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Effects of Foundation Stiffness and Surface Loading on the Behavior of Soil-reinforced Segmental Retaining Walls

기초의 강성과 상재하중이 보강토 옹벽의 거동에 미치는 영향

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요 지

본 논문에서는 유한요소해석을 통해 기초지반의 강성과 상재하중이 블록식 보강토 옹벽에 미치는 영향을 고찰한 내용을 다루었다. 이를 위해 기초지반의 강성과 상재하중의 위치를 변화시키며 매개변수 연구를 수행하였으며 해석결과에서는 벽체의 변위와 보강재의 유발인장력은 기초지반의 강성이 감소함에 따라 증가하는 것으로 나타났다. 한편, 해석결과에 따르면 현재 설계기준에서 적용되고 있는 상재하중 처리 방법은 경우에 따라서 상재하중의 영향을 지나치게 과대평가 하는 것으로 나타났으며 상재하중이 보강영역에 근접하여 작용할 경우 외적안정성 검토시 주의를 요하는 것으로 나타났다. 본 논문에서는 본 연구를 통해 얻어진 결과가 실무적 측면에서 의미하는 바를 심도 있게 고찰하였다.

Abstract

This paper presents the results of investigation on the effects of foundation stiffness and surface loading on the performance of soil-reinforced segmental retaining walls using the finite element method of analysis. A parametric study was performed by varying the foundation stiffness and the location of surface loading. The results of the analyses indicate that the wall deformation and reinforcement tensile load tend to increase with decreasing foundation stiffness with little variation in the horizontal and vertical stress distributions at the back and the base of the reinforced soil zone. Also revealed is that the increment of reinforcement tensile load due to the presence of surface load may be significantly over-estimated when using the conventional approach. Furthermore, the external stability should be carefully examined when a surface loading is present just behind the reinforced soil zone. The implications of the findings from this study to current design approaches are discussed in detail.

Keywords : Geosynthetic-reinforced retaining wall, Finite-element analysis, Foundation stiffness, Surcharge loading, External stability

1. Introduction

The segmental retaining wall market in Korea has been growing rapidly 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

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after construction, covering a range of minor structural damage to total collapse. Much still needs to be investigated to fill the gap between the theory and the practice.

It has been addressed by various researchers (Karpurapu and Bathurst 1995; Rowe and Ho 1997; Yoo and Lee 1999) that the behavior of reinforced soil walls is greatly influenced by the interaction between the components comprising the wall system such as the facing, the reinforcement, and the backfill soil. The degree of interaction between these components also significantly changes with changes in the physical properties of these materials. In recent years, there have been a number of investigations into the behavior of reinforced soil walls using small-to large-scale laboratory model tests (Juran and Christopher, 1989; Bathurst and Benjamin, 1990; Bathurst, 1990; Chou and Wu, 1993; Porbaha and Goodings, 1997), field tests (Simac et al., 1990; Bathurst et al., 1993; Collin and Berg, 1994; Ochiai and Fukuda, 1996), and numerical experiments (Karpurapu and Bathurst, 1995; Ho and Rowe, 1996; Rowe and Ho, 1997; Yoo and Lee, 1999). However, the majority of the investigations, have been conducted assuming that the walls are constructed on a non-yielding foundation. Therefore, the behavior of segmental retaining walls constructed on a less stiff foundation is not fully understood.

Often vertical surcharge loadings are imposed behind the crest of segmental retaining walls. Vertical surcharge loadings may result from heavy isolated footings or continuous footings constructed in close proximity to the crest of the wall. These surcharge loadings generate an increased lateral pressure on the segmental retaining structure. It is generally recommended that the increment of the reinforcement tensile load be calculated based on a 2V:1H pyramid stress distribution or using the Boussinesq solution. These solutions are based on the theory of elasticity and do not account for soil-structure interaction. However, the appropriateness of such an approach, has not been fully investigated. Therefore, there still remains a need for investigation on the effects of foundation stiffness and surcharge loading on the behavior of segmental retaining walls.

