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Behavior of Soil-reinforced Retaining Walls in Tiered Arrangement

계단식 보강토 옹벽의 거동 특성

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요 지

본 연구에서는 계단식으로 시공되는 블록식 보강토 옹벽의 거동 특성에 관한 내용을 다루었다. 계단식 보강토 옹벽의 거동을 고찰하기 위해 유한요소해석을 수행하였으며 그 결과를 토대로 상·하단 옹벽의 이격거리에 따른 거동 특성을 규명하고 현재 적용되고 있는 설계기준에서 제시하는 등가상재하중 개념의 모델의 타당성을 검토하였다. 해석 결과를 토대로 변위 패턴을 분석한 결과 상·하단 옹벽이 인접하여 시공되는 계단식 옹벽의 경우 상·하단 옹벽의 보강토체를 관통하는 전반파괴의 유형을 보이는 것으로 나타나 사면안정해석 개념의 전반파괴에 대한 검토를 요구하고 있는 현 설계기준은 타당한 것으로 나타났다. 한편, 상·하단 옹벽의 상호작용은 하단옹벽의 거동은 물론 상단옹벽의 거동에도 상당한 영향을 미치는 것으로 나타나 상단옹벽을 단일옹벽으로 설계하도록 제안하고 있는 현 설계기준에 대한 검토가 요구되는 것으로 나타났다.

Abstract

This paper presents the results of investigation on the behavior of soil-reinforced segmental retaining walls in tiered arrangement using the finite element method of analysis. 2D finite element analyses were performed on tiered walls with two levels of offset distance. Cases with equivalent surcharge as suggested by the NCMA design guideline were additionally analyzed in an attempt to confirm the appropriateness of the equivalent surcharge model adopted by NCMA. Deformation characteristics of a tiered wall with small offset distance suggest a compound mode of failure and support current design approaches requiring a global slope stability analysis for design. Also revealed is that the interaction between the upper and lower walls significantly affects not only the performance of the lower wall but also the upper wall, suggesting that the upper walls should also be designed with due consideration of the interaction.

Keywords : Finite element analysis, Reinforced earth, Segmental retaining wall, Tiered wall

1. Introduction

Segmental retaining wall market in Korea has been growing drastically since the late 1990s in both engineered and non-engineered applications. Despite the inherent conservatism in the current design approaches, numerous major and minor structural problems have been reported during and after construction, covering a range of structural damages from local failure to total collapse. Much still needs to be investigated to fill the gap between the theory and the practice.

In recent years, there have been a number of in-

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vestigations into the behavior of reinforced soil walls using small to large-scale laboratory model tests (Juran and Christopher, 1989; Bathurst, 1990; Chou and Wu, 1993; Porbaha and Goodings 1997), field tests (Simac et al., 1990; Bathurst, 1992; Collin and Berg, 1994; Ochiai and Fukuda, 1996), and numerical experiments (Karpurapu and Bathurst, 1995; Ho and Rowe, 1997; Rowe and Ho, 1998; Yoo and Lee, 1999). The majority of the investigations, however, have been focused on independent walls and therefore, the behavior of tiered segmental retaining walls has not been fully understood.

The primary objective of this paper is to provide insights into the behavior of geosynthetics reinforced segmental retaining walls in tiered arrangement and to form a database for developing more rational design/analysis method. Attention is focused on two-level tiered segmental block walls reinforced with extensible reinforcement in a granular backfill resting on a non-yielding foundation. The finite element method of analysis was adopted in the present study since numerous researchers have demonstrated that this technique can successfully capture what might otherwise be difficult when adopting physical modeling techniques. Findings from this study are related to the current design approaches, and the appropriateness of the current design approaches is then discussed.

2. Design Concept for Current Design Guidelines

Subsequent sections describe fundamentals of design concept regarding tiered soil-reinforced walls adopted by currently avaliable design guidelines: NCMA (1999) and FHWA (1998). It should be emphasized that these two guidelines strongly suggest that a slope stability analysis, for both mixed and global failure modes, be performed.

2.1 NCMA Design Guideline

NCMA design guideline basically employs an equivalent surcharge approach for the stability calculations, as illustrated in Figure 1. The equivalent surcharge pressure q_{eq} is determined based on the offset distance D between the upper and the lower walls.

Magnitude of the equivalent surcharge q_{eq} is determined based on the offset distance D according to the following criterion.

