A 3D FINITE ELEMENT ANALYSIS OF THE MODULAR BLOCK RETAINING WALLS WITH CORNER TURNS

Submission Date: August 1, 2014
Word Count 3,463 words + 13 tables/figures (250 words each) = 6678 words

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ABSTRACT

The design manuals for Geosynthetic Reinforced Soil retaining walls include the methodology for various conditions except the case where the wall has curved corner turns. Lately, there has been an increase in the frequency of problems associated with these types of walls. One of the typical problems is cracking/separation of the segmental blocks. The most common method for identifying the cause of problems is a 2D plain-strain analysis which is insufficient for the current case. Therefore in this study, a more robust modeling approach was considered. A 3D finite element (FE) model which is capable of modeling corner turns was created. The main elements of the model are modular blocks, interface layers, soil and geosynthetic reinforcements. As the first step, a base model was defined. The base model included reinforcements with the lowest stiffness. The base model was evaluated in terms of block displacements and stresses. In the other models, reinforcement stiffness and the soil modulus were increased or decreased to evaluate its effect on block displacements and stresses. According to the modeling results, the elastic modulus of the reinforcements and the soil modulus are very effective on block separation and cracking. The separation of blocks could be decreased by increasing the reinforcement stiffness and proper soil compaction. It is considered that the cracking of blocks was related to excessive moments developing in those blocks. The moments are reduced when the reinforcement stiffness was increased. It can be concluded that the cracking of blocks is less likely to happen under reduced moments.

INTRODUCTION

In the last three decades, Geosynthetic Reinforced Soil (GRS) walls have become more widespread due to their advantages such as cost-effectiveness, high performance, aesthetic appearance and durability. In practice, such walls are routinely designed using limit-equilibrium analysis [1], [2], [3]. Limit equilibrium analysis methods are very practical in determining the required reinforcement geometry, strength and all the other properties of GRS walls. A Coulomb state of stress is considered for external stability calculations, and a Rankine failure surface is considered for internal stability considerations in Federal Highway Administration [2] and National Concrete Masonry Association design recommendations [4]. In the internal stability analysis, tensile failure and pullout of the reinforcement layers are investigated.

In general, 2-Dimensional (2D) plane strain analyses are performed to evaluate the deformational behavior. Simplifying a 3D stress-strain state problem into a 2D one is considered valid in most cases because the length of a typical wall is quite long compared to its width. Finite Element (FE) analyses are quite popular in analyzing such walls.

Many Research work is available related to the design and behavior of GRS retaining walls. In the FHWA design manual, specific sections have been devoted to the design of GRS walls with complex geometries. These include cases like bridge abutments; superimposed (tiered) GRS walls; walls with uneven reinforcement lengths; back-to-back walls and GRS walls constructed in front of shored walls and stable rock features for steep terrains.

Some research studies such as the results of FE analyses, model walls, shaking table tests etc. have been reported in the literature regarding the design and behavior of GRS walls under static and earthquake loading conditions. In these studies, the effect of different reinforcement types and reinforcement configurations, the effect of backfill and the effect of external loading conditions have been investigated [5-17]. In addition, 3D FE analyses for GRS walls have also been reported in the literature [18], [19]. Surprisingly, none of these studies address the problems regarding the corner parts of GRS walls.

PROBLEMS ENCOUNTERED WITH THE CORNERS OF GEOSYNTHETIC REINFORCED WALLS

Due to topographical restrictions, it may be necessary to include a corner turn in geosynthetic reinforced block faced retaining walls. These corner turns can be made at right angle or greater/smaller angles based on the space requirements. In Figure 1, a wall corner with a 90^o sharp turn is illustrated. The wall height is 13 m and the average reinforcement length ranges between 8 and 9.5 meters. The wall is reinforced with geotextile reinforcements with tensile strengths of 40 and 80 kN/m in the upper and lower sections respectively. At the top and bottom 1/3 of the wall, the reinforcement spacing is 0.2 m whereas in the central, the spacing alternates between 0.2 m and 0.4 m. The wall is founded on a non-uniform weak soil. The wall experienced some cracks in the lower parts of its corner within the first year of its service life. Such cracks often occur as a result of improper placement of reinforcements and poor compaction of soil in the corner zones.