The primary objective of this paper is to provide insight regarding the effects of foundation stiffness and surface loading on the behavior of soil-reinforced segmental retaining walls and to form a database for use in developing a more rational design/analysis method. Attention is focused on a segmental block wall reinforced with extensible reinforcement in a granular backfill resting on a foundation with variable stiffness. The finite element method of analysis was adopted in the present study since numerous researchers have demonstrated that the technique can successfully capture what might otherwise be difficult when adopting physical modeling techniques (Ho and Rowe, 1996; Kapurapu and Bathurst, 1995; Rowe and Ho, 1997; Yoo and Lee, 1999). Comparisons are made between the findings of the numerical analyses and those from simple conventional analyses (i.e., Rankine and Coulomb analyses) in order to provide insight concerning the consequences of neglecting these effects in conventional analyses for the type of wall and conditions examined.

2. Problems Considered

Wall Geometry

In this study, a segmental retaining wall with a height (H) of 8 m resting on a foundation with variable stiffness was considered. The geometry of the wall examined in this study is shown in Figure1 together with the symbols and a set of reference

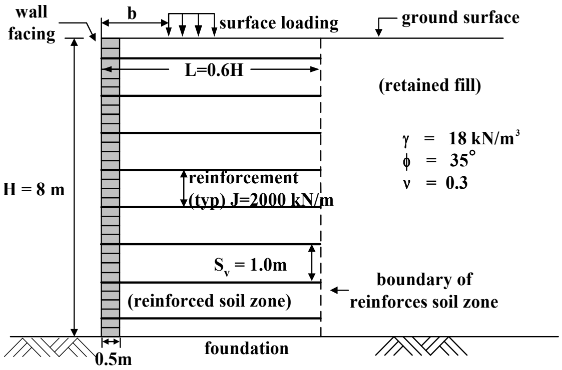


Fig. 1. A Schematic View of Segmental Retaining Wall System

parameters used for the base case. It is assumed that the wall facing is constructed with segmental blocks of 0.25 m (height) × 0.5 m (length), and that the backfill soil was cohesionless and free draining. For simplicity, layers of geogrid with a uniform length (L) to wall height (H) ratio (L/H=0.6) are placed at a uniform vertical spacing of S_v = 1.0 m. Note that the axial stiffness of the geogrid was assumed to be J=2000 kN/m. The reinforcement density Ω, defined as the ratio of geogrid stiffness (J) to vertical spacing (S_v), is Ω=2000 kN/m^2

Parametric Study

A parametric study was performed on the effects of foundation stiffness and surface loading using the finite element method of analysis. In the parametric study, a wide range of boundary conditions was analyzed covering broad foundation and surface loading conditions. For foundation stiffness, a non-dimensional ratio of foundation to backfill stiffness, SR=E_F/E_{BF}, was varied from 1.0 to 1×10^4 to bracket a broad range of foundation conditions encountered in practice.

The effect of surface loading on the behavior of segmental retaining walls was investigated by varying the location (b/H) of a 1.5m-wide strip load acting behind the crest of the wall. Note that the intensity of the strip load was fixed at q=100 kPa, which is well below the ultimate bearing capacity. Table 1 summarizes the conditions analyzed in this study.

Table 1. Summary of Parameters Examined

Parameter	Range of Values
Foundation Stiffness Ratio (SR)	1, 5, 10, 100, 10000
Location of Strip Loading (b/H)	0.13, 0.25, 0.38, 0.5, 0.63, 0.75

3. Finit Element Analysis

Finite Element Model

A commercial finite element code DIANA (DIANA, 1996) was used for this study. DIANA is a multipurpose finite element program for use in a range of geotechncial engineering problems including excavation, tunneling, retaining walls and slopes.

Figure 2 shows the finite element mesh used in the analyses. As can be seen, a very refined mesh

