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Failure mechanisms governing reinforcement length of geogrid reinforced soil retaining walls

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ABSTRACT

Current design practice of reinforced soil retaining walls is based on the limit equilibrium approach. The walls are designed for both external and internal stability criteria. Design reinforcement length should be such that minimum required safety factors are fulfilled for all failure modes. Most agencies require minimum reinforcement length equal to 70 percent of wall height. However, it is not always possible to have enough space behind a wall to accommodate these required reinforcement lengths due to an existing natural rock formation, man-made shoring system, or the presence of another reinforced soil retaining wall. This study was performed to investigate governing failure mode in determining the required minimum reinforcement length and also to investigate the possibility of shortening the specified minimum reinforcement lengths. Effect of different parameters involved in the design of reinforced soil retaining walls on the required minimum reinforcement length and the governing failure mode were studied. Parameters considered included wall height, surcharge, reinforcement vertical spacing, reinforced soil properties, backfill/retained soil properties, and foundation soil properties. Results indicated that both external and internal failure modes can be governing criteria in determining the required minimum reinforcement length depending on the parameters involved for a specific wall. In addition, it may be possible to use reinforcement lengths as low as almost 50 percent of the wall height, instead of 70 percent as required by many agencies around the world. This paper presents the results of parametric studies conducted, including the effect of different parameters on the required minimum reinforcement length and the governing failure criteria.

1. Introduction

The use of reinforced soil retaining walls has increased tremendously since the 1970's. They became the most common wall type preferred, especially for transportation projects, because of their rapid construction, cost-effectiveness, and aesthetics. In addition, their reliability, proven durability, simple construction techniques, good seismic performance, and ability to tolerate large deformations without structural distress also help in facilitating the acceptance of reinforced soil retaining walls [1]. The early reinforced soil retaining walls used metallic strips to reinforce soil and precast concrete panels as facing units to retain the soil at the face of the wall. Welded wire grid reinforcements in the mid-1970's, geosynthetic reinforcements in the 1980's, and segmental retaining wall units in the 1990's were introduced and contributed to the increased use of reinforced soil retaining walls considerably [2].

For the design of reinforced soil retaining walls a minimum reinforcement length, L_{min}, of 0.7H, where H is the wall height, is usually specified or recommended by specifications and guidelines. Although most agencies worldwide require the minimum reinforcement length as 0.7H, some agencies adopted different criteria. For example, Hong Kong guidelines ask for reinforcement lengths as low as 0.5H while Brazilian guidelines ask for a minimum of 0.8H [1]. The Federal Highway Administration (FHWA) 2001 guidelines recommends the minimum reinforcement length-to-wall height ratio as 0.7 and recognize that longer reinforcement lengths are required for structures subject to surcharge loads while shorter lengths can be used in special conditions [3]. The American Association of State Highway and Transportation Officials (AASHTO) 2002 specifications require a minimum reinforcement length of approximately 70 percent of the wall height and not less than 2.4 m [4]. National Concrete Masonry Association (NCMA) 2002 design manual requires minimum reinforcement length as 0.6H, which is an empirical constraint to prevent wall construction in limited spaces [5]. British Standard BS8006 (1995) requires that minimum reinforcement length for walls with normal retaining function should be maximum of 0.7H and 3 m [6]. There are also other publications

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recommending minimum reinforcement lengths longer than 0.7H, e.g. Liu and Evett [7] specifies 0.8H for overall stability.

Reinforced soil retaining walls with limited reinforcement zone was studied by Leshchinsky et al. [8] and they developed design charts acknowledging that the charts are not applicable for all cases. They suggested that the reinforcement must be anchored at its rear end to develop its tensile resistance. Lawson and Yee [9] also suggested that to achieve internal stability, tensile stresses in the reinforcements at the rear of the constrained reinforced zone have to be dissipated either by extending the length of the reinforcements within the reinforced fill zone or by connecting the reinforcements to low capacity anchors or nails fixed into a rigid zone beyond. Ling and Leshchinsky [10] and Ling et al. [11] reported that reinforcement length affects wall lateral displacements and the deformations increase as reinforcement length decreases. A study performed by Chew et al. [12] showed that shortening reinforcement length from 0.7H to 0.5H caused approximately a 50 percent increase in wall deformations. However, a case analyzed by Ling and Leshchinsky [10] with reinforcement length equal to 0.5H gave satisfactory performance considering the maximum displacement and tensile load mobilized in the reinforcement layers. Several other studies showed that for a given reinforcement strength, there is a certain reinforcement length needed to maintain the stability of reinforced structure, and shorter lengths require higher tensile resistance of reinforcement [2,13].

There are several possible failure modes considered in the design of reinforced soil retaining walls to satisfy both external and internal stability. Whitlow [14] indicated that the reinforcement length is governed by the external stability conditions and the vertical spacing of reinforcements is governed by the internal stability conditions. NCMA [5] manual points out that the results of external stability analyses for sliding and bearing capacity failure mechanisms are used to determine minimum reinforcement length. FHWA [3] guidelines state the possibility of internal stability controlling the length of reinforcement in some cases. It appears that there is no consensus among the published literature regarding the governing failure criteria determining the minimum required reinforcement length.

The objective of this study is to characterize the governing failure criteria for the required minimum geogrid reinforcement length of reinforced soil retaining walls and to investigate the possibility of using reinforcement lengths shorter than 0.7H under varying conditions. Variables considered in the study were the wall height, surcharge, reinforcement vertical spacing, reinforced soil properties, retained/backfill soil properties, and foundation soil properties. The current common design practice of reinforced soil retaining walls, which is based on coherent gravity and lateral earth pressure approach, was used for the analyses.

2. Overview of current design practice

Current common design practice of reinforced soil retaining walls is based on coherent gravity and lateral earth pressure approach. With the advances in computing technology, the use of continuum mechanics numerical methods in the analysis and design of reinforced soil retaining walls has been increasing in recent years. Although the finite element method is primarily used for numerical analysis, the finite difference method is also being used. The numerical methods have also been used by researchers to study and to understand the reinforced soil wall behavior under static and dynamic loading conditions [2,10–12,15–21]. Although continuum mechanics numerical methods have been used mostly by researchers to study reinforced soil retaining wall behavior, the coherent gravity and lateral earth pressure approach is the current common practice used in wall design.

Table 1
Performance criteria used in the design of reinforced soil retaining walls.