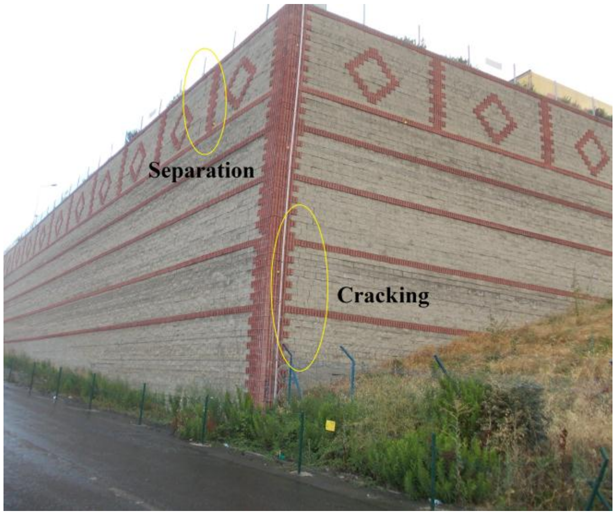


Figure 1 A segmental geosynthetic reinforced wall with a 90^o corner turn

Figure 2 Types of block movement a) Separation, b) Cracking

The cracks located in the upper and lower sections of the wall (Figure 1) are slightly different in nature. It appears that, blocks separate in the upper sections whereas blocks predominantly crack in the lower sections (Figure 2).

3D ANALYSIS

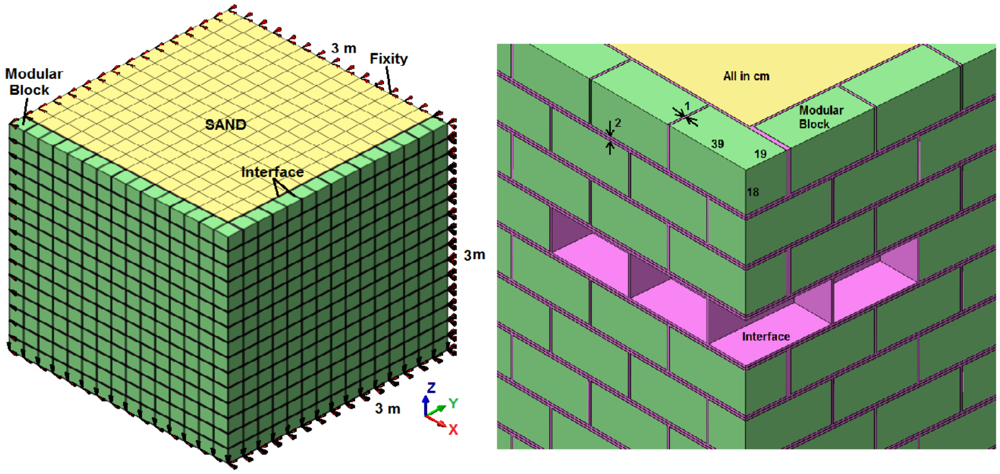
The main goal of this study is to investigate the possible causes of the cracks observed around the wall corners. The crack investigation will be based on a 3D model performed with TNO-DIANA program. Finally, using the model results, some recommendation will be made to prevent these types of cracking on the facing parts of GRS walls.

TNO-DIANA Program

TNO-DIANA is a multi-purpose finite element program which has been continually developed since 1970s. Particularly, in the last decade, by the integration of a user friendly mesh generator, the program turned into a utility that is capable of solving complex geometries with more than 100000 elements. In addition, the program has an extensive element library for structural elements as well as geotechnical constitutive models. The main reason for using DIANA in this study is its capability to solve the non-uniform mesh created for the wall which is structured from modular blocks along with small interface elements in between them.

Geometry

The model dimensions of the 3-Dimensional (3D) modular block retaining wall are 3 m x 3 m x 3 m. A general view of the 3D mesh is illustrated in Figure 3a. The modular blocks which have 18 cm x 19 cm x 39 cm dimensions are lined up staggered over the top of each other (Figure 3b).The 20 cm-long portion of the geosynthetic reinforcement is bounded by 1 cm-thick interface layers from its top and bottom side (Figure 4). The blocks are also separated with 1 cm-thick interface on sides. The connections between the facing blocks and the geosynthetic reinforcements are frictional, in other words, no mechanical connection was considered. Some practical experience and shaking table test results have proven that geosynthetic reinforced walls with a frictional connection resisted to extreme seismic loads without any major problems [20].



a) The Mesh

b) Alignment of blocks

Figure 3 (a) The mesh of the modular block retaining wall, (b) The alignment of blocks

