Numerical Study of Retaining Walls with Non-Uniform Reinforcement

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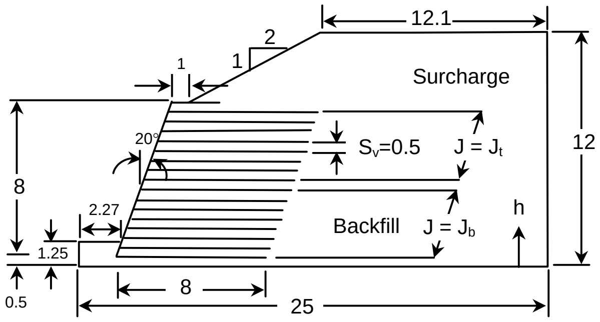
ABSTRACT: The paper presents the results of numerical analyses that investigate the structural response of reinforced-soil wall systems with more than one reinforcement type (non-uniform reinforcement). Reinforced-soil wall models with different reinforcement arrangements and stiffness values are included in the study. The reinforcement types and mechanical properties were selected to match polyester geogrid and woven wire mesh products. The model walls are mainly of wrapped-face type. Additional wall models with tiered and vertical gabion facings are included for comparison purposes. The numerical simulation of wall models using the program FLAC included staged construction of the wall and placement of reinforcement at uniform vertical spacing followed by a sloped surcharge. The wall lateral displacements and back-calculated lateral earth pressure coefficients behind the facing in all non-uniform reinforcement wall models show a clear dependence on relative stiffness values of reinforcement layers at different elevations. An equation is proposed that can be used to estimate the equivalent lateral earth pressure coefficient based on reinforcement stiffness values and non-uniform reinforcement configurations for the wrapped-face wall models in the current study.

1 INTRODUCTION

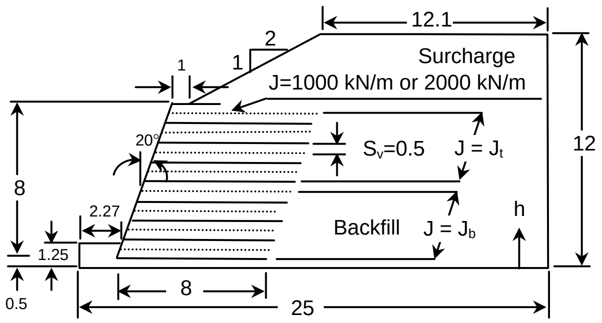
The paper reports the results of a numerical study which examines the possibility of combining stiff and relatively soft reinforcement materials to reduce the cost of reinforcement while maintaining adequate internal stability as well as acceptable wall deformations and reinforcement loads. The term non-uniform reinforcement in the title of the paper is used generically to identify reinforced-soil walls in which two or more reinforcement types are used.

The wall models are largely wrapped-face type with different reinforcement arrangements: single reinforcement type (uniform reinforcement); two reinforcement types placed in top and bottom sections of the wall (grouped reinforcement), two reinforcement types in alternating layers (alternating reinforcement); and, configurations with three reinforcement types (mixed reinforcement). In addition, a limited investigation of the influence of tiered and vertical gabion-faced wall construction was undertaken.

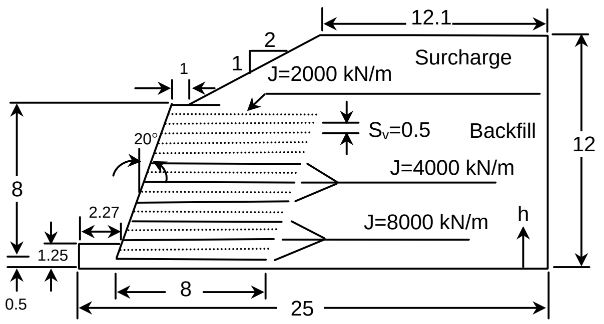
The numerical analyses were carried out using the program FLAC (Itasca 1998). The structural response of wall models at the end of construction is presented in terms of facing lateral displacements, maximum reinforcement load and equivalent earth pressure coefficient, K(h), back-calculated from reinforcement loads. The variation of horizontal lateral earth pressure coefficient,



a) Walls 1, 3-5, 7-11 (wrapped-face, uniform and grouped reinforcement)



b) Walls 2 & 6 (wrapped-face, alternating reinforcement)



c) Wall 12 (wrapped-face, mixed reinforcement)

Figure 1. Walls with uniform and non-uniform reinforcement configurations. Notes: (see also Table 1); all dimensions in metres.

