https://doi.org/10.1051/e3sconf/202336802018

Estimation of Horizontal Displacements for Geosynthetic Reinforced Soil Wall

Erol Guler[1*] and *Murat* Hamderi[2]

[1]George Mason University Fairfax, VA, USA
[2]Turkish-German University, Beykoz, Istanbul, Turkey

Abstract. Nowadays, the geotechnical design trend is increasingly heading towards the serviceability limit state. However, the current practice in the design of geosynthetic reinforced soil (GRS) walls mostly relies on ultimate limit state. Commonly available design software programs provide typical factor of safety values against various failure modes. With increasing height and variability in GRS walls, the deformation characteristics of the GRS walls also become an important parameter in the design. In this paper, an expression has been developed to predict the horizontal deformation of a GRS wall using a set of data obtained from about sixty-four finite element model configurations. The horizontal deformation expression includes wall-height, internal friction angle and elastic modulus of backfill, length, spacing and stiffness of geosynthetic reinforcements. It has been found out that all these parameters contribute to the horizontal displacement of a GRS wall. In addition, some comparisons have been made to reveal the influence of each individual parameter on the horizontal displacement of the wall.

1 Introduction

Geosynthetic reinforced soil retaining walls have become a routine application in all fields of civil engineering including transportation, residential, commercial and industrial site projects. Due to extensible characteristics of the geosynthetic reinforcement, sufficient tensile strain develops in the backfill for the ultimate limit state to occur [1]. This allows active limit state condition to be adopted in design. Accordingly, internal stability analyses are conducted to determine and check the forces acting on the reinforcements in order to avoid tensile overstress, connection failure and pullout. The assumption, in which a planar failure surface crosses through the toe of the wall, was demonstrated to be a reasonable approximation for vertical or near-vertical walls with homogeneous backfill soil [2]. Allen et al. [3] emphasized the importance of stiffness and hence introduced the K-Stiffness Method and subsequent Simplified Stiffness Method [4], [5]. The Simplified Stiffness method is an empirical method to calculate reinforcement loads for geosynthetic reinforced retaining walls under serviceability conditions. However, some research argued that the K-Stiffness Method violates static equilibrium rules [6]. Another phenomenon, not included in those design

* Corresponding author: erolguleristanbul@gmail.com

approaches, is the vertical downward force to the facing blocks and leveling pad resulting from shear displacement of the compressible backfill soil against the facing.
The best design approach would be to consider all the material parameters and the true geometry of the wall. This can be achieved by a stress-strain analysis such as Finite Element (FE) or Finite Difference (FD). However, such analyses are quite complicated and therefore for a routine design they are most likely to be not implemented. Another advantage of a stress-strain analysis is the determination of displacements, which is becoming more and more important in civil engineering design. As a matter of fact, the trend is that a serviceability limit state (SLS) analysis is requested more often nowadays along the ultimate limit state (ULS) analysis. The general trend is that if a structure satisfies the serviceability limit state criteria, it is very likely that the ultimate state condition will also be satisfied.
This paper presents an expression to predict the horizontal displacement of a GRS wall using a set of data obtained from about sixty-four finite element model configurations. The horizontal displacement expression includes wall-height, internal friction angle and elastic modulus of backfill, length, spacing and stiffness of geosynthetic reinforcements. Our intention is that a designer, who normally uses limit equilibrium analysis to design a geosynthetic reinforced soil retaining wall, also calculates the horizontal displacement using the expression given in this paper in order to find out if the design is suitable for the current local conditions.

2 Details of the Finite Element Mesh

Horizontal displacement estimation was realized based on sixty-four FE model configurations created in MIDAS GTS NX FE software. The basic meshing style of all configurations was similar. As an example, the details of the 3 m-high wall mesh are demonstrated in Fig. 1. The mesh was constructed from 2-dimensional (2D) plane-strain square elements with 0.25 m side length. The bottom of the mesh includes linear elastic block elements with 5 MPa modulus of elasticity. The bottom block layer is fixed vertically and horizontally with fixities (Fig. 1 and Fig. 2). The block layer continues to exist on the left-side of the mesh toward the top. Each block element on the left-side is bounded horizontally with a linear interface. The rest of the mesh is composed of backfill elements with Mohr-Coulomb soil properties. The modulus of elasticity and the internal friction angles of the different combinations are given in Table 1. The linear interface also exists between the bottom blocks and the backfill. The geo-reinforcements lay between blocks and the backfill and they are constructed from beam elements with 1 mm thicknesses. The moduli (J_{geo}) of the geo-reinforcements are variable and are tabulated in Table 1. In each configuration, a staged-construction was applied. At each construction stage, a layer in 0.25 m height was activated. After all the layers were activated, the horizontal displacement ($disp_x$) was recorded.

