Engineering Transactions, **72**(1): 3–14, 2024, doi: 10.24423/EngTrans.3155.2024
Institute of Fundamental Technological Research Polish Academy of Sciences (IPPT PAN)
Université de Lorraine • Poznan University of Technology

Research Paper

Numerical Study for Optimal Design of Geosynthetic Reinforced Soil (GRS) Walls

Rashid Hajivand DASTGERDI[1)*], Nima BAHRAMI[2)], Kamran KAZEMI[3)], Muhammad Faisal WAQAR[4,5)], Agnieszka MALINOWSKA[6)]

[1)] *Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH UST*
Krakow, Poland

[2)] *Polytechnic University of Turin*
Turin, Italy

[3)] *Department of Civil and Environmental Engineering, Shiraz University of Technology*
Shiraz, Iran

[4)] *Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences*
Beijing 100029, China

[5)] *University of Chinese Academy of Sciences*
Beijing 100049, China

[6)] *Faculty of Mining Surveying and Environmental Engineering, AGH UST*
Krakow, Poland

[*]Corresponding Author e-mail: dastgerd@agh.edu.pl

The geosynthetic reinforced soil (GRS) system finds applications in numerous geotechnical projects, including retaining walls, road and railway embankments, slope stability structures, landfill structures, etc. This is attributed to its ability to enhance soil bearing capacity while minimizing deformations. Over the recent decades, extensive research has been conducted to comprehensively understand the behavior of GRS systems. In our research, we initially validate two laboratory tests using finite element (FE) modeling and conduct a parametric study. Our findings demonstrate that increasing the stiffness of layers from the bottom to the top of the wall significantly reduces wall displacements, approaching a state where all layers have uniform stiffness.

Additionally, we investigate the plastic zone and the length of geogrids in each layer. Our results indicate that reducing the length of layers from top to bottom, similar to the plastic zone shape, does not impact displacements and forces within the layers. Simultaneously increasing stiffness with height and decreasing geogrid layer lengths within the plastic zone reduces the cost of GRS wall construction.

Keywords: geogrid; geosynthetic reinforced soil (GRS); finite element analysis; parametric study.

1. Introduction

Geosynthetics are extensively used in various geotechnical applications. Employing geogrids in geotechnical applications enhances the mechanical and strength properties of reinforced soil, effectively redistributing loads and reducing soil settlement [1]. Geogrids have been deployed with great success in embankments to create steeper slopes, in pavement design to reduce the thickness of base and sub-base layers, and in retaining walls to construct mechanically stabilized earth (MSE) walls, especially at bridges abutments [2]. MSE walls have become a commonly preferred wall type because of their rapid construction, cost-effectiveness, simple construction techniques, and ability to tolerate larger deformations compared to conventional-type retaining walls [1, 2] without structural distress.

The present study investigates the effective parameters for reducing construction costs while maintaining wall stability. The investigation is carried out in two steps: firstly, by verifying finite element (FE) models for a laboratory-tested MSE wall and secondly, through a parametric study. The verification of the FE model is conducted by using the laboratory testing program of MSE walls at the Geotechnical Research Group of the Civil Engineering Department at the Royal Military College of Canada (RMCC) [3–6]. The parametric study investigates the effect of the length pattern and stiffness pattern of geogrid layers on reducing costs and ensuring wall stability. Following the wall design guidelines and the creation of the initial design, the current research results can be used for technical and economic optimization of the plan.

2. Full-scale model tests

Bathurst and Walters, at RMCC, conducted a full-scale test program on geosynthetic reinforced retaining walls [3–6]. Thirteen full-scale walls were tested under 13 different conditions, and all of them were surcharge loaded. Some of the walls experienced failure due to excessive surcharge load. Bathurst and Walters [3] published 4 out of 13 wall test results. Using these data, numerical models can be verified in further investigations on GRS walls. In our study, we use these results to calibrate our FE models.