Failure mode	Performance criteria
Sliding	Factor of safety $\geq$ 1.5
Overturning	Factor of Safety $\geq$ 2.0
Bearing capacity	Factor of Safety $\geq$ 2.5
Eccentricity, e	$e \leq L/6$ (soil), $e \leq L/4$ (rock)
Pullout	Factor of safety $\geq$ 1.5

(Note: L = reinforcement length)

Current specifications and guidelines used for the design of reinforced soil retaining walls have two primary design requirements: external stability and internal stability. External stability considers the reinforced soil mass as a rigid body subject to lateral earth pressure from backfill/retained soil and surcharge loads. Internal stability considers the position and strength of reinforcement within the reinforced soil mass [22].

The external stability failure modes considered in the design of walls include sliding, overturning, bearing capacity and eccentricity, settlement, and global failures. The bearing capacity and settlement failure modes depend on each other. The walls designed properly considering the bearing capacity and eccentricity failure modes limit the settlements. In addition, remedial measures to limit/reduce settlements are independent of the reinforcement length [3]. Therefore, the settlements are not considered in this study. The global failure mode is also not considered, because it will not be affected significantly, if at all, by the reinforcement length range considered, between 0.5H and 0.7H, and the measures to remediate the global stability problem are independent of the reinforcement length.

The internal stability modes include pullout and rupture failures of reinforcements. Required reinforcement length, position, and strength are determined such that the wall design will satisfy all the failure modes with minimum safety factors given in the specifications. The minimum safety factors, used in this study, given by AASHTO [4] for sliding, bearing capacity, eccentricity, and pullout modes and by NCMA [5] for overturning mode are given in Table 1.

There are also local stability criteria, such as for the connections of the reinforcement and facing unit, considered in the design. Local failure modes are not considered in this study because they do not affect the reinforcement length.

3. Minimum reinforcement length required for failure modes

3.1. External stability

The reinforced soil zone is assumed to behave as one rigid unit in the external stability analysis. Since this zone is supposed to act as one unit, the failure mechanisms used for conventional gravity retaining walls also apply to the external stability analysis of reinforced soil retaining walls [3]. A schematic of a typical reinforced soil retaining wall, along with the forces acting on the wall used for external stability analysis, is shown in Fig. 1. By using the design methods and equations given in FHWA guidelines [3] and AASHTO specifications [4], the minimum reinforcement length required for each failure mode is provided in the following.

Sliding mode:

The Factor of Safety for sliding failure mode (FS_S) is given as [3,4]:

$$FS_S = \frac{\sum \text{Horizontal resisting forces}}{\sum \text{Horizontal driving forces}} = \frac{V_1 \tan \phi}{P_1 + P_2}$$

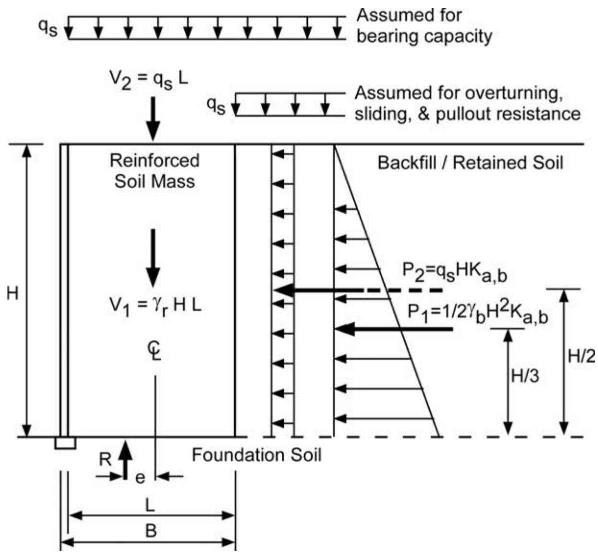

Fig. 1. Reinforced soil retaining wall schematic and forces involved in external stability analysis.

$$= \frac{\gamma_r HL \tan\phi}{0.5\gamma_b H^2 K_{a,b} + q_s H K_{a,b}}$$
$$= \frac{\gamma_r L \tan\phi}{(0.5\gamma_b H + q_s) K_{a,b}} \quad (1)$$

where V_1 = weight of reinforced soil mass; P_1 and P_2 = lateral loads behind the reinforced soil mass; γ_r = reinforced soil unit weight; H = wall height; L = reinforcement length; ϕ = friction angle of reinforced soil or foundation soil, whichever is lower; γ_b = backfill/retained soil unit weight; $K_{a,b}$ = lateral earth pressure coefficient of backfill/retained soil; and q_s = surcharge. From Eq. (1), minimum reinforcement length required to satisfy sliding mode, $L_{min,S}$, can be calculated as:

$$L_{min,S} = \left[\frac{(0.5\gamma_b H + q_s) K_{a,b}}{\gamma_r \tan\phi}\right] \times FS_S. \quad (2)$$

Overturning mode:

The Factor of Safety for overturning failure mode (FS_O) is given as [3,4]:

$$FS_O = \frac{\sum \text{Resisting moments}}{\sum \text{Driving moments}}$$
$$= \frac{V_1(L/2)}{P_1(H/3) + P_2(H/2)}$$
$$= \frac{\gamma_r HL(L/2)}{0.5\gamma_b H^2 K_{a,b}(H/3) + q_s H K_{a,b}(H/2)}$$
$$= \frac{\gamma_r L^2}{HK_{a,b}(1/3\gamma_b H + q_s)}. \quad (3)$$

From Eq. (3) minimum reinforcement length required to satisfy overturning mode, $L_{min,O}$, can be calculated as:

$$L_{min,O} = \sqrt{\left[\frac{HK_{a,b}\,(1/3\gamma_b H + q_s)}{\gamma_r}\right] \times FS_O} \quad (4)$$

Bearing capacity mode:

The Factor of Safety for bearing capacity (FS_{BC}) failure mode is given as [3,4]:

$$FS_{BC} = \frac{\text{Ultimate bearing capacity}}{\text{Foundation pressure}}$$

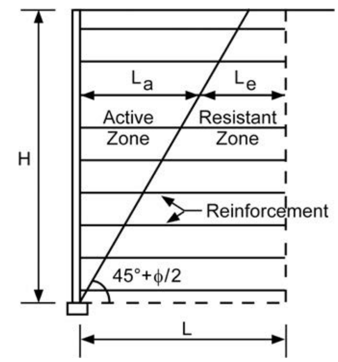

Fig. 2. Location of potential failure surface for internal stability design of reinforced soil retaining walls with geosynthetic reinforcement.

