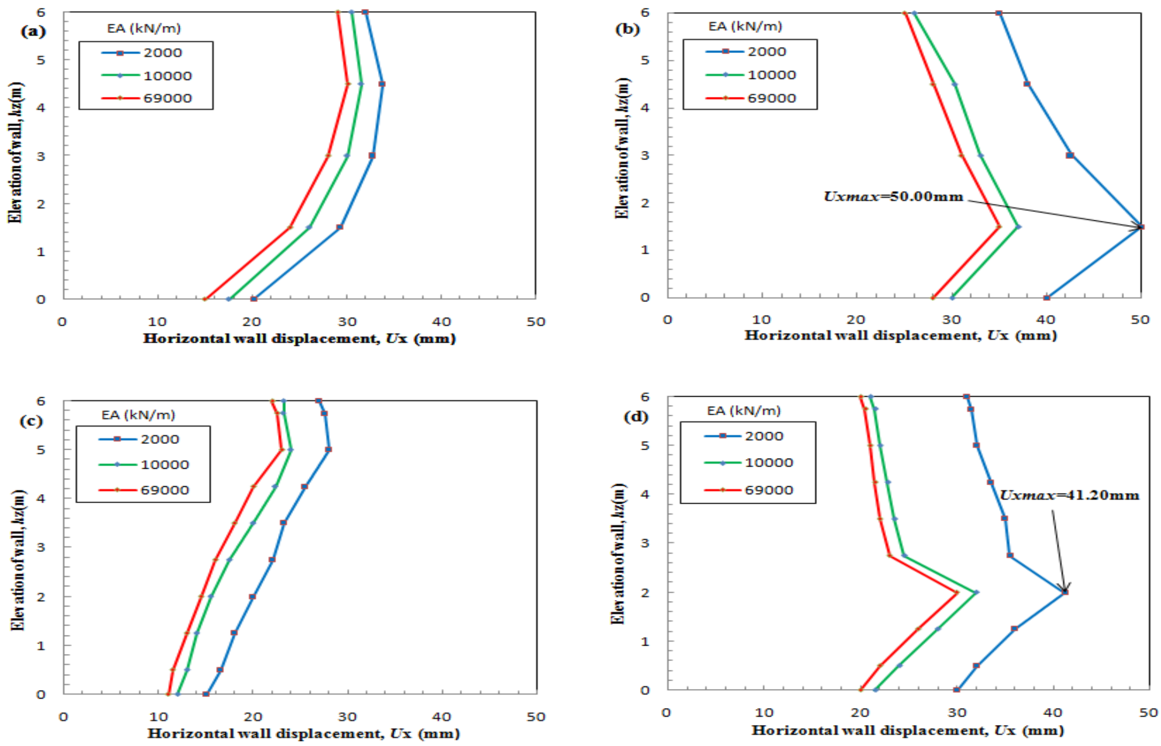


Figure (3): Horizontal displacements for granular backfill: (a) concrete panel facing under self-weight (b) concrete panel facing under seismic condition, (c) modular block facing under self-weigh and (d) modular block facing under seismic condition

A comparison among the numerical results of lateral displacements and tensile load in simple MSEWs and BBMSEWs for different structural parameters under both load conditions is presented in Figure (5). Here, it is worth emphasizing that tensile load represents the maximum force in the second layer of reinforcement from the base. From Figure (5), it is clearly observed that the numerical analysis BBMSEW values are nearly the same as those in MSEWs obtained by Güler et al. (2012); so, the MSEW design can be extended to BBMSEW structures.

The theoretical values of the maximum tension load in each geosynthetic reinforcement layer under static condition using limit equilibrium methods based on Mayerhof Theory incorporated in the NF P94-270 French Guidelines are plotted with a black line in Figures (4.a and 4.c). As these Figures depict, the theoretical solution underestimates the reinforcement loads close to the top of the wall and overpredicts the loads toward the base of the wall for both facing types. In addition, Figure (5.b) shows that the limit equilibrium method overestimates the maximum tension load in the reinforcement. It is noteworthy that due to space limitation, no attempt was made in this study to compare numerical measurements of the tensile load *versus* the theoretical results under dynamic condition.