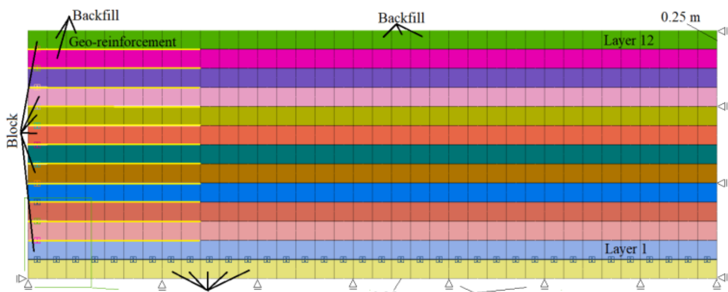

Fig. 1. The mesh details of the 3 m- high geosynthetic reinforced soil wall

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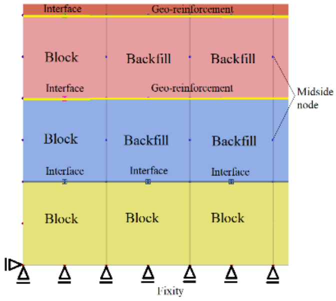

Fig. 2. The elements of the mesh

Table 1. The details of the finite element combinations

No	H (m)	S_v (m)	$E_{backfill}$ (MPa)	J_{geo} (kN/m)	L_r (m)	$\phi_{backfill}$(°)	No	H (m)	Sv (m)	$E_{backfill}$ (MPa)	J_{geo} (kN/m)	L_r (m)	$\phi_{backfill}$(°)
1-3	6	0.25, 0.5, 1	30	500	4.5	32	41-43	9	0.25, 0.5, 1	30	500	6	32
4-8	6	0.5	10, 20, 50, 70, 100	500	4.5	32	44-48	9	0.5	10, 40, 50, 70, 100	500	6	32
9-13	6	0.5	30	100, 300, 400, 1000	4.5	32	49-53	9	0.5	30	100, 300, 400, 1000, 1500	6	32
14-15	6	0.5	30	500	3-6	32	54-55	9	0.5	30	500	4.5, 9	32
16-20	6	0.5	30	500	4.5	24, 26, 28, 30, 38	56-60	9	0.5	30	500	6	24, 38
21-23	3	0.25, 0.5, 1	30	500	2	32	61	5	0.5	30	500	3	32
24-28	3	0.5	10, 40, 50, 70, 100	500	2	32	62	4	0.5	30	500	3	32
29-33	3	0.5	30	100, 300, 400, 1000, 1500	2	32	63	8	0.5	30	500	4.5	32
34-35	3	0.5	30	500	1.5, 3	32	64	7	0.5	30	500	4.5	32
36-40	3	0.5	30	500	2	24, 26, 28, 30, 38							

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2.1 Derivation of the displacement formula

The formula was derived using the maximal horizontal displacement data collected from 64 model combinations. The model combinations include 3, 4, 5, 6, 7 and 8 m (H) high-walls (Table 1). The modulus of elasticity $E_{backfill}$, geo-reinforcement modulus (J_{geo}), internal-friction angle of the backfill ($\phi_{backfill}$), length of the geo-reinforcement (L_r) and vertical geo-reinforcement spacing (S_v) ranged between 10-100 MPa, 100-1500 kN/m, 24°-38°, 1.5-9 m and 0.25-1 m, respectively (Table 1). The horizontal displacement formula is given in Eq. 1. It includes some fitting coefficients presented in Table 2. These coefficients were determined with the Solver program in MS Excel®. The R^2 value between the FE model and that estimated by the formula is 0.9994. The related plot is given in Fig. 4. The same formula derivation method was previously used to derive pile settlement and load, horizontal earth pressures formulas by the second author [1, 2, 3].

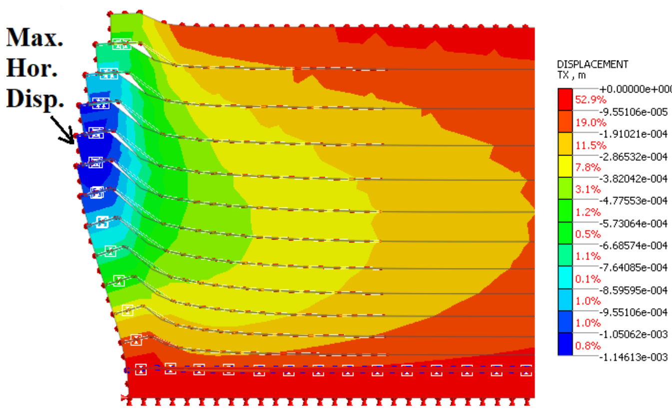

Fig. 3. Typical horizontal displacement plot in a 3 m high wall

$$disp_x = a.\left(\frac{H}{3}\right)^b.(s_v)^c.\left(\frac{E_{backfill}}{30000}\right)^d.\left(\frac{J_{geo}}{100}\right)^e.(L_r)^f.\left(\frac{\emptyset_{soil}}{32}\right)^g + h \quad (1)$$

Table 2. The fitting coefficients of the formula

a	b	c	d
0.00915218	3.02384115	0.70776171	-0.04497259
e	f	g	h
-0.664299883	-0.03795818	-2.09864450	-0.00018877