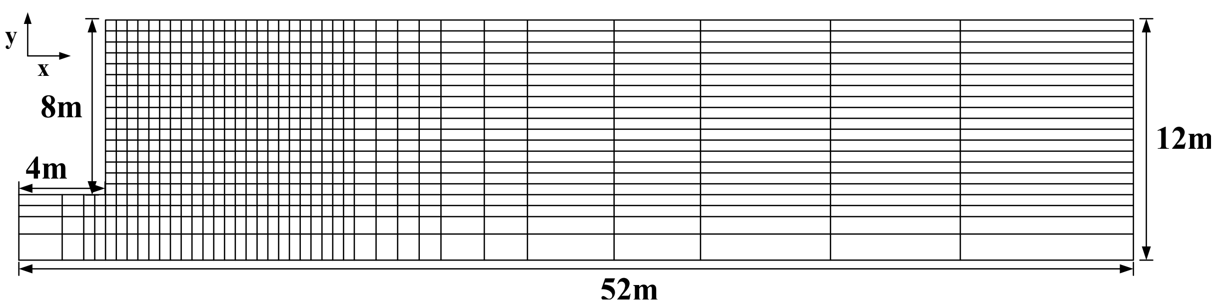


Fig. 2. Finite Element Mesh Used

consisting of approximately 980 nodes and 1050 elements was adopted to minimize the effect of mesh dependency on the results of finite element analysis. In the finite element model, the foundation soil was assumed to extend to 0.5H below the wall base. The lateral boundary is located at approximately 3.0H in front of the wall face.

The backfill soil and the wall facing were discretized using four-noded isoparamatric plane strain elements, while two-noded truss elements were used for the reinforcements. In addition, the interface behavior between block/backfill, reinforcement/backfill, and backfill/foundation was modeled using four-node Goodman type interface elements (Goodman et. al., 1968). Figure 3 illustrates the details of the wall/backfill 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 internal angle of friction (ϕ), using the relationship proposed by Bolton (1986) with a constant critical state friction angle ϕ_{cv}=30, i.e.

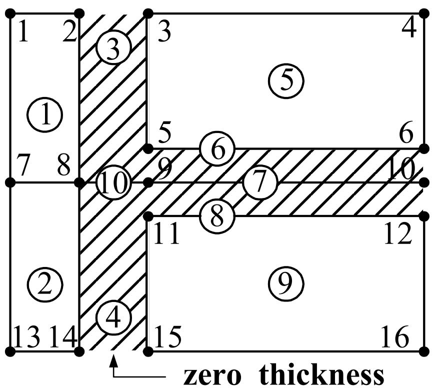
$$\phi = \phi_{cv} + 0.8\Psi \quad (1)$$

The wall facing, reinforcement, and interfaces were assumed to follow a linear elastic behavior. Table 2 summarizes material properties used in the analyses.

Modeling of Construction Sequence

It is recognized that in numerical analyses, the final computed results are different for a solution based upon sequential construction and one based upon single stage construction (Desai and Christian 1977). Therefore, for realistic solutions to segmental retaining wall problems, the construction sequences should be simulated as carefully as possible.

In the present analysis, the step-by-step wall



Element	Type	Nodes
1	quadrilateral	1-7-8-2
2	quadrilateral	7-13-14-8
3	interface	2-8-3-5
4	interface	8-14-11-15
5	quadrilateral	3-5-6-4
6	interface	5-6-9-10
7	uniaxial bar	9-10
8	interface	9-10-11-12
9	quadrilateral	11-15-16-12
10	nodal link	8-9

Fig. 3. Modeling Detail for Reinforcement/Block/Backfill Soil Junction

Table 2. Material Properties Used

	Material Property					
	E_{BF} (kPa)	ϕ (degree)	γ (kN/m^3)	EI (kN−m^2/m)	K_s (kPa/m)	K_n (kPa/m)
Soil	3×10^4	35	18			
Wall				5,500		
S/W Interface					1×10^4	1×10^{10}
S/R Interface					1×10^5	1×10^{10}

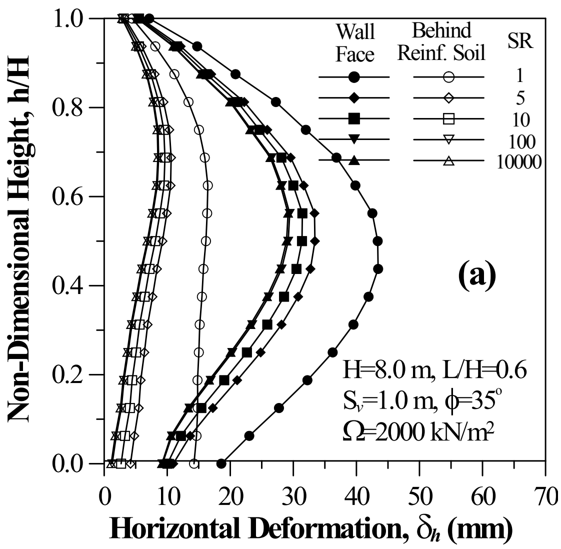
Note: S/W=soil/wall; S/R=soil/reinforcement construction sequence was carefully simulated by adding soil, block, and reinforcement layers until design wall height was reached using the phased analysis option, which is a special feature offered by DIANA. A phased analysis comprises several calculation phases. Between each phase 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 surface loading, the surface load was incrementally applied upon completion of wall construction.