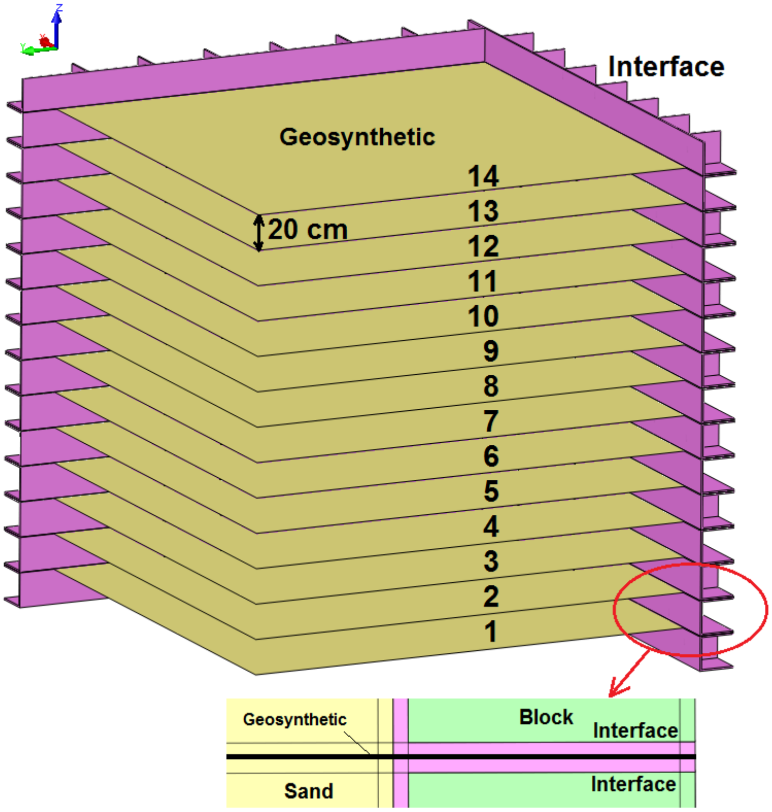


Figure 4 The geosynthetic reinforcement layout and details

Material Properties

The 3D mesh consists of granular material, interface, block and geosynthetic reinforcement materials. The nonlinear Mohr-Coulomb soil model (linearly elastic-perfectly plastic) was used for the backfill granular material and interface material. Granular soil properties were assigned to the backfill material. The model was run for 4 different soil modulus levels which were 20000, 40000, 60000 and 80000 kPa respectively. These soil modulus levels used in this study represent a stiffness grade ranging from loose to dense. The elastic modulus of the interface element was 1/200 times of the elastic modulus of surrounding blocks. Linear elastic properties were associated with block and geosynthetic reinforcement elements. The granular material, block and interface elements were meshed with 3D prismatic elements. The geosynthetic reinforcement element was created from a 2D flat shell element with plain strain characteristics. The stiffness values assigned to the geosynthetic reinforcement elements were able to represent a wide range of geosynthetics including woven geotextiles, polypropylene geogrids and high strength polyester geogrids. The properties of these elements are given in Table 1.

TABLE 1 3D MODEL MATERIAL PROPERTIES

Member	Constitutive Model	Modulus or Stiffness (kPa and kN/m respectively))	Poisson's ratio	Internal friction angle (°)	Cohesion (kPa)	Unit weight (kN/m^3)
Granular Material	Non-linear Mohr-Coulomb	20000 40000 60000 80000	0.3	36	5	18
Block	Linear Elastic	200000	0.15	-	-	20
Interface	Non-linear Mohr-Coulomb	1000	0.25	30	5	20
Geosynthetic Reinforcement	Linear Elastic	100 250 500 1000 2000	0.15	-	-	1.2

Loading

In the numerical solving phase, the self-weight of the model was applied in ten incremental steps to enhance the numerical convergence. Construction steps have not been simulated. The model does not include any surcharge or any additional external force other than its self-weight.

Boundary Conditions

The two perpendicular planes on the back sides are restricted only at out-of-plane directions. This allows the back side to move freely in the vertical and horizontal directions minimizing the occurrence of inaccurate stresses over the boundaries. The bottom of the model is restricted in x, y and z directions in order to eliminate a foundation failure which is not much of an interest in this study.

Model Combinations

The 3D model was run for 5 different geosynthetic reinforcement stiffness (E_{geo} = 100, 250, 500, 1000 and 2000 kN/m) and 4 different granular backfill moduli (E_{soil} = 20000, 40000, 6000 and 80000 kPa). It is considered that the corresponding compaction levels for the given soil moduli are poorly-compacted; moderate compacted, well-compacted and very well-compacted respectively.