<u>(a) Internal stability:</u>

$D > L_1$: no influence $q_{d1} = 0, \quad q_{l1} = 0$

$.3L_1 < D < L_1$: partial surcharge

$$q_{d1} = \frac{(L_1 - D)}{L_1} (\gamma_{1(2)} H_2)$$

$$q_{l1} = \frac{(L_1 - D)}{L_1} (q_{l2}')$$

$D < .3L_1$: full surcharge $q_n = \gamma_{i(2)} H_2 \quad q_{l1} = q_{l2}$

<u>(b) External stability:</u>

$J > (L_1 + X_1)$: no influence $q_{d1} = 0, \quad q_{l1} = 0$

$(L_1 + .5X_1) < J < (L_1 + X_1)$: partial surcharge

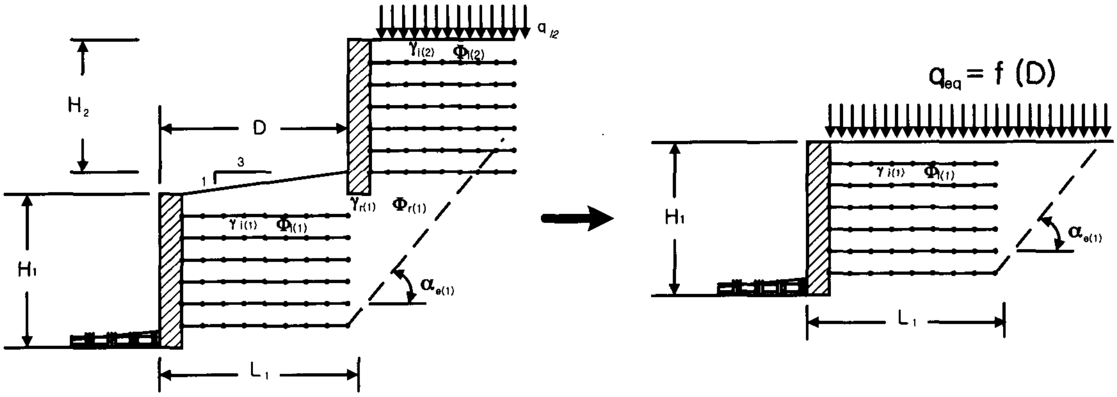


Fig. 1. Equivalent surcharge concept (NCMA)

$$q_{d1} = \frac{(L_1 + X_1 - D)}{X_1} \, (\gamma_{1(2)} H_2)$$

$$q_{l1} = \frac{(L_1 + X_1 - D)}{X_1} \, (q_{l2}')$$

J < (L_1 + .5 X_1) : full surcharge: $q_n = \gamma_{i(2)} H_2 \;\; q_{l1} = q_{l2}$

Note) • $0.3\,L_1$ and $0.5\,X_1$ are empirically selected for conservative design

• $X_1 = (H + D/S)/\tan\,\alpha_{e(1)}$, S = 500 (for level backfill)

2.2 FHWA Design Guideline

(1) External Stability

FHWA design guideline (FHWA, 1998) requires to determine the required reinforcement length L for the external stability based on the following criteria.

- Case 1: $D > H_1 \tan(90 - \phi)$

  ⇒ No interaction. Walls are independently designed.

- Case 2: $D \le \frac{1}{20}(H_1 + H_2)$:

  ⇒ Design for a single wall with a height of H= H_1+H_2.

- Case 3: $D > \frac{1}{20}(H_1 + H_2)$

  ⇒ For lower wall: $L_1 \ge 0.6 H_1$

  For upper wall: $L_2 \ge 0.7 H_2$

(2) Internal Stability

For internal stability calculations, additional vertical stresses at depths due to the upper wall are computed based on the criteria shown in Figure 2. The location of the potential failure surface required for the pullout capacity calculation is selected based on the offset distance D as shown in Figure 3. Note, however, that these criteria are geometrically derived and empirical in nature.

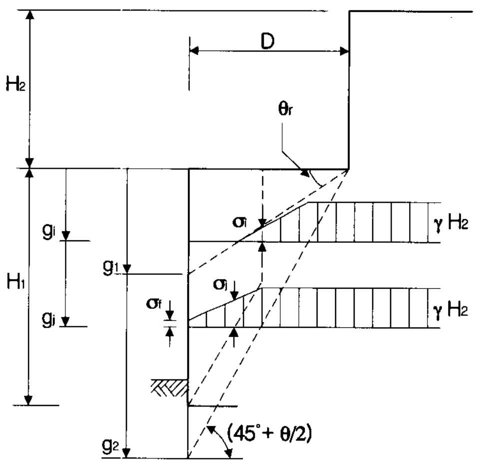
3. Problems Considered

3.1 Wall Geometry

Two-level tiered walls constructed on a rigid foundation are considered in this study. The lower and upper wall heights are 8 and 5.5m, and the walls are assumed to be constructed using segmental blocks of 0.25m (height) × 0.5m (length) together with cohesionless and free draining backfill soil. The geometry of the walls examined in this study is shown in Figure 4 together with the symbols and a set of reference parameters used. For simplicity, layers of geogrid with a uniform length of L/H=0.6 are placed at a uniform vertical spacing of S_v = 1.0m. Note that the axial stiffness of the geogrid was assumed to be J=2000kN/m.

3.2 Parametric Study

Two levels of offset distance D are considered (i.e.,



CASE1 $D \le H_2 \tan(45^\circ - \frac{\phi_r}{2})$, $\sigma_i = \gamma H_2$

CASE2 $H_2 \tan(45^\circ - \frac{\phi_r}{2}) < D \le H_2 \tan(90^\circ - \phi_r)$

