Research Article

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A 3D numerical analysis of the compaction effects on the behavior of panel-type MSE walls

<https://doi.org/10.1515/geo-2020-0192>

received June 17, 2020; accepted September 17, 2020

Abstract: Soil is weak in tension but strong in compression. The resistance to tensile deformation of soil is given by the tensile force of the reinforcement in the reinforced soil, and the tensile force of the reinforcement is generated by the frictional force at the soil-reinforcement interface. When the soil-reinforcement is effectively interacted by the compaction, the deformation of the soil becomes equal to the tensile deformation of the reinforcement material, which means that the soil is bound to the tensile force of the reinforcement material and thus has a great resistance to the tensile deformation. Therefore, compaction is one of the major parameters affecting the behavior of the mechanically stabilized earth (MSE) wall. In this study, a series of numerical analyses was performed to investigate the compaction effect on the behavior of the MSE walls. The results showed that the horizontal displacement of the MSE wall significantly increased during the construction and decreased because of surcharge load application after the construction. In addition, the strains of reinforcement increased significantly during the construction and decreased slightly because of surcharge load application after the construction. Therefore, it is important to consider the compaction loads when modeling the MSE walls, so that the lateral displacement at wall facing will not be underestimated during construction and will not be overestimated because of surcharge load application after the construction.

Keywords: MSE wall, compaction effects, geogrids, steel strips, geo-strips, Plaxis 3D, numerical analysis, numerical modeling

1 Introduction

Compaction loads are not permanent loads and often not considered on the design loads of mechanically stabilized earth (MSE) walls. Only stipulated guidelines are imposed on the proper application of compaction equipment during construction to prevent wall damage or failure. It has been documented that an increasing number of geosynthetic-reinforced MSE wall failures had poor and moderate compaction [1,2]. Case studies also showed that inconsistent or poor compaction contributed to the failures of MSE walls [3–6].

For decades, several analytical, experimental, and numerical investigations were conducted by various researchers on the effects of compactions on the behavior of reinforced soil retaining walls or MSE walls [7–10]. Bathurst et al. [11], Ehrlich et al. [12], and Mirmoradi and Ehrlich [13] conducted an experimentation on geogrid-reinforced soil (GRS) wall and the effects of compaction near the facing considering light compaction and heavy compaction, and applied surcharge loading. The findings in their experiments showed that compaction promoted lateral displacement during the construction and reduced lateral displacement because of surcharge load application after construction. On the contrary, Mirmoradi and Ehrlich [8,9] modeled a GRS wall using Plaxis 2D with compaction-induced stress in the backfill. The results of their numerical analyses using 55 kPa uniform surcharge pressure showed that it overestimates the measured values. Later, Nascimento et al. [10] conducted similar study on the compaction effect of GRS wall with 50 kPa surcharge loading. The pressure is probably great which lead to excessive predictions. Moreover, it has been documented that soil compaction has effects on the lateral earth pressures [14–20]. Investigations were also conducted on the effects of compaction on the reinforcement loads [11,21–23]. Abdelouhab et al. [24] and Seed et al. [4] showed that the compaction loadings should be considered in numerical modeling to estimate with accuracy and to model properly the response of the compacted soils and the deformation of the structure.

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Figure 1: Plaxis 3D geometry model and components of MSE wall.

Numerical investigations using finite element method (FEM) have been widely used to predict and/or validate the behaviors of MSE walls. However, numerical investigations on the effects of compaction particularly on MSE walls using FEM in 3D software are rarely undertaken. Thus, the study was carried out to have a profound understanding on the behavior of the panel-type MSE wall using FEM in Plaxis 3D software. The study considered three different reinforcements: (1) 1.20 m-width geogrid; (2) 0.10 m-width geo-strip; and (3) 0.05 m-width steel strip reinforcements. In addition, the study considered four different compaction methods: (1) no compaction; (2) 10 kPa compaction load; (3) 20 kPa compaction load; and (4) 35 kPa compaction load (details of the compaction loads are given in Section 2.5).

2 Numerical modeling

2.1 MSE wall geometry model and boundary conditions

The Plaxis 3D software was used for the numerical analysis of the MSE wall models. The 3D numerical modeling is ideal for modeling geotechnical structures that have 3D geometry conditions such as the MSE wall with discrete or discontinuous reinforcements. In this paper, the MSE walls were designed to satisfy the internal and external

stability based on Das [25], FHWA-NHI-10-024 [26], and Murthy [27]. Concurrently, the MSE walls were modeled based on the example procedures in Plaxis 3D Reference and Tutorial Manuals [28,29]. The details of the systematic construction procedure are given in Section 2.6.

The dimensions of the MSE wall model were designed to have a proportional and plain geometry condition. The height, H , of the MSE wall model was assumed 6.0 m above the soil foundation with three layers of superimposed precast concrete panel wall facings. The width, W , of the MSE wall model was assumed 6.0 m wide and the backfill length, BL , was assumed 12.0 m ($2H$) long. The distance from the wall to the boundary was assumed $2H$ to have enough space for the MSE wall deformations to occur at the backfill without the influence of boundary effect [30]. The soil foundation was modeled with a height of 6.0 m ($1H$), width of 6.0 m ($1H$), and length of 24.0 m ($4H$) (see Figure 1). There are 12 layers of reinforcements spaced 0.5 m vertically, starting from 0.25 m height from the base of the wall. The reinforcement length is fixed to 4.50 m ($0.75H$) in all layers [26]. The vertical spacing between reinforcements is 0.50 m on-centers, whereas the horizontal spacing varies depending on the type of reinforcement being modeled.