As shown in Fig. 1, the wall height is 3 m and the width is 6 m. The soil used is uniformly graded coarse angular sand. The geogrid employed in this test is made of polypropylene material with a strength of 12 kN/m and a stiffness of 20.4 kPa at 2% strain. The soil is layered with four geogrid layers spaced 0.75 m apart vertically. In this study, we simulated two types of walls for calibration: a full-height panel wall and an incremental wall. Both walls have a thickness of 0.15 meters [3, 4, 7].

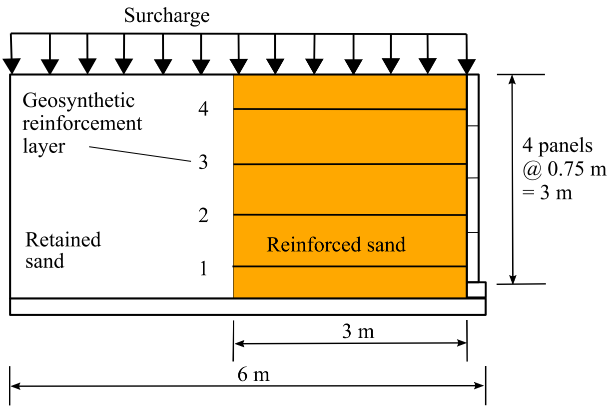

FIG. 1. The geometry of GRS walls constructed at RMCC [3].

The instruments inserted and attached to the walls were used to measure strain in the reinforcement layers, lateral deflections of wall facing, vertical deformations and earth pressure within the soil mass [3, 6, 8].

3. Finite element models

We employed ABAQUS software, a robust FE modeling program, to construct our FE models. In our case, the GRS wall models were developed under 2D plane strain conditions, as GRS walls typically maintain a constant geometry along their length, resulting in negligible out-of-plane deformations. We considered frictionless interactions between the box and soil for vertical walls, with the bottom fixed between the soil and box. The box was fully fixed in all directions. We restrained the lower surface of the wall in the vertical direction only, as there was no toe to prevent lateral motion during the test [3, 7].

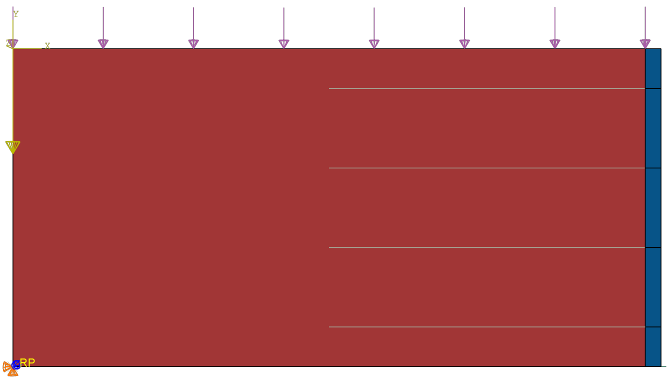

FIG. 2. Model created in ABAQUS software for incremental wall.

The interaction between the soil and the wall was considered using the penalty method in the FE model. The interior surface of the wall was designated as the master surface, while the exterior surface of the soil was chosen as the slave surface. Tangential contact between these two surfaces was defined with a friction angle of 56° [3]. For normal contact, a hard contact formulation was employed. To facilitate interaction between the soil and geogrid, the embedded region method was employed to eliminate the possibility of slippage between them. Furthermore, at the connection points where the geogrid meets the wall, the tie method was implemented [3, 7].

The solid element with reduced integration (CPE4R) was selected to simulate the soil and the wall elements in the model. Since the geogrids can only be subjected to tensile loads, the geogrid was modeled using the truss element (T2D2). For meshing, we used smaller elements, bringing them closer to the panel walls to increase the result accuracy. The meshing for the model is shown in Fig. 3.

