Numerical Analysis of Mechanically Stabilized Earth Walls in Hybrid Retaining Wall Systems

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Abstract. Hybrid retaining walls comprising a lower soil-nail wall (SNW) and a mechanically stabilized earth wall (MSEW) on top are typically needed in combined cut and fill wall sections such as in road widening. However, available literature and design guidelines on MSE walls in such hybrid systems are limited. The purpose of this research is to numerically-investigate the behavior of MSE walls in hybrid retaining wall systems during and after construction. Two-dimensional finite element models of different wall configurations are analyzed using PLAXIS 2D software. The base-line model is verified against a published case history of a monitored MSE wall with good agreement. The effect of the nail length to total height (L_N/H_T), SNW facing slope (ω), reinforcements vertical spacing (V_L), reinforcements stiffness (J), and MSEW facing slope (ψ) on the tensile forces in the MSEW are studied. The results of tensile force distribution of MSE wall are presented at this paper. The calculated tensile forces from the numerical modeling are compared with calculated values from MSEW design methods using the Simplified method, Structure stiffness method, and K-stiffness method. Furthermore, the tensile forces of numerical modeling are higher than the tensile forces of the K-stiffness method (empirical method) and equal or less than the tensile forces of Simplified Method and Structure stiffness method (Limit equilibrium method).

1 Introduction

Hybrid retaining wall systems are typically used in cases where combined cut and fill are required, for example to allow for road widening using soil nail wall (SNW) as a lower wall and a mechanically stabilized earth wall (MSEW) above the soil nail wall as shown in Fig. 1. The limited use of hybrid retaining wall system in projects is largely due to lack of an established design procedure for these structures. Hybrid retaining walls are still considered "experimental" and many questions regarding its design and performance remain unanswered. Alhabshi (2006) mentioned that the basic design concept consists of transferring the tensile forces in the reinforcements into the soil through the mobilized friction at the interfaces and the factor of safety (FoS) for global stability of the reinforced soil structure highly depends on the pullout resistance or tensile strength of the reinforcements. He also studied the effect of soil nail wall

parameters on the behavior of hybrid retaining wall system. Jayawickrama (2009) stated that the combination of MSEW and SNW may provide a more economical design in cut/fill situations than the traditionally used full-height MSEWs or SNWs. He carried out an instrumentation and monitoring effort with the objective of improving understanding of hybrid wall design and performance with limited and questionable data points (Bathurst 2016). Wei (2013) stated that the behavior of these wall to retain a soil volume are so far similar because both techniques are based on the concept of using soil reinforcement as passive inclusions in the soil mass to create a gravity structure and hence improve soil stability.

Further development of design procedures for hybrid walls requires additional understanding of the wall behavior. This paper presents a 2D finite Element model to evaluate the performance of the MSEW in an hybrid retaining wall system. The focus of this paper is on the developed tensile forces in the MSEW and how it is affected by wall configuration. The finite element model is validated against a published case history of a monitored MSE wall. The results obtained from the validation model were compared with measurements obtained from the published field data, including wall deformations and strains in the reinforcement. The model is used to investigate the effect of nail length to total height (L_N/H_T), SNW facing slope (ω), reinforcements vertical spacing (V_L), reinforcements stiffness (J), and MSEW facing slope (ψ) on reinforcement's tensile force. The calculated tensile forces are compared with values from MSEW design methods using the Simplified method, Structure stiffness method, and K-stiffness method.
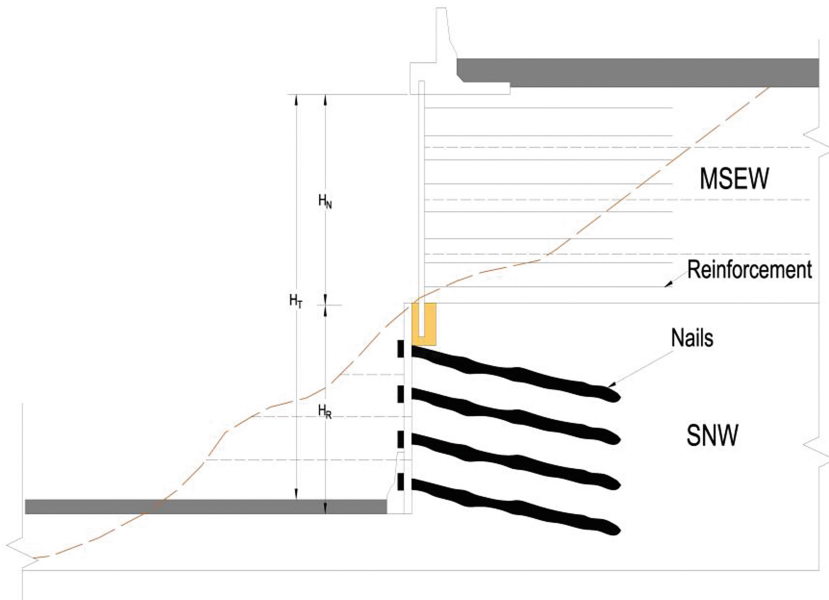