$$= \frac{q_{ult}}{\sigma_v} = \frac{q_{ult}}{\frac{V_1 + q_s L}{L - 2e}}$$
$$= \frac{0.5\gamma_f (L - 2e) N_\gamma}{\frac{\gamma_r H + q_s}{(1 - 2e/L)}} \quad (5)$$

where q_{ult} = ultimate bearing capacity; σ_v = foundation/bearing pressure; γ_f = foundation soil unit weight; e = eccentricity; and N_γ = bearing capacity factor. The foundation pressure given in Eq. (5) is based on the Meyerhof stress distribution, which considers a uniform base pressure distribution over an effective base width [3,4]. From Eq. (5) minimum reinforcement length required to satisfy bearing capacity mode, $L_{min,BC}$, can be calculated from:

$$L^2_{min,BC} - \left[4e + \left(\frac{\gamma_r H + q_s}{0.5\gamma_f N_\gamma}\right) FS_{BC}\right] L_{min,BC} + 4e^2 = 0. \quad (6)$$

The eccentricity also has to be checked during the design and has to be within the limits of performance criteria given in Table 1. The eccentricity, e, is given as [3,4]:

$$e = \frac{P_1\,(H/3) + P_2\,(H/2)}{V_1 + q_s L}$$
$$= \frac{0.5\gamma_b H^2 K_{a,b}\,(H/3) + q_s H K_{a,b}\,(H/2)}{\gamma_r HL + q_s L}$$
$$= \frac{0.5H^2 K_{a,b}\left(\frac{1}{3}\gamma_b H + q_s\right)}{L\,(\gamma_r H + q_s)}. \quad (7)$$

From Eq. (7) minimum reinforcement length required to satisfy the eccentricity criterion, $L_{min,E}$, (for soil foundation, where $e = L/6$) can be calculated as:

$$L_{min,E} = \sqrt{\left[\frac{0.5H^2 K_{a,b}\,(1/3\gamma_b H + q_s)}{(\gamma_r H + q_s)}\right] \times 6}. \quad (8)$$

3.2. Internal stability

Two failure modes, rupture and pullout, are considered for internal stability in the design of reinforced soil retaining walls. When tensile force in reinforcement exceeds friction force between the reinforcement and soil, the reinforcement is pulled out of the soil mass, resulting in a pullout failure. When the tensile force in the reinforcement becomes larger than the reinforcement strength, elongation or breakage occurs in the reinforcement causing rupture failure. Fig. 2 shows a potential failure surface in the reinforced soil zone for a wall with geosynthetic reinforcement.

Because the rupture failure occurs when tensile force of the reinforcement exceeds reinforcement strength, the rupture failure is not directly affected by the reinforcement length. Therefore, only the effect of pullout failure mode on the required minimum reinforcement length was considered in this study. However, rupture failure should also be checked during the design by comparing the reinforcement strength to the tensile force in the reinforcement. Vertical spacing between reinforcement layers should be decreased if reinforcement strength is less than the tensile force or reinforcement with higher allowable tensile strength should be selected. Reinforcement tensile loads calculated during the parametric study presented in this paper ranged from 8.4 kN/m to 62.3 kN/m, with an average of 25.1 kN/m. The geogrid reinforcement products commercially available have allowable strengths covering the tensile load range calculated.

Pullout mode:

The minimum reinforcement length required to satisfy the pullout mode, $L_{min,P}$, can be calculated as [3,4]:

$$L_{min,P} = L_a + L_e \tag{9}$$

where L_a and L_e are reinforcement lengths in active and resistant zones, respectively, as shown in Fig. 2. L_a is calculated based on the geometry of active failure line and L_e is given as [3,4]:

$$L_e = \frac{T_{max}}{F^* \alpha \sigma_v C R_c} \times FS_P \tag{10}$$

where T_{max} = maximum applied reinforcement load ($T_{max} = \sigma_h S_v$, where σ_h = horizontal stress and S_v = vertical reinforcement spacing); $F*$ = pullout resistance factor; α = scale correction factor; σ_v = vertical stress; C = surface area geometry factor; R_c = coverage ratio; and FS_P = factor of safety for pullout. In this study continuous geogrid reinforcement is considered. For geogrid reinforcement: $F^* = 0.8 \tan\phi_r$ (ϕ_r = reinforced soil friction angle), $\alpha = 0.8$, $C = 2$, and $R_c = 1$ [4]. The required safety factor for pullout failure mode is recommended by AASHTO [4] specifications as 1.5 and L_e should not be less than 0.9 m.

The vertical stress, σ_v, is the vertical earth pressure, i.e. overburden pressure, at the reinforcement. It is calculated by multiplying soil unit weight and depth from top of wall to the reinforcement level designed. The surcharge pressures from live loads, such as traffic loads, are not included in the vertical stress. The horizontal stress, σ_h, at the reinforcement level designed is calculated by multiplying the vertical stress plus the surcharge pressure, i.e. $\sigma_v + q_s$, by the lateral earth pressure coefficient of the reinforced soil. For the geogrid reinforcement, the lateral earth pressure coefficient of the reinforced zone is equal to the Rankine active lateral earth pressure coefficient given as

$$K_a = \frac{1 - \sin\phi}{1 + \sin\phi} \tag{11}$$

where K_a = active earth pressure coefficient; and ϕ = soil friction angle.

4. Parametric study

4.1. Method of approach

Effect of various parameters on the required minimum reinforcement length for each failure mode considered in the design has been investigated through a parametric study. The parametric study was conducted by selecting a baseline case which is compared with other cases where parameters investigated were changed. The values selected for the baseline case were average values of the range of each parameter studied. The parameters studied included wall height, surcharge, reinforcement vertical spacing, reinforced soil unit weight, reinforced soil friction angle, backfill/retained soil unit weight, backfill/retained soil friction angle, foundation soil unit weight, and foundation soil friction angle. The effect of each parameter was studied by deviating its value from the baseline case while all others were kept the same.