CASE3 $D > H_2 \tan(90^\circ - \phi_r)$, $\sigma_i = 0$

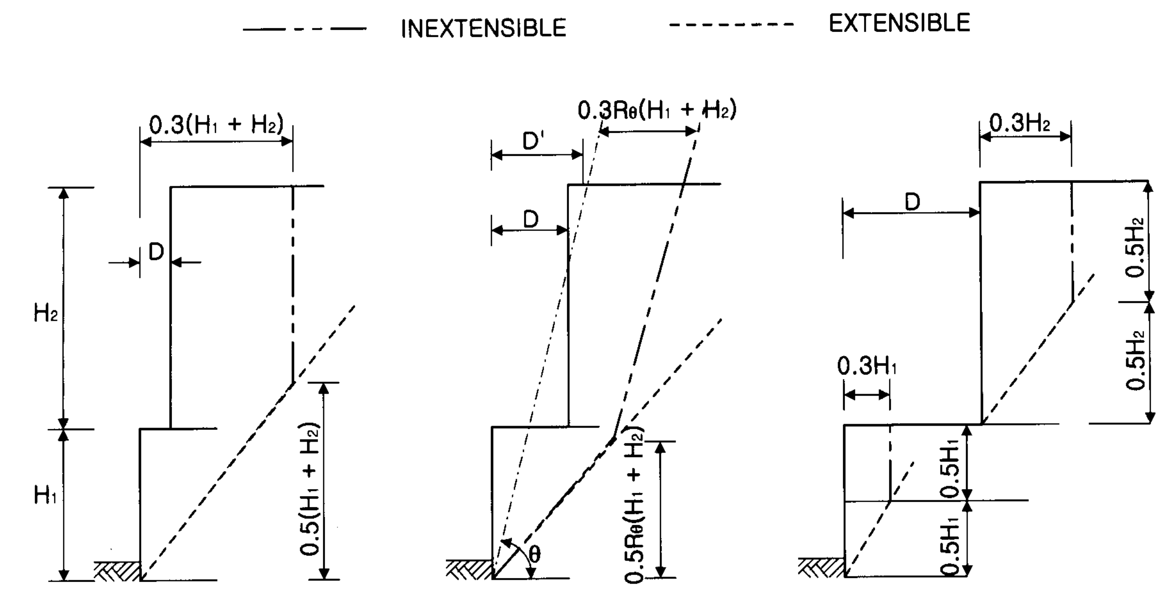
$g_1 = D \tan \phi_r$

$g_2 = D \tan(45^\circ + \frac{\phi_r}{2})$

$\sigma_i = \frac{g_i - g_1}{g_2 - g_1} \gamma H_2$

Φ_r=internal friction angle of backfill soil

Fig. 2. Calculation model for vertical stress increase due to upper wall (FHWA)



$(a)\ D \leq \dfrac{H_1 + H_2}{20}$ $\quad$ $(b)\ \dfrac{H_1 + H_2}{20} \leq D \leq H_1 \tan(45^{\circ} - \dfrac{\phi_r}{2})$ $\quad$ $(c)\ D > H_1 \tan(45^{\circ} - \dfrac{\phi_r}{2})$

$$D' = 2D \frac{H_2}{H_1 + H_2} \qquad R_\theta = \frac{\theta - \phi}{90^{\circ} - \phi}$$

Fig. 3. Potential failure surface (FHWA)

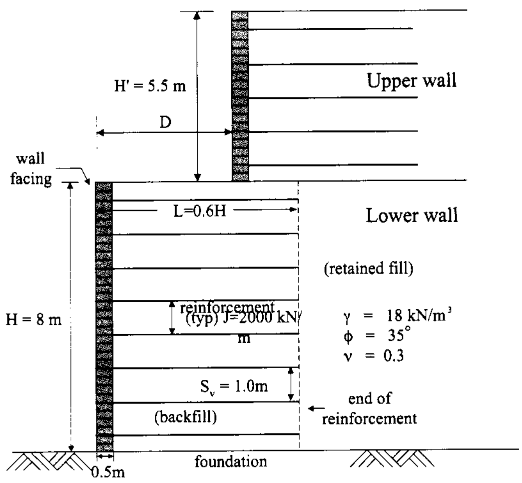
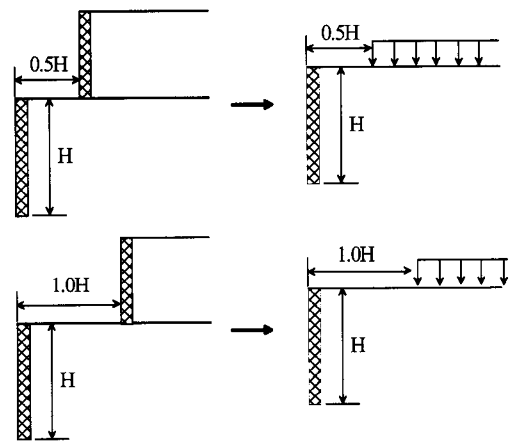


Fig. 4. A schematic view of wall system



(a) Full model (b) Equivalent surcharge

Fig. 5. Conditions considered

$D=0.5H_1$ and $1.0H_1$) in this study in an attempt to investigate the variation of degree of interaction between the upper and lower walls with respect to the offset distance. As presented earlier, the NCMA design guideline employs a concept of equivalent surcharge, in which the upper wall is replaced by an equivalent surcharge with an intensity depending on the distance between the lower and upper walls. Therefore, additional cases with equivalent surcharges computed based on the NCMA guideline are anlyzed to evaluate the validity of current design approach. Figure 5 summarizes the conditions considered in the present study.

4. Finite Element Analysis

4.1 Finite Element Model

The commercial finite element code DIANA (DIANA 1996) developed by TNO Building & Construction Research Co. and Delft Technical University was used for this study. DIANA is a multi-purpose finite element program that can be used for a range of geotechncial engineering problems including excavation, tunneling, retaining walls, and slopes. DIANA has been proven to be appropriate for analyzing soil-reinforced segmental retaining walls in a number of studies (Yoo and Lee, 1999; Yoo, 2001).

Figure 6 shows a finite element mesh used in the analysis. As can be seen, a very refined mesh was adopted to minimize the effect of mesh dependency on the results of finite element analyses. In the finite element model, the foundation soil was assumed to extend to one-half times the lower wall height (H_1) below the wall base while the lateral boundary was at approximately $3.0H_1$ away from the lower wall face.

The backfill soil and the wall facing were discretized using eight-noded isoparamatric plane strain elements (CQ18E), while two-noded truss elements (L4TRU) were used for the reinforcements. In addition, the interface behavior between block/backfill, reinforcement/backfill, and backfill/foundation was modeled using six-noded Goodman-type interface elements (CL12I; Goodman et. al. 1968). Figure 7 illustrates the details of the wall/backfill and the soil/reinforcement interface modeling.