RESULTS

Many different scenarios may be put forward to explain the occurrence of cracks on modular blocks. Among these scenarios, the most reasonable reason would be the poor compaction of the backfill. Since poor compaction causes excessive deformations, it may result with cracking of modular blocks. In order to simulate this condition, the soil modulus of the granular backfill was changed in the model according to the compaction levels mentioned in the previous section. Figure 5 illustrates the evolution of resultant displacement with increasing soil modulus. Generally, there is an outward movement on sides and it reaches to its peak value on the corner. The resultant wall displacement is also given in Figure 6. The resultant displacement of the wall decreases with increasing soil modulus and ranges between 2-7 mm. On the other hand, the excessive displacement scenario is not self-sufficient to explain the cracking of blocks while the development of excessive stresses on the cracking blocks should also be confirmed.

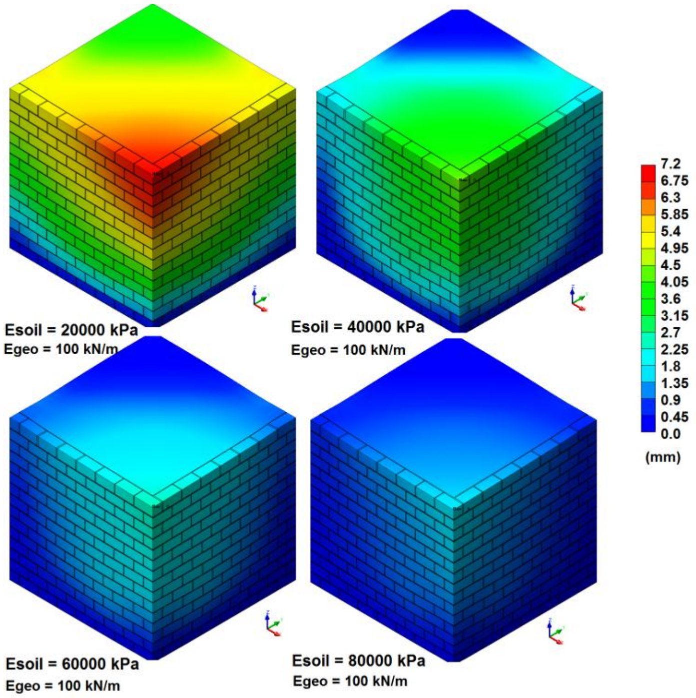


Figure 5 Illustration of resultant displacements in walls with varying soil modulus

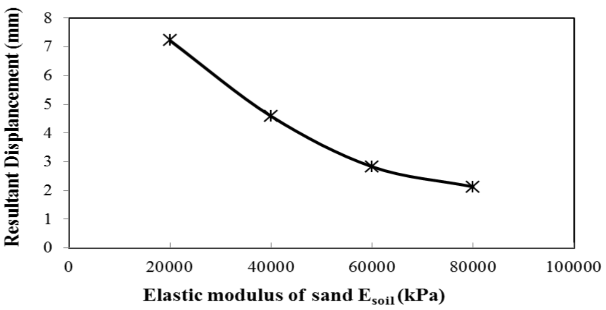


Figure 6 Plot of resultant displacement on walls with varying soil modulus

The stress distribution of the wall with at different soil modulus levels are given in Figure 7. According to Figure 7, the blocks on the sides and the corner of the wall experience tensional and compressional stresses respectively. Especially, on the lower part of the corner, compressional stresses develop and they tend to disappear when the soil modulus is increased. Surprisingly, the location of the tensional and compressional stresses is very similar to the locations of the cracks observed in the wall shown in Figure 1.