The boundary conditions are modeled wherein the vertical sides of the MSE wall model and soil foundation along the X - Z plane at $Y = 0$ and $Y = 6$ are fixed on Y -direction and along Y - Z plane at $X = 0$ and $X = 24$ are fixed on X -direction. Therefore, only the surface of the wall facing, the top surface of soil foundation, and

the top surface of the backfill soil were free to move in all directions (see Figure 1). Here the soil foundation was assumed to be made of bedrock to eliminate the influence of foundation deformation on the behavior of the MSE wall. In addition, the influence of the pore water pressure was not considered in the analysis. All MSE wall models were assumed to have the same soil backfill, soil foundation, and wall facing material properties to avoid complexity with the results. The MSE wall models were analyzed in 24 construction phases (details of the 24 steps are given in Section 2.6). In each phase, the pressures and deformations were carried over to the next phase until the end of the construction. In other words, no corrections were done on each phase during the construction. Elastoplastic drained analysis was used in this study and consolidation of soil was not considered; therefore, time of construction does not have substantial effects on the behavior of the numerical models. In addition, the Plaxis 3D models contained 10-noded elements (Case 1-A-D = 28,863 elements, Case 2-A-D = 32,637 elements, and Case 3-A-D = 34,658 elements). The numerical models have an average element size of 0.24, 0.23 and 0.22 m for Case 1-A-D, Case 2-A-D, and Case 3-A-D, respectively. The definitions of Case 1-A-D, Case 2-A-D, and Case 3-A-D are discussed in detail in the following sections.

2.2 Reinforcement models and material properties

In this study, a suggested panel-type MSE wall using wider geogrids reinforcement was compared with panel-type MSE wall using the conventional geosynthetic strip and steel strip reinforcements. Henceforth, three cases of discrete or discontinuous reinforcements were considered and analyzed in this study. Figure 2 shows the three cases of reinforcements and arrangements of discrete reinforcements. The first case was designated as Case 1 (see Figure 2(a)) using the suggested design of panel type MSE wall reinforced with 1.20 m-width geogrids. The 1.2 m-width geogrid reinforcements were arranged in staggered manner with center-to-center horizontal spacing, S_h , equivalent to 1.50 m. The second case was designated as Case 2 (see Figure 2(b)) using the existing design of panel-type MSE wall reinforced with the 100 mm-width geosynthetic strips. The geo-strips were arranged in a linear manner with center-to-center horizontal spacing, S_h , equivalent to 0.75 m. Finally, the third case was designated

as Case 3 (see Figure 2(c)) using the existing panel-type MSE wall reinforced with 50 mm-width steel strips. The steel strips were arranged in linear manner with center-to-center horizontal spacing, S_h , equivalent to 0.75 m.

In modeling the reinforcements, the created surfaces are then assigned as the so-called geogrid elements with elastic material property in Plaxis 3D (see Figure 2) [30,31]. Geogrid elements are structures that are slender with an axial stiffness and can sustain only tensile forces. Generally, geogrid elements are used to model soil reinforcements [28]. The discrete reinforcements, geogrids, geo-strips, and steel strips were assumed fixed to the precast concrete panel facing. The basic parameter required in modeling geogrid element is the axial stiffness, EA. The axial stiffness (EA) of the reinforcement is the product of the elastic modulus (E) and the cross-sectional area ($A = t \cdot w$) of the reinforcement. The axial stiffness of Case 1, having 1.20 m-width and 1.45 mm-thick geogrid reinforcement, was determined by translating the axial stiffness of 1,360 kN/m [32] from sheet into discrete reinforcement. Case 2 uses geosynthetic strip reinforcement with a cross-sectional area 300 mm² and elastic modulus of 2.5 GPa [24]. For this case, the reinforcement axial stiffness is doubled because of its arrangement as shown in Figure 2(b); therefore, the computed axial stiffness for geo-strips reinforcement is 1,500 kN/m. Finally, Case 3 uses a steel strip reinforcement with high elastic modulus of 210 GPa and a small cross-sectional area of 200 mm² [24]. The computed axial stiffness of one steel strip material is 42,000 kN/m. The reinforcement material properties are summarized in Table 1.

2.3 Backfill and foundation soil material properties

Soil material models characterize the stress-strain constitutive behavior of the soil. In this study, reinforced backfill and retained backfill soils were assumed to have the same material properties. The constitutive model used to simulate the behavior of the soil backfill is the Mohr-Coulomb (MC), a linear elastic perfectly plastic model with drained material type behavior. The parameters used for the backfill are tabulated in Table 2. The unit weight was assigned 19 kN/m³ for the general properties [31,33]. The backfill was assumed with the elastic modulus of 20,000 kN/m² and Poisson's ratio of 0.30 [30,34,35]. Damians et al. [31] used a cohesion value that is high enough to ensure stability of the numerical

Figure 2: Details on reinforcement type and arrangement using precast concrete panel type wall facing: (a) Case 1, (b) Case 2, and (c) Case 3.

Table 1: Reinforcement material properties

Parameter	Name	Unit	Reinforcements		
			Geogrids (Case 1)	Geo-strips (Case 2)	Steel strips (Case 3)
Material model	Model	—	Geogrid	Geogrid	Geogrid
Material type	Type	—	Elastic	Elastic	Elastic
Width	w	mm	1,200	100	50
Thickness	t	mm	1.45	3.0	4.0
Length	L	m	4.50	4.50	4.50
Vertical spacing	S_v	m	0.50	0.50	0.50
Horizontal spacing	S_h	m	1.50	0.75	0.75
Young's modulus	E	MPa	938	2,500	210,000
Cross-sectional area ($A = t \cdot w$)	A	mm ²	1,740	300	200
Axial stiffness	EA	kN/m	1,632	750 ^a	42,000

^a For a single geosynthetic strip. The numerical model was assigned 1,500 kN/m for the overlapping geosynthetic strips.

model during the simulation of the MSE wall when no compaction is considered or during the application of very low loading pressure. Thus in this study, a cohesion of 10 kPa was used. More so, the friction angle of 36° and dilatancy angle of 6° were used similar to the parameters used by Damians et al. [31,33] and Abdelouhab et al. [24]. The foundation material was categorized under total stress parameters and modeled as Jointed Rock material with non-porous drainage type in Plaxis 3D wherein pore pressures cannot occur. The bedrock soil foundation was assumed in this study to eliminate the influence of soil foundation deformation on the behavior of the MSE wall. The assumed bedrock properties are also presented in Table 2.