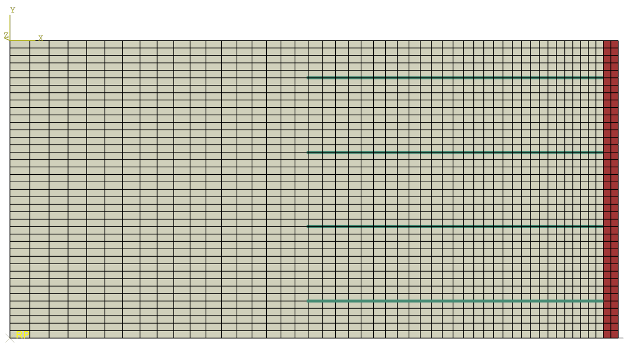

FIG. 3. FE Mesh of the model.

We adopted the Mohr-Coulomb criteria as the soil constitutive model and used linear elastic properties for the wall and geogrid. Additionally, the box was modeled as a rigid part, eliminating the need for material to be assigned. In Tables 1 and 2, the material properties of the soil and the wall are provided [3, 7].

Table 1. Input parameters for the soil.

Parameter	Unit	Value
Unit weight	kN/m^3	18
Elastic modulus	MPa	90
Poisson's ratio	–	0.35
Friction angle	degree	56
Dilation angle	degree	22
Cohesion	kPa	2

Table 2. Input parameters for the wall.

Parameter	Unit	Value
Unitweight	kN/m^3	24
Elastic modulus	MPa	25 000
Poisson's ratio	–	0.2

3.1. Validation results

Figure 4 demonstrates the horizontal deformation of the incremental wall subjected to a 70 kPa surcharge load, providing valuable insights into the structural response and deformation characteristics under this specific loading condition.

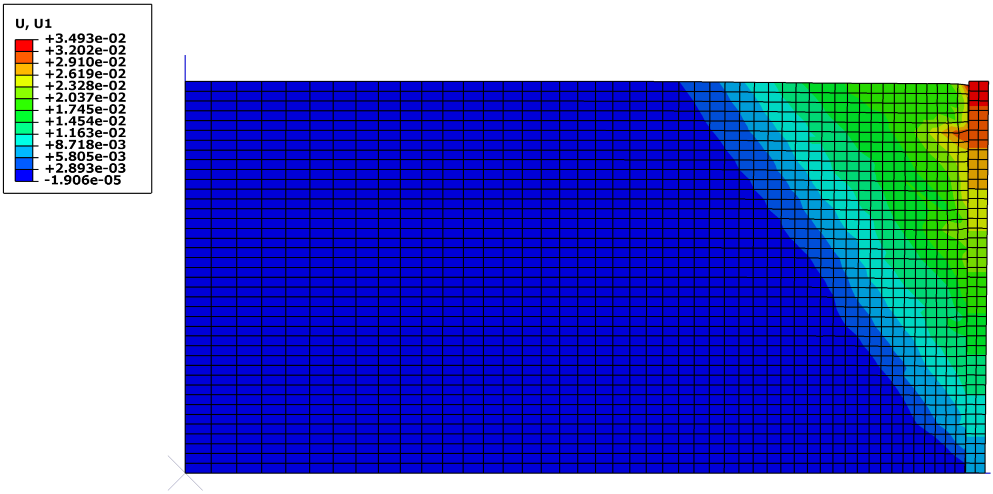

FIG. 4. Horizontal deformation for the incremental wall under a 70 kPa surcharge load.

Figures 5 and 6 illustrate the lateral deformation of the FE models for both full-height and incremental walls under surcharges. The numerical results show a good agreement with the actual measurements of the wall deformations. Any slight differences between the results could be due to using the Mohr-Coulomb constitutive model as the soil failure criterion.

4. PARAMETRIC STUDY

After modeling the tests and performing validation to ensure model accuracy, the next step involves studying and modifying the numerical models to find a strategy to reduce costs and optimize the design of reinforced soil walls.