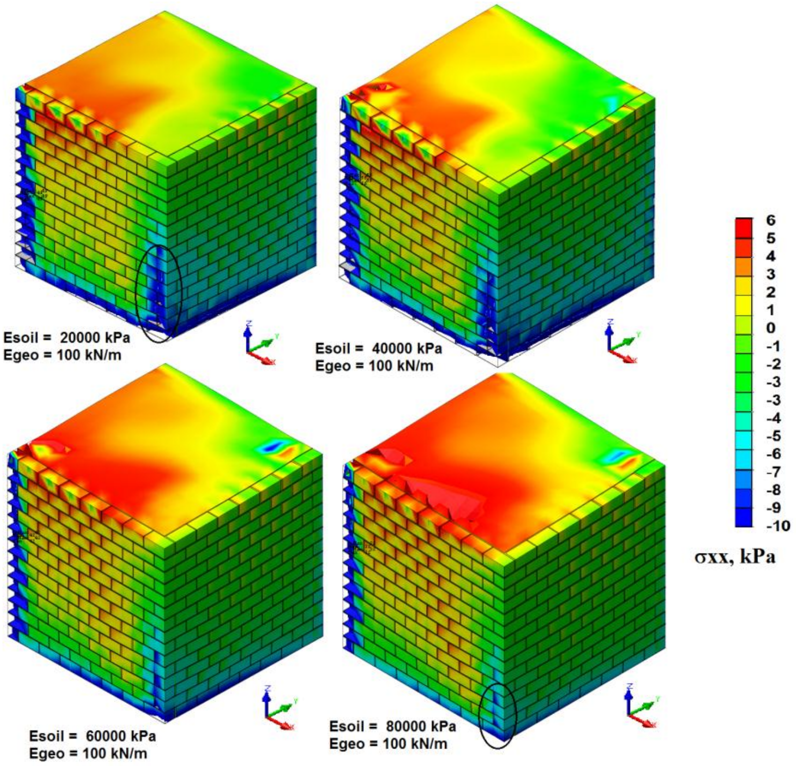


Figure 7 Illustration of stresses in walls with varying soil modulus

As the second step, the effect of geosynthetic reinforcement modulus was investigated. The model with moderately compacted granular fill (soil modulus =40000 kPa) was run for geosynthetic reinforcement stiffness levels of 100, 250, 500, 1000 and 2000 kPa. The model run with the geosynthetic reinforcement stiffness of 100 kN/m has the highest wall displacement (4.6 mm) on the corner. The maximum displacement drops down to 0.8 mm for the model which was run with a geosynthetic reinforcement stiffness of 2000 kN/m. This indicates a 6-fold drop in displacement for a 20-fold increase in the geosynthetic reinforcement stiffness. The effect of the geosynthetic reinforcement stiffness is illustrated in Figure 8. The displacement pattern on the corner drastically changes with increasing elastic modulus where the two faces of the wall intersect (Figure 8). The relation between geosynthetic reinforcement stiffness and the vertical displacement is given in Figure 9.

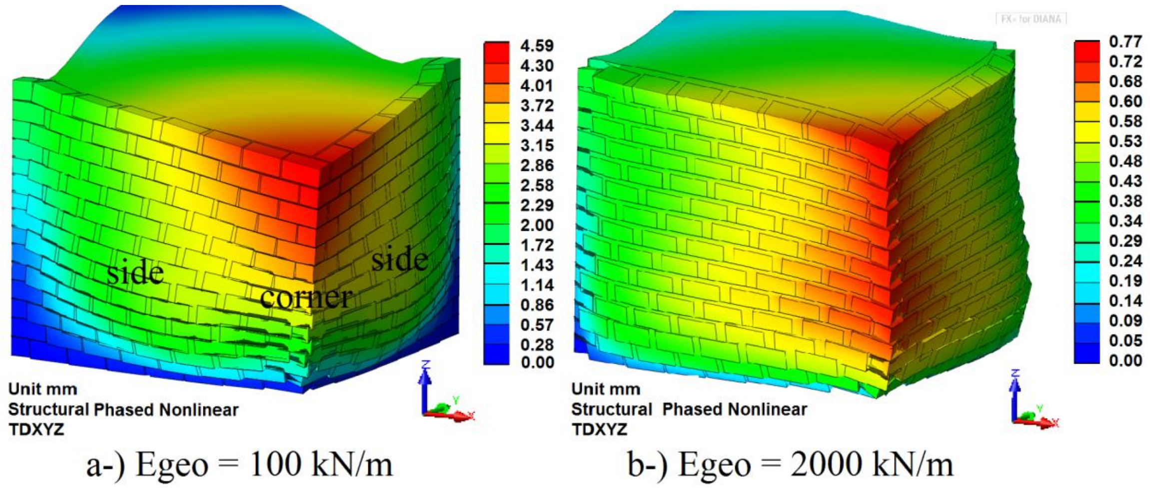


Figure 8 Resultant displacements at a-) the model run with E_{geo}=100 kN/m geosynthetic reinforcement b-) E_{geo}=2000 kN/m geosynthetic reinforcement (In both analyses E_{soil} = 40000 kPa)