The non-linear behavior of the backfill soil was modeled using a Mohr-Coulomb failure criterion and the non-associated flow rule proposed by Davis (1968). The dilatancy angle (ψ) of the soil was related to the friction angle, using the relationship proposed by Bolton (1986) assuming a constant critical state friction angle ϕ_{cv}=30, as in Eq. (1). The internal friction angle of ϕ=35° was selected with due consideration of the typical design practice.

$$\phi = \phi_{cv} + 0.8\psi \tag{1}$$

The wall facing, reinforcement, and interfaces were assumed to follow linear elastic behavior. Table 1

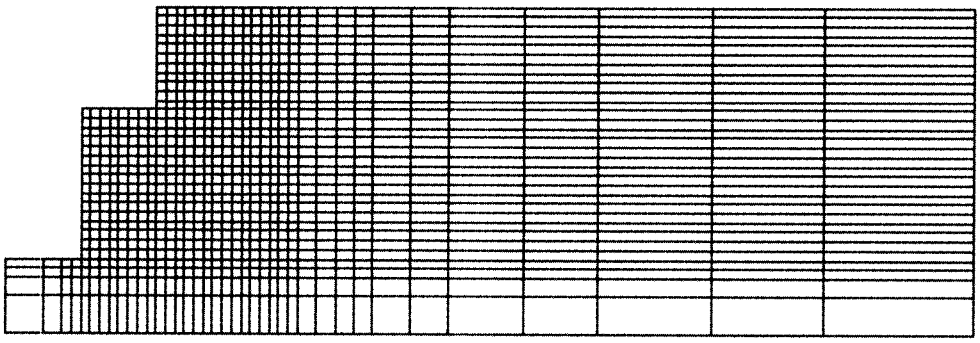
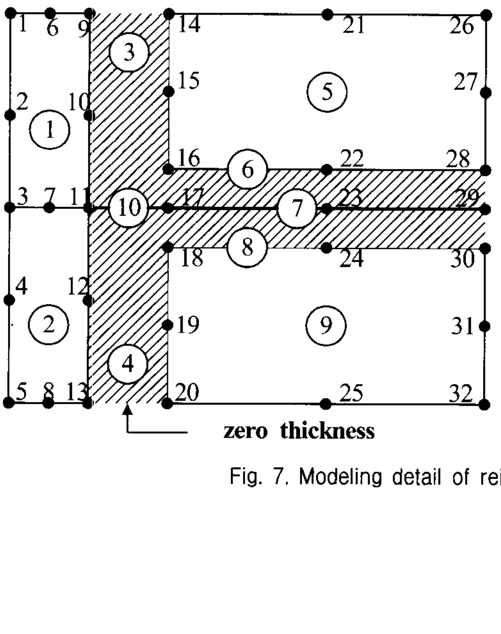


Fig. 6. A typical finite element mesh



Element	Type	Nodes
1	quadrilateral	9-1-3-11-6-2-7-10
2	quadrilateral	11-3-5-13-7-4-8-12
3	interface	16-14-9-11-15-10
4	interface	20-18-11-13-19-12
5	quadrilateral	26-14-16-28-21-15-22-27
6	interface	17-29-28-16-23-22
7	uniaxial bar	17-29-23
8	interface	18-30-29-17-24-23
9	quadrilateral	30-18-20-32-24-19-25-31
10	nodal link	11-17

Fig. 7. Modeling detail of reinforcement/block/backfill soil junction

Table 1. Mechanical properties of wall components

	E_s (kN/m²)	ϕ (degree)	Ψ (degree)	γ (kN/m³)	EI (kN-m²/m)
backfill	3×10^4	35	6	18	–
wall facing	–	–	–	21	5,500
	K_s (kN/m²/m)			K_n (kN/m²/m)	
backfill/wall	1×10^4			1×10^{10}	
backfill/reinforcement	1×10^5			1×10^{10}	

summarizes material properties used in the analysis. Note that the shear and normal stiffness values for the interface (K_s and K_n) were selected based on the result of literature review.

4.2 Modeling of Construction Sequence

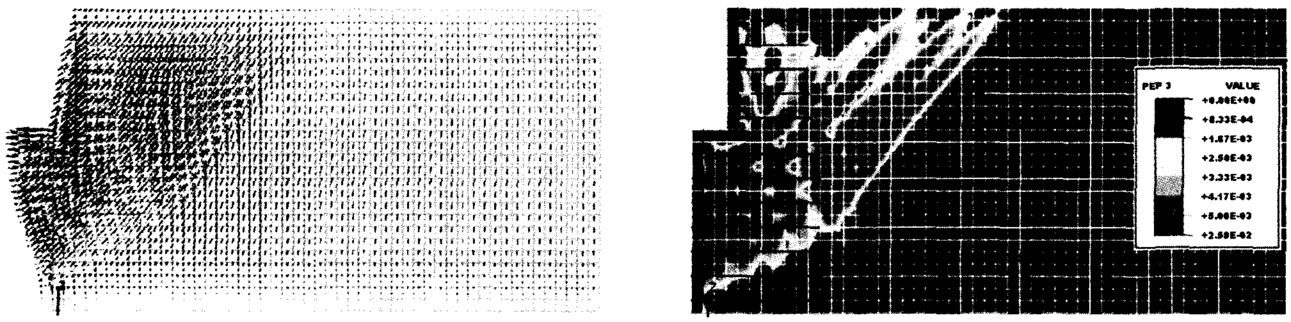
It has been recognized that the results of finite element analyses on problems involving sequential construction are significantly affected by the manner in which the construction sequence is modeled in the analysis. Finite element analyses on soil-reinforced segmental retaining walls should therefore fully consider the construction sequence.