K(h), with backfill depth and reinforcement stiffness is examined. The results of this study are used to propose an equation that can be used to estimate lateral earth pressures for the calculation of reinforcement loads for non-uniform reinforced wrapped-face walls with the configurations investigated.

2 WALL MODELS

2.1 *General description and geometry*

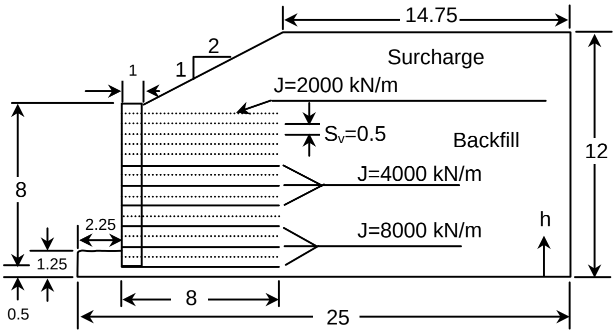
A total of sixteen model wall configurations were included in the study (Table 1). The parameter set consists of fourteen 8m-high wrapped-face model walls (Walls 1-12, 15 and 16, Figure 1a). One model wall with a gabion facing (Wall 13, Figure 1d) was investigated to examine the influence of facing type and vertical wall batter on wall behaviour. Finally, a model wall with a combined wrapped-face and gabion facing configuration (Wall 14, Figure 1e) was also included in the study to examine the influence of a tiered wall configuration on structure response.

Each of the wrapped-face model walls had an inclined facing with a batter angle β = 20°. Each structure included a broken-back slope (*sloped surcharge*) with an initial 2H:1V slope.

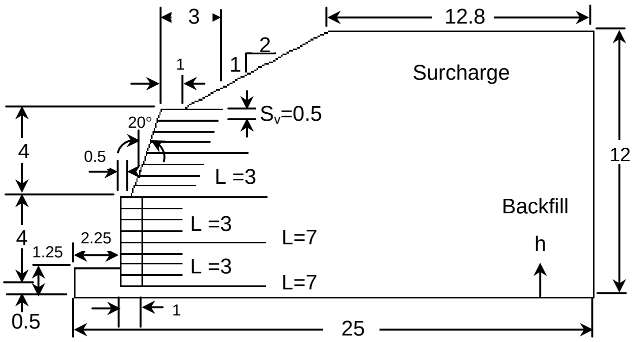
A fixed boundary condition representing a rigid foundation was assumed at a depth of 0.5 m below the lowermost reinforcement layer in all wall models. In addition, the foundation soil zone in numerical models was extended to a distance of 2.25 m in front of the wall toe and to a depth of 1.25 m above the foundation. The wall models had a total width of 25 m, in order to contain any shear failure wedge that developed in the retained backfill.

2.1.1 *Reinforcement stiffness and arrangement*

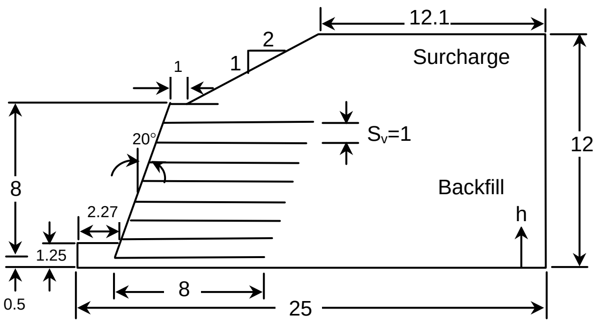
The reinforcement length, L, in all wall models (except for Wall 14) was 8 m, which corresponds to a length to height ratio L/H=1 for the reinforced soil zone. This reinforcement length value is larger than the minimum length required by FHWA (1996) for static stability. The vertical spacing, S_v, between the reinforcement layers was constant and equal to 0.5 m in all model configurations except Walls 15 and 16.



d) Wall 13 (vertical gabion-faced, mixed reinforcement)



e) Wall 14 (tiered wrapped/gabion-faced wall, uniform reinforcement)



f) Walls 15 & 16 (wrapped-face, uniform reinforcement, S_v = 1m)

Figure 1. (continued) Wall configurations with mixed and uniform reinforcement. Notes: (see also Table 1); all dimensions in metres.

The reference reinforcement stiffness values were chosen from properties reported for woven wire mesh and polyester geogrid reinforcement products (Agostini et al. 1987, Terram 1994, Maccaferri 1995, Lo et al. 1990). However, additional stiffness values are included in this investigation to extend the range of the parametric study.

2.1.1.1 Figure 1a

Walls 1, 3-5 and 7-11 include uniform reinforcement layers and two reinforcement types in each wall placed in different arrangements. One reinforcement type is associated with the top half of the reinforced soil zone and the second type with the bottom half in the grouped reinforcement configurations.

