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Research Article

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Experimental study on the behavior of MSE wall having full-height rigid facing and segmental panel-type wall facing

https://doi.org/10.1515/geo-2020-0278 received September 28, 2020; accepted July 18, 2021

Abstract: The amount of the lateral displacements on the mechanically stabilized earth (MSE) wall depends on the reinforcement extensibility and length, reinforcement-tofacing connection, and the wall facing, among others. In this study, the deformation behavior of MSE wall models was focused considering two types of wall facing and three types of reinforcement. A series of small-scale model tests were undertaken on the MSE wall having a full-height rigid (FHR) facing and a segmental panel-type (SPT) wall facing. At the same time, the models were using discrete geogrids, geosynthetic strips, and steel rods as reinforcement. The results showed that the geogrids-reinforced MSE wall with FHR facing exhibited the highest load capacity with the least vertical displacements. The MSE wall models with steel reinforcements generally exhibited the least lateral displacements at wall facing than those with geosynthetics reinforcements. Finally, the results showed that MSE wall models with FHR facing have generally lesser lateral displacements at the wall facing compared to those with SPT wall facing.

Keywords: MSE wall, FHR facing, segmental panels, discrete reinforcements, model test, lateral displacement, bearing capacity

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1 Introduction

The Saemangeum Development Project in South Korea builds the world's longest seawall (33.9 km) connecting Gunsan and Buan to create reclaimed land (291 km²) and lake (118 km²), by developing 3.3 km² of Gogunsan islands outside the seawall and 4.4 km² of the new port. It is a national project to build the "global luxury Saemangeum" that will emerge as an economic center in Northeast Asia. Its project is underway for road, railway, and port constructions for internal development. The construction of the railway is going to happen in Saemangeum. Henceforth, land reclamations and the development of new international cities like Saemangeum could be a great opportunity for the application of mechanically stabilized earth (MSE) walls on railway and road projects. Although MSE walls have been used in Korea on highways for about four decades now [1], the MSE wall technology is not yet fully embraced in railway projects.

The MSE walls having a staged constructed fullheight rigid (FHR) facing have been widely used in Japan and have performed well during the 1996 Great Kobe and the 2011 Great East Japan earthquakes [2–4]. About 320 failed geosynthetics-reinforced mechanically stabilized earth (MSE) walls were recorded in 2018 worldwide, wherein 75% were using modular concrete blocks [5,6]. The majority of the MSE wall failures considering the facing type are using segmental or modular blocks. In this case, failure may occur because not all blocks are attached to the reinforcements. The vertical spacing of reinforcements is generally high wherein several blocks are not directly connected to the reinforcements. These blocks were connected using pins, yet the connecting pins were too short to hold each other during excessive deformations at the wall facing. In addition, reinforcements are connected to the pin at the weak transverse member (rib) of the geogrids. A strong connection is important between the reinforcements and the facing element. The detachment of the wall facing from the

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reinforcement commonly occurred on the MSE wall having segmental panel-type wall facing. Several situations wherein the backfill soils raveled out through the gap between adjacent panels especially during heavy rains or flood, or even because of the wide gap between panels. The loss of a large quantity of backfill soil will eventually cause wall collapse. It has to be considered also that direct construction of the MSE wall with FHR facing is also susceptible to large wall deformations after the propping has been removed. In addition to the type of construction, it makes compaction difficult near the wall facing. Hence, poor or inadequate compaction of the backfill has been a major cause of wall failures as mentioned earlier. Nevertheless, the conventional retaining walls are out of the options because it has been proven to be more expensive, uneconomical especially on highrise wall, may need pile foundation, and could not withstand high seismic forces [1–7].

The MSE wall system is composed majorly of backfill soil, reinforcement, and facing system whose performance depends on the interaction among the components, particularly between soil and reinforcement [8]. The reinforcements improved the mechanical properties of the reinforced soil mass by compensating the tensile strength and developing shear resistance from the friction at the soil-reinforcement interface to support the soil mass against deformations. This improvement is caused by the interaction at the interface between the reinforcement and the soil wherein stresses are transferred by friction or passive resistance [7,9,10]. The magnitude of the horizontal deformation at wall facing depends on the reinforcement extensibility, reinforcement length, reinforcement stiffness, reinforcement-to-facing connection details and the wall facing details, compaction efforts, and other significant parameters [8,9,11–13].