Fig. 1. Hybrid retaining wall system

2   Methodology

Two dimensional finite element software Plaxis 2D was used to model the hybrid wall system with focus on the tensile forces developed in the upper MSEW. The model was verified against a monitored case history of a full scale modular-block MSEW. The facing of the MSEW was modeled using linear-elastic non-porous solid elements, or using plate elements. Solid elements are defined using unit density, stiffness modulus, and Poisson's ratio. Plate elements are defined using axial stiffness and bending stiffness. The stiffness modulus of block facing is reduced to 1/10 of that calculated for the concrete modular block according to Yoo (2004) to take into account of the discrete nature of the modular block facing, thus is taken as 1×10^6 kPa. The soil structure interaction is modeled by interface elements with Mohr column model for the block-to-block interface and default interface with interaction coefficient (R) for the block-to-soil interface. The reinforcement layers are modeled by geogrid elements with elastic axial stiffness (EA). The soil parameters were concluded from the results of stress-strain response from plane-strain tests on the soil samples (Bathurst 2009). The hardening soil model was applied to fit measurements from laboratory tests. The wall was modeled in a staged-construction sequence in lifts considering the compaction stresses.

The modeling of SN wall was verified against a monitored case history of a full scale experimental soil nail wall was constructed as part of the French national research project on soil nail (CLOUTERRE) that was conducted between 1986 and 1991. Due to studying the behavior of MSEW, the verification for MSEW are presented here.

3   Model Verification

Bathurst (2000) reported measurements from experimental full-scale modular-block reinforced soil walls constructed as part of a research program carried out at the Royal Military College. The geogrid reinforced wall No. 1 was 3.60 m high, 3.30 m width, 6.0 m wide, with target facing batter of 8° from vertical and constrained between two lateral walls covered with plywood, Plexiglas, and lubricated polyethylene sheets over the side walls. This configuration was intended to ensure plane stain conditions and minimized the friction between the backfill soil and the sides. The base of the wall was seated on a rigid concrete floor to make construction of the wall as easy as possible and simplify the interpretation of wall performance. The wall facing consisted of a column of discrete dry-stacked, solid masonry concrete blocks with 300 mm wide, 150 mm high, 200 mm long, and weighed 20 kg. The geogrid reinforcements were made of polypropylene (PP) placed at a vertical spacing and length of 0.60 m and 2.52 m respectively. Tables 1, 2 and 3 show the properties of structural elements. Figure 2 shows a cross section of the geosynthetic reinforced wall 1. Laboratory tests were carried out on the soil backfill to measure the soil parameters. The compacted dry unit weight of the backfill was 16.8 kN/m^3, the angle of friction was determined from plan strain tests to be 44°, and the stress- strain behavior was measured by plane strain tests on sand specimens with secant stiffness E_{50} = 42.5 MPa at confining stress σ_3 = 80 kPa (Bathurst 2009). Table 4 shows the summary of the parameters that were adopted in the numerical analysis.

Table 1. The elastic parameters for facing and interface

Parameters	Unit	Modular block facing	Block to block interface
Model	–	Liner elastic	Mohr Coulomb
Drainage type	–	Non-porous	Non-porous
Unit weight, γ_{sat}	kN/m^3	21.80	21.80
Young's modulus, E	kPa	1×10^5	1×10^5
Cohesion, C′	kPa	–	46
Effective angle of shearing resistance, Ø′	Degrees	–	57
Dilatancy angle, ψ	Degrees	–	0
Poisson's ratio, ν_{ur}	–	0.15	0.15
Interface, R$_{inter}$	–	1	1

Table 2. The elastic parameters for plate facing

Parameters	Unit	Facing
Axial stiffness (EA)	kN/m	30000
Bending stiffness (EI)	kN/m/m	225
Poisson's ratio, ν	–	0.15

Table 3. The input parameters for geogrid element.