The shear strength of the actual soil-structure interface is generally less than the surrounding soil [28,30,31,33,36]. A study conducted by Yu and Bathurst [37] and Yu et al. [34] on geogrid reinforcements was able to replicate the results of the experiment using a strength reduction

factor of 0.67. Therefore, in this study, the interface between the backfill soil and reinforcements as well as the wall facing elements was assumed to be 0.7 of the strength of the adjacent soil material. Moreover, the interface for the bedrock foundation was assumed rigid and was assigned with $R_{inter} = 1$ in Plaxis 3D [30,32,33].

2.4 Wall facing and bearing pad material properties

The MSE wall was modeled with segmental panel-type wall facing. The wall facing was designed as a rectangular precast concrete with dimensions of 1.50 m width, 2.0 m height, and 140 mm thickness. The wall facing material was modeled as structural plate element in Plaxis 3D. The plate was specified as linear elastic and can resist forces in tension and compression. The unit

Table 2: Soil and structural elements' material properties

Parameter	Name	Unit	Backfill soil	Soil foundation	Concrete panel	Bearing pads
Material model	Model	—	Mohr–Coulomb	Jointed rock	Plate	Beam
Material type	Type	—	Drained	Non porous	Isotropic; Linear	Linear
Unit weight	γ	kN/m ³	19	25	24	11.76
Young's modulus	E	kN/m ²	20×10^3	60×10^6	35×10^6	45×10^3
Poisson's ratio	ν	—	0.30	0.30	0.15	—
Cohesion	c	kN/m ²	10	500	—	—
Friction angle	ϕ	°	36	40	—	—
Dilatancy angle	ψ	°	6	—	—	—
Strength reduction factor	R_{inter}	—	0.7	1.0	—	—
K_0	—	—	0.4122	1.0	—	—
Thickness	d	m	—	—	0.14	0.02

weight of 24 kN/m^3 , elastic modulus of 35 GPa , and Poisson's ratio of 0.15 were used [31]. The properties of the wall facing are specified in Table 2.

One important element in the construction of segmental concrete panel-type wall facing is the bearing pads. Generally, at least two bearing pads are placed on horizontal gaps between panels to prevent direct contact between panels, reduce down drag forces, and ensure minimum panel-to-panel vertical gap [26,30,31,33,34]. Damians et al. [30,31] modeled the bearing pads as beam elements in Plaxis 2D whose equivalent axial stiffness was computed to appear continuous as in 2D. In this study, the bearing pads were modeled as beam elements in Plaxis 3D whose cross-sectional area was calculated considering the perpendicular surface to the axial beam direction. In addition, the parameters for the beam's moment of inertia (I_2 and I_3) were taken from the moment of inertia against bending around the second and third axis (please refer to Plaxis Reference Manual [28]). The material properties of the bearing pads are presented in Table 2.

2.5 Description of compaction loadings

According to Castellanos [38], the compaction equipment used within 1.0 m from the wall facing should be a vibratory roller or plate weighing less than $1,000$ pounds (4.45 kN), and from beyond the 1.0 m from the wall facing panels a roller up to 8.0 tons (78.45 kN) may be used subject to satisfactory performance. Correspondingly, Chmielewska and Wysocka [15] provided the parameters of typical compactors used for retaining wall compaction as presented in Table 3. Equipment similar to VMS 71 can be used within 1.0 m from wall facing, whereas the other heavier equipment can be used beyond 1.0 m from wall facing. In addition, Bathurst et al. [7] used hand-tamped (manual) compaction method for the first 0.5 m distance

from the wall facing and used vibrating plate (light) and vibrating rammer (heavy) beyond 0.5 m distance from wall facing. The pressure applied for the hand-tamped compaction was not provided by Bathurst et al. [7], but the vibrating equipment pressures were given as presented in Table 3.

Damians et al. [30] modeled the reinforced soil wall with reduced soil property near the wall facing to represent the lower compaction effort near the wall. In this study, soil properties were the same for the entire backfill soil, and the physical compaction loads were applied uniformly on top of every 0.25 m lift of backfill soil. The compaction loads were immediately removed after the placement of the next lift of backfill soil during construction. As shown in Figure 1, the compaction loadings were categorized into two: Load 1 refers to compaction loads applied within 1.0 m from wall facing with maximum load of 20 kPa and Load 2 refers to compaction loads applied beyond 1.0 m from wall facing with maximum load of 35 kPa . Here, Load 1 represents light compaction method near the wall facing to prevent damage to reinforcement and wall connection and to avoid excessive wall deformation that will lead to failure. On the contrary, Load 2 represents heavy compaction methods applied beyond 1.0 m from wall facing. Heavy compaction methods are safe when applied far from the wall facing. In addition, there were 12 numerical models simulated using MC model to investigate the effects of compaction loads on the behavior of MSE wall. These numerical models were subjected to specific compaction loading as specified in Table 4 and Figure 1.