The objective of this article is to present the deformation behavior of MSE wall models using a simple experimental comparison between the FHR facing and segmental panel-type (SPT) wall facing. In this study, six small-scale models were simulated having three different types of reinforcement, such as discrete geogrids, geosynthetic strips, and steel rods, and two different types of wall facing, such as the SPT wall facing and FHR facing. The experiment focused on the comparison of the vertical and horizontal deformations of the six models. For simplicity, all models have the same loading condition and experimental setup.

2 Experiment setup and methodology

2.1 The specimen box

A customized specimen box was used to enclose the MSE wall model. The specimen box is walled with a stainless steel sheet at rear and at the sides and a polycarbonate sheet in front for viewing purposes as shown in Figure 1. The specimen box is rectangular with internal dimensions of 1.5 m in length, 0.5 m in width, and 1.0 m in height. The front wall is made of a 10 mm thick transparent polycarbonate sheet, through which the interior could be observed, and is reinforced with equal angle steel bars and steel channels. The top of the specimen box is kept open for the operation, while two pieces of detachable equal-angle steel bars are placed as reinforcement during testing. The bottom plate is made of a stainless steel plate and braced with steel channels on-center. The walls are reinforced with steel framings and secured to prevent deformation and undesirable movements of the specimen box during testing. The specimen box is placed on top of the supporting platform made of a 15 mm thick steel plate with rollers and stabilizing locks.

2.2 The test setup

The model test setup was composed of the model specimen, the loading system, and the instrumentation as shown in Figure 2. The setup simulates a small-scale model of MSE wall having a height of 60 cm from the base and a width of 50 cm. The reinforced sand backfill has a length of 42 cm, and the retained sand backfill has a length of 45 cm, with a total backfill length of 88 cm. The MSE wall model rests directly on top of the steel plate, which represents a model built on top of a bedrock foundation. There was no soil foundation considered in the model test to avert the influence of foundation deformation on the behavior of the MSE wall model. A loading plate was placed at the top-center of the MSE wall model with an equal distance of 0.15H from the rear wall boundary and from the wall facing. The loading plate is made of steel with a thickness of 15 mm, a width of 40 cm, and a length of 70 cm. The load was applied on the model through a steel loading plate for at least 19 min or 50 kN,

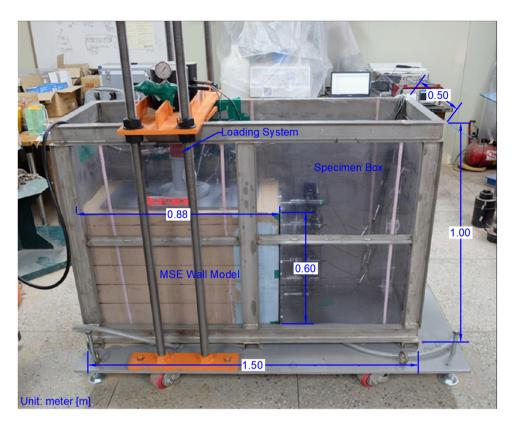


Figure 1: Specimen box for the model test.

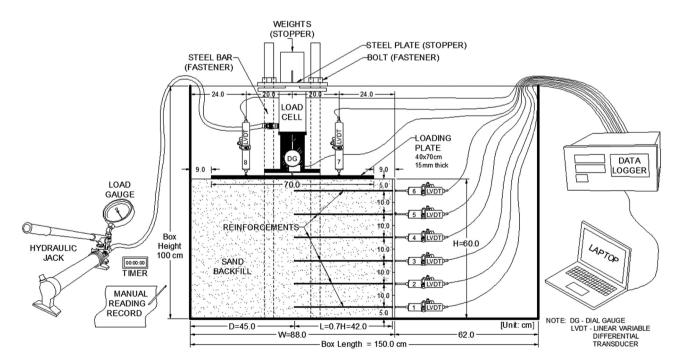


Figure 2: Schematic drawing of the model setup, loading system, and instrumentation.

whichever comes first, and was recorded manually with 10 s interval. The pressure applied to the model was measured through the load gauge with a maximum capacity

of 50 kN. The load gauge was mounted to the hydraulic jack. The hydraulic jack was manually controlled with a loading speed of 1 min per millimeter, which is done with

the aid of a dial gauge and a timer. In addition, six 50 mm-LVDTs were used to measure the lateral displacement at the wall facing and were installed horizontally at the wall facing, with a vertical spacing of 10 cm on centers. Furthermore, two 100 mm-LVDTs were used to measure the vertical displacements at the loading plate and were installed vertically on the top of the loading plate at distances 24 and 64 cm from the wall facing. Finally, a dial gauge (DG) was placed on the middle of the loading plate to show the actual settlement during loading. All the instruments were connected to the data logger. The data logger was connected to the laptop, where the readings were recorded having a 1s reading interval of all the instruments.