In the present analysis, the step by step wall construction sequence was carefully simulated by activating soil, block, and reinforcement layers at designated stages using the phased analysis option, which is a special feature offered by DIANA. A phased analysis comprises several calculation phases. Between the phases the finite element model changes by addition or removal of elements, constraints and/or loading conditions. In each phase, a separate analysis is performed, in which the results from previous phases are automatically used as initial values. For analysis of the cases with equivalent surcharge, the surcharge was incrementally applied upon completion of the lower wall construction.

5. Results and Discussion

5.1 Deformation Behavior

Figures 8 and 9 illustrate the displacement vector plots and the maximum shear strain ($\varepsilon_1 - \varepsilon_3$) contour plots for cases with two levels of D=0.2H₁ and 1.4H₁, respectively. As seen in Figure 8, for the case for D=0.2H₁, significant wall movements occur both in the lower and upper walls. Of particular interest to note is the upper wall deformation pattern, which shows significant lateral movements at the wall base. Such a pattern is associated with the lateral movement of the lower wall as well as the settlement of the upper wall and is discussed further later in this paper. Such a trend is better illustrated in a contour plot of maximum shear strain ($\varepsilon_1 - \varepsilon_3$) as shown in Figure 8(b). A well defined shear band is developed, which initiates at the toe of the lower wall and then propagates behind the reinforced soil block of the upper wall with an angle equivalent to that of the



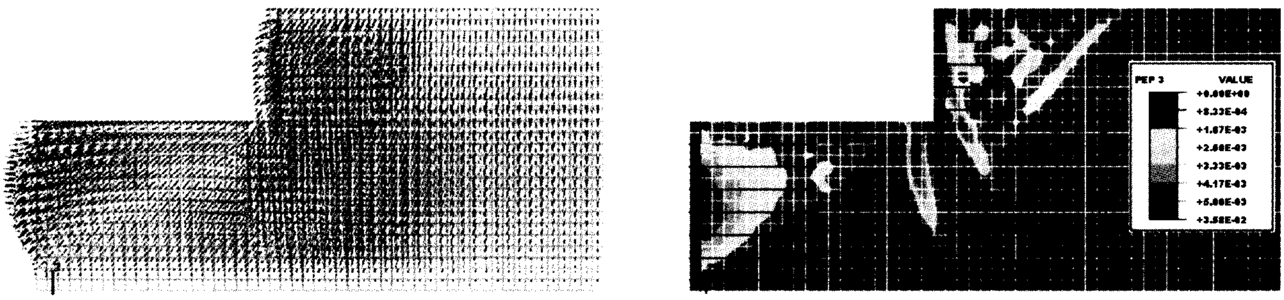
(a) Displacement vector (b) max. shear strain contour

Fig. 8. Displacement vector and max. shear strain contour for D=0.2H₁

Rankine active failure line. These plots suggest that the global sliding failure mode is more likely for tiered walls having a relatively short offset distance. This trend supports the current design approaches, which require a slope stability analysis for the global and compound modes of failure for walls in tiered arrangement. In the case of $D=1.4H_1$, the upper and lower walls appear to exhibit independent failure mode, as illustrated in Figure 9. It should, however, be noted that the upper wall undergoes considerable settlements, and that a localized plasitc zone is developed under the upper block wall. These results suggest that a protective measure underneath the upper wall be provided to limit such excessive settlements.

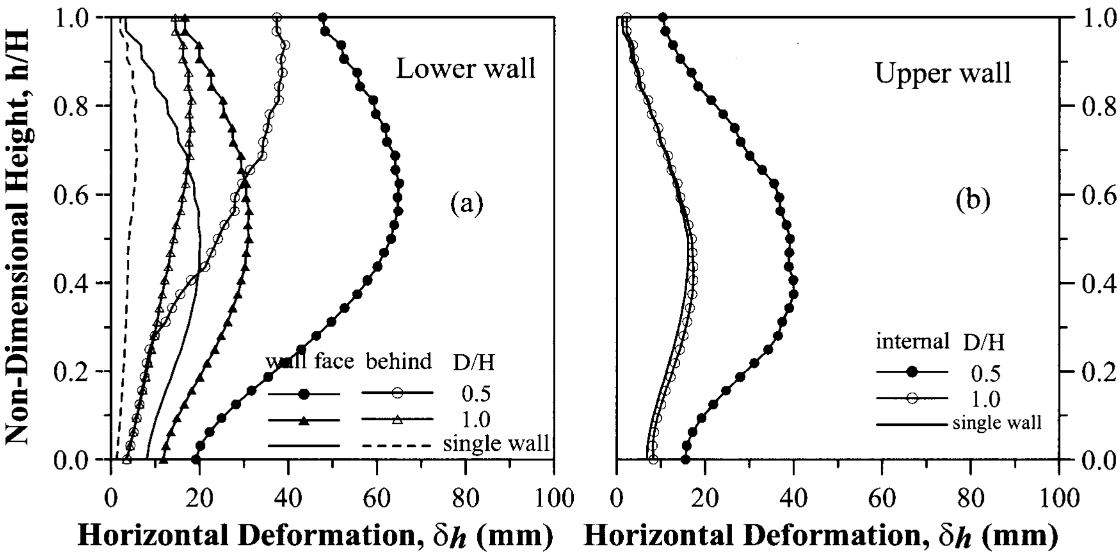
Sources of the horizontal wall deformation include horizontal strains within the reinforced soil block as well as the rigid body movement of the reinforced soil block itself due to the lateral thrust acting at the back of the reinforced soil zone. Interaction between the lower and upper walls in a tiered wall system may significantly increase the horizontal wall deformation depending on the level of offset distance.