2.6 Plaxis 3D staged construction

Similar to actual site construction, the numerical model was simulated with 24 phases of staged construction and computed using plastic calculations in Plaxis 3D

Table 3: Parameters of typical compaction equipment

Equipment type	Static/operating weight (kN)	Centrifugal force (kN)	Roller/plate width (mm)	Dynamic contact pressure/load (kPa)
VMS 71 ^a	4.40	11.61	710	22.50
RD 11A ^a	10.19	13.00	900	25.80
CC 1000 ^a	17.50	17.00	1,000	34.50
VPG 155A ^b	0.70	15.00	460×620	55.00
ES 45 Y ^b	0.50	11.50	250×330	144.00

^aData taken from Chmielewska and Wysocka [29]. ^bData taken from Bathurst et al. [7].

Table 4: Cases of numerical model subjected to different compaction loadings

Reinforcement		Compaction load			Wall height (m)	Backfill soil model	Foundation
Case no.	Material	Model	Load 1 (kPa)	Load 2 (kPa)			
Case 1	Geogrids	A	None	None	6	Mohr–Coulomb	Bedrock
		B	10	10			
		C	20	20			
		D	20	35			
Case 2	Geo-strips	A	None	None	6	Mohr–Coulomb	Bedrock
		B	10	10			
		C	20	20			
		D	20	35			
Case 3	Steel strips	A	None	None	6	Mohr–Coulomb	Bedrock
		B	10	10			
		C	20	20			
		D	20	35			

Notes: Load 1 refers to compaction loads applied within 1 m from wall facing. Load 2 refers to compaction loads applied beyond 1 m from wall facing.

(see Figure 3). To model the segmental precast-concrete panel-type wall facing at the start of construction, the first layer of wall facing panels was activated, alternately 2.0 m high (full panel) and 1.0 m high (half-panel). Then the first volume of backfill lift was activated. Here, a 0.25 m-thick lift was placed behind the first layer of precast concrete panels. Compaction loadings were applied uniformly on top of each layer and immediately removed as soon as the next lift of backfill soil were placed [10,36,39–41]. The first set of reinforcements was then activated. By doing this, the reinforcements located on the first layer of backfill lifts were installed and arranged in accordance with Figure 2. The succeeding 0.25 m-thick backfill lifts and layers of reinforcements were gradually added until the surface of the backfill reaches the top of the first layer of concrete panel wall facings. Then, the next layer of concrete panels was activated, as well as the bearing pads at the horizontal panel-to-panel joints. Similar procedures were undertaken for the succeeding 0.25 m-thick soil backfills and layers of reinforcements having a vertical spacing of 0.50 m until the full wall height of 6.0 m was completed. At the final stage of construction, the compaction loadings were removed. Finally, a uniform load of 50 kPa was applied on top of the MSE walls to represent the surcharge loads. A partially constructed Plaxis 3D model of the MSE wall is shown in Figure 4 showing the discrete arrangement of the reinforcements and the staggered installation of the wall facing elements.

3 Numerical results and discussion

3.1 Horizontal displacement (dx) at wall facing

3.1.1 At the end of construction

The effects of soil compaction on MSE wall are very evident on the horizontal displacements, dx , at the wall facing at the end of construction. After the series of numerical analyses, Figures 5–7(a) show the predicted dx at wall facing and the final wall facing profile at the end of construction for Case 1–A–D, Case 2–A–D, and Case 3–A–D, respectively. Here, Cases 1–3 refer to the MSE wall models reinforced with (1) discrete geogrids, (2) geosynthetic strips, and (3) steel strips, respectively. In addition, Cases A–D refer to the compaction load condition such that Cases 1–3-A refer to MSE wall models simulated without compaction load. Then Cases 1–3-B refer to MSE wall models subjected to 10 kPa compaction load, Cases 1–3-C were subjected to 20 kPa compaction load, and Cases 1–3-D were subjected to 20–35 kPa compaction loads (see also Table 4). Based on the final profiles of the wall facing, it can be observed that the dx increased significantly when the compaction load increased from 0 to 35 kPa during the construction. It can be noted that the maximum dx of each models were generally located within the range of $0.36H$ – $0.44H$, $0.44H$ – $0.63H$, and

Figure 3: Plaxis 3D staged construction flowchart.

$0.38H$ – $0.48H$ of the wall facing for Case 1-A-D, Case 2-A-D, and Case 3-A-D, respectively. More so, the final profile of the wall facing at the end of construction showed an arching curve with a negligible dx at the base and a remarkable dx at the top of the wall facing. It can also be observed that Case 3-A-D exhibited the least dx/H of 0.01–0.26% at the end of construction, followed by Case 1-A-D with 0.01–0.34% dx/H , and Case 2-A-D with the highest dx/H of 0.04–0.82%. The results implied that the heavier the compaction loads were

applied, the greater dx can be observed [7], yet all models were stable and within the range of allowable deformation.

Moreover, the comparison on the increase in dx because of the compaction effect is plotted in Figures 5–7(b). Here, the horizontal displacement ratio, HDR, is computed as

$$\text{HDR} = \frac{dx_c}{dx_0}, \quad (1)$$

Figure 4: Partially constructed MSE wall model in Plaxis 3D.