2.3 The test cases

In this study, there are six model test cases having different types of reinforcement and wall facing as summarized in Table 1. Case 1 refers to the MSE wall model using geogrids reinforcement and FHR wall facing. Case 2 refers to the MSE wall model using geo-strips reinforcement and FHR wall facing. Case 3 refers to the MSE wall model using steel rods reinforcement and FHR wall facing. Case 4 refers to the MSE wall model using geogrids reinforcement and SPT wall facing. Case 5 refers to the MSE wall model using geo-strips reinforcement and SPT wall facing. Finally, Case 6 refers to the MSE wall model using steel rods reinforcement and SPT wall facing. Furthermore, each model cases have six layers of reinforcements having a uniform vertical spacing of 10 cm and a uniform length of 42 cm. The length of reinforcement was considered to be 0.7*H* according to FHWA [9].

2.4 The wall facing materials

The two types of wall facing material used in the model tests are shown in Figure 3. The first wall type is a fullheight rigid (FHR) facing (see Figure 3(a)), which was made of rectangular steel plate with a thickness of 10 mm, a height of 600 mm, and a width of 500 mm. There were forty-eight holes punched through the wall facing for the reinforcement connections and were arranged uniformly having a horizontal spacing of 62 mm and vertical spacing of 100 mm. The second wall type is segmental-panel type (SPT) wall facing, which were composed of 24 segmental panels with interlocking connections (see Figure 3(b)). One segmental panel was made of rectangular steel plate with a thickness of 12 mm, a height of 100 mm, and a width of 124 mm. There were two holes punched through each segmental panel for the reinforcement connections. The segmental panels had protruding parts on top and at the side to connect and interlock with each other. The fully constructed SPT wall facing had a total height of 600 mm and a total width of 500 mm.

2.5 The reinforcement arrangement and wall facing connection

The typical arrangement of the three different reinforcements and the connection scheme at the wall facing are shown in Figure 4. The arrangement of the reinforcements was referred from a related study of MSE wall reinforced with geogrids, geo-strips, and steel strips [14]. The first type of reinforcement used 2 mm-thick geogrids with a width of 113 mm, at left and right sides, and a width of 50 mm, at the center Figure 4(a). It has the horizontal spacing (Sh), equivalent to 152.50 mm from center to center of the geogrids. For the wall facing and reinforcement connection, the metal square U-bolts were fastened to the facing material, then geogrids were wrapped around the square U-bolts having an equal overlapping length of 420 mm. Small wires were used to tie the folded geogrids together. The second type of reinforcement used 8 mm width geosynthetic strips (geo-strips). The geo-strips were arranged uniformly having a horizontal

| Table 1: List of mode | l test cases | and s | pecifications |
|-----------------------|--------------|-------|---------------|
|-----------------------|--------------|-------|---------------|

| Name | Reinforcements | | | | Wall facings | | |
|--------|----------------|----------------------------|--------------------------|-------------|------------------|----------------|------------|
| | Туре | Horizontal spacing (mm) | Vertical spacing (mm) | Length (mm) | Туре | Height (mm) | Width (mm) |
| Case 1 | Geogrids | 152.5 | 100 | 420 | FHR facing | 600 | 500 |
| Case 2 | Geo-strips | 62.0 | | | | | |
| Case 3 | Steel rods | 62.0 | | | | | |
| Case 4 | Geogrids | 152.5 | 100 | 420 | Segmental panels | 600 | 500 |
| Case 5 | Geo-strips | 62.0 | | | (6 layers) | | |
| Case 6 | Steel rods | 62.0 | | | | | |

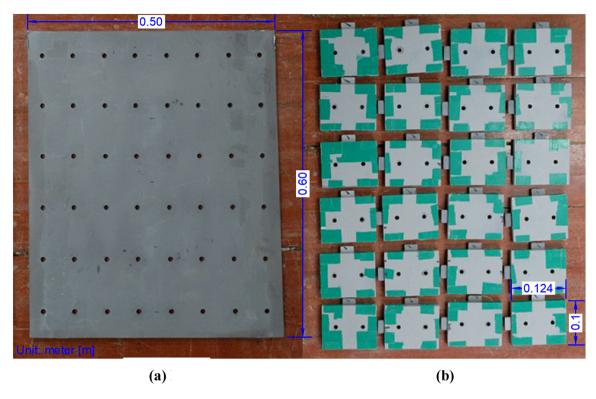


Figure 3: Types of wall facing used in the study: (a) FHR facing and (b) SPT wall facing.