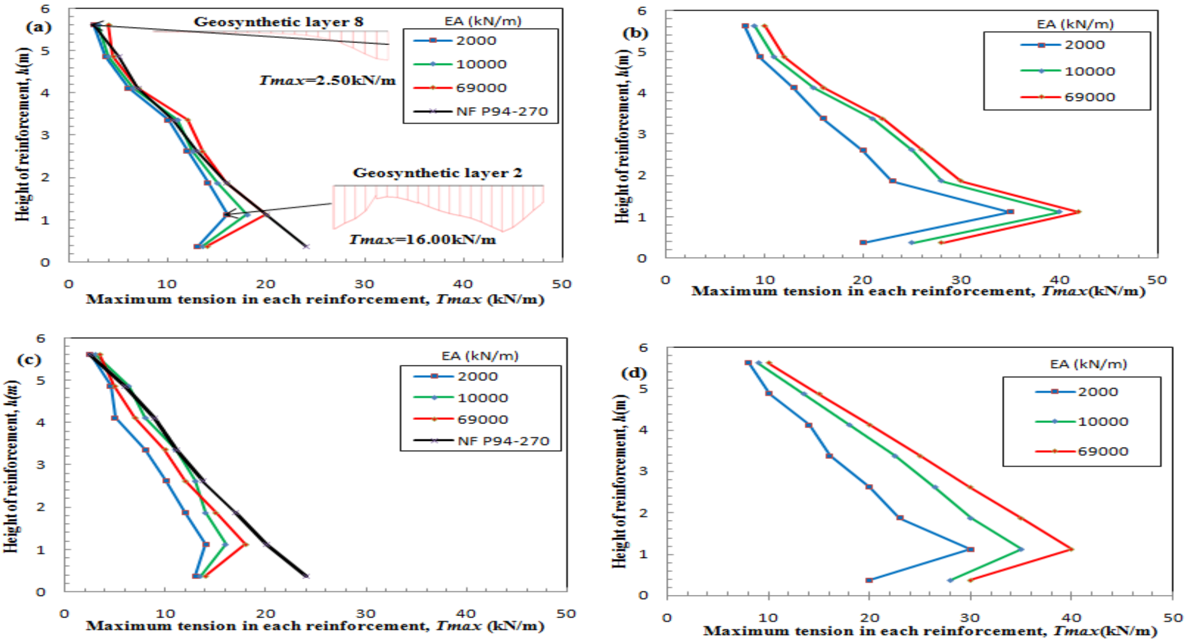


Figure (4): Distribution of the tensile force on reinforcement: (a) concrete panel facing under self-weight, (b) concrete panel facing under seismic excitation, (c) modular block facing under self-weight and (d) modular block facing under seismic excitation for granular soil

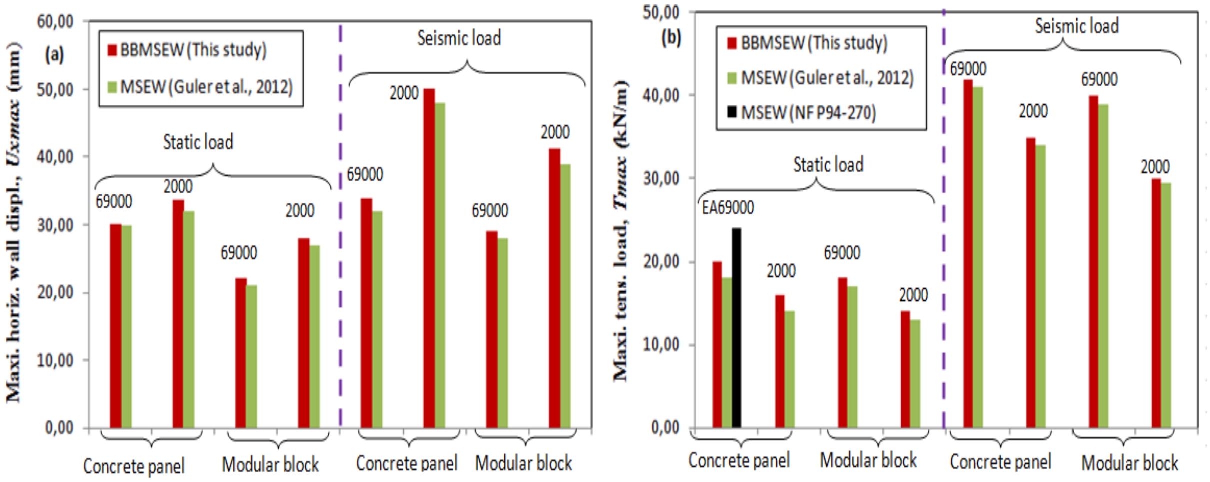


Figure (5): Reported numerical results in MSEWs and current numerical and analytical results in BBMSEWs: (a) maximum displacement and (b) maximum tension load