where dx_c is the horizontal displacements at wall facing when compaction loads were applied (Case 1–3-B, Case 1–3-C, and Case 1–3-D) and dx_0 is the horizontal displacement at wall facing when no compaction was applied (Case 1–3-A). Generally, the HDR is greater than 1.0, which inferred that an apparent increase in dx at wall facing occurred when the compaction loads were applied. In addition, it can be observed that the HDR is increasing from the base toward the top of the wall facing. Figure 5(b) shows that the dx at wall facing for Case 1-A–D showed an average HDR of 1.13, 1.51, and 1.99 at $0.50H$ as the compaction load increased from 0 to 10, 20, and 35 kPa, respectively. In addition, the dx at wall facing showed an increase of 1.01–1.60 and 1.26–2.38 at $0.25H$ and $0.75H$, respectively, as the compaction load increased from 0 to 35 kPa. Similarly, Figure 6(b) shows an average HDR of 1.14, 1.70, and 2.55 at $0.50H$ for Case 2-A–D as the compaction load increased from 0 to 10, 20, and 35 kPa, respectively. In addition, the dx at wall facing showed an increase of 1.03–2.08 and 1.26–3.02 at $0.25H$ and $0.75H$, respectively, as the compaction load increased from 0 to 35 kPa. Finally for Case 3-A–D, the dx at wall facing increased by 1.18, 1.53, and 1.92 at $0.50H$ as the compaction load increased from 0 to 10, 20, and 35 kPa, respectively (see Figure 7(b)). In addition, the dx at wall facing showed an increase of 0.98–1.50 and 1.38–2.35 at $0.25H$ and $0.75H$,

respectively, as the compaction load increased from 0 to 35 kPa. The HDR results inferred that Case 2 reinforcement is more sensitive to compaction loadings, whereas Case 1 and Case 3 exhibited almost similar behavior when subjected to compaction loadings. The trend line equations were derived from the results plotted for every HDR of different reinforcement materials subjected to different compaction loadings and surcharge loading. It can be observed that the HDR trend lines for models subjected to compaction loadings during the construction are linearly increasing from the base toward the top of the wall (see Figures 5–7(b)) and ranges from 0.78 to 3.49. The HDR results inferred that Case 2 reinforcement is more sensitive to compaction loadings, whereas Case 1 and Case 3 exhibited almost similar behavior when subjected to compaction loadings during the construction. Here, Case 2 showed more than two times greater dx than Case 1 and Case 3. This is because Case 2 has narrow width and, at the same time, has low axial stiffness value compared to the other two reinforcement materials.

3.1.2 After surcharge load application

The important effects of compaction during the construction of MSE walls were seen after the surcharge load has

Figure 5: Horizontal displacement at wall facing and HDR for Case 1-A-D at the end of construction: (a) horizontal displacement at wall facing for Case 1-A-D, and (b) HDR for Case 1-A-D.

been applied. The surcharge load in this study represents the vertical loads from sloping backfill, buildings, or other infrastructures for highways and railways that can be applied on top of the MSE wall. Therefore, a surcharge load of 50 kPa was assumed and was applied uniformly on top of the MSE wall after the construction. The effects of compaction on the dx at wall facing after surcharge load application are plotted in Figures 8–10. Here, the final profile of the wall facing shown in Figures 8–10(a) exhibited an arching curve with a negligible dx at the base and a remarkable dx at the top of the wall facing. The maximum dx at wall facing were also observed at 0.75 – $0.79H$ for Case 1-A-D, $0.86H$ for Case 2-A-D, and 0.67 – $0.73H$ for Case 3-A-D as shown in Figures 8(a), 9(a), and 10(a), respectively. Moreover, the results in Figures 8–10(a) show that the models without compaction loads applied (Case 1–3-A) exhibited the largest dx at wall facing. At the same time, the models

Figure 6: Horizontal displacement at wall facing and HDR for Case 2-A-D at the end of construction: (a) horizontal displacement at wall facing for Case 2-A-D, and (b) HDR for Case 2-A-D.

with the largest compaction loads applied (Case 1–3-D) exhibited the least dx at wall facing. The results inferred that when soil compaction was performed during the construction of MSE wall, there would be less dx observed at wall facing when subjected to surcharge loading. In addition, the higher the compaction load was applied, the lesser dx was observed at the wall facing after the surcharge loading.

The comparison on the decrease in dx because of the compaction effect is plotted in Figures 8–10(b). Here, the HDR (refer to equation 1) was plotted less than 1.0, which implied that the models with applied compaction loads (Case 1–3-B, Case 1–3-C, and Case 1–3-D) have less dx than those of the models without compaction (Case 1–3-A). Moreover, Figure 8(b) shows that Case 1-D over Case 1-A has an average HDR of 0.36, which means that the dx at wall facing after the surcharge load application were reduced by an average HDR of 0.64 (64%) when the

Figure 7: Horizontal displacement at wall facing and HDR for Case 3-A-D at the end of construction: (a) horizontal displacement at wall facing for Case 3-A-D, and (b) HDR for Case 3-A-D.

model was subjected to 20–35 kPa compaction loads during the construction. Similarly, Figure 9(b) shows that Case 2-D over Case 2-A has an average HDR of 0.55, which means that the dx at wall facing were reduced by an average HDR of 0.45 (45%), and Figure 10(b) shows that Case 3-D over Case 3-A has an average HDR of 0.20, which means that the dx at wall facing after the surcharge load application were reduced by an average HDR of 0.80 (80%). The results implied that the effects of compaction loads after the application of surcharge load are more effective on Case 1 reinforcement and most effective on Case 3 reinforcement wherein both showed more than 0.50 (50%) reduction of HDR. The trend line equations were derived from the results plotted for every HDR of different reinforcement materials subjected to different compaction loadings and surcharge loading. It can be observed that the HDR trend lines for models subjected to surcharge loading after the construction are almost straight vertically from the base toward the top of the

Figure 8: Horizontal displacement at wall facing and HDR for Case 1-A-D after 50 kPa surcharge load application: (a) horizontal displacement at wall facing for Case 1-A-D, and (b) HDR for Case 1-A-D.

wall (see Figures 8–10(b)) and ranges from 0.17 to 0.92. After the application of surcharge load, the results implied that the effects of compaction loads are more effective on Case 1 reinforcement and most effective on Case 3 reinforcement.