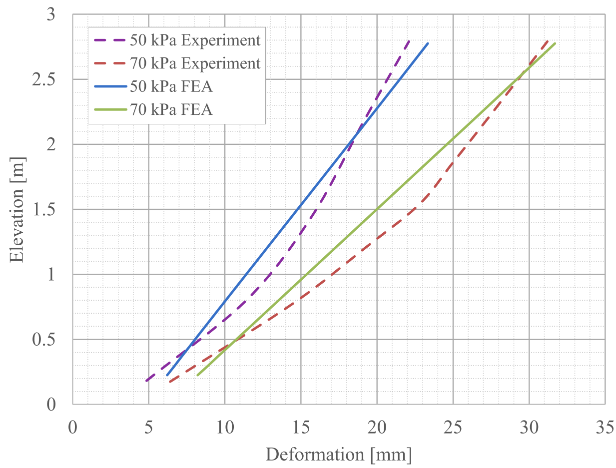

FIG. 5. The measured and modeled lateral deformation of the full-height panel wall.

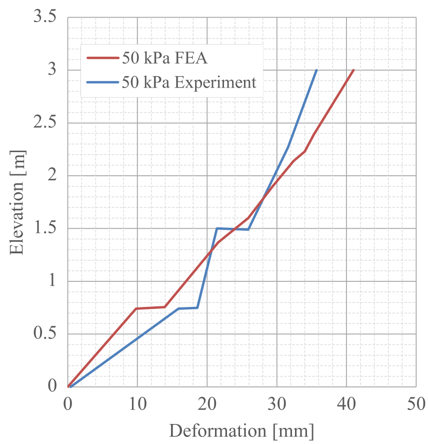

FIG. 6. The measured and modeled lateral deformation of the incremental wall.

4.1. Geogrid stiffness

Previous studies have shown that wall displacement decreases as the stiffness of geogrid layers increases [5]. Our examination yielded the same results, confirming these findings. Also, by examining the induced forces in the geogrids, it was observed that the induced forces in each layer increased by moving the geogrid layers away from the wall floor. We also know that if assume constant stiffness, increasing the force increases the displacement in the layers. Here, we decided to increase the stiffness of the geogrid layers from the bottom to the top of the wall in proportion to the increase in inductive forces, and observed that the displacements decreased significantly, approaching a state in which all layers have the same stiffness (see Figs. 7 and 8). Furthermore, the forces inside the geogrids did not undergo substantial changes. In conventional designs, however, the stiffness across all layers is usually considered the same. Since geogrids with higher hardness and strength costs more, our technique offers an approach that reduces material costs.

Figures 7 and 8 depict the results for both full-height and incremental walls. According to the figures, curve 1E indicates that the stiffness of all layers is uniform and equal to 20.4 kPa, which is the state in which the walls are tested. Moreover, curve 4E represents a condition where the stiffness of all layers is quadrupled. The gradient curve illustrates that layer 4 has a stiffness of 20.4 kPa, layer 3 has a stiffness of 40.8 kPa, layer 2 exhibits a stiffness of 61.2 kPa, and layer 1 showcases a stiffness of 81.6 kPa, respectively (as seen in Fig. 1).

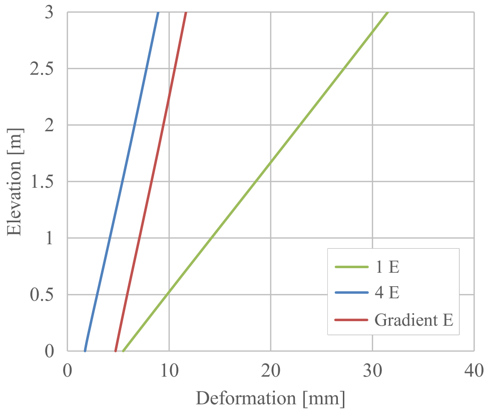

FIG. 7. The full-height wall displacement for different layer stiffness.