The parametric study performed showed trends of how each parameter studied affects the required minimum reinforcement length for all the failure modes considered. As mentioned above, these trends and results were obtained by using the average values of all parameters studied. Based on the trends obtained from these first set of results, two more sets of parametric studies performed; one with more "unfavorable" conditions where the parameters selected would result in longer reinforcement lengths and one with more "favorable" conditions where the parameters selected would yield shorter reinforcement lengths to satisfy the failure modes investigated.

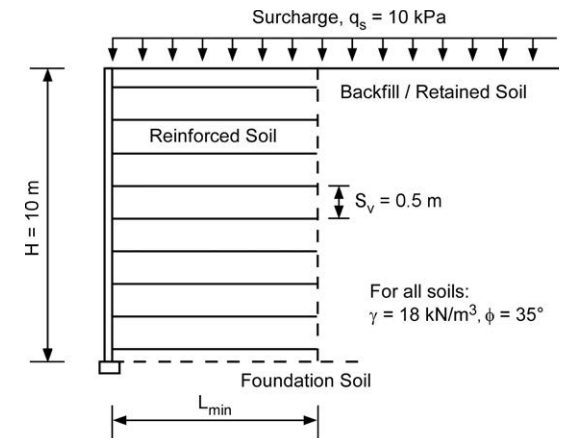

Fig. 3. Dimensions and parameters used for the baseline case.

Table 2
Properties used for the baseline case and parametric study.

Parameter	Baseline case value	Parametric study range
Wall height, H	10 m	5–15 m
Surcharge, q_s	10 kN/m^2	0–20 kN/m^2
Reinforced soil:		
Unit weight, γ_r	18 kN/m^3	16–20 kN/m^3
Friction angle, ϕ_r	35°	25°–45°
Backfill/retained soil:		
Unit weight, γ_b	18 kN/m^3	16–20 kN/m^3
Friction angle, ϕ_b	35°	25°–45°
Foundation soil:		
Unit weight, γ_f	18 kN/m^3	16–20 kN/m^3
Friction angle, ϕ_f	35°	25°–45°
Reinforcement:		
Vertical spacing, S_v	0.5 m	0.2–0.8 m

4.2. Parameter value ranges and baseline case

The dimensions and parameters used for the baseline case (average conditions) are shown in Fig. 3. Wall height, H, of 10 m was used in the baseline case. Surcharge, q_s, and reinforcement vertical spacing, S_v, were 10 kPa and 0.5 m, respectively. For all soils (reinforced soil, backfill/retained soil, and foundation soil) only cohesionless soils were considered. The unit weight, γ, and friction angle, ϕ, of all soils were 18 kN/m^3 and 35°, respectively. The active earth pressure coefficient of backfill soil, $K_{a,b}$, was 0.27 for soil friction angle of 35°, using Rankine lateral earth pressure theory given in Eq. (11). Reinforcement interface friction angle, δ, was equal to the reinforced soil internal friction angle, ϕ_r. Table 2 shows the properties and their values used in the baseline case and the ranges used in parametric study.

5. Results

5.1. Summary

Fig. 4 through Fig. 9 show the analysis results as a ratio of the required minimum reinforcement length, L_{min}, to the wall height, H, for all the parameters studied. The effect of each parameter on the required minimum reinforcement length and the governing failure mode are discussed in the following sections. The influence of each parameter was investigated by changing its value from the baseline case while all other parameters remained unchanged. Results show that the minimum reinforcement lengths, L_{min}, can vary significantly by the change of some variables. In addition, some of the variables can result in a shift of failure mode governing the required minimum reinforcement length. The results show that the pullout, internal failure mode, is usually the governing criterion in determining the required minimum reinforcement length. However, soil properties, especially the friction angle, can affect the governing failure mode. The study results show that although pullout, internal failure mode, is usually the governing failure mode, the eccentricity or the bearing capacity, external failure modes, can also govern the design in determining the required minimum reinforcement length of a reinforced soil retaining wall.

5.2. Effect of wall height

The effect of wall height on the required minimum reinforcement length ratios to satisfy the performance criteria are presented in Fig. 4 for wall heights ranging from 5 to 15 m. The results show that the required minimum reinforcement length ratios decrease as the wall height increases. The governing failure mode, the one which requires the highest reinforcement length ratio, is the pullout failure mode for the wall height range studied. The highest length ratio required to satisfy minimum required reinforcement length is approximately 0.65H, when the wall height is lowest, and the ratio is usually lower than 0.6H.

5.3. Effect of backfill/retained soil

The effect of backfill/retained soil unit weight (ranging from 16 to 20 kN/m^3) on the required minimum reinforcement lengths to satisfy the performance criteria are presented in Fig. 5(a). The required reinforcement length increases for all external failure modes as the soil unit weight increases. Since the horizontal forces acting on the reinforced soil mass increase due to the higher backfill soil unit weight, the use of longer reinforcement is required to increase the reinforced soil mass resulting in higher resisting forces and moments to satisfy the stability. The pullout failure is not affected by the change in the backfill/retained soil unit weight. This is expected since the reinforcement length is not a function of this soil unit weight as shown in Eqs. (9) and (10). The pullout failure mode is the governing failure mode in determining the required minimum reinforcement length for the range of unit weight considered. The reinforcement length of 0.58H satisfies the stability of all failure modes for unit weight range considered. It should be noted, however, that if higher unit weights were considered in the analyses then the eccentricity, external failure mode, would be the governing failure criterion, requiring longer reinforcement lengths [Fig. 5(a)].

The effect of backfill/retained soil friction angle on the required minimum reinforcement lengths to satisfy the failure modes are presented in Fig. 5(b). The friction angle range considered was between 25° and 45°. The results show that the required reinforcement length decreases for all external failure modes as the backfill/retained soil friction angle increases. This is due to a reduced lateral earth pressure coefficient of increased friction angles. Similar to the unit weight of soil, the reinforcement length required for pullout failure mode is not affected by the change in backfill/retained soil friction angle. Fig. 5(b) shows that the governing failure mode can be either an external or internal mode, depending on the friction angle value. While pullout is the governing failure mode for backfill/retained soils with high friction angles, for soils with low friction angles eccentricity governs the required minimum reinforcement length.