spacing (Sh), of 62 mm on centers as shown in Figure 4(b). For the wall facing and reinforcement connection, the geo-strip was inserted in the hole of the wall facing material and on a 10 mm diameter metal nut. The geo-strip was then inserted back on the same hole, while the nut was left on the front side of the wall facing. The geo-strip was folded equally with the same length of 420 mm. Finally, the third type of reinforcement used a 9 mm diameter steel threaded rods arranged uniformly with horizontal spacing (Sh), of 62 mm on centers, similar to Case 2 (see Figure 4(c)). Here, the steel threaded rod was directly inserted into the hole and fastened to the wall facing material using a 10 mm diameter bolt nut. Furthermore, all reinforcements have uniform vertical spacing (Sv), of 100 mm and a reinforcement length (L), of 420 mm (see Table 1).

2.6 Model test construction

First step in the construction was to set up the wall facing support system. Using wooden bars, the wall facing support was setup to prevent wall deformation or movement during construction. A magnetic spirit level was used to ensure the plumbness of the wall during and after construction. Then, the first layer of SPT wall facing or the

whole FHR facing was placed inside the specimen box where the line marked for wall facing was indicated. The reinforcements were installed including the accessories for the wall joint connection. The reinforcements were ensured to be horizontally leveled and not crumpled. The sand backfill was slowly poured behind wall facing with the constant free-falling height of 50 cm from the surface to achieve a uniform density for all the model test cases. The reinforcement installation and sand backfill application continued until the final layer was reached. At the final layer, the sand backfill surface was leveled. Then, using a spirit level, the evenness of the sand backfill surface was ensured before placing of the loading plate. After the MSE wall model has been constructed, the wall facing support system was slowly removed. The six 50 mm LVDTs were then installed horizontally at the wall facing. The first LVDT was installed at 5 cm from the base of the wall. Then the succeeding LVDTs were installed having a vertical spacing of 10 cm from each other. The six LVDTs were wired connecting to the data logger and were tested to ensure that they were fully functional. An initial reading was conducted on the lateral displacement of the wall facing before placing the loading equipment on top of the MSE wall model. Slowly, the loading plate was placed at the center of the sand backfill keeping 0.15H distance from the wall facing

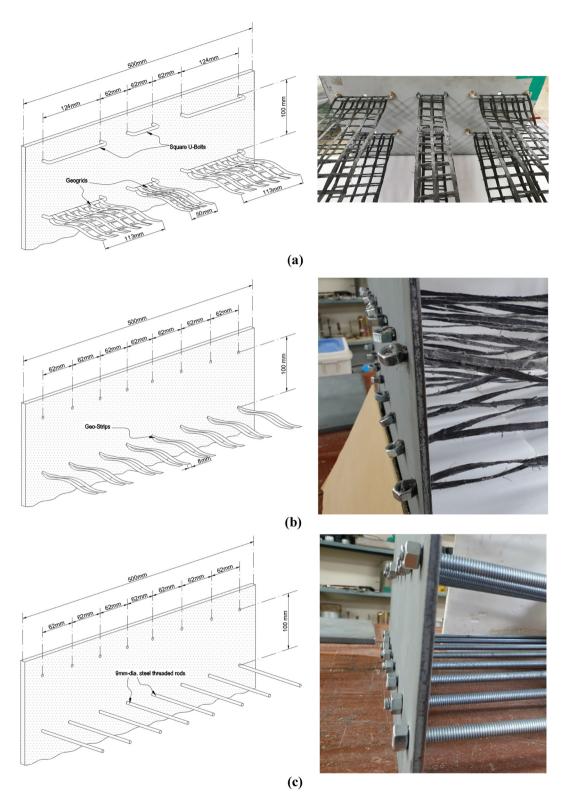


Figure 4: Reinforcement type, arrangement, and reinforcement-wall connection: (a) geogrids, (b) geo-strips, and (c) steel rods.

and from the rear end. Then, a 12 mm thick circular steel plate and the tubular steel spacer were placed at the center of the loading plate. Then, the load cell was slowly

placed on top of the spacer. Finally, a 29.5 mm² steel plate was placed on top of the load cell to close the small gap before the stopper plate (see Figure 2). Note that the