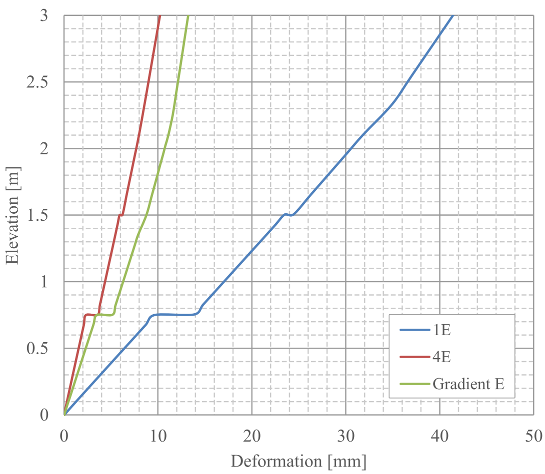

FIG. 8. The incremental wall displacement for different layer stiffness.

4.2. Geogrid length

Observing the induced strains in geogrids reveals that the length of engagement decreases from the top to the bottom layer. This reduction in engagement is proportional to the size of the plastic zone, as indicated by the area outlined with a red dashed line (see Figs. 9 and 10).

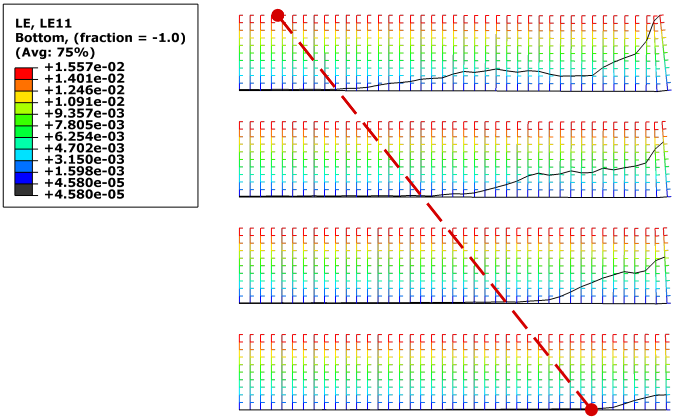

Fig. 9. Elastic strain induced in geogrid layers for the full-height wall.

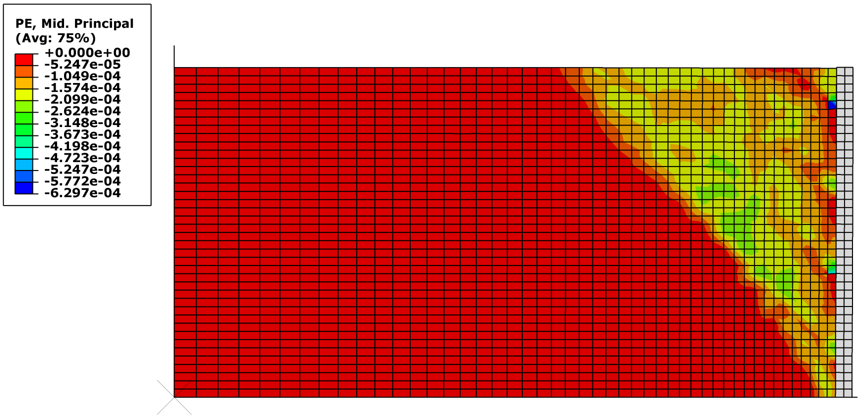

Fig. 10. Average plastic strains in the soil for the full-height wall.

To investigate the effect of geogrid length on the results, we kept the length of geogrid 4 unchanged at 3 m and reduced the lengths of geogrids 3, 2, and 1 to 2.5 m, 2 m, and 1.5 m, respectively. Figure 11 shows the model with different geogrid lengths. The displacement obtained after reducing the lengths equals the displacement of the wall before reducing the lengths.