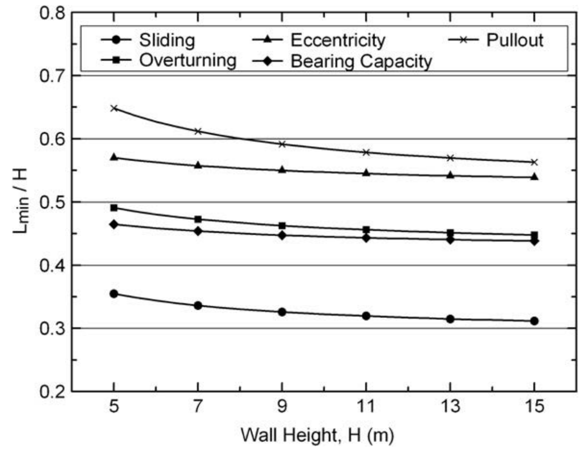

Fig. 4. Effect of wall height on required minimum reinforcement length (average conditions).

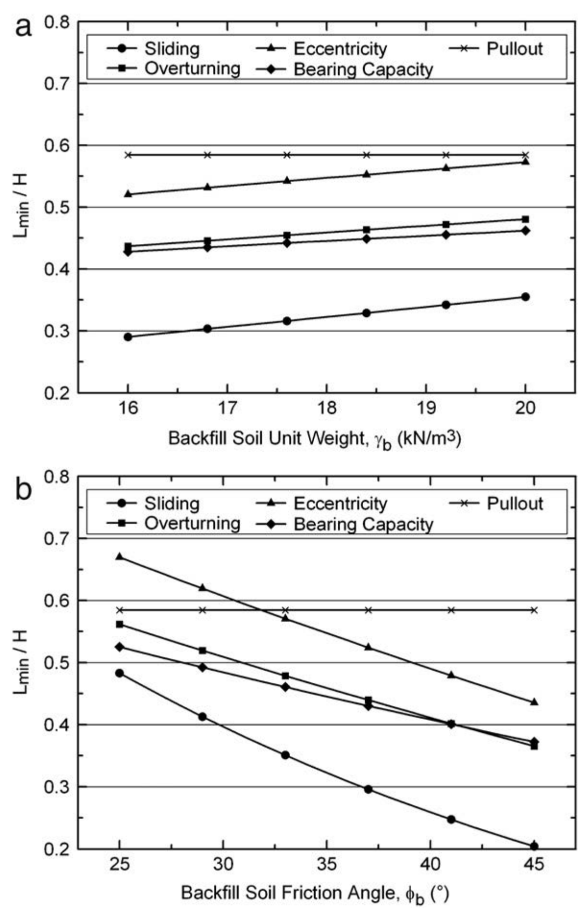

Fig. 5. Effect of backfill/retained soil (a) unit weight and (b) friction angle on required minimum reinforcement length (average conditions).

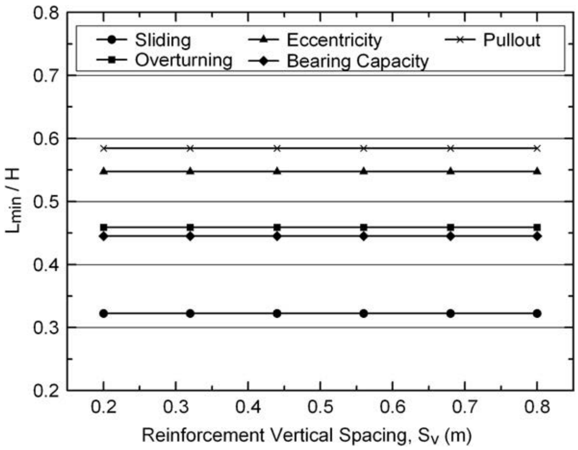

Fig. 6. Effect of reinforcement vertical spacing on required minimum reinforcement length (average conditions).

5.4. Effect of reinforcement vertical spacing

The effect of reinforcement vertical spacing on the required minimum reinforcement length ratios to satisfy the performance criteria are presented in Fig. 6. The vertical spacing range of 0.2 m–0.8 m was considered during the parametric study. AASHTO [4] guidelines require vertical spacing to be no more than 0.8 m. The results show that a change in vertical reinforcement spacing does not affect the required minimum reinforcement length for the external stability modes. Although Fig. 6 also suggests that a change in reinforcement spacing does not affect the pullout mode, the calculated reinforcement lengths in the restraint zone (Fig. 2) were all less than the minimum length of 0.9 m specified. Therefore, a minimum length of 0.9 m was used and the spacing effect on the pullout mode is not reflected in the results. The minimum reinforcement length required is less than 0.6H, as shown in Fig. 6.

5.5. Effect of reinforced soil

The effect of reinforced soil unit weight (ranging from 16 to 20 kN/m^3) on the minimum reinforcement length is shown in Fig. 7(a). An increase in the unit weight of reinforced soil decreases the required reinforcement length for all the external failure modes. The largest decrease occurs in sliding (approximately 20 percent) and smallest decrease occurs in bearing capacity (approximately five percent). A change in reinforced soil unit weight slightly affects the required reinforcement length for pullout failure mode; however this effect is not reflected in the results because of the minimum reinforcement length of 0.9 m required in the restraint zone. Pullout is the governing failure mode in determining the required reinforcement length and, within the range studied, the required minimum reinforcement length is less than 0.6H.

Due to the increased vertical loads, one might have expected reinforcement lengths to increase for bearing capacity mode as the reinforced soil unit weight increases. However, a decrease in the eccentricity due to the increased soil load affects both the ultimate bearing capacity and the total vertical loads at the foundation, resulting in lower required reinforcement lengths.

The effect of reinforced soil friction angle on the required minimum reinforcement lengths to satisfy the failure modes are presented in Fig. 7(b). Sliding is the only external failure mode affected by the change of reinforced soil friction angle and it occurs when the reinforced soil friction angle is less than the foundation soil friction angle. Fig. 7(b) shows that a change in the slope for