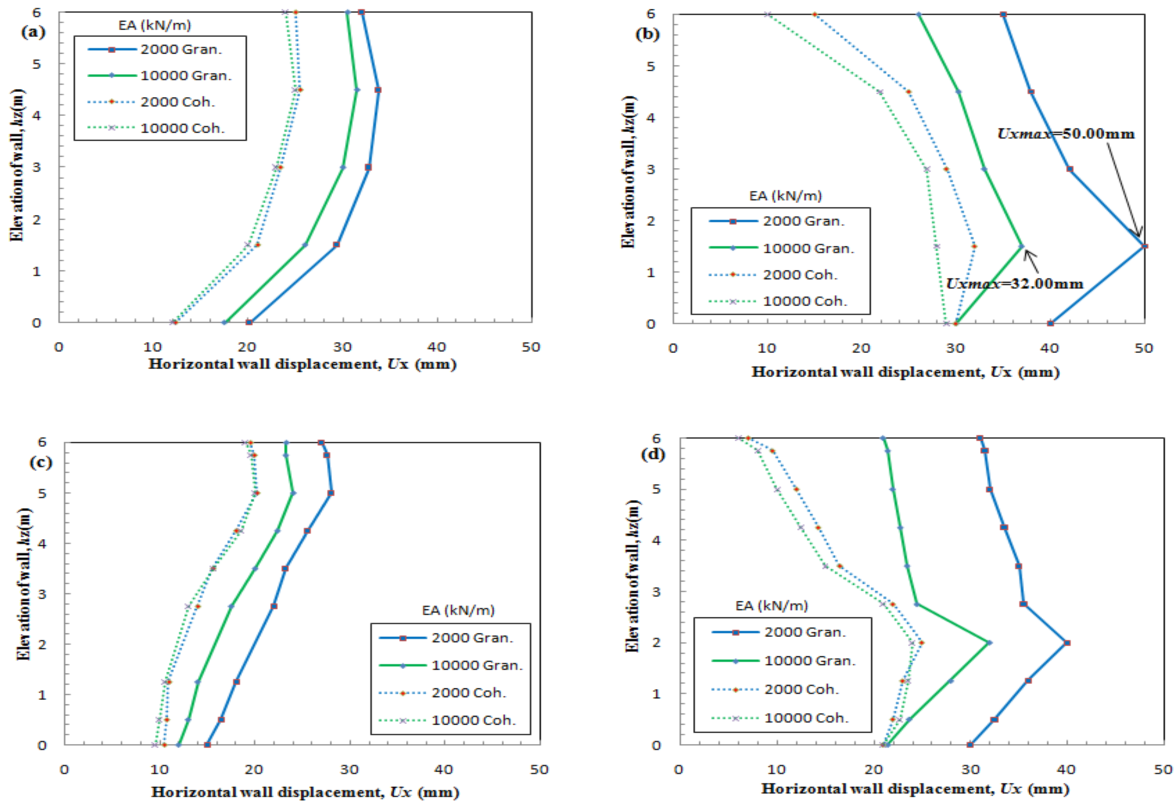


Figure (6): Wall displacement: (a) concrete panel facing under static condition, (b) concrete panel facing under seismic condition, (c) modular block facing under static condition and (d) modular block facing under seismic condition

The Effect of Backfill Type

In order to examine the influence of backfill soil on the response of BBMSEWs, two extreme soil were used; namely, granular and cohesive soils. Granular soils are widely used in the practice of MSEWs with different products of reinforcement, while employing corrodible metallic reinforcement with cohesive backfill considering dry condition is not practical. Therefore, only geotextile and geogrid reinforcements were used for the analysis.

Lateral facing displacement profiles at the end of construction and after applying seismic load determined for both types of backfill with concrete panel and modular block facings are shown in Figure (6). From this figure, it can be shown that the lowest values of the magnitude of displacement are yielded for cohesive backfill. On the other hand, when this type of backfill was selected, the horizontal wall displacement was unaffected by the reinforcement stiffness (Figures 6.a, 6.c and 6.d), except for walls with concrete panel facing under seismic load (Figure 6.b).