Table 2: Reinforcement material physical properties

| Parameter | Name | Unit | Rei | | |
|-----------------------------------|------|------|--------------------------|------------|------------|
| Material | _ | _ | Geogrids | Geo-strips | Steel rods |
| Width | W | mm | 113 (sides), 50 (center) | 8 | 9 |
| Thickness/diameter | t | mm | 2 | 2 | 9 |
| Tensile strength (KS S ISO 10319) | Τ | kN/m | 72.87 | 112.16 | _ |
| Strain (KS S ISO 10319) | ε | % | 7.9 | 5 | _ |
| Load capacity | _ | kN | _ | _ | 2.65 |

stopper plate was fixed and fastened to the specimen box. After the loading system was completely set up, the two 100 mm LVDTs were installed vertically on top of the loading plate at 24 and 64 cm distance from the wall facing, and finally, the DG was installed below the load cell. The actual completed model test set up is shown in Figure 1. The instruments were tested to ensure full functionality before the loading started. A preloading, until 0.5 mm settlement, was conducted on all model cases in addition to the existing weights of the loading plate and the materials above it, which were approximately 1 kN. After the preloading has been recorded, the instruments were reset back to zero. Then, the manual loading was applied on the model with a speed of 1 mm/min until the settlement, S, of 19 mm or until 50 kN was reached, whichever came first. The loading was limited up to 50 kN to avoid deformation of the frames, which might lead to unrealistic results. Afterward, the final applied load was held constant, and the reading continued until the end of 1 h to check if there were further deformation that occurred after the final loading.

3 Experiment materials and properties

3.1 The reinforcement materials

The properties of the reinforcement materials used in the model test are summarized in Table 2. The results on a

wide-width tensile test (KS K ISO 10319) on the geogrid material obtained a tensile strength of 72.87 kN/m at 7.9% strain. The geo-strip used in the study was the longitudinal rib of a geogrids whose results on the tensile test (KS K ISO 10319) showed 112.16 kN/m tensile strength at 5% strain. Finally, a commercial round steel-threaded rod was used as the third reinforcing material whose calculated load capacity is 2.65 kN.

3.2 The sand backfill material

Sand was used in the study because it has been documented as an effective backfill material. The properties of the sand are presented in Table 3. The sand particles were finer than the No. 20 sieve with 100% passing, but were generally retained in the No. 40 sieve with 6.4% passing. The sand was classified, using the USCS, as poorly graded sand (SP). Moreover, a triaxial test was conducted on the sand material under consolidated-drained (CD) condition. The sand samples were tested with four different confining pressures: 50, 100, 150, and 200 kPa, and these results are plotted in Figure 5. The cohesionless sand obtained a friction angle of 37.5 degrees. In this study, the sand backfill was not subjected to compaction loads. To have a uniform density for all models, the sand was poured directly into the specimen box with a constant falling height of 50 cm from the surface. The relative density was obtained based on the air pluviation method [15,16]. The method resulted in a loose to medium relative density with a calculated dry unit weight of 14.51 kN/m³.

Table 3: Sand material properties

| USCS class | D ₆₀ (mm) | D ₃₀ (mm) | D ₁₀ (mm) | C _u | C _c | Dry unit weight (kN/m³) | Specific gravity | Cohesion (kPa) | Friction angle (degrees) |
|---------------|----------------------|----------------------|----------------------|----------------|----------------|-------------------------|---------------------|-------------------|-----------------------------|
| SP | 0.63 | 0.51 | 0.44 | 1.40 | 0.94 | 14.51 | 2.715 | 0 | 37.5 |

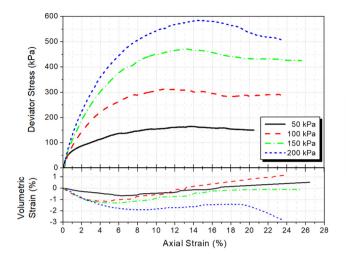


Figure 5: Triaxial test results: deviator stress and volumetric strain versus axial strain graph.

4 Experiment results and discussion

4.1 Vertical displacement on top of MSE wall model

The vertical displacement of the loading plate will be designated, in the following context of this article, as settlement (*S*) and the settlement ratio is expressed in

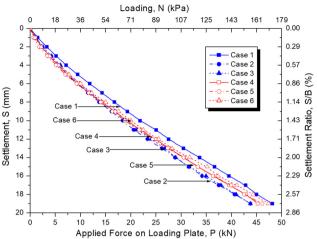


Figure 6: Load-settlement curve up to 19 mm settlement.

percentage and is computed as S/B, where B is the length of the loading plate, equivalent to 700 mm. The load–set-tlement curves obtained after the series of model tests are plotted in Figure 6. The load–settlement curves are graphed based from the applied load (P) on the loading plate against the settlement (S), of the loading plate. The loading, N, was obtained based on the applied load (P), over the area of the loading plate.