Figures 10 and 11 present horizontal deformation profiles at the wall face, within and behind the reinforced soil block for $D=0.5H_1$ and $1.0H_1$, respectively. Also included in these figures are the deformation profiles for independent walls with the corresponding height for comparison. Note that horizontal deformation within the reinforced soil block (i.e., internal horizontal deformation) is obtained by subtracting the horizontal deformation behind the reinforced soil block from that at the wall face. As shown in Figure 10, the effect of the upper wall



(a) Displacement vector (b) max. shear strain contour

Fig. 9. Displacement vector and max. shear strain contour for $D=1.4H_1$



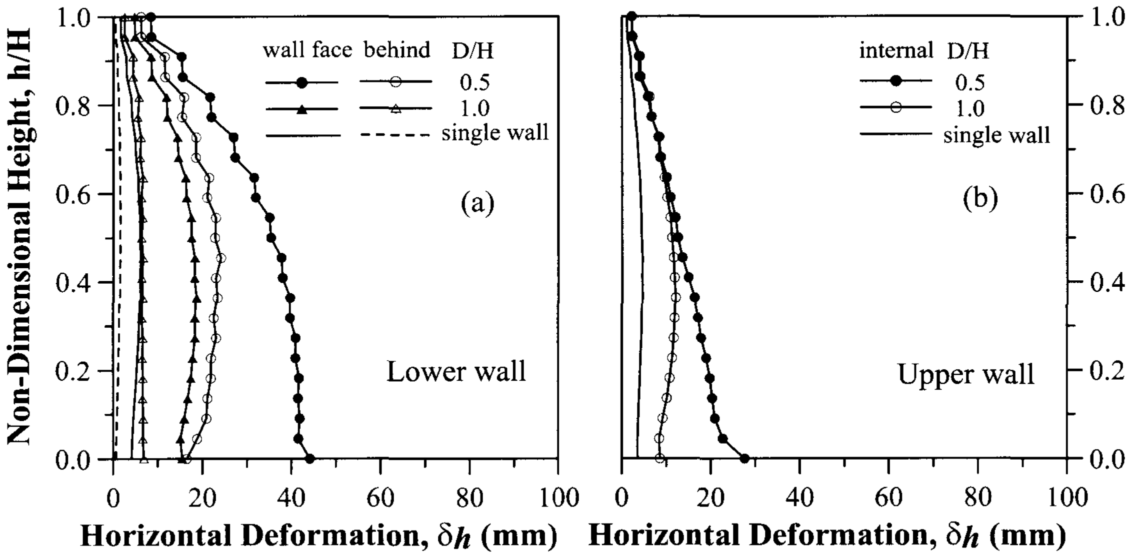
(a) Wall face and behind reinforced soil block (b) Within reinforced soil block

Fig. 10. Variation of horizontal deformation profile with D/H_1 for lower wall

on the lower wall is to increase the horizontal deformation within and behind the reinforced soil block and thus the horizontal deformation at the wall face, indicating that the upper wall significantly influences both the internal and external stability of the lower wall. Note that the internal deformation for the case of $D=1.0H_1$ appears to be negligible, and that the increase in the horizontal deformation at the wall face is largely due to the movement of the reinforced soil block. This trend suggests that the external stability is more influenced by the presence of the upper wall than the internal stability especially for cases with moderate to large levels of offset distance.

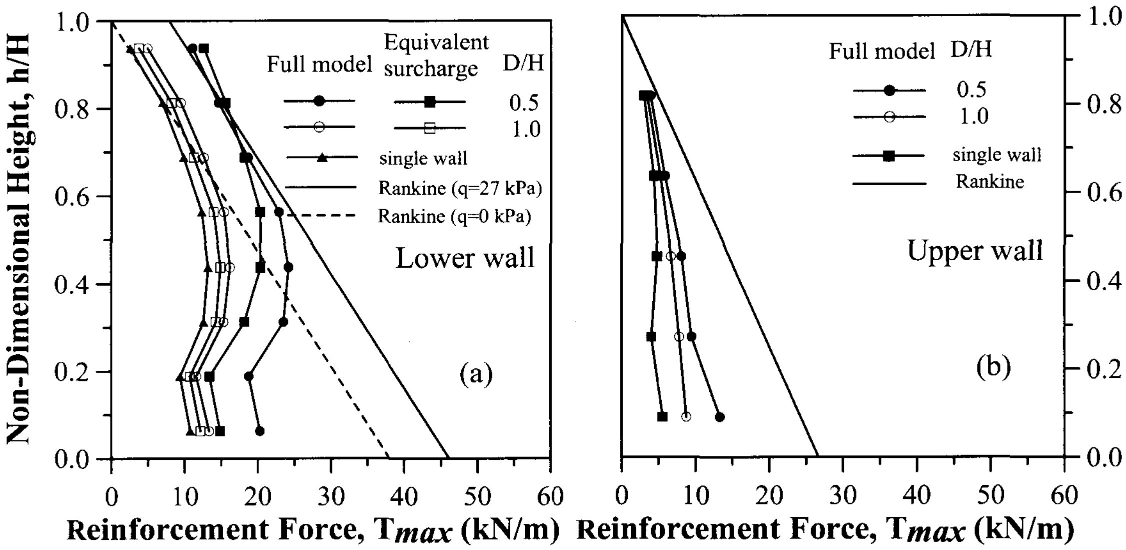
5.2 Reinforcement Force

Figure 12 presents maximum reinforcement force distributions for the tiered walls together with those obtained assuming each wall being a single wall on a rigid foundation. Also shown in this figure are the results of analysis on a model with an equivalent surcharge based on the NCMA design approach (NCMA, 1997).