Great attention was given to the positive effect of cohesive backfill under dynamic condition when the maximum wall deformation was decreasing significantly compared with that for granular soil (Figures 6.b and 6.d). In addition to being given by Güler et al. (2012), this interesting result is mentioned and discussed by some researchers (e.g. Mitchell and Zornberg, 1995) who have shown that fine grained soil can be successfully used as backfill material provided adequate drainage in the body of the structure.

For all models tested, maximum tensile loads were relatively smaller when cohesive backfill was selected for both load conditions (Figure 7). For instance, under dynamic condition, in case of concrete panel and geogrid reinforcement, the maximum tension load in the second layer is estimated for cohesive backfill at 40.1 kN/m, while the same quantity is calculated as 30.1 kN/m for granular soil with a decrease of about 25% (Figure 7.b).

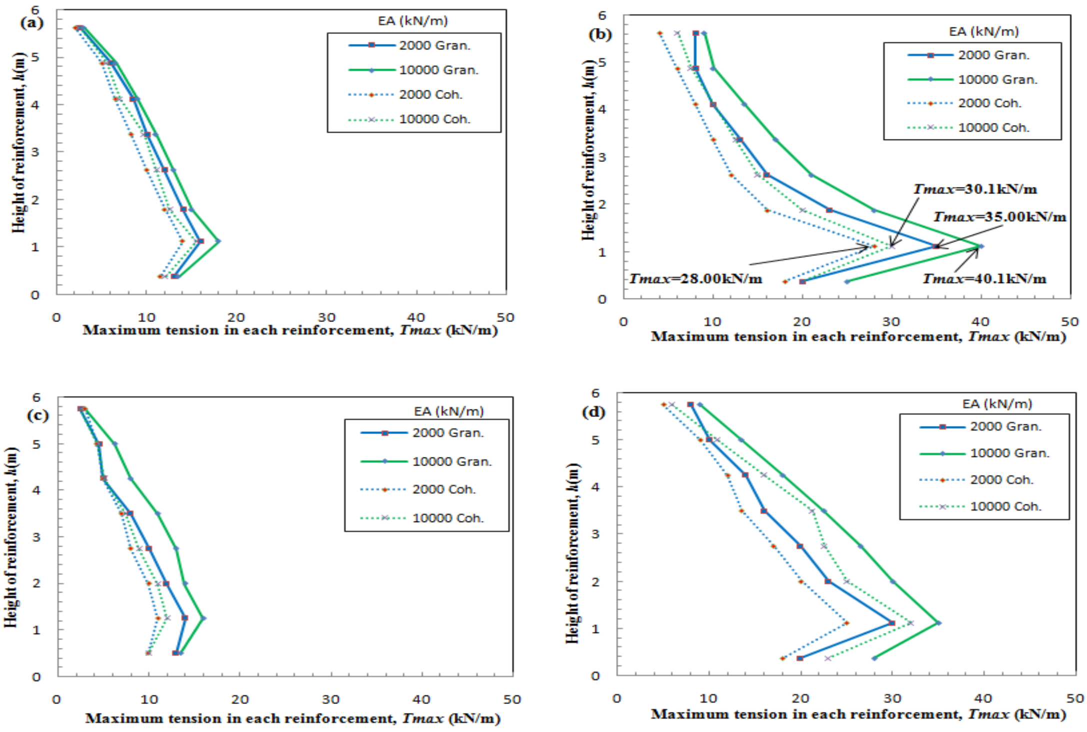


Figure (7): The reinforcement tensile loads: (a) concrete panel facing under self-weight, (b) concrete panel facing under seismic excitation, (c) modular block facing under self-weight and (d) modular block facing under seismic condition

Effect of the Distance between Opposing Walls

The distance between opposing walls for all the models mentioned above was *D*=3.6 m. The effect of the distance was investigated by decreasing *D* to 0 m in four models with granular backfill subject to seismic excitation. These models have concrete panel and modular block facing types with geotextile and metallic reinforcements.

The lateral facing displacement perspective for the four models was plotted in Figure 8. Comparison shows that decreasing the distance reduces significantly the wall deformations for all models. For example, in case of modular block facing and geotextile reinforcement, decreasing the distance, *D*, from 3.6 m to zero leads to a decrease in the lateral displacement from 41.2 mm to 14.2 mm (about 65% decrease) (Figure 8.b).