During the load application, the loading plate penetrated deeper through the backfill sand and the settlement slowly increased in accordance with the amount

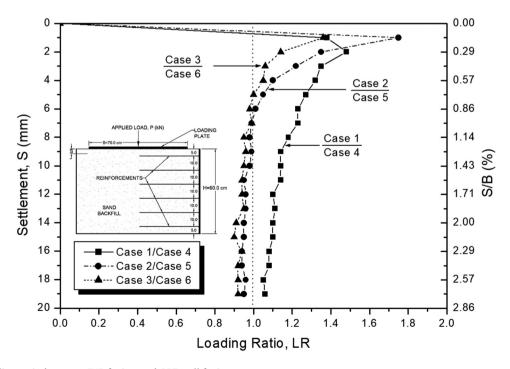


Figure 7: Loading ratio between FHR facing and SPT wall facing.

of applied load. The load-settlement curves in Figure 6 showed that Case 1, the MSE wall model having FHR facing and reinforced with discrete geogrids, consistently

exhibited the best result against all other models and obtained the highest applied load of 172 kPa at the end of 19 mm settlement. Then, Case 2 and Case 3, which have

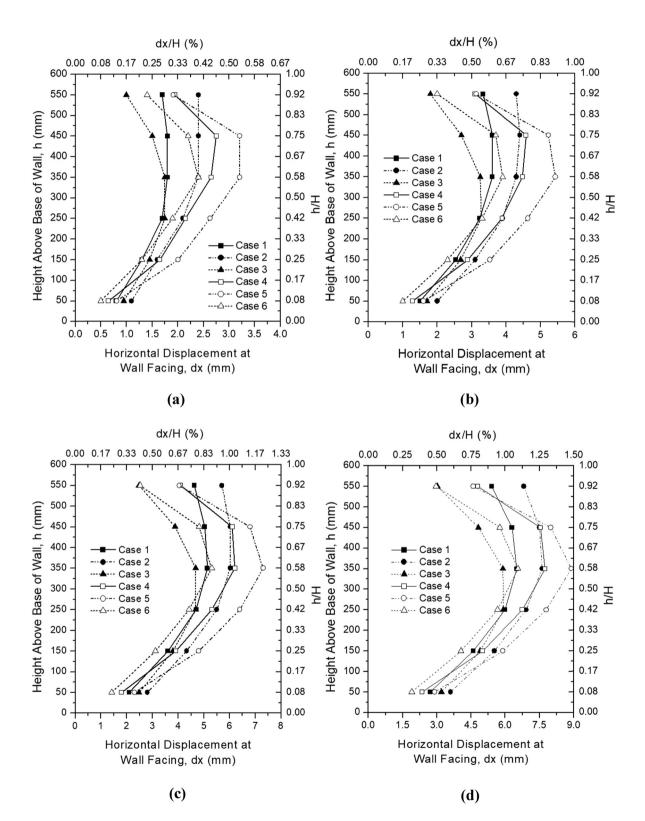


Figure 8: Variation of lateral displacement at wall facing with applied load: (a) P = 10 kN, (b) P = 20 kN, (c) P = 30 kN, and (d) P = 40 kN.

FHR facing, showed similar deformation behavior. While Case 4, Case 5, and Case 6, all MSE wall models having SPT wall facing, showed similar deformation behavior. The results inferred that geo-strips reinforcement is generally the weakest compared to discrete geogrids and steel rods.

4.2 Settlement-loading ratio

The influence of the wall facing type used in the MSE wall, having a similar reinforcement type, was analyzed

using the load ratio (LR) as shown in Figure 7. Here, the LR was computed as follows:

$$LR = \frac{L_{\text{FHR}}}{L_{\text{SPT}}} \tag{1}$$

where $L_{\rm FHR}$ is the bearing capacity of MSE wall models with FHR facing at a certain settlement level and $L_{\rm SPT}$ is the bearing capacity of MSE wall models with SPT wall facing at a certain settlement level. At the beginning of loading, the LR for the three types of reinforcement using FHR facing (Case 1–3) against the SPT wall facing (Case 4–6) are greater than 1.0. This inferred that the FHR facing showed higher strength than the SPT wall facing