Although the finite element model adopted in this study has not been fully calibrated to any field or laboratory model walls, the components of the wall were carefully modeled with due consideration of other available finite element models published elsewhere (Kapurapu and Bathurst, 1995; Rowe and Ho, 1997).

4. Effect of Foundation Stiffness

Wall Deformation and Reinforcement Tensile Load

Sources of the horizontal wall deformation include horizontal strains within the reinforced soil zone as well as the rigid body movement of the reinforced soil zone itself. This movement is due to lateral thrust acting at the back of the reinforced soil zone. Figure 4 presents horizontal deformation (δ_h) profiles at the wall face and behind the reinforced soil zone. Also shown in this figure are the corresponding internal horizontal deformation profiles of the reinforced soil zone. Note that the internal horizontal deformation profiles are obtained by subtracting the horizontal deformation behind the reinforced soil zone from that at the wall face. As expected, the trend of decreasing horizontal deformation at the wall face with increasing the foundation stiffness ratio *SR* is evident. However, horizontal deformation is largely insensitive to a change in *SR* when *SR*=100 or greater. Of particular interest is that the change in



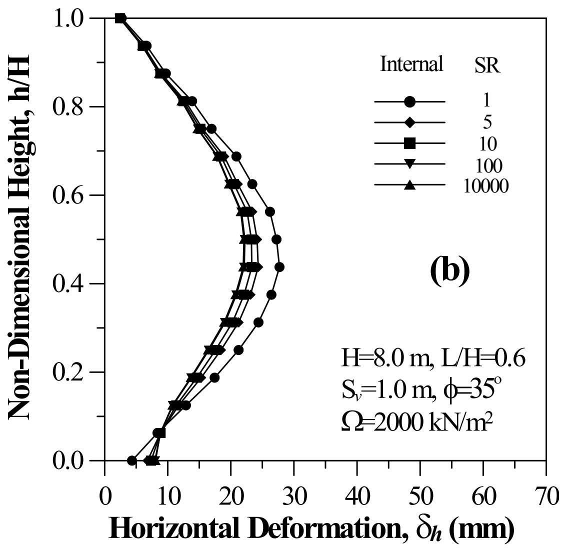


Fig. 4. Variation of Horizontal Deformation Profile with Foundation Stiffness for Ω=2000, kN/m^2: (a) At wall face and Behind Reinforced Soil Zone; (b) Within Reinforced Soil Zone