Parameters	Unit	Facing
Elastic axial stiffness	kN/m	97

A two dimensional finite element model was built to simulate this case study. The case study of the geosynthetic reinforced soil wall was established such that the boundary conditions do not influence the wall behavior. The length of the mesh extended from the left boundary at x = −1.0 m to the right boundary at x = 6.0 m, while the height of the mesh was falling between two boundaries at z = 0 and z = 3.60 m. Figure 3 illustrates the finite element mesh for blocks facing and plate facing. The results of the numerical mode of the wall were compared with the results of field monitoring in terms of horizontal deformation at facing (Fig. 4) and reinforcement strains at the end of construction (Fig. 5). The computed deformation shows a good match compared to the monitored values with estimated difference ranging from 7.0% to 21% for modeling using solid elements and ranging from 3.0% to 10% for modeling using plate elements as shown at Fig. 5. The computed reinforcement strains show a reasonable match compared with the monitored values with estimated difference ranged from 2% to 5% except layers 4 and 5 that show estimated difference ranged from 10% to 15%. The higher values of reinforcements strain at the facing were caused by the connection between the facing and the geogrid as shown at (Fig. 5). According to the above results, the Plaxis 2D model can be considered adequate to simulate the geosynthetic reinforced soil wall with hardening soil model and plate element for MSEW facing.
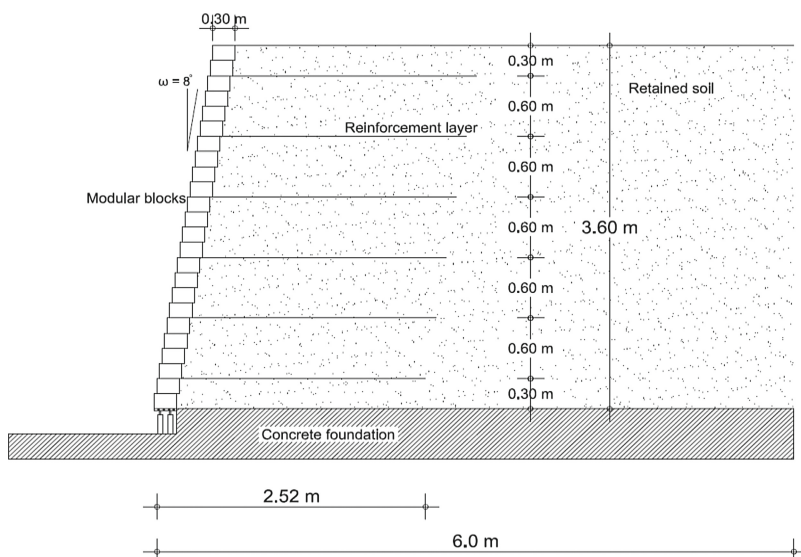
Fig. 2. Cross section of wall geometry of RMCC Wall 1.

Table 4. Summarized material properties adopted for the soil.

| Parameters	Unit	Backfill
Model	–	HS
Drainage type	–	Drained
Unit weight, γ_{sat}	kN/m^3	16.80
Secant stiffness in standard drained triaxial test, E_{50ref}	MPa	42.5
Tangent stiffness for primary oedometer loading, E_{oedref}	MPa	42.5
Unloading/reloading stiffness, E_{urref}	MPa	127.5
Power for stress-level dependency of stiffness, m	–	0.5
Effective cohesion, C'	kPa	2
Effective angle of shearing resistance, $\varnothing'$	degrees	44
Dilatancy angle, ψ	degrees	11
Poisson's ratio, ν_{ur}	–	0.25
Reference pressure, P_{ref}	kPa	80
Earth pressure coefficient at rest, K_0	–	0.305
Interface, R_{inter}	–	0.67
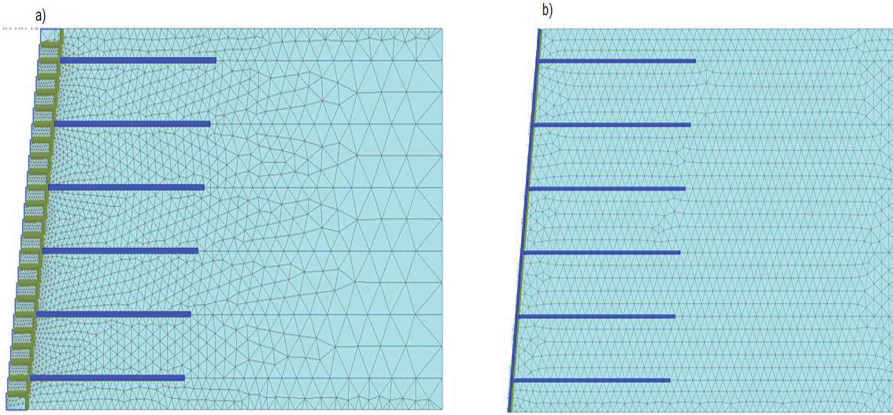
Fig. 3. Numerical model of geosynthetic reinforced soil wall; (a) Blocks facing (b) Plate facing
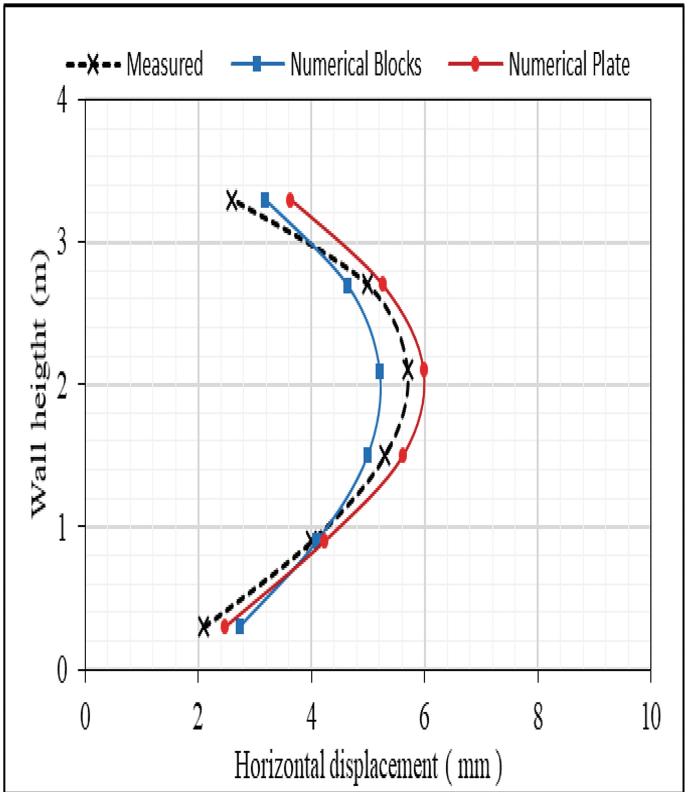