Figures 12 and 13 show the inductive forces in the geogrid layers for the three modes of full-height and incremental walls. The 'base model mode' shows

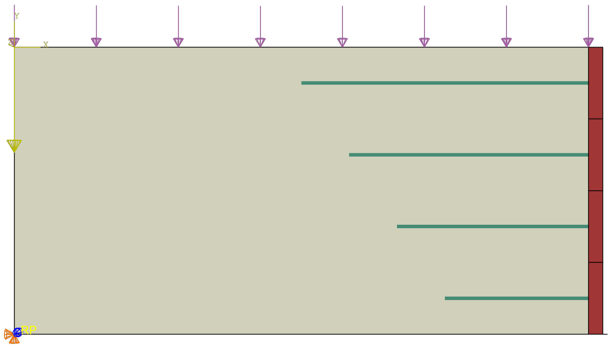

FIG. 11. The incremental wall model with reduced geogrid lengths (ladder mode).

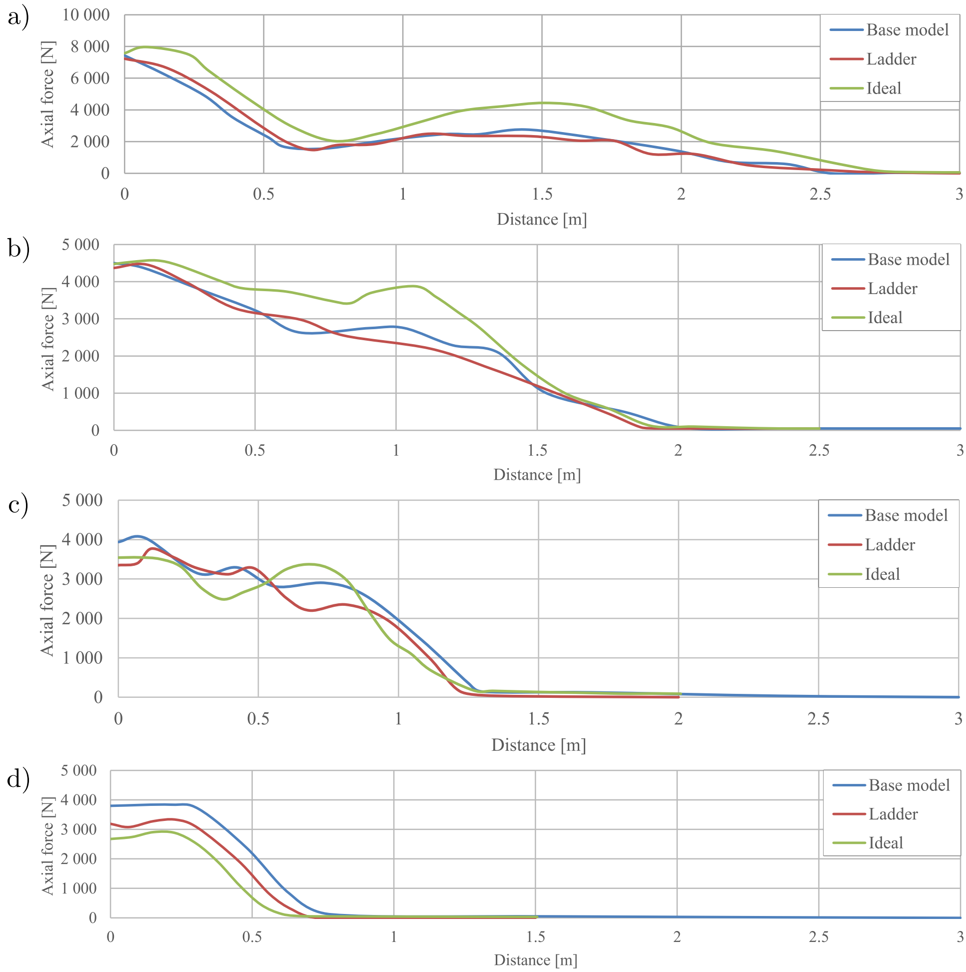

FIG. 12. Inductive forces of geogrids in three modes for full-height wall:
a) geogrid layer 4, b) geogrid layer 3, c) geogrid layer 2, d) geogrid layer 1.