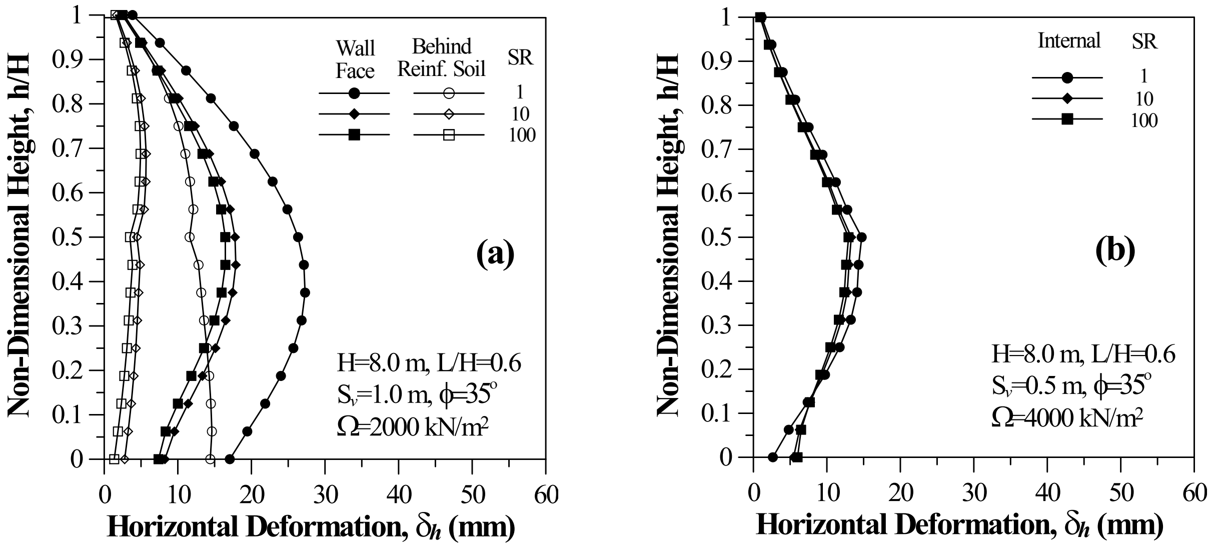


Fig. 5. Variation of Horizontal Deformation Profile with Foundation Stiffness for Ω=4000 kN/m^2: (a) At wall face and Behind Reinforced Soil Zone; (b) Within Reinforced Soil Zone

δ_h at the wall face due to a change in SR mainly arises from changes in the deformation behind the reinforced soil zone with little increase within the reinforced zone, indicating that the foundation stiffness does not significantly affect the internal stability. It is therefore expected that the horizontal deformation behind the reinforced soil zone contributes a significant portion of the deformation at the wall face for a wall constructed on a poor foundation.

A similar trend is observed for walls with greater reinforcement density Ω=J/S_v (i.e., smaller vertical reinforcement spacing of S_v=0.5 m), as seen in Figure 5. Of key phenomenon, however, is that the internal horizontal deformation remains constant over the range of foundation stiffness ratios with significant increase in the horizontal deformation behind the reinforced soil zone. This trend indicates that the contribution of the horizontal deformation within the reinforced soil zone to the wall deformation becomes insignificant as the reinforcement density increases.

The effect of foundation stiffness on the maximum horizontal deformation $\delta_{h,m}$ at the wall face is illustrated for two levels of Ω in Figure 6 which shows the variation of normalized maximum horizontal deformation ratio at the wall face *DR* with *SR*. Note that the ratio *DR* is the ratio of maximum horizontal deformation $(\delta_{h,m})_F$ of a given condition to that for an infinitely rigid foundation $(\delta_{h,m})_R$, defined as DR=$(\delta_{h,m})_F/(\delta_{h,m})_R$. Figure 6 shows that the wall deformation ratio DR rapidly decreases with increasing foundation stiffness ratio SR and approaches DR=1.0

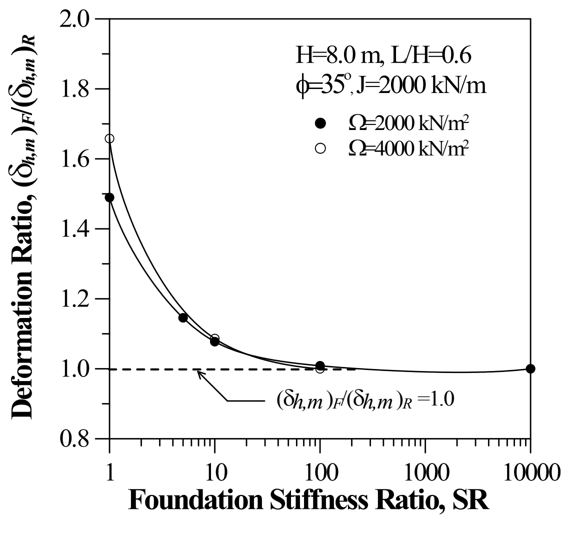


Fig. 6. Variation of Maximum Horizontal Wall Deformation Ratio with Foundation Stiffness

when the foundation stiffness ratio reaches approximately SR=100, regardless of the reinforcement density Ω. No significant positive effect of increasing the reinforcement length in reducing the influence of poor foundation conditions was observed in a series separate analyses. It is therefore recommended that any poor foundation material be replaced with structural fill to avoid possible problems associated with poor quality foundation.