(a) Wall face and behind reinforced soil block (b) Within reinforced soil block

Fig. 11. Variation of horizontal deformation profile with D/H_1 for upper wall



(a) Lower wall (b) Upper wall

Fig. 12. Variation of reinforcement force distribution with D/H_1

Note that an equivalent distributed surcharge of q=27 kN/m^2 is used for the internal stability calculation for D=0.5H_l whereas no influence is assumed for D=1.0H_l according to the NCMA design approach. The design earth pressure envelope based on the Rankine active state of stress is also presented in this figure for comparison. Note that significantly smaller reinforcement forces are developed especially in the lower half reinforcements than those inferred from the Rankine active state of stress. This might be, as pointed out by Bathurst (1990, 1992), due to the toe reaction provided by the modular block wall.

As would be expected for the lower wall shown in Figure 12(a), a considerable increase in the reinforcement force is observed for D=0.5H_l, as much as 100%, as compared to that for the single wall. The increase for D=1.0H_l, however, appears to be negligible, as can be expected from the internal horizontal deformation profile. A comparison between the full model and the equivalent surcharge model for D=0.5H_l reveals that the equivalent surcharge model somewhat underestimates the reinforcement forces. This is a direct consequence of not being able to consider soil-structure interaction in the equivalent surcharge model. It is of importance to note that the reinforcement forces slightly exceed that inferred from the Rankine active state of stress in the upper part of the wall for both cases of D=0.5H_l and 1.0H_l. Considering that the currently available design approaches for single walls tend to overestimate reinforcement forces, the current design approach for tiered walls may not be conservative. Further investigation is required to draw a general conclusion.

The reinforcement force distributions for the upper walls are illustrated in Figure 12(b) together with that for a single wall on a rigid foundation. As indicated in this figure, for both cases, significantly larger forces are developed in the tiered walls than for the single wall with corresponding height especially at the lower part of the wall. Even for D=1.0H_l, the force distribution significantly departs from that of the single wall. This phenomenon is a direct consequence of the increased lateral wall movements in the lower wall. Larger reinforcement forces should therefore be expected for the upper wall in a tiered wall than for a single wall with the same height. Such a trend is consistent with the observation in the horizontal deformation and highlights the need for increasing reinforcement density at the lower part of the upper tier wall to improve the internal stability.

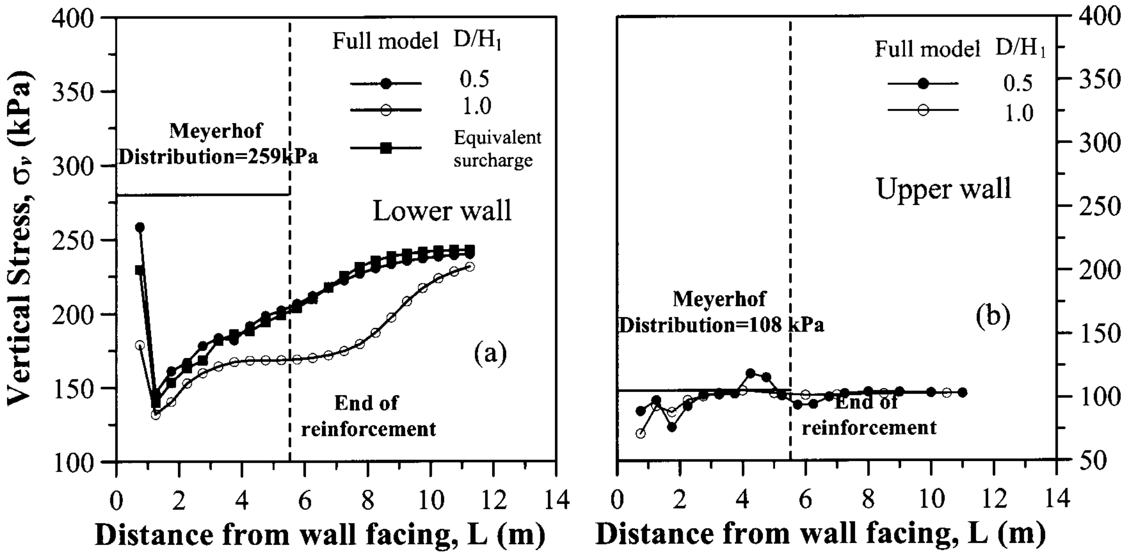
5.3 Stress Distribution

Design of a reinforced soil wall requires to examine the external stability of a monolithic gravity structure, comprising the facing unit, reinforcement, and backfill soil, against three modes of failure; base sliding, overturning, and bearing capacity. Since the horizontal and vertical stresses at the back and the base of the reinforced soil block play important roles in the external stability analysis, the stress distributions should be carefully examined. In the current design approaches, the vertical and horizontal stress distributions at the back and the base of the reinforced soil block are estimated based on the Meyerhof distribution and the Rankine or Coulomb active stress state, respectively.

Typical vertical stress distributions at the base of the reinforced soil block for the lower wall are shown in Figure 13(a). Also shown in this figure are those inferred from the equivalent surcharge approach. The general distribution pattern within the reinforced block is such that the vertical stress is maximum in the vicinity of the wall facing, largely due to the lateral thrust acting at the back of the reinforced soil block, and drops to a minimum value, and then increases with distance thereafter. It appears that the equivalent surcharge approach with the Meyerhof assumption yields a reasonable estimate of the maximum vertical stress $\sigma_{v,max}$ for D=0.5H_l but tends to overestimate for D=1.0H_l, implying that the equivalent surcharge approach may give a conservative estimate of $\sigma_{v,max}$ for cases with large offset distance D. For the upper walls shown in Figure 13(b), the distribution pattern is a bit different from that of a single wall on a rigid foundation, showing the maximum vertical stress $\sigma_{v,max}$ near the edge of reinforced soil block. The stress redistribution due to the settlement of the underlying soil as well as the lateral wall movements may be responsible for such a trend.