Therefore, the results on dx at the wall facing clearly showed the importance of soil compaction during the construction of MSE wall after the surcharge load application. The numerical results were in good agreement with the findings of Ehrlich et al. [8] such that compaction promoted lateral displacement during the construction and reduced lateral displacement because of surcharge load application after construction. If the compaction loadings were ignored during the construction, the results on the dx are lesser in magnitude, whereas if the compaction loadings were considered, the results on the dx are higher in magnitude. Therefore, the results on the dx at wall facing may be underestimated during the construction. On the contrary, if the compaction

Figure 9: Horizontal displacement at wall facing and HDR for Case 2-A-D after 50 kPa surcharge load application: (a) horizontal displacement at wall facing for Case 2-A-D, and (b) HDR for Case 2-A-D.

loadings were ignored during the construction and after the application of surcharge load, the results on the dx are higher in magnitude, whereas if the compaction loadings were considered, the results on dx are lesser in magnitude. Therefore, the results on the dx at wall facing may be overestimated after the application of surcharge load. Therefore, soil compaction should be considered in numerical analysis to obtain the accurate result or prediction of the deformations on MSE walls [4,24]. This inferred that soil compaction is also important in numerical analysis and more importantly in the field construction.

3.2 Maximum reinforcement strains

The maximum strains for each layer of reinforcements located at the centerline of the MSE wall were extracted

Figure 10: Horizontal displacement at wall facing and HDR for Case 3-A-D after 50 kPa surcharge load application: (a) horizontal displacement at wall facing for Case 3-A-D, and (b) HDR for Case 3-A-D.

and the results are plotted in Figures 11(a) and 12(a). The figures showed the maximum reinforcement strains for Case 1-A-D, Case 2-A-D, and Case 3-A-D at the end of construction and after the surcharge load application, respectively. In general, the application of compaction loads during construction has remarkable effects on the reinforcement strains. The results in Figure 11(a) show that using three different types of reinforcements, the reinforcement strains increased correspondingly as the compaction loads increased. The larger the compaction loads were applied, the greater reinforcement strains were shown. Moreover, the end effect of compaction is still visible after the surcharge load application. Figure 12(a) shows the maximum reinforcement strain that occurred between end of construction and surcharge load application. It can be observed after the surcharge load application that the models subjected with larger compaction loads exhibited lesser incremental reinforcement strains

Figure 11: Maximum reinforcement strain and RSR for Case 1, Case 2, and Case 3 at the end of construction: (a) maximum reinforcement strain at the end of construction, and (b) RSR at the end of construction.

near the top of the wall. The results showed that using three different types of reinforcements, the incremental

reinforcement strains showed a decrease as the compaction loads increased apparently at the top reinforcement

Figure 12: Maximum reinforcement strain that occurred between end of construction and surcharge load application and RSR for Case 1, Case 2, and Case 3 after surcharge load application: (a) maximum reinforcement strain that occurred between end of construction and surcharge load application, and (b) RSR after surcharge load application.

layers and less significant at the lower reinforcement layers. It can be observed that compaction has more effects on Case 2-A–D reinforcement strains than those of Case 1-A–D and Case 3-A–D. Note that the reinforcements used in this study have different widths and stiffness (refer also to Table 1). This may imply that geo-strip reinforcements exhibited high strains because it has low stiffness and narrow width.

Furthermore, the comparison on the increase in reinforcement strains because of the compaction effect is plotted in Figures 11(b) and 12(b). Here, the reinforcement strain ratio, RSR, is computed as

$$\text{RSR} = \frac{\varepsilon_c}{\varepsilon_0}, \quad (2)$$

where ε_c is the reinforcement strain when compaction loads were applied (Case 1–3-B, Case 1–3-C, and Case 1–3-D) and ε_0 is the reinforcement strain when no compaction was applied (Case 1–3-A). The trend lines were extracted for every RSR of different reinforcement materials subjected to different compaction loadings and surcharge loading (see Figures 11(b) and 12(b)).

In Figure 11(b), the compaction during construction showed more effects on the reinforcement strains of Case 2 models wherein the top reinforcement layers exhibited higher RSR than those at the bottom reinforcement layers and ranges from 1.04 to 3.03. On the contrary, Case 1 and Case 3 models showed that RSR is higher at the top reinforcement layers and then slowly decreases toward the bottom reinforcement layers. Here, Case 1 exhibited the least RSR which ranges from 0.77 to 2.07, whereas Case 3 has RSR ranges from 0.84 to 2.21. The results showed that the RSR is generally greater than 1.0, which implied that the strains of the three different types of reinforcements increased correspondingly up to 1.32, 1.88, and 2.64 as the compaction loads increased from 0 to 10, 20, and 35 kPa, respectively, during the construction. Moreover, Figure 12(b) shows that the effects of compaction are significant at the top reinforcement layers. This means that models subjected to higher compaction loads during the construction resulted in lesser reinforcement strains when subjected to surcharge loads after the construction at the top reinforcement layers. Moreover, it can be observed that the RSR after surcharge load application is lesser at the top reinforcement layers and slowly increases toward the bottom reinforcement layers, which ranges from 0.62 to 1.08, 0.79 to 1.12, and 0.50 to 1.38 for Case 1, Case 2, and Case 3, respectively. Here, the results showed that some reinforcement layers obtained RSR less than 1.0 and some obtained RSR more than 1.0. This implied that when the compaction load was applied

during construction, a reduction in the maximum reinforcement strains up to 0.50 RSR (50%) at the top and 0.38 RSR (38%) at the bottom reinforcement layers occurred when a surcharge loading was applied after the construction. However, at the same time, when the compaction load was applied during construction, the reinforcement layers between $0.125H$ and $0.58H$ showed an increase in the maximum reinforcement strains after the application of surcharge load depending on the type of reinforcement.