Fig. 4. Comparison between the computed lateral displacement and measured results at the wall facing
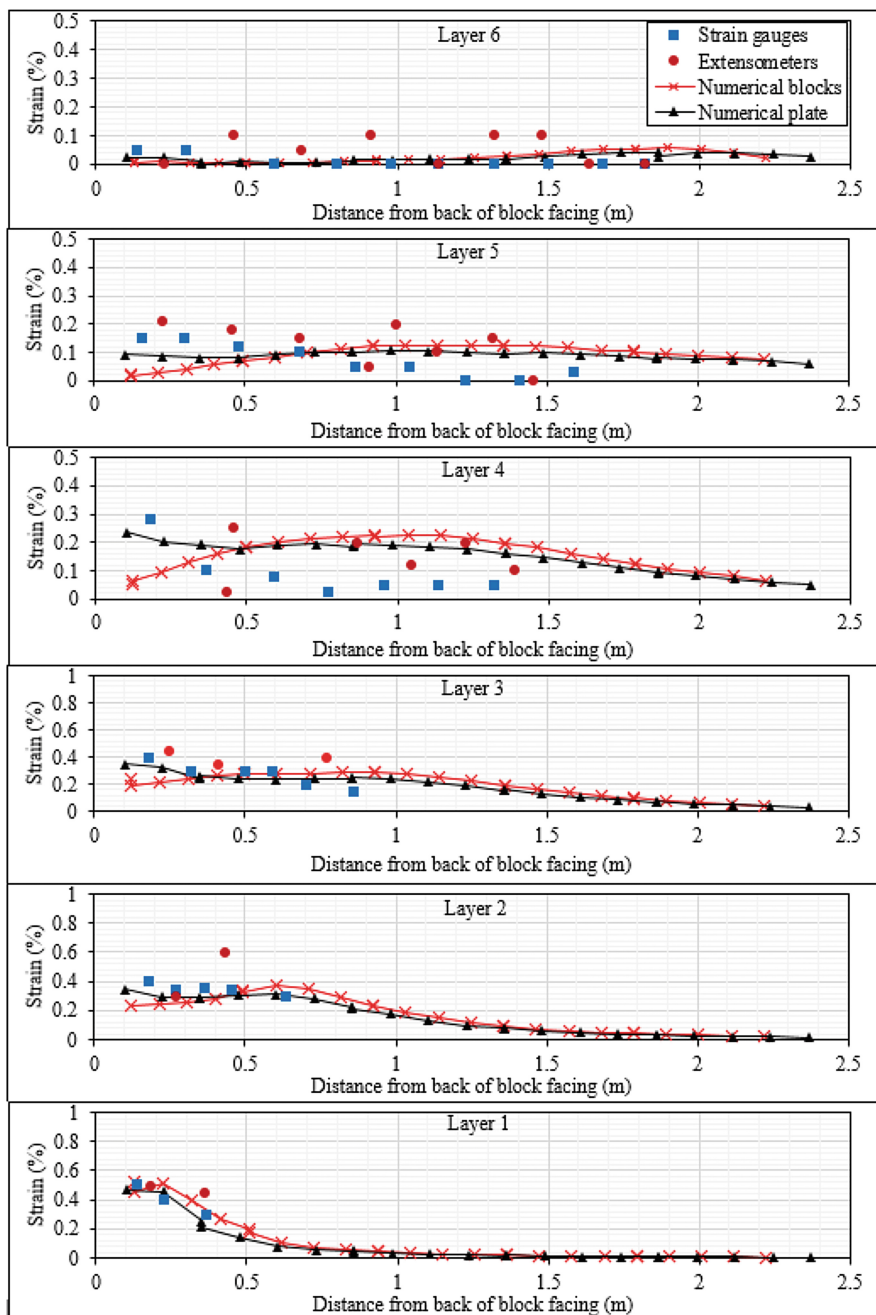
Fig. 5. Comparison between the computed reinforcements strains and measured results