Walls 4 and 8 contain uniform reinforcement with stiffness values equal to the average of stiffness values in Walls 1-3 and 5-7, respectively (Table 1).

Wall 9 is a variation of Wall 8, and contains two slightly different reinforcement stiffness values in a grouped reinforcement configuration.

Walls 10 and 11 are uniformly reinforced with each of the component reinforcement types used in Walls 5-7.

2.1.1.2 Figure 1b

Walls 2 and 6 are constructed with an alternating reinforcement arrangement composed of layers of relatively stiff and soft reinforcement materials.

2.1.1.3 Figure 1c

Wall 12 is a wrapped-face wall constructed with a mixed reinforcement arrangement using three different stiffness values that decrease in magnitude towards the top of the wall.

2.1.1.4 Figure 1d

Wall 13 is identical to Wall 12 but with a vertical gabion-face.

2.1.1.5 Figure 1e

Wall 14 is an actual project cross section, which is included in this study as an example of a typical tiered wall configuration. The wall consists of an inclined wrapped-face section seated on a gabion facing system with a combination of short secondary reinforcement lengths (L=3 m) and longer primary reinforcement layers placed at vertical spacings of 2 m. The shorter reinforcement layers

Table 1. Wall model reinforcement stiffness and arrangement

Wall No.	Figure 1	Reinforcement configuration	Reinforcement stiffness at bottom, J_b (kN/m)	Reinforcement stiffness at top, J_t (kN/m)
1	a	grouped	5500	1000
2	b	alternating	5500, 1000	5500, 1000
3	a	grouped	1000	5500
4	a	uniform	3250	3250
5	a	grouped	8000	2000
6	b	alternating	8000, 2000	8000, 2000
7	a	grouped	2000	8000
8	a	uniform	5000	5000
9	a	grouped	5500	5000
10	a	uniform	2000	2000
11	a	uniform	8000	8000
12	c	mixed	8000, 4000, 2000	
13	d	mixed	8000, 4000, 2000	
14	e	uniform	5500 (primary and secondary reinforcement)	
15	f	uniform	5500 with S_v = 1.0m	
16	f	uniform	8000 with S_v = 1.0m	

(L=3 m) in the gabion wrapped-face sections of the wall are different products (i.e. woven wire mesh and polyester geogrid) but have the same stiffness values (J=5500 kN/m).

2.1.1.6 Figure 1f

Walls 15 and 16 are uniform reinforcement walls with a reinforcement spacing twice as large as the reference spacing used in the other model walls (i.e. S_v=1 m).

2.2 *Soil*

The backfill soil and the sloped surcharge are modeled as purely frictional, elastic-plastic materials with the Mohr-Coulomb failure criterion. The friction angle, dilation angle and unit weight of backfill (including the sloped surcharge) were assumed as ϕ=32°, ψ=12° and γ=18 kN/m, respectively. The bulk modulus and shear modulus values of the backfill material were assumed as B=16 MPa and G=9.6 MPa, respectively.

Greater strength and elastic property values were assigned to the foundation region in wall models with a gabion facing in order to provide sufficient foundation bearing resistance directly below the facing (i.e. ϕ=35°, c=5 kPa, ψ=12°, B=800 MPa and G=480 MPa).

The rockfill in the gabion system was modeled as a frictional material with a Mohr-Coulomb failure criterion similar to the backfill but with a higher friction angle (i.e. ϕ=40°).

2.3 *Numerical approach*

The numerical simulations were carried out using the program FLAC (Itasca 1998) and assumed plane-strain conditions. The simulations modeled the sequential bottom-up construction of the wall facing, soil, reinforcement and sloped surcharge. A fixed boundary condition in the horizontal direction was assumed at the numerical grid points at the backfill far-end boundary. The backfill of each wall model was elevated in lifts of 0.5 m and the reinforcement layers were placed in the model as each reinforcement elevation was reached.

The numerical models at each stage were solved to equilibrium with a prescribed tolerance before placing the next lift of soil and reinforcement layers. The wrapped-face portion of each reinforcement layer at the facing (i.e. between two subsequent soil layers) was assigned the same mechanical properties as those of the lower layer.