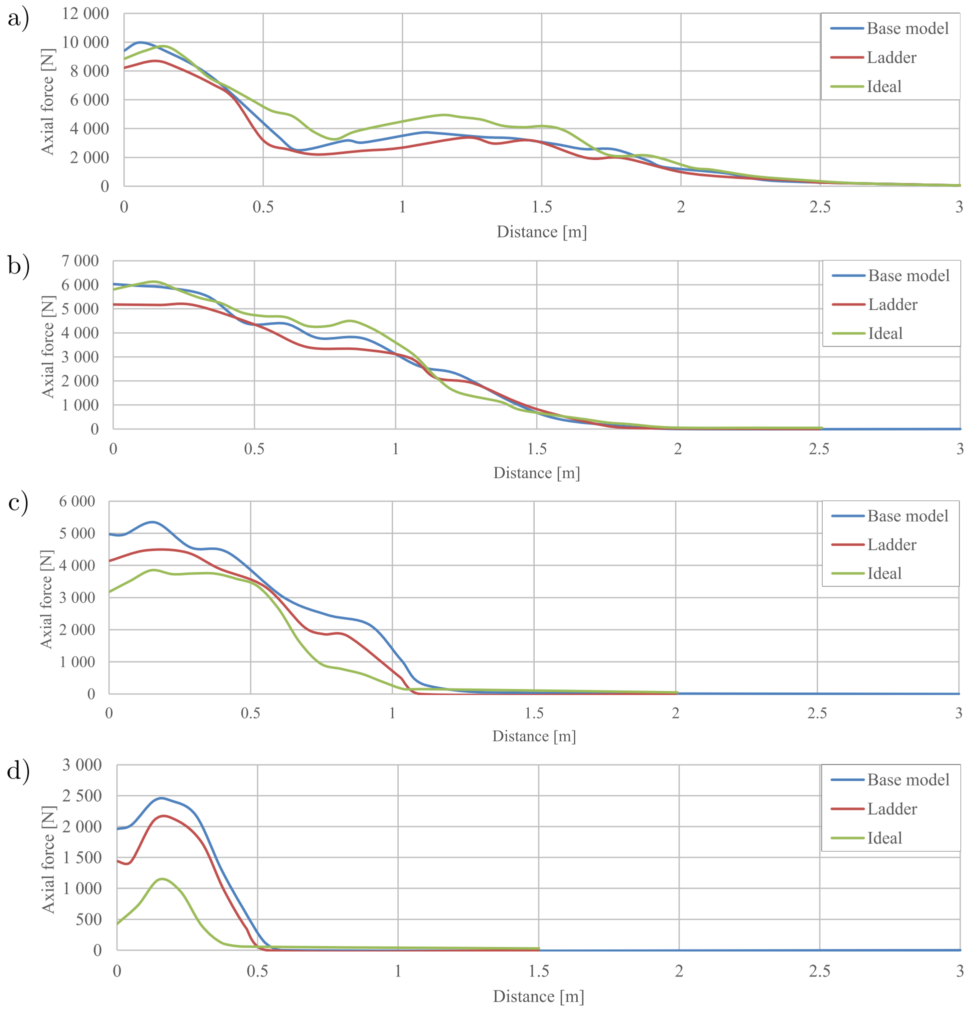

Fig. 13. Inductive forces of geogrids in three modes for incremental wall:
a) geogrid layer 4, b) geogrid layer 3, c) geogrid layer 2, d) geogrid layer 1.

the forces in the experimental tests (Figs. 2 and 3). The 'ladder mode' is a state in which the length of the geogrids is gradually reduced from top to bottom, as shown in Fig. 11, and the 'ideal state' combines the ladder state with an increase in stiffness from bottom to top, as discussed in the previous section. As observed in the above figures, the force distribution is nearly equal in all cases. Only in the lower layers of the geogrid, where the inductive force is low, a slight difference can be seen in the maximum inductive forces.

The above results indicate that reducing the length of geogrids from top to bottom, as in the form of the plastic zone, does not alter the displacement and inductive forces in the layers. This technique can also be used to reduce construction costs.