The effect of foundation stiffness on the maximum reinforcement tensile load distribution is shown in Figure 7 for two levels of Ω. The general distribution pattern does not follow the linear trend implied by the Rankine active state of stress or Coulomb active wedge analysis, but rather tends to be more or less a parabolic shape. In addition, the difference between finite element analyses and the conventional analyses increases with depth and becomes greatest at the wall base. The largest difference at the wall base level is due primarily to the toe resistance provided at the wall base. Note that such a toe resistance may be provided by wall embedment in the field construction. The significance of toe resistance on the overall stability of reinforced wall has been addressed by Kapurapu and Bathurst (1996). Also seen is that the reinforcement tensile load decreases and becomes far more uniform as Ω increases. Furthermore, as expected, for Ω=2000 kN/m^2, a decrease in foundation stiffness results in an increase in the reinforcement tensile load with the greatest increase at the level 0.3H above the wall base. Such a pattern is consistent with the observation for the horizontal wall deformation. In addition, the reinforcement tensile load distribution remains practically the same when SR$\geq$10. For Ω=4000 kN/m^2, on the other hand, no variation of the reinforcement tensile load is observed, suggesting that the foundation stiffness does not significantly affect the internal stability. This trend is consistent with the deformation pattern. Although the maximum reinforcement tensile load falls within the trend line inferred from the Rankine active state of stress or Coulomb active wedge analysis, even for the worst case, the negative impact of the foundation flexibility on the wall performance in the field environment would be expected far more sever than observed in the present study.

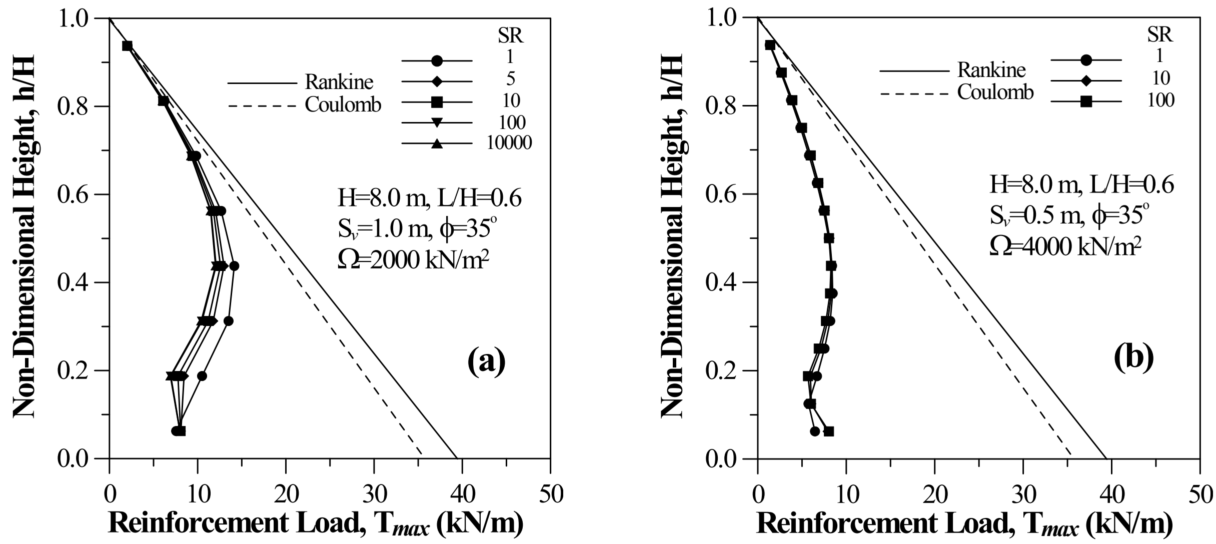


Fig. 7. Variation of Reinforcement Tensile Load Distribution with Foundation Stiffness: (a) Ω=2000 kN/m^2; (b) Ω=4000 kN/m^2

Vertical and Horizontal Stress Distributions

The design of a reinforced soil wall requires analysis of the external stability of a monolithic gravity structure, comprising the facing unit, reinforcement, and backfill soil, against base sliding, overturning, and bearing capacity. Since the horizontal and vertical stresses at the back and the base of the reinforced soil zone play important roles in the external stability analysis, more accurate evaluation of the stress distribution is essential. In the current design approaches, the horizontal and vertical stress distributions at the back and the base of the reinforced soil zone are estimated based on the Rankine or Coulomb active stress state and the Meyerhof distribution, respectively. The effect of foundation stiffness on the stress distribution is examined.