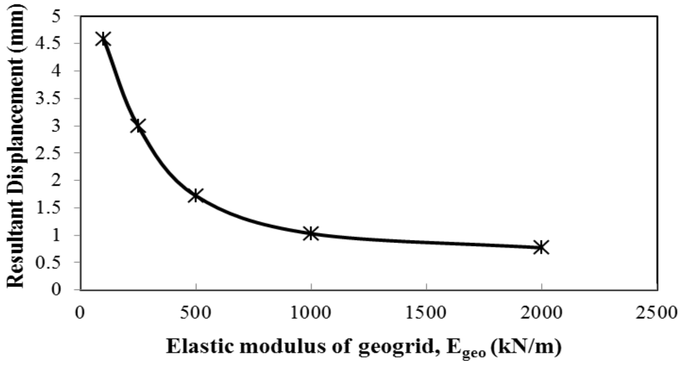
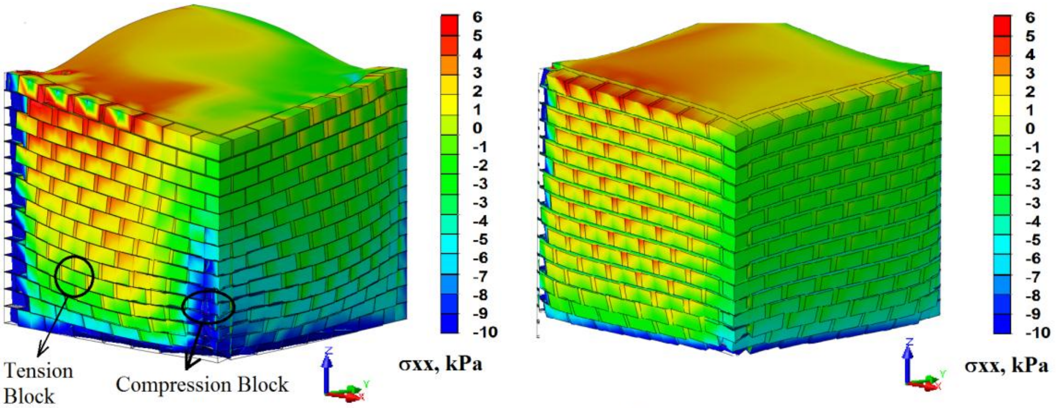


Figure 9 Resultant displacements at a-) the wall system with E_{geo}=100 kN/m geosynthetic reinforcement b-) E_{geo}=2000 kN/m geosynthetic reinforcement (In both analyses $E_{granular\ material}$ = 40000kN/m^2)

Although the evaluation of block displacement distribution for tracing back the cracks is a reasonable method, an additional check on stresses should be performed. The distribution of the σ_{xx} stresses in x direction, are given in Figure 10. According to Figure 10, the variability of σ_{xx} stresses on blocks is much greater when a lower geosynthetic stiffness is used.

Due to the horizontal earth pressure, the blocks on the sides and the corner are pushed outwards, as a result, horizontal tensile stresses occurs (Figure 10). On the other hand, a small portion of the blocks on the lower side of the corner experience compression. In addition, the number of blocks experiencing compression decreases when a stiffer geosynthetic is used (Figure 10a and 10b).

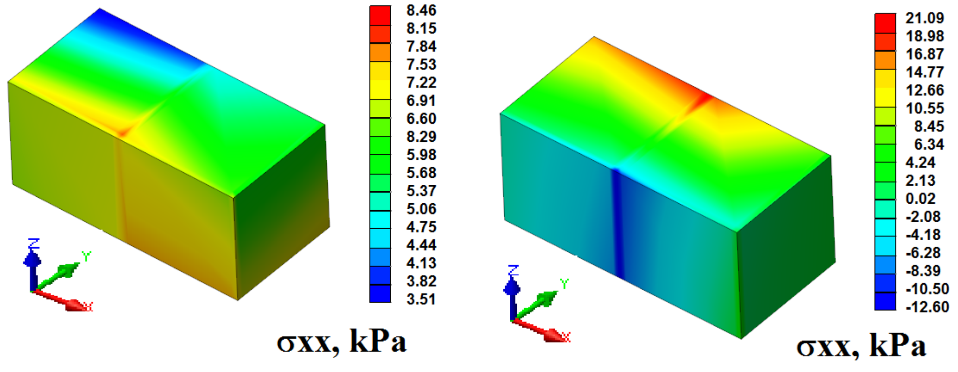
In efforts to understand the wall behavior, two blocks from the side and the corner locations (Figure 10a) have been put under focus respectively (Figure 11). These blocks belong to the model run with 100 kN/m geosynthetic stiffness. The block on the side of the model is under tension as seen in Figure 11a. In contrast, the block on the corner is under the combined effect of tension and compression (Figure 11b). The combined effect produces some bending moment which can eventually lead to the cracking of the block. Moverover, the absolute stress values on the corner block are much greater than what is observed for the side block.



a) Egeo = 100 kN/m

b) Egeo=2000 kN/m

Figure 10 a-) Stresses in the wall sytem with a-) E=100 kN/m geosynthetic reinforcement b-) E=2000 kN/m geosynthetic reinforcement