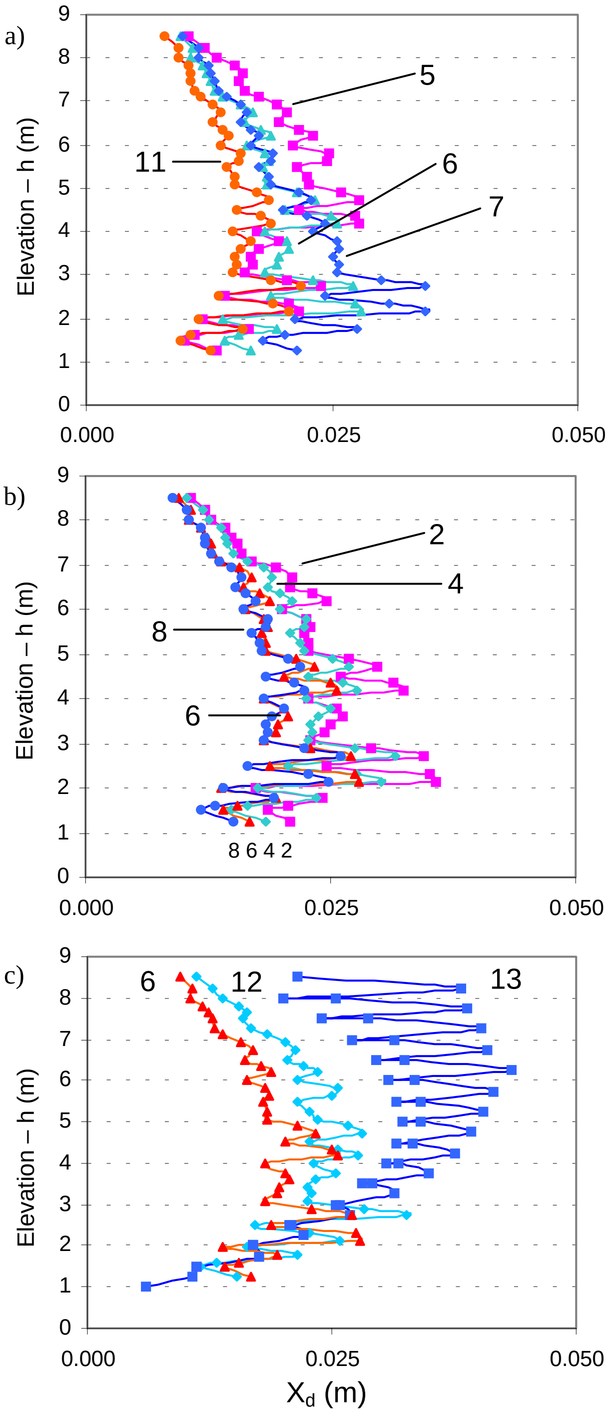


Figure 2. Lateral displacement profiles of reinforced model walls (numbers on plots refer to wall models in Table 1).

The reinforcement layers including the wrapped-face portions and gabion facing were modeled using linear elastic, perfectly plastic (FLAC) cable elements with negligible compression strength. The cable elements representing the reinforcement interacted with the backfill material through (FLAC) grout interfaces. The stiffness and strength of the grout interface - which was modeled as a spring-slider system - were set to k_b = 100 MPa and s_b = 1 MPa, respectively.

The numerical results presented in the paper correspond to the end of construction for each wall after the placement of the entire sloped surcharge.

3 RESULTS

3.1 *Wall lateral displacements*

Figure 2 shows the calculated lateral displacement of walls, X_d, at end of construction. Parameter h in the figure is elevation measured from the base of the wall (Figure 1). The data in the figure is restricted to numerical results of selected walls to illustrate important differences in wall response.

In Figure 2a, Wall 11 - with uniformly stiff reinforcement over the entire height - shows the smallest amount of lateral displacement. Replacing half of the reinforcement layers with a less stiff reinforcement material (Walls 5-7) increases the wall lateral displacement. However, the maximum displacement value and the displacement distribution pattern depend on the reinforcement arrangement. Placing the less stiff reinforcement in the upper half of the wall (Wall 5) results in local bulging of the facing in the upper half of the wall height. The wall lateral displacement within the lower half does not increase noticeably (compared to Wall 11). Placing the less stiff reinforcement in the lower half of the wall height (Wall 7) results in a considerable increase in wall lateral displacement in the lower half of the wall height (by about 70% on average in comparison with Wall 11). Distributing the less stiff reinforcement material evenly between stiff reinforcement layers (Wall 6) results in the same pattern of displacement profile as the uniform reinforcement case but with an increase in the magnitude of wall lateral displacement at all reinforcement elevations.