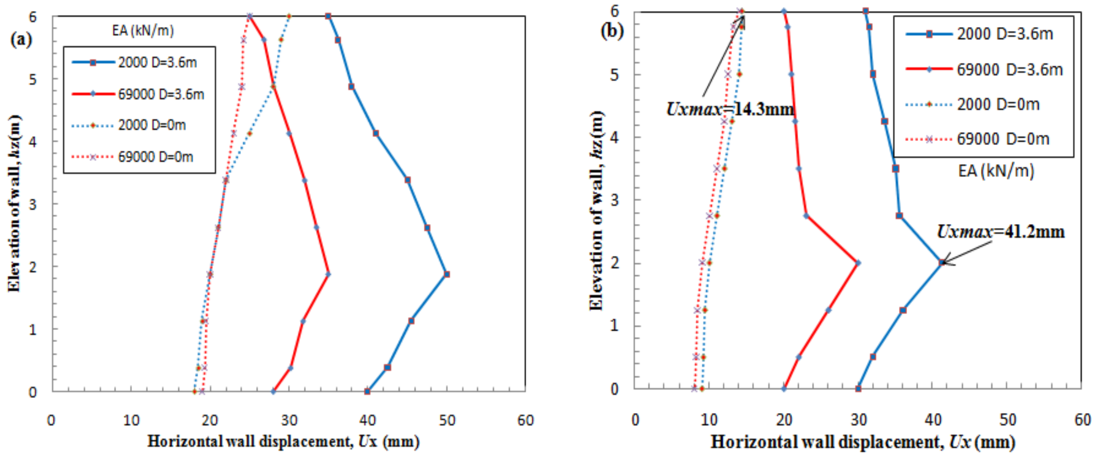


Figure (8): Lateral facing displacements with respect to the distance between walls at the end of seismic excitation for granular backfill: (a) concrete panel facing and (b) modular block facing

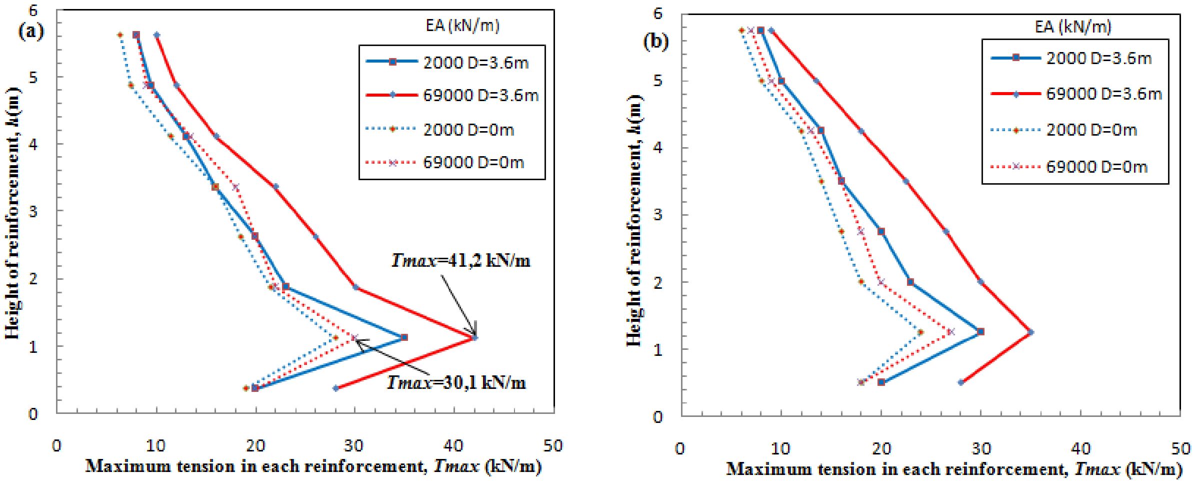


Figure (9): The reinforcement tensile loads with respect to the distance between walls at the end of seismic excitation for granular backfill: (a) concrete panel facing and` (b) modular block facing

The maximum reinforcement load distributions recorded during dynamic loading are plotted in Figure (9).