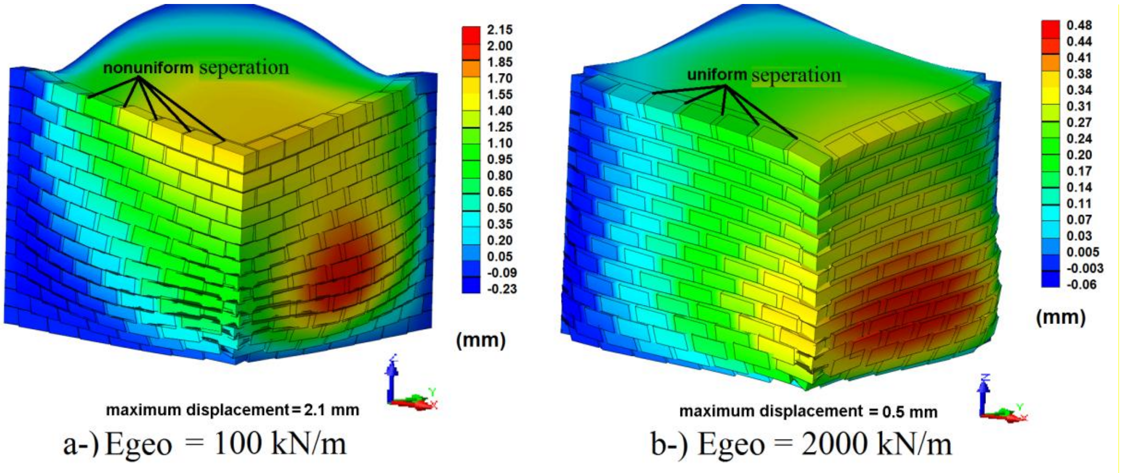


a) block under tension

b) block under tension & compression

Figure 11 a) A block from the side of the wall, b-) A block from the corner of the wall

Figure 12 illustrates the displacements on the wall systems along the x direction under the self-weight of the wall. On the side facing, away from the corner, the maximum displacement occurs at one third of the height from the bottom. This behavior is in agreement with the two dimensional behavior. However this behavior changes towards the corner. From Figure 12, it can be observed that movement of blocks is more uniform when a geosynthetic reinforcement with 20 times higher elastic modulus is used. It is considered that in the uniform movement case, the local separation of blocks is less likely to occur.



a-) Egeo = 100 kN/m b-) Egeo = 2000 kN/m

Figure 12 Displacements along the x direction a-) the wall system with E_{geo}=100 kN/m geosynthetic reinforcement b-) E_{geo}=2000 kN/m geosynthetic reinforcement

CONCLUDING REMARKS

In this study, a 3D finite element modeling of a 3 m x 3 m x 3 m segmental block wall has been performed to evaluate the separations/cracks observed on the corner turns of such walls. The concluding remarks must not be perceived as a final technical recommendation, they rather highlight the possible causes of the problem. Using the results of the 3D model, the following conclusions can be drawn:

- On the sides away from the corner, the maximum displacement occurs at one third of the height from the bottom. This behavior is also observed in 2D Finite Element analyses and in real walls.
- The horizontal displacements of the blocks on the crest increase towards the corner. In case, a backfill material with higher elastic modulus is used, the displacements are reduced and a more uniform block movement is achieved. This indicates that proper compaction is also essential for the proper behavior of corner walls.
- It was observed that by increasing reinforcement stiffness, a better performance could also be achieved.
- Generally, tensile stresses develop on the side blocks. Compressive and tensile stresses develop on the blocks close to the bottom of the wall corner. This stress state produces moments which may cause cracking of concrete blocks.
- It can be concluded that the separation of blocks on the crest can mainly be attributed to poor compaction and/or low geosynthetic reinforcement stiffness. The model run with stiffer granular material and/or reinforcement provided less and more uniform displacements over the wall crest.

- Another benefit of using stiffer reinforcement is the reduced stresses acting on the facing blocks. As the elastic modulus of the reinforcement increases, the compressional forces on the lower parts of the corner turn disappear. This may help prevent the cracking of blocks.

- As a general conclusion it can be stated, that some visual problems may be observed in the modular block retaining walls with corner turns, such as the separation of blocks which looks like cracks on the wall or physical cracking of facing blocks. These defects are more pronounced for poorly compacted backfill and reinforcements with small elastic modulus, and tend to disappear when better compaction is applied and the elastic modulus of the reinforcement is increased.