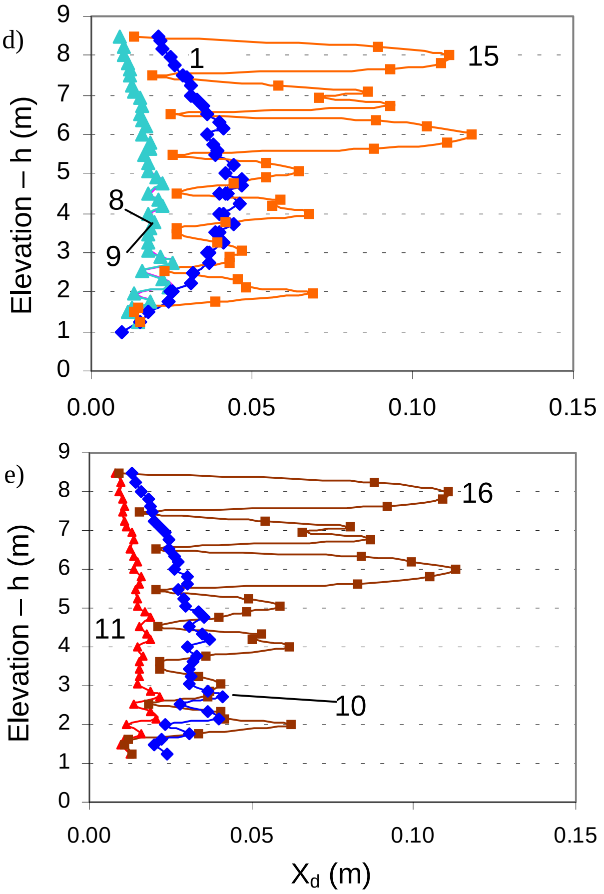


Figure 2. (continued) Lateral displacement profiles of reinforced model walls (numbers on graphs refer to wall models in Table 1).

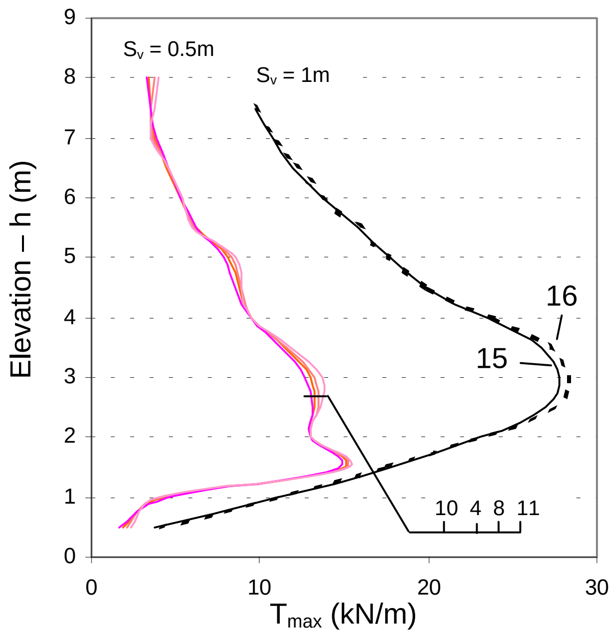
Overall, wall lateral displacement for the alternating reinforcement arrangement (Wall 6) is less than the displacement of either of the grouped reinforcement arrangements (Walls 5 and 7). Therefore, an alternating reinforcement scheme appears to be a more effective reinforcement arrangement than grouped schemes with the same amount of reinforcement material to limit wall lateral displacements.

Comparison of displacement results for Walls 2 and 4, and 6 and 8 in Figure 2b shows the influence of using an alternating reinforcement arrangement with the same average reinforcement stiffness as an otherwise nominal identical configuration with a uniform reinforcement type. The alternating reinforcement configurations showed a slightly larger amount of deformation at end of construction. However, compared to the magnitude of differences between other pairs of wall models, the differences were small enough that it is reasonable to assume for the reinforcement configurations investigated that each alternating reinforcement configuration gave a similar deformation response to the equivalent (on average) uniform reinforcement spacing arrangement.