As can been seen, decreasing the distance to zero involves a reduction in the maximum tension load in the reinforcement. For example, the corresponding maximum axial loads measured in the second layer of metallic reinforcement with concrete panel facing for *D*=3.6 m and *D*=0 m were 41.2 kN/m and 30.1 kN/m, respectively. This reflects a decrement of about 27% in maximum tensile load value due to distance variation (Figure 9.a). Figure (9) illustrates that there is no significant influence of reinforcement stiffness on the tensile load required in the reinforcement when back-to-back becomes closer. As a result, the distance between walls has an important effect on the BBMSEW response, mainly on external stability (i.e., lateral displacement).

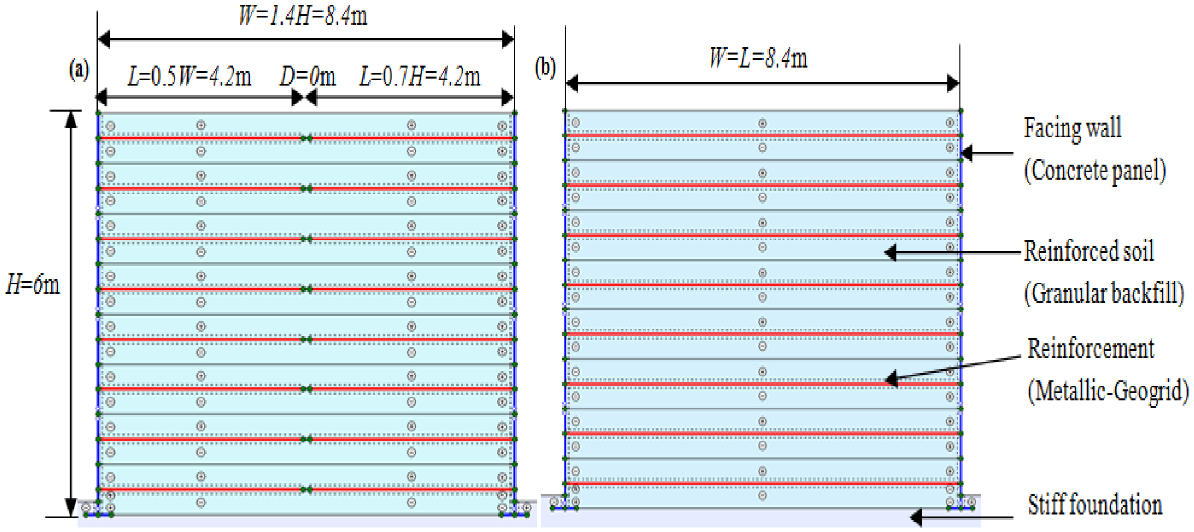


Figure (10): Schematic of BBMSEWs with *D*=0m: (a) unconnected reinforcement and (b) connected reinforcement

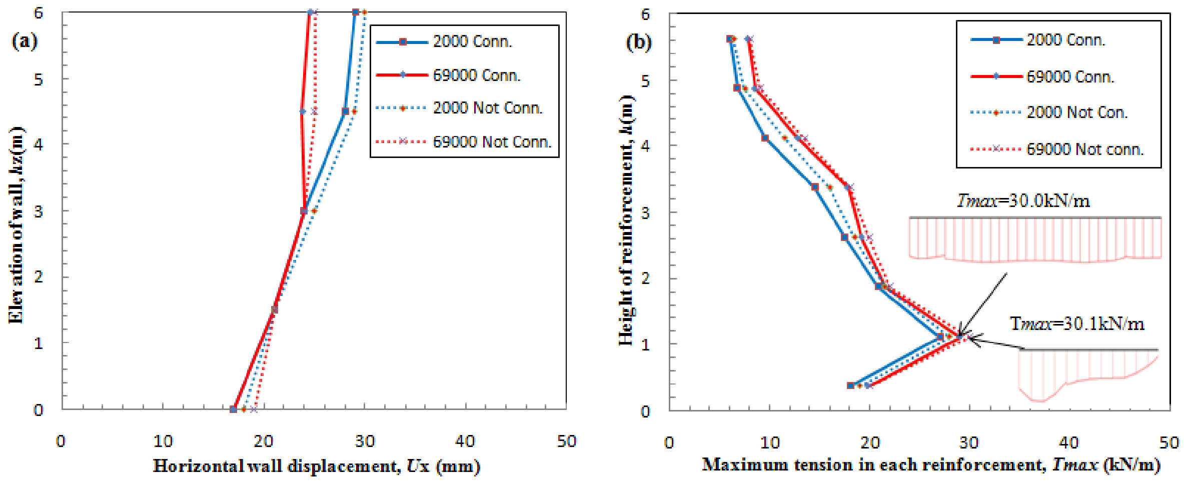


Figure (11): The effect of the connection of reinforcement in the middle for granular backfill with concrete panel facing under seismic condition: (a) horizontal wall displacements and (b) tensile loads in the reinforcement (conn.: connected reinforcement; not conn.: unconnected reinforcement