References

[1] AASHTO. *Standard Specifications for Highway Bridges, 17th edition*, 2002.

[2] *Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes,* Federal Highway Administration (FHWA) Demonstration Project 82, Washington, DC, USA, 2010.

[3] Adams, M., J. Nicks, T. Stabile, J. Wu, W. Schlatter, J. Hartmann, *Geosynthetic Reinforced Soil Integrated Bridge System Interim Implementation Guide, Federal Highway Administration, Mclean*, VA, 2011.

[4] National Concrete Masonry Association (NCMA). *Seismic Design Of Segmental Retaining Walls,* TEK 15-9A, 2010, http://www.ncma.org.

[5] El-Emam, M.M. and R.J. Bathurst. Facing contribution to seismic response of reduced-scale reinforced soil walls, *Geosynthetics International* 12 (3), 2005, 215–238.

[6] Guler, E., M. Hamderi, and M.M Demirkan. Numerical analysis of reinforced soil-retaining wall structure with cohesive and granular backfills, *Geosynthetics International*, Vol. 14, No. 6, 2007, pp.330-345.

[7] Guler, E. and A.K. Enunlu. Investigation of dynamic behavior of geosynthetic reinforced soil retaining structures under earthquake loads, *Bulletin of Earthquake Engineering*, Vol. 7, Issue 3, 2009, pp. 737-777.

[8] Guler, E., E. Cicek, M.M. Demirkan and M. Hamderi. Numerical analysis of reinforced soil walls with granular and cohesive backfills under cyclic loads, *Bulletin of Earthquake Engineering*, Vol. 10-3, 2012, pp. 793-811.

[9] Guler E. and O. Selek. Reduced-Scale Shaking Table Tests on Geosynthetic-Reinforced Soil Walls with Modular Facing." *J. Geotech. Geoenviron. Eng.*, Vol.140(6), 2014.

[10] Koseki, J., R. J. Bathurst, E. Guler, J. Kuwano, and M. Maugeri. Keynote lecture: Seismic stability of reinforced soil walls, *8th Int. Conf. on Geosynthetics*, Yokohama, Japan, Millpress, Rotterdam, Netherlands, Vol. 1, 2006, pp. 51-77.

[11] Ling, H. I., H. Liu, and Y. Mohri, Parametric studies on the behavior of reinforced soil retaining walls under earthquake loading, *J. Eng. Mech.*, Vol.131, 2005a, pp. 1056–1065.

[12] Ling, H. I., Y. Mohri and D. Leshchinsky. Large-scale shaking table tests on modular block reinforced Soil retaining walls, *J. Geotech. Geoenviron. Eng.*, Vol.131, 2005b, pp. 465–476.

[13] Ling, H. I., S. Yang, D. Leshchinsky, H. Liu, and C. Burke. Finite element simulations of full-scale modular-block reinforced soil retaining walls under earthquake loading, *J. Eng. Mech.*, 10.1061, 2010, pp.653–661.

[14] Ling, H. I., D. Leshchinsky, Y. Mohri, and J. P. Wang, Earthquake response of reinforced segmental retaining walls backfilled with substantial percentage of fines, J. Geotech. Geoenviron. Eng., 10.1061, 2012, pp. 934–944.

[15] Nova-Roessig, L. and N. Sitar. Centrifuge model studies of the seismic response of reinforced soil slopes. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132 (3), 2006, pp. 388–400.

[16] Walters, D. L., T. M. Allen, and R. J. Bathurst. Conversion of geosynthetic strain to load using reinforcement stiffness. *Geosynthetics International*, 9(5-6), 2002, 483–523.

[17] Watanbe, K., Y. Munaf, J. Koseki, M. Tateyama, and K. Kojima. "Behaviors of several types of model retaining walls subjected to irregular excitation." *Soils and Foundations*., 43(5), 2003, pp.13–27.

[18] Fan, C.C. Performance of a two-tier geosynthetic reinforced segmental retaining wall under a surcharge load: Full-scale load test and 3D finite element analysis. *Computers and Geotechnics*, Vol. 33, 2006, pp. 69-85.

[19] Yoo, C., and S. B. Kim. Performance of a two-tier geosynthetic reinforced segmental retaining wall under a surcharge load: Full-scale load test and 3D finite element analysis, *Geotextiles and Geomembranes,* 2008, Vol. 26, pp.460-472.

[20] Guler, E., D. Alexiew and E. Basbug. Behavior of geogrid reinforced segmental block walls under earthquake loads. *Geoeuro 5, 5th European Geosynthetics Congress*, Valencia Spain, 2012, pp. 793-811.