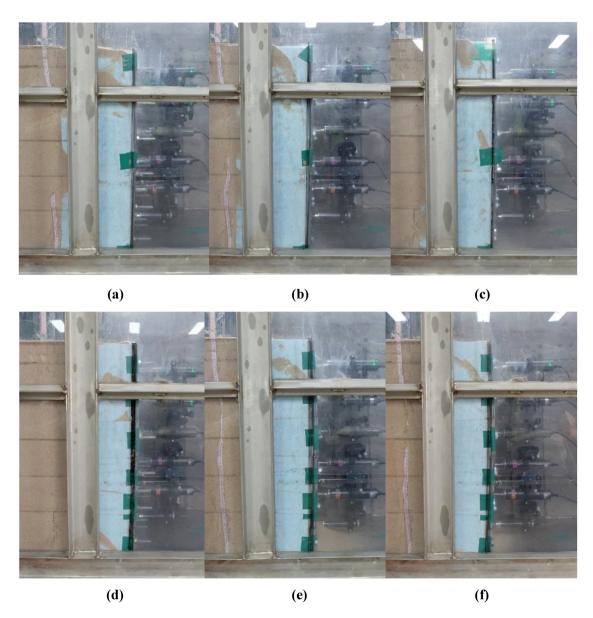


Figure 9: Photos of the final wall facing profile after the loading: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5, and (f) Case 6.

at the early stage of the loading. Then as the load and the settlement increased beyond 0.86% *S/B*, the LR for Case 2/Case 5 and Case 3/Case 6 turned out to be less than 1.0. In Figure 8, it can be observed that the top layer of SPT wall facing moved inward, while the middle layers moved outward, which is due to flexibility at its connection between panels. It allows the top layer of strips reinforcement, for SPT wall facing, to remain intact with the backfill and help in resisting the vertical load. Yet the strips reinforcement, for FHR facing, were pulled together with the top part of FHR facing outward; thus, the settlement was great. Conversely, the LR for Case 1/Case 4 remains greater than 1.0. This may imply that for discrete geogrid reinforcement, FHR facing consistently performed better than SPT wall facing up to 19 mm settlement.

4.3 Lateral displacements at wall facing with incremental loading

The lateral displacements (dx) at wall facing were basically caused by the load applied on top of the MSE wall model and were also influenced by the types of reinforcement and wall facing material used. Concurrent with the increasing settlement of the loading plate during the load application was the increasing lateral displacement at the wall facing. It is evident that the application of every 10 kN load induced a remarkable increase in the lateral displacements at wall facing. The percentage differences between the applied loads on every 10 kN were calculated based on the increment of lateral dis-

placement. The results showed the average percentage increase was 81–91%, 41–49%, 25–30%, and 17–21% for 10, 20, 30, and 40 kN load applied, respectively. It can be observed that the increment on lateral displacements depreciates after the succeeding 10 kN load is applied.

To clearly understand the behavior of the dx for each model test cases, the incremental dx after every 10 kN of applied loading is shown in Figure 8. The points on the dx curves were the readings obtained from the six LVDTs installed at the wall facing with elevation of 50 mm (0.08H), 150 mm (0.25H), 250 mm (0.42H), 350 mm (0.58H), 450 mm (0.75H), and 550 mm (0.92H). The results inferred that the application of linearly increasing load on top of the MSE wall exhibited great effects especially at the middle half (0.25-0.75H) of the wall facing profile. It can be observed that a significant increase in dx was visible after the first 10 kN load has been applied and increased more after the succeeding 10 kN has been applied. Moreover, it can be observed that the models with FHR facing (Case 1–3) exhibited more dx near the base of the wall than the models with SPT wall facing (Case 4–6). Generally, the models with FHR facing exhibited lesser dx curves than the models with SPT wall facing (also see Figure 10). In addition, the maximum dx generally occurred between 0.58 and 0.75H.

Nevertheless, after the load application, the final wall facing profile for each model cases are shown in Figure 9. The photos showed that the wall facing remained intact after the loading was applied, yet exhibited significant lateral displacements. A sketch is shown in Figure 10 to visualize the difference of the wall facing profiles between FHR facing and SPT wall facing at the end of 40 kN loading.

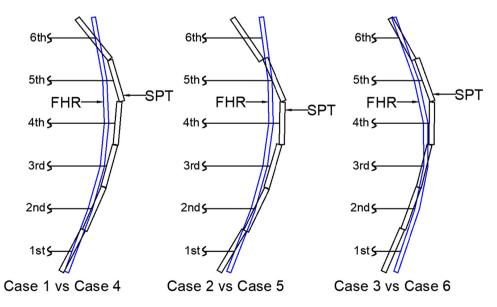


Figure 10: Sketch of the wall facing profile between full height rigid (FHR) facing and segmental panel-type (SPT) wall facing at 40 kN load.