4   Parameters Effect on Reinforcement's Tensile Force

4.1   Hybrid Baseline Retaining Wall

The hybrid baseline wall was modeled based on two wall models SNW and MSEW with 10.0 m height divided equally between the MSEW and SNW with 5.0 m height to be a reference wall for results comparison. The nails and reinforcements lengths were chosen with L_N/H_T ratio to be 0.6 and L_R/H_R ratio to be 1.20 respectively. The horizontal and vertical spacing for nails was 1.0 m, nails inclination with horizontal 10° and the vertical spacing for reinforcements was 0.60 m. Figure 6 shows the hybrid baseline wall configuration. The structural element for nails was plate element with equivalent stiffness in axial and bending using steel bar No. 9 (29 mm) and the geogrid axial stiffness for GRSW reinforcements was 1000 kN/m. A hinged connection between the MSEW facing and the SNW facing to prevent any transfer for bending moment. The structural element for MSEW facing and SNW was plate element with equivalent stiffness in axial and bending using 0.15 m thickness. Tables 5 and 6 show a summary of the soil properties and structure parameters that were adopted in the hybrid baseline wall. Figure 7 shows the results of tensile forces distribution for reinforcements with height.
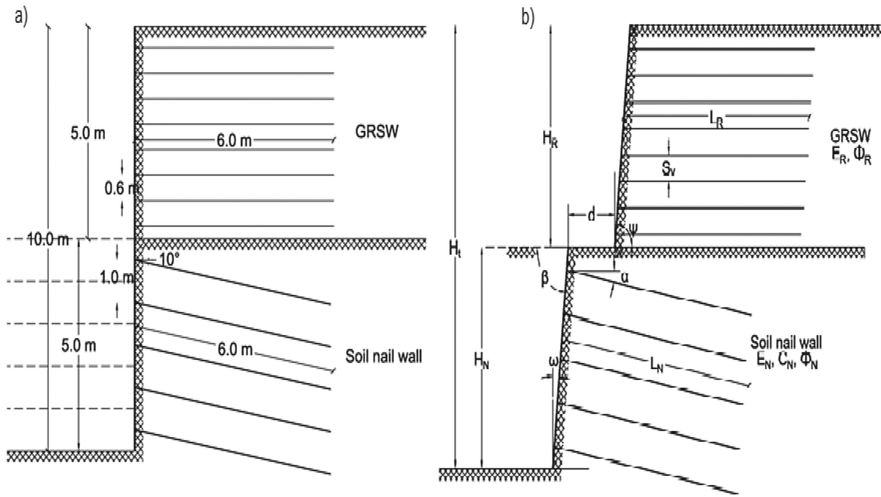

Fig. 6. Hybrid retaining wall: (a) Baseline wall; (b) General configuration

4.2   Results of Sensitivity Analysis

In order to highlight and investigate the influence of some parameters that may be of a noticeable impact on the response and results of MSEW, a numerical sensitivity study was carried out for some parameters such as; nail length to total height (L_N/H_T), SNW facing slope (ω), reinforcements vertical spacing (V_L), reinforcements stiffness (J), MSEW facing slope (ψ). The results of tensile forces are summarized and presented in

Table 5. Summarized soil properties adopted for the hybrid baseline wall

Parameters	Unit	MSEW	SNW
Model	–	HSM	HSM
Drainage type	–	Drained	Drained
Unit weight, γ_{sat}	kN/m^3	18.00	18.0
Secant stiffness in standard drained triaxial test, E_{50ref}	MPa	25	25
Tangent stiffness for primary oedometer loading, E_{oedref}	MPa	25	25
Unloading/reloading stiffness, E_{urref}	MPa	75	75
Power for stress-level dependency of stiffness, m	–	0.5	0.5
Effective cohesion, C′	kPa	2	5
Effective angle of shearing resistance, Ø′	degrees	35	35
Dilatancy angle, ψ	degrees	5	5
Poisson's ratio, ν_{ur}	–	0.30	0.30
Reference pressure, P_{ref}	kPa	100	100
Earth pressure coefficient at rest, K_0	–	0.426	0.426
Interface, R_{inter}	–	0.67	0.55

Table 6. Summarized structural properties adopted for the hybrid baseline wall

Parameters	Unit	MSEW facing	SNW facing	Nail element	Reinforcement element
Axial stiffness (EA)	kN/m	3×10^6	3×10^6	132×10^3	1000
Bending stiffness (EI)	kNm^2/m	5625	5625	6.94	–
Poisson, s, ν	–	0.15	0.2	0.2	–

the form of charts with different parameters including the baseline wall parameters with blackline as an easy reference to comparison. The variable values of effective parameters on tensile force of reinforcements are stated in Table 7, also the effect of each parameter on the tensile force distributions on MSEW are shown in Fig. 8.

The increasing of the nail length to height ratio (L_N/H_T) leads to decrease the tensile forces on MSEW till reaching nail length to height (L_N/H_T) equals 0.6 therefore any additional increase after that value will not have significant effect to tensile forces on GRSW as shown in Fig. 8a, and during the decreasing of the nail length to height ratio (L_N/H_T) from 1.0 to 0.6, the maximum tensile forces are located in the middle of wall with difference between 4.5% to 7.5% from the baseline wall forces, but at nail length to height ratio (L_N/H_T) less than 0.6, the maximum tensile forces are located in the lower part of wall with difference between 45% to 270% from the baseline wall forces. This behavior could be attributed to (L_N/H_T) ratio that acts as toe restraint for MSEW.
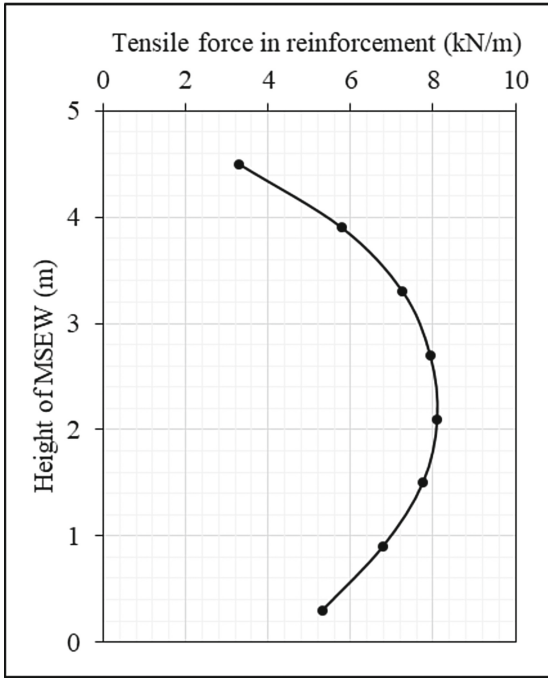
Fig. 7. The tensile force distribution of reinforcements with height