3.3 Effects on different reinforcement types on the dx at wall facing

This study considered three different reinforcements to show the effects of reinforcement type on the behavior of MSE wall when subjected to compaction loadings. Here, Case 1 refers to the MSE wall models reinforced with discrete geogrids, Case 2 refers to the MSE wall models reinforced with geosynthetic strips, and Case 3 refers to the MSE wall models reinforced with steel strips. Using the three different types of reinforcements, two wall conditions were compared such as Case 1–3-A for MSE wall models without compaction and Case 1–3-C for MSE wall models subjected to compaction loadings during the construction. The comparison on dx at wall facing at the end of construction and after surcharge load application is shown in Figures 13 and 14, respectively. During construction (see Figure 13(a)), Case 2-A exhibited larger dx than those of Case 3-A and Case 1-A. At the same time, Case 3-A showed lesser dx than Case 1-A. Moreover, Case 2-C exhibited larger dx than those of Case 3-C and Case 1-C. At the same time, Case 3-C showed lesser dx than Case 1-C. After the surcharge load application (see Figure 14(a)), Case 2-A and Case 2-C exhibited larger dx than those of Case 3-A–C and Case 1-A–C. Here, Case 1-A exhibited lesser dx than Case 3-A, whereas Case 3-C showed almost similar dx with Case 1-C. The graphs showed that Case 2 models using geo-strip reinforcements were more sensitive to compaction loading. This may be because of low stiffness and narrow width of the reinforcement. On the contrary, Case 1 and Case 3 models exhibited distinctive behavior at the end of construction and after the surcharge application. Note that Case 3, using steel strips reinforcement, has 26 times larger stiffness than Case 1, using geogrids reinforcement; however, Case 3 also has 8.7 times smaller cross-sectional area than Case 1. The results may imply that during the construction, the steel strip reinforcement showed lesser dx

Figure 13: Comparison on lateral displacement at wall facing with and without compaction at the end of construction: (a) horizontal displacement at wall facing, and (b) HDR.

at wall facing than those of the geosynthetic reinforcements, and after the surcharge load application, the geogrids reinforcement showed lesser dx at wall facing with high loading than those of the geo-strips and steel strips reinforcements. It can be inferred that when soil compaction will be applied on MSE wall during construction, the type of reinforcement has to be considered to avoid excessive dx at wall facing. In this case, reinforcement with high-stiffness and wider width performed better when high compaction loads or large external forces were applied on the MSE wall.

Furthermore, to compare the effects of compaction on the different types of reinforcements, the HDR of Case 1–3–C over Case 1–3–A at the end of construction was extracted from Figures 5–7(b) and was plotted together in Figure 13(b). It can be observed that Case 2

Figure 14: Comparison on lateral displacement at wall facing with and without compaction after surcharge load application: (a) horizontal displacement at wall facing, and (b) HDR.

reinforcement is more sensitive to compaction loads and exhibited the largest HDR values at the end of construction. Here, Case 1 and Case 3 reinforcement showed almost similar average HDR of 1.51 and 1.53, respectively. It is remarkable that above $0.50H$, Case 3 reinforcement is more sensitive than Case 1 reinforcement. Yet at below $0.50H$, Case 1 reinforcement became more sensitive than Case 3 reinforcement when 20 kPa compaction loads were applied during the construction. Moreover, the HDR of Case 1–3–C over Case 1–3–A after the surcharge load application was extracted from Figures 8–10(b) and was plotted together in Figure 14(b). After the surcharge load application, the Case 2 reinforcement exhibited the least amount of reduced dx at wall facing with the average 0.76 HDR, and the Case 3 reinforcement showed the largest amount of reduced dx at wall facing with the average of

0.45 HDR. The HDR results only showed the amount reduced on dx at the wall facing when 20 kPa compaction loads were considered during the construction. The reduction of dx at wall facing for the steel reinforcements may be higher than those of the geogrids reinforcements; however, the final profile of the wall facing on both geogrids and steel strip reinforcements are almost identical.

3.4 Lateral earth pressure at wall facing

It has been shown that compaction increases the lateral earth pressure on backfill soil [39,40,42]. In this study, the effects of compaction on the lateral earth pressure at the end of construction and after the surcharge load application are shown in Figure 15(a and b). The at-rest and active earth pressures were computed using the following equations [25]:

$$p_{\text{at-rest}} = (q + \gamma H)K_0, \quad (3)$$

$$p_{\text{active}} = (q + \gamma H)K_a - 2c'\sqrt{K_a}, \quad (4)$$

$$K_0 = (1 - \sin \varphi), \quad (5)$$

$$K_a = \tan(45 - \varphi/2)^2, \quad (6)$$

wherein K_0 , coefficient of earth pressure at rest, was 0.4122 in the initial condition of Plaxis 3D simulation, whereas K_a , coefficient of active pressure, was computed using Rankine's formula where $\varphi = 36^\circ$. For the active earth pressure, the cohesion in this case was not considered, and thus $2c'\sqrt{K_a} = 0$. The rest of the parameters of the backfill soil are summarized in Table 2.