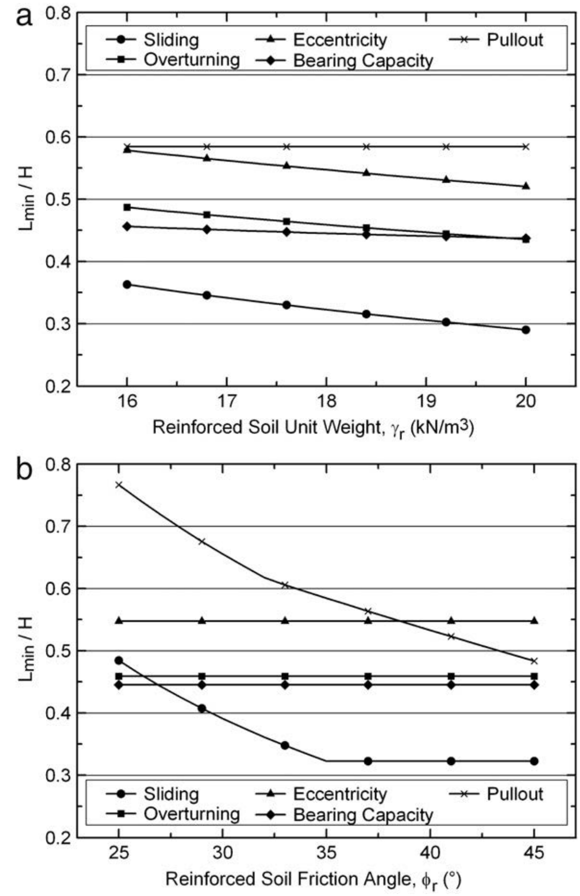

Fig. 7. Effect of reinforced soil (a) unit weight and (b) friction angle on required minimum reinforcement length (average conditions).

the sliding mode occurs at 35°. This is because of the use of minimum angle among the interface friction of reinforcement, internal friction angle of reinforced soil, and internal friction angle of foundation soil when the sliding failure mode is considered. The overturning and bearing capacity/eccentricity modes are not affected by the changed reinforced soil friction angles. As the reinforced soil friction angle increases the required reinforcement length decreases because of a reduction in lateral earth pressure coefficient and a reduction in reinforcement length, L_a, in the active zone (Fig. 2). Fig. 7(b) shows that a governing failure mode in determining the minimum required reinforcement length can be either an external or internal mode depending on the reinforced soil friction angle. While the pullout governs the minimum required reinforcement length at low friction angles, the eccentricity governs at higher friction angles.

5.6. Effect of surcharge

The effect of surcharge, ranging from 0 to 20 kN/m^2, on required minimum reinforcement length is presented in Fig. 8. An increase in surcharge requires longer reinforcement lengths to satisfy the stability for all the external and internal failure modes, due to the increased horizontal stresses. A change in slope for the pullout mode occurs around 15 kN/m^2, because of the minimum length of 0.9 m required in the resistant zone (Fig. 2).

5.7. Effect of foundation soil

The effect of foundation soil unit weight on minimum reinforcement length is shown in Fig. 9(a). An increase in the unit

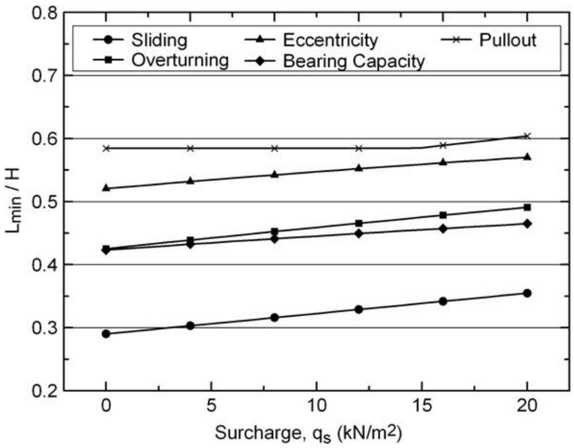

Fig. 8. Effect of surcharge on required minimum reinforcement length (average conditions).

weight of foundation only slightly affects the bearing capacity mode and has no effect on the other failure modes. Pullout is the governing failure mode for the parameter range considered. The results show that the use of minimum reinforcement lengths less than 0.6*H* is possible.

Fig. 9(b) shows the effect of foundation soil friction angle on the required minimum reinforcement lengths to satisfy the failure modes. A change in foundation soil friction angle affects the sliding and bearing capacity failure modes. As expected, the foundation soil friction angle has the most significant effect on the bearing capacity mode and the required reinforcement length decreases significantly as the friction angle increases. More than a fifty percent decrease in the minimum reinforcement length occurs for the bearing capacity mode within the friction angle range of 25° to 45° considered in this study. The pullout, eccentricity, and overturning modes are not affected by the change in foundation soil friction angle. Fig. 9(b) shows that the governing failure mode can be either external or internal mode depending on the friction angle of the foundation soil. While bearing capacity is the governing failure mode in determining the required minimum reinforcement length for foundation soils with low friction angles, pullout is the governing failure mode for soils with high friction angles.

6. Sensitivity analyses

The results of the parametric study performed using the baseline case (average conditions) showed that the required reinforcement length ratio decreases as the wall height increases, backfill soil unit weight decreases, backfill soil friction angle increases, reinforcement vertical spacing decreases, reinforced soil unit weight increases, reinforced soil friction angle increases, surcharge decreases, foundation soil unit weight increases, and foundation soil friction angle increases.

Based on these results and trends, two more sets of parameters were selected to perform a parametric sensitivity study to investigate the effect of the parameters on the minimum required reinforcement lengths and the governing failure modes under those conditions. The first set of values were selected such that analyses would result in longer required reinforcement lengths, compared to the baseline case (average conditions), and therefore were called "unfavorable" conditions. The values selected were at the mid-value of the average value considered in the baseline case and either low or high end based on the effect of each parameter. For example, reinforced soil friction angle of 30°, a value between the baseline case value of 35° and the lowest parametric study

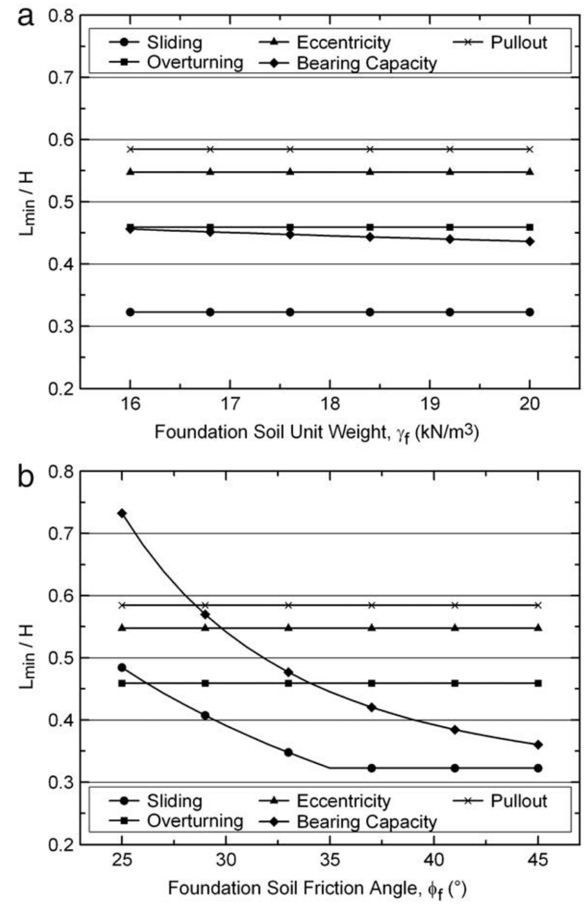

Fig. 9. Effect of foundation soil (a) unit weight and (b) friction angle on required minimum reinforcement length (average conditions).