5. Conclusion

The following conclusions are made from the study:

- Regarding the results, it was observed that forces inside the geogrids decrease from top to bottom. In general, constant forces are needed to support the wall, and increasing the stiffness of the layers has a negligible effect on force increase unless we severely limit the displacements. More force at constant stiffness results in increased displacements. Therefore, with constant inductive force, increasing stiffness in the geogrid reduces displacement. As the inductive force increases from bottom to top, the stiffness must also be increased correspondingly. It was observed that this pattern significantly reduced displacements. These results are very close to the state where we increase the stiffness of all layers simultaneously.
- In addition, it was observed that the involved length of geogrids decreases from top to bottom, similar to the shape of the plastic zone. So, for each geogrid layer, we considered a safe length outside the plastic zone, from the point where the strain reaches zero. Consequently, the general shape of the layers became a ladder-shaped pattern with the same shape as the plastic zone. For this type of geogrid pattern, the results showed that the wall displacement and inductive forces in the geogrid layers were similar to a state where the layers had equal lengths.
- Simultaneously considering an increase in stiffness with height and a decrease in the length of layers in the form of plastic zones proved to be a cost-effective approach for constructing GRS walls.

Author agreement

The authors have reviewed and approved the final version of the manuscript submitted for publication. They warrant that this article is their original work, has not been previously published and is not currently under consideration for publication elsewhere.

Conflicts of interest

The authors declare that there are no conflicts of interest associated with this study.

Funding

This research received no external funding.

Data availability statement

Some or all of the data, models, or code that support the findings of this study are available from the corresponding author upon request.

References

1. Ashaari Y., *Aspects of the Behaviour of Reinforced Earth Walls*, Ph.D. thesis, Department of Civil and Mining Engineering, University of Wollongong, 1990, https://ro.uow.edu.au/theses/1228.

2. Berg R.R., Samtani N.C., Christopher B.R., *Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes*, *Volume II*, United States Department of Transportation, Federal Highway Administration, **1**, 2009, https://rosap.ntl.bts.gov/view/dot/49730.

3. Bathurst R.J., Walters D.L., Lessons learned from full scale testing of geosynthetic reinforced soil retaining walls, [in:] *Proceedings of the ISRM International Symposium*, ISRM-IS, Melbourne, Australia, 2000, https://onepetro.org/ISRMIS/proceedings-abstract/IS00/All-IS00/50343.

4. Bathurst R.J., Hatami K., Parametric analysis of reinforced soil walls with different height and reinforcement stiffness, [in:] *Proceedings of the 8th International Conference on Geosynthetics*, Yokohama, Japan, pp. 1343–1346, 2006, https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=316e257674cbb416c397ec32a5b69665601700d8.

5. Bathurst R.J., Jarrett P.M., Benjamin D.J., A database of results from an incrementally constructed geogrid-reinforced soil wall test, [in:] *Proceedings of Soil Reinforcement: Full Scale Experiments of the 80's. Reports of the International Conference Organized on the Initiative of the European Technical Committee of the SIMSTF*, Paris, France, vol. 1, pp. 401–430, 1993.

6. Hatami K., Bathurst R.J., Parametric analysis of reinforced soil walls with different backfill material properties, [in:] *Proceedings of the NAGS Conference*, Las Vegas, Nevada, pp. 1–15, 2006, http://www.geosynthetica.com/Uploads/HatamiBathurst.pdf.

7. Elshafey M., Elnaggar M., Abdelaziz A.Y., Numerical investigation of quay walls reinforced with geosynthetic, *Alexandria Engineering Journal*, **60**(2): 2303–2313, 2021, doi: 10.1016/j.aej.2020.12.023.

8. Bathurst R.J., Instrumentation of geogrid-reinforced soil walls, *Transportation Research Record*, (1277): 102–111, 1990, http://onlinepubs.trb.org/Onlinepubs/trr/1990/1277/1277-013.pdf.

Received May 11, 2023; accepted version October 13, 2023.
Online first January 17, 2024.