The numerical results showed that using three different types of reinforcement, the lateral earth pressures exhibited a nonlinear and slow-arching L-shaped stresses at the wall facing (see Figure 15(a and b)). The lateral earth pressures at wall facing starts with a slight curve that drops from the top of the wall until about $0.125H$ and increases rapidly toward the base of the wall. Generally, the lateral earth pressure at wall facing is within the active earth pressure zone from the top of the wall facing down to $0.125H$. It can be observed that there are significant effects in the lateral earth pressures below $0.125H$, which are generally greater than the active earth pressure. The curves created by the lateral earth pressure in this study were apparently different from the arching of soil introduced by some researchers [43–45] because the maximum lateral earth pressure was shown at the base of the wall. However, the lateral earth pressure curves in this study were slightly similar to that of Damians et al. [30]. Moreover, it was evident in the study that the lateral

Figure 15: Lateral earth pressure at wall facing at the end of construction and after surcharge load application: (a) lateral earth pressure at wall facing at the end of construction, and (b) lateral earth pressure at wall facing after surcharge load application.

earth pressure increased slightly with the application of compaction loads. The lateral earth pressures of Case 1–3-A and Case 1–3-C behaved such that from the top of wall facing down to $0.125H$, the lateral earth pressures were less than the active earth pressures. However, toward the base of the wall, Case 1–3-A was higher than the active earth pressure zone but was less than the at-rest earth pressure zone, whereas in Case 1–3-C, the lateral earth pressures toward the base of the wall were beyond the at-rest earth pressure zone. Similarly in Figure 15(b) after the surcharge load application, the lateral earth pressures for Case 1–3-A and Case 1–3-C toward the base of the wall are beyond the active earth pressures and the at-rest earth pressure zone, respectively.

Figure 16: Plaxis 2D numerical model of Case 2-D.

Generally, the lateral earth pressure is less than the computed active earth pressures except at the base and top of the wall. It should be taken into consideration during the design and construction of the MSE wall especially at the base of the wall which are larger than the computed active earth pressures.

3.5 Comparison of 2D and 3D on the horizontal displacement (dx) at wall facing

3.5.1 Plaxis 2D numerical model

The 2D FEM has been widely used in numerical analysis because it is simpler and quicker than 3D FEM. Although several similar studies used 2D models of MSE wall [30,33], this study used 3D numerical models because the MSE wall has 3D geometry conditions considering the discrete or discontinuous reinforcements. In this section, the difference in 2D and 3D results will be discussed briefly to have an understanding on the difference in the predicted results for the horizontal displacement at wall facing. To compare the difference between the 2D and 3D numerical results, a 2D model of Case 2-D was considered

because it showed the greatest dx in the 3D analysis. The 2D model was created using the same geometry condition, staged construction, and material parameters as with the 3D model described in Section 2. A 2D numerical model is also presented in Figure 16.

3.5.2 Comparison of Plaxis 2D and 3D results

Figure 17 shows the final wall facing profile of Case 2-D models at the end of construction. The wall facing profile of both models is quite different but not very far from each other. The 2D model has stiffer curve, is less bulged, and has greater dx at the top of the wall, whereas the 3D model is more bulged at mid-height and has lesser dx at the top of the wall. The maximum dx for 2D model is at $0.88H$, whereas the 3D model is at $0.63H$. Yet both 2D and 3D models showed the maximum dx at 0.82% (dx/H). In this case, the Plaxis 2D plain-strain model contained 2,729 15-noded elements and an average element size of 0.3249 m, whereas the Plaxis 3D model contained 32,168 10-noded elements and an average element size of 0.2318 m. The difference in the numerical results may be because of FEM discretization and the transformation of discrete reinforcement in 3D to continuous reinforcement in 2D. Therefore, the focus of the study is not mainly

Figure 17: Wall facing profile of Case 2-D models at the end of construction using Plaxis 2D and Plaxis 3D.

on the discrepancy between the 2D and 3D numerical results but on the behavior of the MSE wall numerical models when subjected to different compaction loading and surcharge loading.

4 Conclusion

In this study, there are 12 MSE wall models that were simulated in Plaxis 3D using FEM to analyze the effects of compaction load on the behavior of the panel-type MSE wall considering three different types of reinforcements subjected to different compaction loads during construction and a surcharge load after the construction. The series of numerical analyses on MSE walls depicted the following main conclusions:

- The horizontal displacements at wall facing were influenced by the application of compaction loads. The heavier compaction load induces greater horizontal displacements at the wall facing during construction. The horizontal displacements at wall facing increased up to 3.5 times as the compaction load increased from 0 to 35 kPa according to the material of the reinforcement.
- The important effects of compaction are evident after the application of surcharge load. The MSE walls without compaction loads exhibited higher horizontal displacements than those of MSE walls subjected to compaction loads. The horizontal displacements at wall facing decreased up to 80% (by average) as the compaction

load increased from 0 to 35 kPa according to the material of the reinforcement.

- The maximum reinforcement strains increased from 0.77 to 3.03 times during the construction and decreased up to 50% after the surcharge load application, when compaction load increased from 0 to 35 kPa according to the material of the reinforcement.
- The lateral earth pressure at the wall facing is generally less than the computed active earth pressures except at the base and top of the wall. The lateral earth pressures at the base of the wall were predicted to be larger than the computed at-rest earth pressures and should be carefully considered during the design and construction.
- The MSE wall using steel strip reinforcement with high-stiffness and MSE wall using geogrids reinforcements with wider width both performed better than the geostrips reinforcements when subjected to compaction loads.
- Therefore, it is important to consider soil compaction during the construction of the MSE wall. The MSE wall deformation behavior is judged to be underestimated during construction and overestimated after construction especially when a surcharge load will be applied on top of the MSE wall without compaction load.

Acknowledgments: This study was supported by the Brain Korea 21 FOUR Project (4299990614343) funded by the Ministry of Education and National Research Foundation of Korea (NRF) and Korea Institute of Energy Technology Evaluation and Planning (KETEP), and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (20183010025200).

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