value of 25°, was used since the required reinforcement length increases as the friction angle decreases. Similarly, the second set of values were selected such that analyses would result in shorter required reinforcement lengths, compared to the baseline case (average conditions), and therefore were called "favorable" conditions. The parameters selected were at the mid-value of the average value considered in the baseline case and either low or high end based on the effect of each parameter. For example, reinforced soil friction angle of 40°, value between baseline case value of 35° and the highest parametric study value of 45°, was used since the required reinforcement length decreases as the friction angle increases. The parameter values used for favorable and unfavorable conditions are given in Table 3.

The sensitivity analyses results showed that, similar to the average conditions presented earlier, the change in unit weight of soils involved (reinforced, backfill/retained, and foundation soils) does not effect the required minimum design reinforcement length. The reason is that the minimum reinforcement length in the resistant zone, L_e, of 0.9 m, and therefore the pullout failure mode, governs the required minimum reinforcement length. The results of the sensitivity analyses using unfavorable and favorable conditions, for varying wall height, surcharge, reinforcement vertical spacing, and soil internal friction angles are shown in Fig. 10.

The results of the sensitivity analyses for unfavorable conditions show that the required minimum reinforcement length increases for all the cases studied relative to the baseline cases (average conditions), as expected. When the favorable conditions exist, the required minimum reinforcement length decreases for all the cases studied relative to the baseline case, again as expected. Fig. 10

Table 3
Properties used for overall favorable and unfavorable conditions.

Parameter	Unfavorable conditions	Favorable conditions	Parametric study range
Wall height, H	7.5 m	12.5 m	5–15 m
Surcharge, q_s	15 kN/m^2	5 kN/m^2	0–20 kN/m^2
Reinforced soil:			
Unit weight, γ_r	17 kN/m^3	19 kN/m^3	16–20 kN/m^3
Friction angle, ϕ_r	30°	40°	25°–45°
Backfill/retained soil:			
Unit weight, γ_b	19 kN/m^3	17 kN/m^3	16–20 kN/m^3
Friction angle, ϕ_b	30°	40°	25°–45°
Foundation soil:			
Unit weight, γ_f	17 kN/m^3	19 kN/m^3	16–20 kN/m^3
Friction angle, ϕ_f	30°	40°	25°–45°
Reinforcement:			
Vertical spacing, S_v	0.65 m	0.35 m	0.2–0.8 m

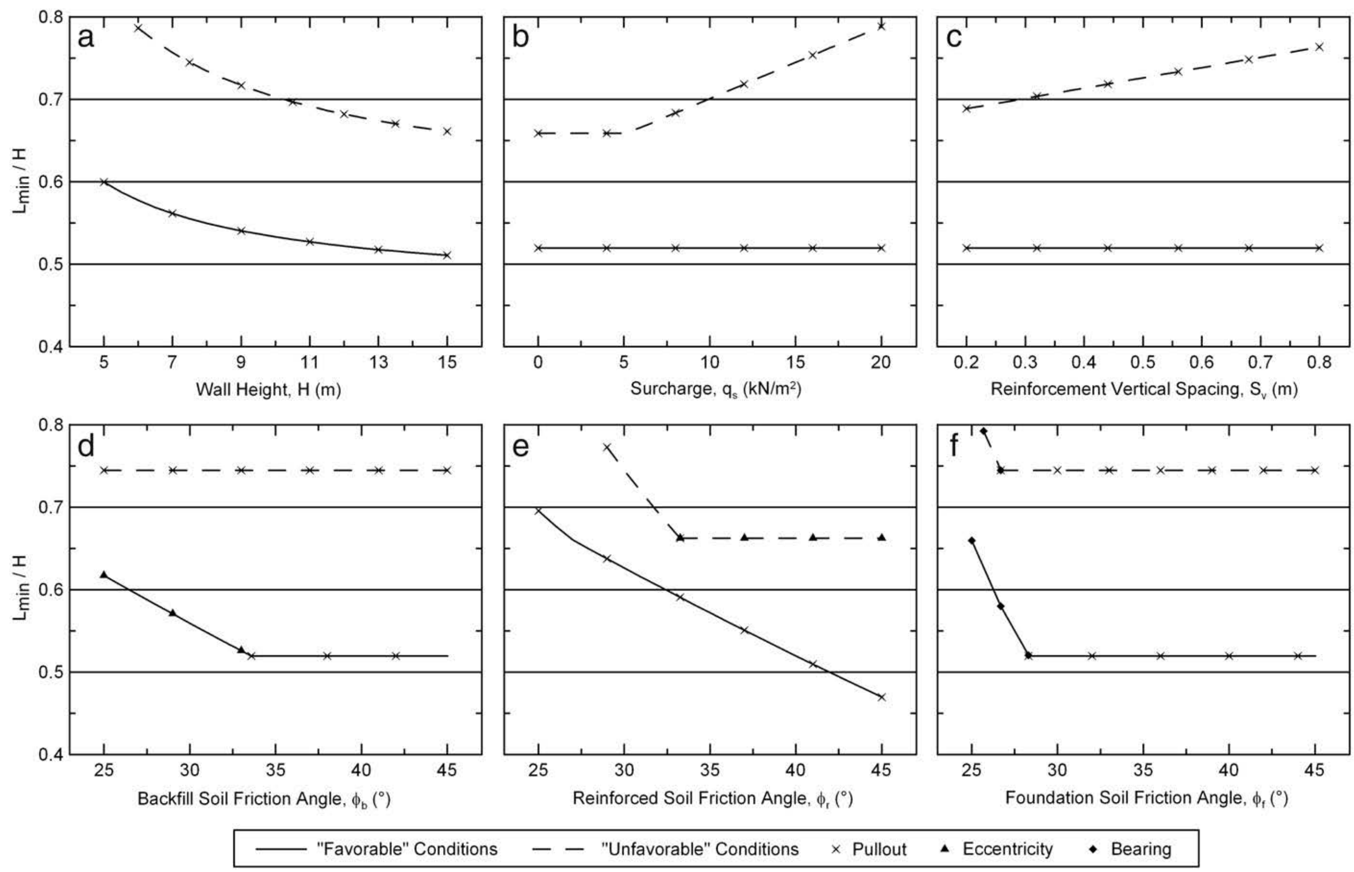

Fig. 10. Effect of parameters studied on minimum required reinforcement length (sensitivity analyses).