5 Conclusion

The main conclusions drawn from the series of experimental analyses on six small-scale models of the MSE wall having FHR facing and SPT wall facing are as follows:

- For the vertical displacement, the MSE wall model having FHR facing and discrete geogrids reinforcement showed higher load capacity compared to other models. At the beginning of the vertical displacement, the models with FHR facing showed a larger load than those of the models with SPT wall facing.
- The MSE wall models using steel reinforcements generally exhibited the least lateral displacements at wall facing than those of the geosynthetic reinforcements.
 The MSE wall models using geo-strip reinforcements generally exhibited large lateral displacements at wall facing than other reinforcements.
- Generally, the models with FHR facing exhibited lesser dx curves than the models with SPT wall facing. In addition, the maximum lateral displacements at wall facing occurred between 0.58 and 0.75H.
- It was found that the lateral displacement at wall facing was more affected by the type of reinforcement and the type of wall facing used in the MSE wall compared to the vertical displacement.

Acknowledgment: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF2021R1A6A1A0304518511).

Conflict of interest: Authors state no conflict of interest.

References

[1] Shin EC, Cho SD, Lee KW. Case study of reinforced earth wall failure during extreme rainfall. Proceeding of TC302 Symposium Osaka 2011: International Symposium on Backwards Problem in Geotechnical Engineering and Monitoring of Geo-Construction; 2011. p. 146–53.

- [2] Tatsuoka F, Tateyama M, Uchimura T, Koseki J. Geosyntheticreinforced soil retaining walls as important permanent structures. Geosynth Int. 1997;4(2):81–136.
- [3] Tatsuoka F, Tateyama M, Mohri Y, Matsushima K. Remedial treatment of soil structures using geosynthetics-reinforcing technology. Geotext Geomembr. 2007;25:204–20.
- [4] Tatsuoka F, Tateyama M, Koseki J, Yonezawa T. Geosyntheticreinforced soil structures for railways in Japan. Transp Infrastruct Geotechnol. 2014;1:3–53.
- [5] Koerner RM, Koerner GR. A data base, statistics and recommendations regarding 171 failed geosynthetic reinforced mechanically stabilized earth (MSE) walls. Geotext Geomembr. 2013;40:20-7.
- [6] Koerner RM, Koerner GR. An extended data base and recommendations regarding 320 failed geosynthetic reinforced mechanically stabilized earth (MSE) walls. Geotext Geomembr. 2018;46:904–12.
- [7] Holtz RD. 46th Terzaghi lecture: geosynthetic reinforced soil: from the experimental to the familiar. J Geotech Geoenviron Eng. 2017;143(9):03117001-1-21.
- [8] Kibria G, Hossain S, Khan MS. Influence of soil reinforcement on horizontal displacement of MSE wall. Int J Geomech. 2014;14(1):130–41.
- [9] Berg RR, Christopher BR, Samtani NC. Design of mechanically stabilized earth walls and reinforced soil slopes – volume I, FHWA-NHI-10-024 FHWA GEC 011-Vol I. Washington, DC: National Highway Institute, Federal Highway Administration, US Department of Transportation; 2009.
- [10] Das BM. Principles of foundation engineering, Sl. 7th edn. Stamford, CT, USA: Cengage Learning; 2012.
- [11] Bilgin Ö, Mansour E. Effect of reinforcement type on the design reinforcement length of mechanically stabilized earth walls. Eng Struct. 2014;59:663-73.
- [12] Abdelouhab A, Dias D, Freitag N. Numerical analysis of the behavior of mechanically stabilized earth walls reinforced with different types of strips. Geotext Geomembr. 2011;29(2):116–29.
- [13] Sadat MR, Huang J, Bin-Shafique S, Rezaeimalek S. Study of the behavior of mechanically stabilized earth (MSE) walls subjected to differential settlements. Geotext Geomembr. 2018;46:77–90.
- [14] Won MS, Langcuyan CP. A 3D numerical analysis of the compaction effects on the behavior of panel-type MSE walls. Open Geosci. 2020;12:1704–24.
- [15] Won MS. Effects of reinforcement on bearing capacity of loose sand foundation and deformation behavior of buried flexible pipes. J Test Eval. 2010;38(2):232–41.
- [16] Won MS, Langcuyan CP, Gao YC. A study on the utilization of clayey soil as embankment material through model bearing capacity tests. Appl Sci. 2020;10(7):2315.