Table 7. Summarized structural properties adopted for the hybrid baseline wall

Parameter	Value					
Nail Length/Total height (L_N/H_T)	0.30	0.40	0.50	0.60	0.75	1.00
Setback distance (d, m)	0	2	4	6	10	0
SNW Facing slope (ω)	0	15	30	45		
Reinforcements vertical spacing (V_L)	0.4	0.6	0.8			
reinforcements stiffness (J)	250	500	1000	2000	3000	
MSEW facing slope (ψ)	45	60	70	80	90	

The increasing of the SNW facing slope (ω) leads to increase the tensile forces on MSEW as shown in Fig. 8b, and during increasing the facing slope, the maximum tensile forces are increasing and located in the middle of wall with difference 8% to 21% from the baseline wall forces, but the tensile forces at the lower layer are decreasing with difference 13.5% to 41% from the baseline wall forces. This behavior could be attributed to increasing the settlement below GRSW due to lateral squeeze type failure which leads to increase the tensile forces on reinforcement to resist the shear.
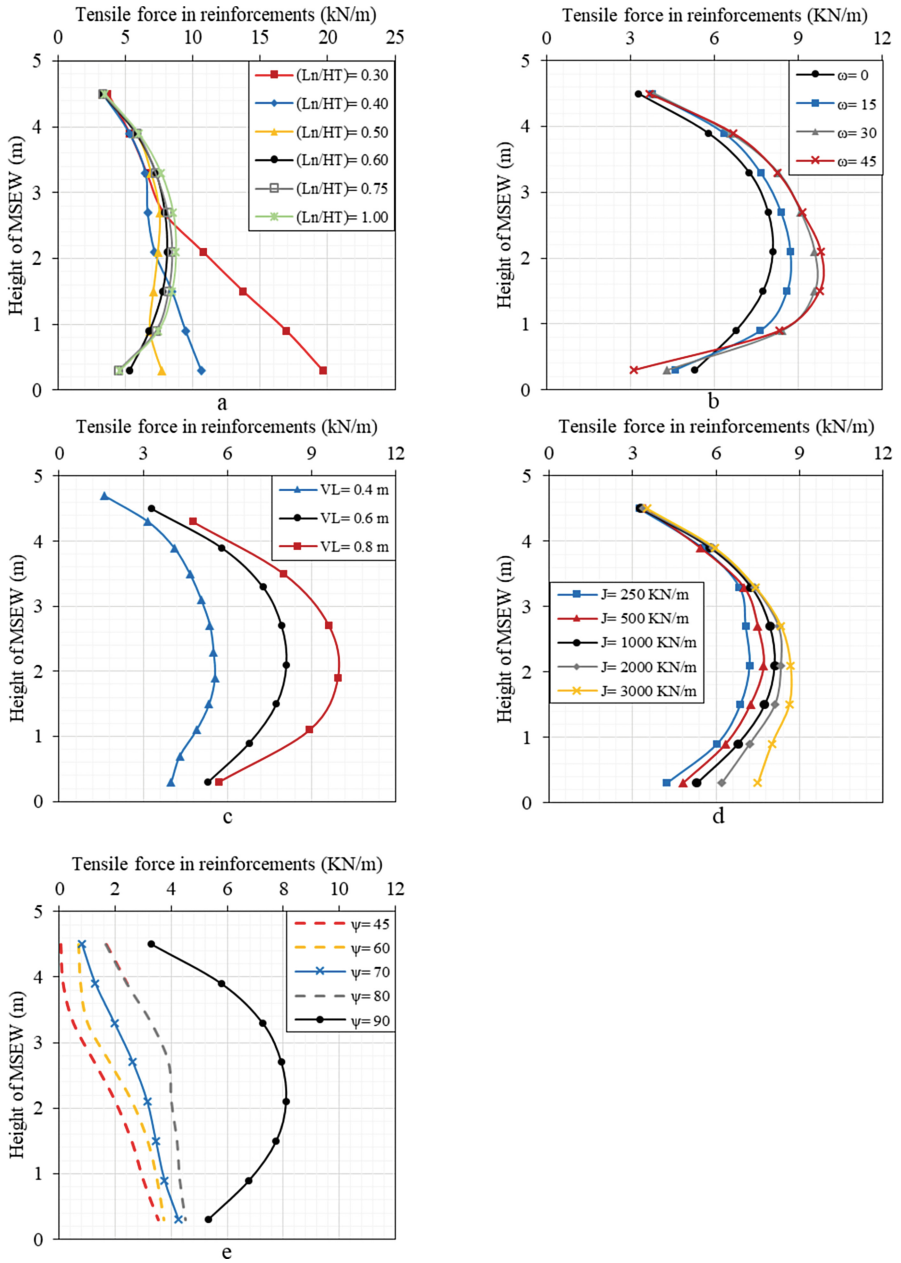
Fig. 8. The tensile force distribution of reinforcements with height at: (a) Nail length to total height; (b) SNW facing slope; (c) Reinforcement vertical spacing; (d) Reinforcement stiffness; (d) MSEW facing slope
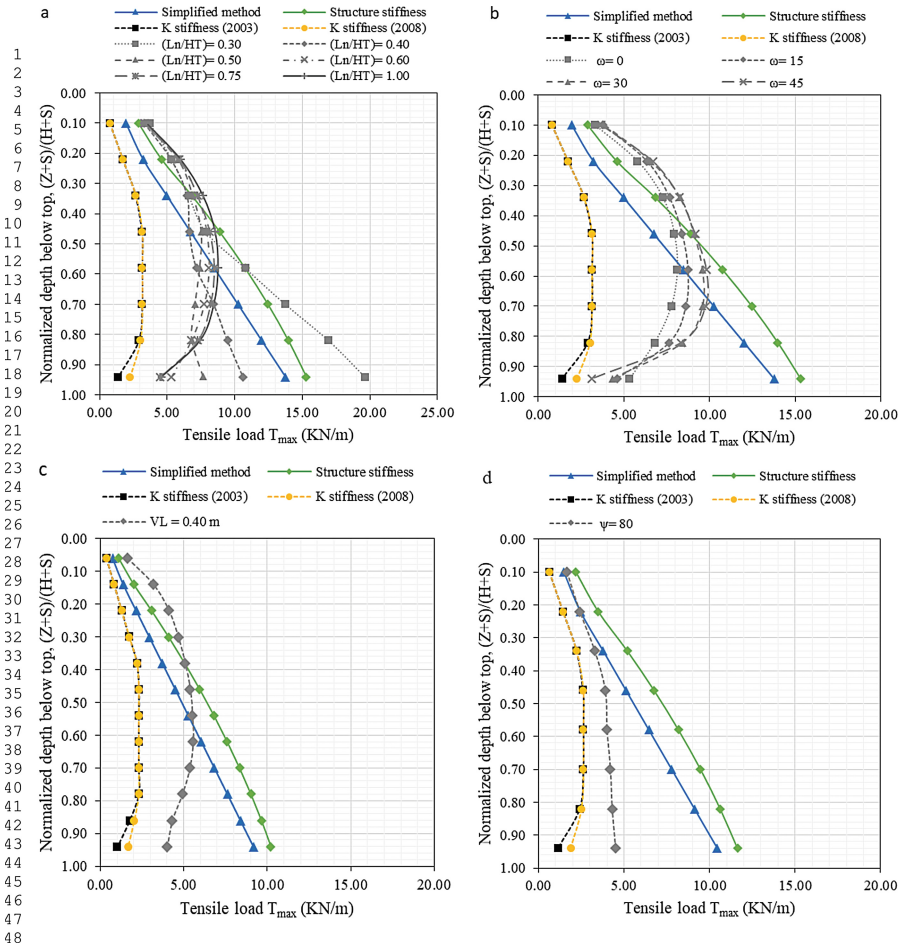
Fig. 9. Comparison of reinforcement tensile forces between design method and numerical analyses at: (a) Nail length to total height; (b) SNW facing slope; (c) Reinforcement vertical spacing $V_L = 0.4$ m; c) MSEW facing slope $\psi = 80°$

The increasing of the reinforced vertical spacing leads to increase the tensile forces in reinforcements at MSEW as shown in Fig. 8c. During the increasing of the reinforced vertical spacing, the maximum tensile forces are located in the middle of wall with difference between 23.0% to 31.5% from the baseline wall forces. This behavior could be attributed to increasing decreasing the earth pressure at smaller vertical reinforcement spacing resulting in confining soil between reinforcements which lead to reduce the soil deformation and the mobilized tensile force in reinforcements.

The increasing of the reinforcement stiffness leads to increase the tensile forces in reinforcements at GRSW as shown in Fig. 8d. During the increasing of the reinforced stiffness, the maximum tensile forces are located in the middle of wall with difference between 7.0% to 11.0% from the baseline wall forces. This behavior could be attributed

to increasing the reinforcement stiffness which leads to decrease the developed strains and increase the mobilized tensile forces on reinforcements.