shows that pullout is the primary failure mode for the majority of cases in determining the minimum required reinforcement length. However, depending on the friction angle of backfill soil [Fig. 10(d)] and reinforced soil [Fig. 10(e)], eccentricity can be a governing mode in determining the required minimum reinforcement length. In addition, if foundation soils with relatively low friction angles are present below the wall, bearing capacity can be a governing criterion [Fig. 10(f)].

7. Summary and discussion of results

The parametric study results presented in Fig. 4 through Fig. 10 show that although internal failure (pullout) mode is the most common governing criterion in determining the required minimum reinforcement length, the external failure modes (eccentricity and bearing capacity) can also govern depending on the parameter values involved in the design of a reinforced soil retaining wall. The results also show that soil friction angle, whether it is backfill, reinforced, or foundation soil, has the most significant effect on the required minimum reinforcement length. The friction angle also affects the type of governing failure mode, whether internal or external, that determines the required minimum reinforcement length.

Parametric study performed using a wide range of variables and a combination of parameter values resulting in various conditions (average, unfavorable, and favorable) show that there are cases where the minimum reinforcement length can be shorter than the 70 percent of the wall height specified by many standards, such as AASHTO [4] and British Standard BS8006 [6]. Table 4 shows various parameter range combinations that will satisfy the safety factors of all failure modes considered for three different wall height ratios, L/H, of 0.75, 0.60, and 0.52. It should be noted that these values would satisfy the performance criteria used which are given in Table 1. The parameter values given in Table 4 are the base values

Table 4
Minimum reinforcement lengths for various parameter combinations.

Parameter	L/H = 0.75	L/H = 0.60	L/H = 0.52
Wall height, H	> 7.5 m	> 10 m	> 12.5 m
Surcharge, q_s	< 15 kN/m^2	< 10 kN/m^2	< 5 kN/m^2
Reinforced soil:			
Unit weight, γ_r	> 17 kN/m^3	> 18 kN/m^3	> 19 kN/m^3
Friction angle, ϕ_r	> 30°	> 35°	> 40°
Backfill/retained soil:			
Unit weight, γ_b	< 19 kN/m^3	< 18 kN/m^3	< 17 kN/m^3
Friction angle, ϕ_b	> 30°	> 35°	> 40°
Foundation soil:			
Unit weight, γ_f	> 17 kN/m^3	> 18 kN/m^3	> 19 kN/m^3
Friction angle, ϕ_f	> 30°	> 35°	> 40°
Reinforcement:			
Vertical spacing, S_v	< 0.65 m	< 0.50 m	< 0.35 m
Governing failure mode	Pullout	Pullout	Pullout

used in the parametric study of each group: unfavorable, average, and favorable conditions.

Since pullout is the primary failure mode governing the design reinforcement length, it may be possible to use even lower L/H ratios by employing methods to increase pullout capacity, e.g. connecting the reinforcements to low capacity anchors or nails fixed into the rigid zone behind the wall [9], when limited space behind the wall exists for reinforcement.

International design criteria for the required minimum reinforcement length range from 0.5H to 0.8H [1]. The results obtained from this study indicate that reinforcement lengths as low as almost 0.5H can be used if favorable conditions exist. This reinforcement length of 0.5H agrees with guidelines given by Canada and Hong Kong for the design of geosynthetic reinforced soil retaining walls [1].

Current design practice of reinforced soil retaining walls, based on limit equilibrium analysis using the coherent gravity and lateral earth pressure approach, does not provide information on wall deformations, and earlier studies showed that reinforcement length affects the lateral wall deformations significantly [10–12]. Although it has been reported that shortening reinforcement length from 0.7H to 0.5H can cause approximately a 50 percent increase in wall deformations [12], it has also been reported that studies performed with reinforcement length equal to 0.5H gave satisfactory performance considering the maximum displacement mobilized in the reinforcement layers [10]. The reinforced soil retaining walls have an ability to tolerate large deformations without structural distress; however, special attention should be given to wall deformations when shorter reinforcement lengths are used.

8. Conclusions

Governing failure mode in determining the minimum design reinforcement length for various parameters involved in the design of reinforced soil retaining walls has been studied. A series of equations were derived using current design practice to calculate the required minimum reinforcement length for each performance criterion. Governing failure modes determining the reinforcement lengths and shortest possible lengths that can be used for walls under varying conditions were investigated. Based on the variables and ranges considered for the parametric study performed during this study, the following conclusions are drawn:

- The minimum required reinforcement length can be governed by both external and internal failure modes, based on the parameter values involved and would be case specific.
- The pullout, internal stability mode, is the most common failure mode that generally governs the minimum reinforcement length in geogrid reinforced walls. However, designers should be aware that the governing failure mode may shift from pullout to eccentricity or bearing capacity failure modes (external stability) depending on the parameters involved.
- Friction angle of soils involved, especially in the reinforced zone, has the most influence on the minimum reinforcement length. By using soils with higher friction angle in the reinforced zone, it is possible to reduce reinforcement lengths up to 30 percent for some conditions.
- The minimum reinforcement length required usually ranges between 0.5H to 0.7H, depending on the properties involved.
- It is possible to use reinforcement lengths less than 0.7H, usually specified by the codes. Reinforcement lengths approximately 0.5H are possible with the current performance criteria, if favorable conditions exist. If lower safety factors are allowed, it may be possible to reduce the reinforcement lengths even further. When shorter reinforcement lengths are used, special attention should be given to wall deformations, as the wall deformations increase as reinforcement lengths decrease.

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