Effect of the Connection of Reinforcement

When the distance between two opposing walls *D* equals 0 m, the reinforcements from both sides would meet in the middle. For ease of construction, these reinforcement layers are often not connected. BBMSEW designers might be tempted to use single layers of reinforcement that are connected to both wall facings. Berg et al. (2009) indicated that the connection of reinforcements might induce an unyielding condition (at-rest earth pressures, K_o condition).

Available studies did not expect the effect of the connection and the reinforcement stiffness on the behavior of connected walls under seismic loading. Hence, the effects of these two parameters on the lateral displacement and the reinforcement tensile load for both connected and unconnected BBMESWs were analyzed in this section. Schematic configurations of both cases are shown in Figure (10). As illustrated in Figure (11.a), the perspective of lateral movement tends to be the same for both connected and unconnected cases. Comparison shows that the maximum lateral deformation for connected walls was about 14% less than that for unconnected walls.

As can be seen in Figure (11.b), the distribution of tensile load along the wall depth and the maximum tensile forces in the reinforcements remains the same for both connected and unconnected walls.

In limit-state condition and under working stress, Han and Leschnisky (2010) and Benmebarek et al. (2016) showed a similar trend for unconnected and connected walls, because the pullout from the middle of the walls becomes impossible.

In connected walls, reinforcement was found to be utilized effectively, as the tensile force profile was found to be uniform along the length of the reinforcement (Figure 11.b), which is in concordance with the numerical analysis results reported in Sravanam et al. (2019, 2020) under working stress condition.

In this section, it should be noted that the effect of reinforcement stiffness on lateral displacement and on tensile load developed in the reinforcement was negligible.

CONCLUSIONS

In the current paper, it was attempted to improve the understanding of the behavior of Back-to-Back Mechanically Stabilized Earth Walls (BBMSEWs) because of the very limited number of numerical studies on this subject. For this purpose, this study utilizes a two-dimensional Finite Element Method (FEM) incorporated in PLAXIS 2DV8 to evaluate the influence of not only major structural component parameters of BBMSEWs, but also the decreasing of the distance between two opposing walls. An attempt was also made to evaluate the effect of the connection of the reinforcements in the middle.

Parametric static and seismic analyses were carried out on 6 m high BBMSEWs constructed with two different backfills, a range of reinforcement stiffness values and two different wall facings. The results have been reported in terms of horizontal wall displacements and tensile loads in the reinforcements. The following main conclusions can be drawn from the study:

1. Using stiffer reinforcements (metallic) decreased significantly the magnitude of lateral displacement, while the maximum tension load in the reinforcements was slightly reduced.
2. The response of BBMSEWs is highly dependent on the wall facing type, particularly when using flexible reinforcements.
3. The models with cohesive backfill yielded lower maximum wall displacements and tension loads in geosynthetics. That's why fine grained soil can be successfully used as backfill material provided adequate drainage in the body of the BBMSEW structure.
4. Decreasing the distance between opposing walls notably affects the BBMSEW performance involving decreases in the displacement response and the tensile load in the reinforcements.
5. The connection of the reinforcements in the middle ensures the mobilization of the full strength of reinforcement and reduces only the maximum horizontal displacement. Given this complex arrangement of reinforcement, it is therefore better to avoid the design of BBMSEWs with connected reinforcements.
6. During this numerical study, it was also found that the analytical solutions are conservative to design BBMSEWs and similar qualitative responses of BBMSEWs were reported in MSEWs, so that the design method of simple MSEWs can be extended to more complex structures.

Finally, more studies are needed to evaluate the influence of other factors on the seismic behavior of BBMSEWs while checking other performance criteria, such as the lateral earth pressure and the safety factor to improve the understanding of the behavior of this type of retaining walls.

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