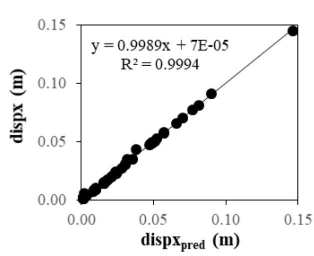

Fig. 4. Horizontal displacement calculated by the FE program vs. estimated by the formula

2.2 Results

The model combinations presented in Table 1 were derived by each time modifying a single parameter of the baseline combination. The components of the baseline combination are [H=6 m, S_v = 0.5 m, E_{soil} = 30 MPa, J_{geo} = 500 kN/m, L_r = 4.5 m, $\phi_{backfill}$=32°]. As an example, the change in the horizontal displacement ($disp_x$) of the baseline combination is plotted with respect to the wall height (H) in Fig 5. According to the plot, there is a parabolic relationship between $disp_x$ and H. Fig. 6 demonstrates the relationship between vertical geo-reinforcement spacing (S_v) and $disp_x$. According to the figure, there is a linear relationship between S_v and $disp_x$. The influence of S_v on $disp_x$ is quite small when the wall height is around 3 m. It is more pronounced when the wall height is equal or greater than 6 m. The influence of the modulus of elasticity of the backfill ($E_{backfill}$) on $disp_x$ is more visible when the $E_{backfill}$ values is smaller than 30 MPa (Fig.7). Above all, one of the most influential parameters on $disp_x$ is the internal friction angle of the backfill ($\phi_{backfill}$) (Fig. 8). In contrast, the length of the geo-reinforcement (L_r) has the least influence on $disp_x$ (Fig. 9). One other important parameter on $disp_x$ is the modulus of the geo-reinforcement (Fig. 10).

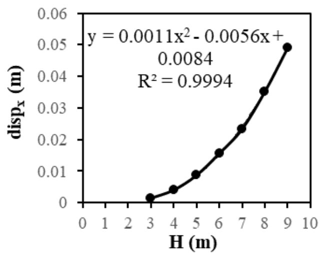

Fig 5. Horizontal wall displacement ($disp_x$) vs. wall-height H

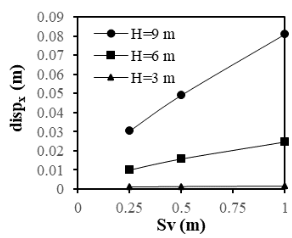

Fig 6. Horizontal wall displacement ($disp_x$) vs. vertical geo-reinforcement spacing S_v

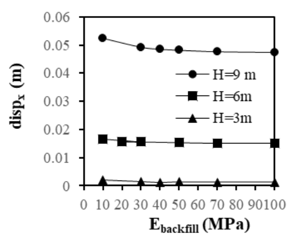

Fig 7. Horizontal wall displacement ($disp_x$) vs modulus of elasticity of the backfill ($E_{backfill}$)

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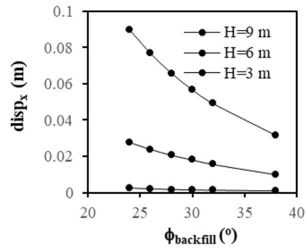

Fig 8. Horizontal wall displacement (disp$_x$) vs internal friction of the backfill ($\phi_{backfill}$)

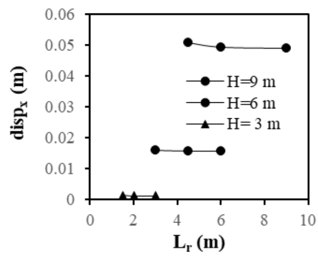

Fig 9. Horizontal wall displacement (disp$_x$) vs geo-reinforcement length (L_r)

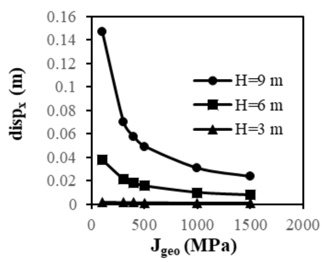

Fig 10. Horizontal wall displacement (disp$_x$) vs geo-reinforcement modulus (J_{geo})

3 Conclusion

In this paper, an expression has been developed to predict the horizontal deformation of a GRS wall using a set of data obtained from about sixty-four finite element model configurations. The input parameters include the modulus of elasticity, geo-reinforcement modulus, internal-friction angle of the backfill, length of the geo-reinforcement and vertical geo-reinforcement spacing. In the light of the findings, the following conclusions can be drawn:

- The most influential input parameter on the horizontal wall-displacement is the wall-height. There is a parabolic relationship between the horizontal wall-displacement and the wall-height.
- Other critically influential parameters on the horizontal wall-displacement are the internal friction angle, the vertical spacing and the modulus of the geo-reinforcement.
- The length of the geo-reinforcement does not make much difference when the reinforcement length is greater than 2/3 of the wall-height.

- The modulus of elasticity of the backfill is not very influential on the horizontal wall-displacement when the value is greater than 30 MPa.
- This study offers a horizontal wall-displacement formula for GRS walls. As a future study, the displacement formula should be verified with physical GRS wall models.

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