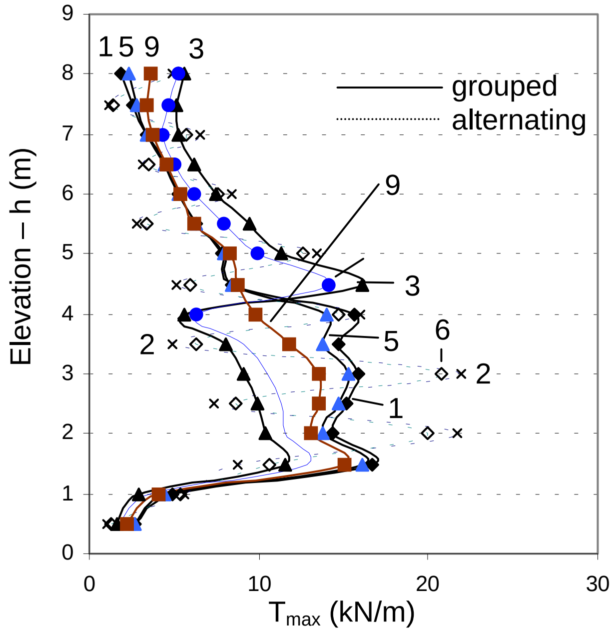
The influence of reinforcement arrangement on wall displacements for a wrapped-face wall is illustrated in Figure 2c. Wall 6 constructed with two reinforcement layers in an alternating reinforcement scheme gave generally lower displacement values than the nominal identical wall (Wall 12) with a mixed reinforcement arrangement.

The effect of facing type and batter on wall displacement can also be examined in Figure 2c. Wall 12 with an inclined wrapped-face at 20° to the vertical generated less lateral displacement at the end of construction than Wall 13 constructed with a vertical gabion facing. It may be concluded that the effect of an inclined face is more effective than a vertical wall constructed with a relatively stiffer gabion column in reducing wall displacements. The displacement plots also show that the pattern of displacement profiles is very different. The maximum end-of-construction displacement occurred much higher up the face of the gabion wall (~ 0.75H) compared to the wrapped-face wall (~ 0.35H). The displacement of the wrapped-face wall is considered to be due to lateral spreading of the backfill under soil self-weight while the pattern of displacement for the vertical gabion wall is due to rotation of the facing column about the toe.

Figure 2d shows that the displacement profiles for Walls 8 and 9 constructed with very similar reinforcement stiffness values and a uniform and grouped reinforcement arrangement, respectively, are indistinguishable (within 10% in this analysis). Comparison of the plots in the figure shows that the combined influence of reduced reinforcement length and tiered wall construction (Wall 14) resulted in greater facing displacements than Wall 9. However, comparison of displacements for Walls 14 and 15 shows that the combined influence of tiered wall construction and reduced reinforcement spacing was more effective in reducing deformations than a less steep wrapped-face structure constructed with a wider reinforcement spacing.



a) uniform reinforcement



b) grouped and alternating reinforcement

Figure 3. Distributions of maximum reinforcement load (wrapped-face walls only)

Figure 2e illustrates the influence of reinforcement stiffness and spacing on wall deformation. Not unexpectedly, comparison of the wall displacements for the uniformly reinforced wall with stiffer (Wall 11) and weaker (Wall 10) reinforcement shows that the stiffer reinforcement wall deflected less. Doubling the spacing of the reinforcement layers in Wall 16 (compared to Wall 11) resulted in greater displacements. Furthermore, peak displacements for Wall 16 were greater than those recorded for Wall 10 that was constructed with a reinforcement with 25% of the stiffness of Wall 16 and twice the number of reinforcement layers. Hence, based on this comparison, increasing the number of reinforcement layers may be a more effective way to reduce wall deflections than simply increasing the reinforcement stiffness.

3.2 *Reinforcement loads*

Figure 3 shows the distributions of maximum reinforcement load, T_{max}, for the wrapped-face walls at the end of construction. The plots in Figure 3a summarize the reinforcement loads for walls with a single reinforcement type and two different reinforcement spacing values. In general, reinforcement loads increase linearly with depth until the rigid frictional foundation boundary is approached. Earth pressures developed at the bottom of each wall are carried by the model boundary and reinforcement loads at the bottom of the wall are correspondingly attenuated. At the end of construction, the magnitude and distribution of maximum reinforcement load for the same geometrical arrangement of reinforcement is essentially independent of reinforcement stiffness for the range J=1000 to 8000 kN/m in this study. This observation is consistent with the results of an earlier numerical study which included predictions of the static reinforcement loads behind idealized propped-panel walls at the end of construction (Bathurst and Hatami 1998). However, the same earlier study revealed that the distribution of reinforcement loads was essentially uniform suggesting that the type of facing (e.g. propped panel or flexible wrapped-face) will have a large influence on both the distribution and magnitude of reinforcement loads. This conclusion is supported by the results of recent full-scale geosynthetic reinforced-soil wall tests reported by Bathurst et al. (2000)