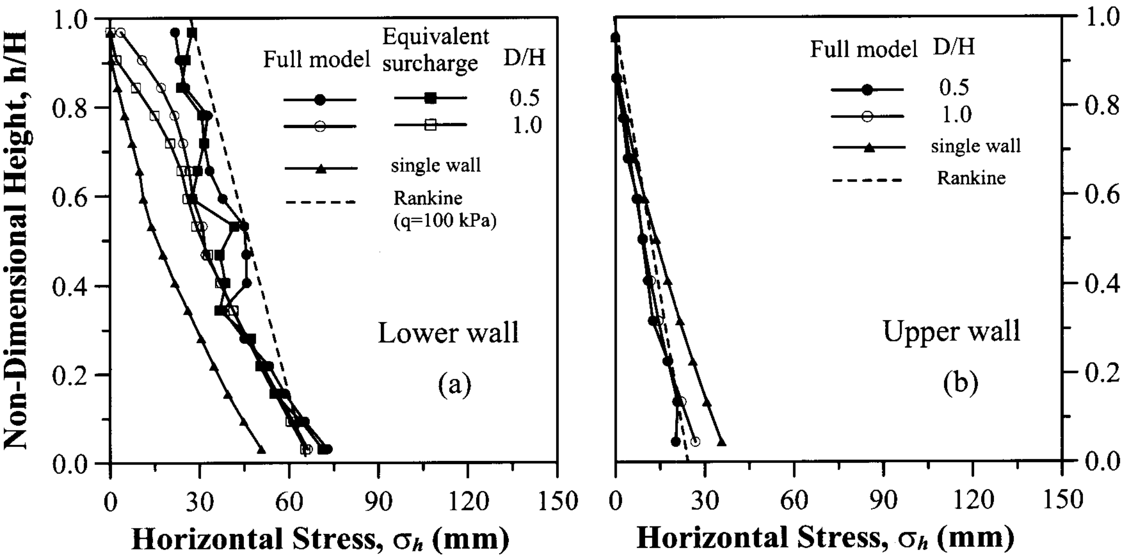
As has been observed, although the maximum vertical stress $\sigma_{v,max}$ does not exceed that inferred from the Meyerhof distribution, it appears that the Meyerhof distribution tends to significantly overestimate the average vertical stress within the reinforced soil block. Note that the "average" overburden stress is required when assessing the resistance against base sliding along the foundation or the resistance against slippage of the reinforcement. The use of Meyerhof assumption when calculating the average overburden stress, therefore, may yield inappropriate design, as indicated by Rowe and Ho (1998).

Horizontal stress distributions at the back of reinforced soil block are presented in Figure 14. As illustrated in Figure 14(a) for the lower wall, the horizontal stress significantly increases over the entire wall height for both cases of $D=0.5H_l$ and $1.0H_l$, following those inferred from the Rankine active state of stress. Note that a considerable increase is observed even for the case of



(a) Lower wall (b) Upper wall

Fig. 13. Variation of vertical stress distribution at the base of reinforced soil block with D/H_l



(a) Lower wall (b) Upper wall

Fig. 14. Variation of horizontal stress distribution at the back of reinforced soil block with D/H_l

$D=1.0H_1$, in which the upper wall is located at the edge of the Rankine active zone behind the reinforced soil block, implying that the external stability is somewhat influenced by the presence of the upper wall. This trend is not captured in the NCMA design guideline and suggests that an attention be placed on the external stability of tiered walls with moderate to large offset distance. Further inspection reveals that the equivalent surcharge model yields similar results to those of the full model. It is therefore concluded that the equivalent surcharge approach can give reasonable estimates of the horizontal stresses at the back of the reinforced block for use in the external stability calculations.

Figure 14(b) shows the horizontal stress distributions for the upper wall. As has been seen, the distribution pattern follows those inferred from the Rankine active state of stress for both cases but with somewhat smaller stresses. Note that the horizontal stress distribution remains practically the same regardless of the offset distance D. Furthermore, the horizontal stresses at the base level are significantly smaller than those for a single wall, due primarily to the lateral movement of the reinforced soil block. No special attention appears to be required for the external stability of the upper wall.

6. Conclusions

The behavior of soil-reinforced segmental retaining walls in tiered arrangement has been presented. It includes horizontal deformation, reinforcement force, horizontal and vertical stresses at the back and the base of the reinforced block. The results of the finite element analyses indicated that the interaction between the upper and lower walls significantly influences both the internal and external stability of the lower wall. It is important findings that a global sliding mode of failure is likely for walls with relatively small offset distance, and that the interaction between the two walls results in a significant increase in the horizontal deformation at the wall face and the reinforcement forces for the lower wall. Furthermore, larger reinforcement forces in the upper wall should be expected than those for a single wall with the same height. Greater reinforcement density is therefore required for the upper tier wall to provide resistance against lateral movements than that for a single wall with the same height on a rigid foundation. None of the current design guidelines addresses such a trend. Also revealed is that the current design approaches based on the equivalent surcharge tend to underestimate the reinforcement forces when compared to the results of finite element analyses on full models. The equivalent surcharge approach however appears to give reasonable estimates of vertical and horizontal stress distributions for use in the external stability analysis.

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