Table 8. Comparison between design methods of MSEW

Method	Assumptions	Factors ignored
Simplified method	• Limit equilibrium method • Wall foundation is rigid or unyielding does not influence the magnitude and distribution of reinforcement loads • MSE structures are tolerant to deformations • Earth pressure coefficient varies with depth based on type of reinforcement stiffness till 6.0 m	• Effect of change parameters • Construction sequence/compaction effect • Different soil/facing type • Deformation • Foundation compressibility • Foundation movement (Toe restraint) • Reinforcement stiffness
Structure stiffness	• Limit equilibrium method • Wall foundation is rigid or unyielding does not influence the magnitude and distribution of reinforcement loads • MSE structures are tolerant to deformations • Earth pressure varies with depth based on reinforcement stiffness	• Effect of change parameters • Construction sequence/compaction effect • Different soil/facing type • Deformation • Foundation compressibility • Foundation movement (Toe restraint) • Reinforcement stiffness
K-Stiffness method	• Empirical method by using a database of 11 full-scale geosynthetic walls • Results of simple statistical analyses for various wall components and their influence on reinforcement loads • Wall foundation is rigid or unyielding does not influence the magnitude and distribution of reinforcement loads	• Construction sequence/compaction effect • Deformation • Foundation compressibility • Foundation movement (Toe restraint)

The increasing of the facing slope leads to increase the tensile forces on MSEW as shown in Fig. 8c. During increasing the facing slope, the maximum tensile forces are located in the lowest layer of wall till facing slope value 80° after that value the maximum tensile forces are located in the middle layer of wall. This behavior could be attributed to decreasing the value of active earth pressure coefficient which leads to decrease the acting earth pressure on reinforcements.

5   Comparison with Design Methods

A comparison was carried out between the numerical analyses results and some of design methods such as; Simplified Method, Structure stiffness method (FHWA 1990), and K-Stiffness method (Bathurst 2003; 2008) through the tensile forces on reinforcements with the major affected parameters stated earlier in the previous section as shown in Fig. 9. Table 8 shows the difference between methods assumptions and the factors ignored in the design methods which leads to tensile forces on the design methods differ from tensile forces of the numerical analyses. The numerical analyses results show that the tensile forces on reinforcements are higher than the tensile forces of the K-stiffness method (empirical method) and equal or less than the tensile forces of Simplified Method and Structure stiffness method (Limit equilibrium method).

6   Conclusions

This study is mainly concerned with numerically simulating the behavior mechanically stabilized earth wall in Hybrid retaining wall system during and after construction. A two-dimensional finite element analysis using PLAXIS 2D software was used to simulate a published case history of a monitored MSE wall No. 1 that constructed as part of geotechnical research program that carried out by the Royal Military college of Canada that was conducted between 1999 and 2000. The numerical test results were compared with the field monitoring results from horizontal deformation at facing, reinforcement strains at the end of construction which showed a good match that reflected a justified authentication for the modelling approach and software. Hybrid baseline wall was modeled based on two wall models SNW and MSEW. A numerical sensitivity study was carried out for some parameters such as; nail length to total height (L_N/H_T), SNW facing slope (ω), reinforcements vertical spacing (V_L), reinforcements stiffness (J), MSEW facing slope (ψ).

Increasing of the nail length to height ratio (L_N/H_T) leads to decrease the tensile forces on MSEW till reaching nail length to height (L_N/H_T) equals 0.6 therefore any additional increase after that value will not have significant effect to tensile forces on GRSW. Nail length to total height ratio (L_N/H_T) is acting as toe restraint/stiffness that effect on the magnitude and distribution of reinforcements. In general, at value of (L_N/H_T) ratio is greater than or equal 0.6, reinforcement load distributions at MSEW becomes trapezoidal in shape (i.e. fixed toe) and at value of (L_N/H_T) ratio is less than 0.6, reinforcement load distributions at MSEW becomes more triangular in shape. Increasing of the SNW facing slope (ω) leads to increase the tensile forces on MSEW

and during increasing the facing slope, the maximum tensile forces are increasing and located in the middle of wall with difference 8% to 21% from the baseline wall forces, but the tensile forces at the lower layer are decreasing with difference 13.5% to 41% from the baseline wall forces.

Increasing of the reinforcement vertical spacing (V_L) leads to increase the tensile forces in reinforcements at MSEW. During the increasing of the reinforced vertical spacing, the maximum tensile forces are located in the middle of wall with difference between 23.0% to 31.5% from the baseline wall forces.

Increasing of the reinforcement stiffness (J) leads to increase the tensile forces in reinforcements at GRSW. During the increasing of the reinforcement stiffness, the maximum tensile forces are located in the middle of wall with difference between 7.0% to 11.0% from the baseline wall forces.

Increasing of the MSEW facing slope (ψ) leads to increase the tensile forces of reinforcements at MSEW. During increasing the facing slope, the maximum tensile forces are located in the lowest layer of wall till facing slope value 80° after that value the maximum tensile forces are located in the middle layer of wall.

Regarding to the numerical simulating of the behavior for mechanically stabilized earth wall in Hybrid retaining wall system, the numerical results are more accurate than other design methods as it considers the factors that may be neglected by these methods such as; foundation compressibility, foundation movement (Toe restraint), and MSEW deformation.

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