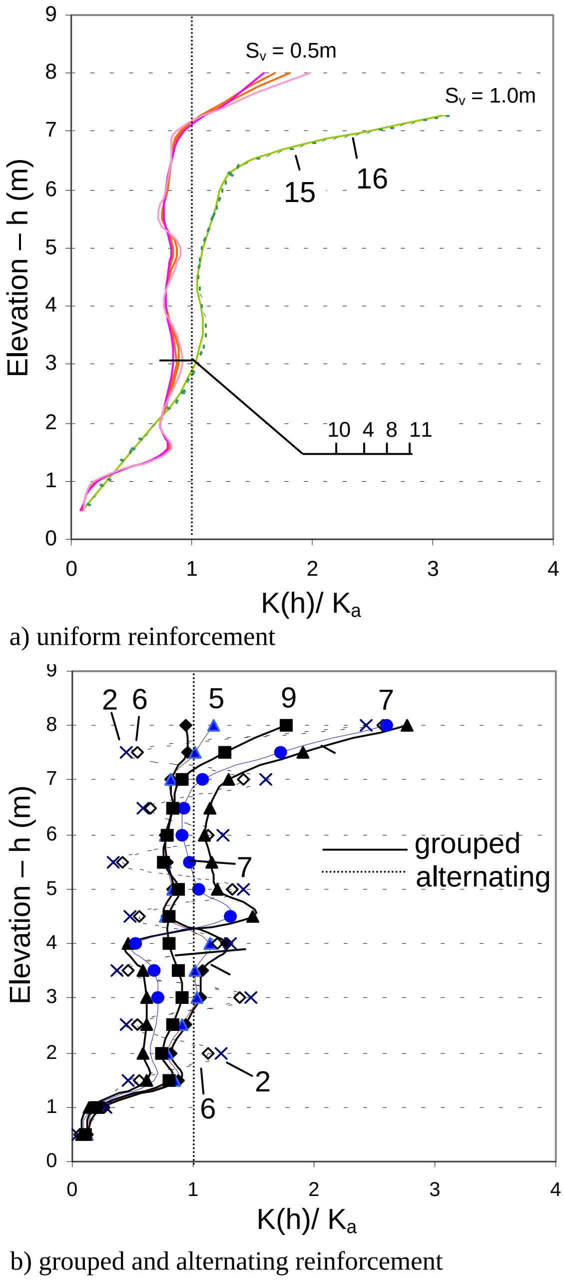


Figure 4. Normalized equivalent lateral earth pressure coefficient.

that have examined the influence of hard-face and wrapped-face construction on the development of reinforcement loads.

The presence of grouped or alternating reinforcement arrangements causes a deviation from the general pattern and magnitude of reinforcement loads described above (see Figure 3b). Grouped reinforcement schemes with different stiffness sections in the top and bottom of the wall show that the stiffer reinforcement sections attract more load than the adjacent less stiff reinforcement. For example in Walls 1 and 5 the maximum reinforcement load is greater and practically constant over the lower half of the wall height. The reason is that these walls undergo considerable displacement in the upper half due to the soft reinforcement in that region (see Wall 5, Figure 2a). This puts additional load on the upper reinforcement layers in the lower half of the wall and changes the generally linear load variation with depth to a more uniform distribution.

For walls with a spacing S_v = 0.5 m, the largest reinforcement loads and the largest local deviations from a smooth distribution of load occur for alternating reinforcement schemes (Wall 2 and 6 in Figure 3b). It appears that the stiff and soft reinforcement layers in an alternating reinforcement wall act as primary and secondary reinforcement layers, respectively, with the stiffer reinforcement layers attracting larger lateral earth loads. It can be argued that the effective spacing, S_v, between primary layers results in stiff reinforcement layer loads that are equivalent to the load distribution that may be expected for a uniform reinforcement wall with $0.5 < S_v < 1$ m (e.g. compare uniform reinforcement Wall 11 with S_v = 0.5 m and Wall 16 with S_v = 1m with Wall 6).

3.3 *Lateral earth pressure coefficient*

Figure 4 shows the distribution of normalized lateral earth pressure coefficient $K(h)/K_a$ acting behind each wall where:

$$K(h) = T_{max}(h) / \gamma (H - h) S_v \qquad (1)$$

Here, $T_{max}(h)$ is the maximum reinforcement load at elevation h, γ is the soil unit weight, H is the wall height, S_v is the vertical spacing between reinforcement layers and K_a is the active Rankine earth pressure coefficient.

For uniform reinforcement configurations (Figure 4a), the lateral earth pressure coefficient increases with reinforcement spacing which can be expected from the data in Figure 3a and Equation 1. For the range of reinforcement stiffness values examined, a uniform reinforcement distribution in wrapped-face walls results in values of K(h) that are independent of reinforcement stiffness. In addition, for a given reinforcement spacing, K(h) is reasonably constant at a value close to that for K_a with the exception of reinforcement layers close to the top and bottom of the wall. Reinforcement forces at the top of walls that are in excess of values calculated from earth pressure theory have been noted in earlier numerical simulation work by Bathurst and Hatami (1998) and from actual full-scale experimental wall tests (Bathurst et al. 2000).

The variation of normalized lateral earth pressure coefficient with depth in Figure 4b shows a clear influence of relative reinforcement stiffness values in all reinforced wall models with non-uniform reinforcement configurations. In Walls 2 and 6 with alternating reinforcement, K(h) depends on the stiffness of the reinforcement layer at elevation h. The stiffer reinforcement layers and soft reinforcement layers correspond to reasonably constant but different values of K(h). In Walls 3 and 7, K(h) has two distinct and practically constant values whereas in Walls 1 and 5 with softer reinforcement grouped in the top section of the wall, K(h) decreases linearly with depth in the bottom half. This is due to constant maximum reinforcement load over the lower half of the wall height as explained in Section 3.2. According to Equation 1, a constant reinforcement load with depth is equivalent to K(h) values that decrease with depth.

The variation of K(h) with the stiffness of reinforcement layers for non-uniform reinforced retaining walls can be formulated as:

$$K_i/K_{av} = C(J_i/J_{av})^{\alpha} \qquad (2)$$

where $K_i = K(h_i)$ is the earth pressure coefficient corresponding to reinforcement layer i calculated from Equation 1 and J_i is the corresponding stiffness value. Parameters K_{av} and J_{av} are average values of K_i and J_i over a selected middle height of the walls. The reinforcement load data within 1 m of the top and bottom of each wall model were disregarded in calculating the values of K_{av} to exclude boundary effects. The values of C and α were obtained based on a regression analysis of model results and are presented in Table 2. Inspection of the values of C and α in the table indicates that the value of coefficient C is essentially constant and very close to 1 for all non-uniform reinforced wall configurations included in the study. This confirms that equivalent lateral earth pressure coefficient behind non-uniform reinforced wrapped-face walls is largely dependent on J and not directly dependent on depth. The value of exponent α depends on the reinforcement arrangement. In a nearly-uniform reinforcement design (Wall 9), the value of α is almost zero which indicates a uniform distribution of lateral earth pressure coefficient throughout the middle wall height and is independent of reinforcement stiffness, J. When reinforcement is grouped into two separate regions with large differences in stiffness values, the lateral earth pressure coefficient, K(h), will be stiffness dependent. The value of K(h) is also influenced by non-uniform reinforcement arrangement. This dependence is least when the soft reinforcement is placed in the top half of the wall height (Walls 1 and 5 with $\alpha \sim 1/8$). The value of K(h) is more strongly dependent on J in the case of alternating reinforcement as compared to grouped reinforcement arrangements for the same set of reinforcement material types (Walls 2 and 6 with $\alpha \sim 2/3$). When the reinforcement layers are placed in a mixed configuration (Walls 12 and 13) or the stiffer reinforcement is collectively placed on the top of the softer reinforcement (Walls 3 and 7), K(h) is moderately dependent on J ($\alpha \sim 1/3 - 1/2$).

4 CONCLUSIONS

The results of analyses have shown that placing soft reinforcement layers between relatively stiffer reinforcement layers is a more efficient strategy to reduce wall lateral displacements compared to

Table 2. Wall model earth pressure parameters (non-uniform reinforcement)

Wall No.	Reinforcement configuration	Earth pressure parameters (Equation 2)	
		C	α
1	grouped	1.03	0.1291
2	alternating	1.0583	0.668
3	grouped	1.0716	0.4432
5	grouped	1.0191	0.1216
6	alternating	1.0428	0.6345
7	grouped	1.0421	0.3320
9	grouped	0.998	-0.0276
12	mixed	1.0315	0.4476
13	mixed	1.0048	0.4649

comparable grouped reinforcement schemes. The displacement shape of wall with an alternating reinforcement scheme was similar to that of a uniformly reinforced wall with the same average reinforcement stiffness and did not generate the large bulging shape of comparable grouped reinforcement schemes. Reinforcement loads and equivalent lateral earth pressure coefficient values for uniform or near-uniform reinforcement schemes were independent of reinforcement stiffness for the same reinforcement spacing. However, the results of the analyses indicated a clear dependence of reinforcement load and equivalent earth pressure coefficient value on the relative stiffness of reinforcement layers placed in grouped or mixed configurations. For non-uniform reinforced walls with large differences in reinforcement stiffness values (greater than a factor of 2 in this study), K(h) for a reinforcement layer increases with reinforcement stiffness value, J, and its dependence on J varies with the reinforcement arrangement.

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