Typical vertical and horizontal stress distributions for a number of different foundation stiffness ratios SR are shown in Figure 8. Generally, the vertical stress distribution does not appear to be greatly influenced by the foundation stiffness, showing essentially similar results for a range of foundation stiffnesses as shown in Figure 8(a). In addition, for a given condition, a considerable magnitude of vertical stress is developed near the wall, which may be largely due to the lateral thrust acting at the back of the reinforced soil zone. A similar distribution has been reported by Rowe and Ho (1997) for continuous panel walls. 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 over-estimate the average vertical stress within the reinforced soil zone. 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 in calculating the average overburden stress, therefore, may yield inappropriate design, as indicated by Rowe and Ho (1997).

In summary, the findings in this study suggest that the foundation stiffness has greater impact on the horizontal deformation of the reinforced soil zone than on the internal stability. Of practical significance associated with the foundation stiffness is the

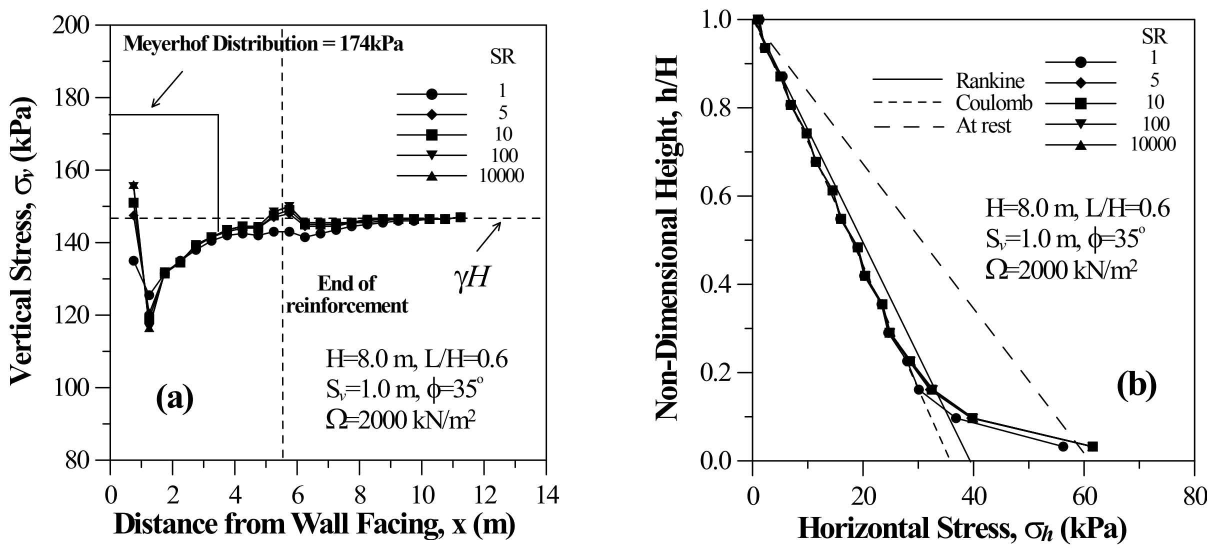


Fig. 8. Variation of Stress Distribution with Foundation Stiffness: (a) Vertical Stress at Base of Wall; (b) Horizontal Stress at Back of Reinforced Soil Zone

construction of tiered wall, which an upper wall is constructed on top of underlying wall. Without any ground improvement strategy for the crest of the underlying wall, the behavior of upper wall may be adversely affected by the flexibility of backfill soil for the underlying wall. A possible measure to avoid such a problem in a tiered wall construction would be to increase the reinforcement density of the upper part of lower wall to improve the stiffness of reinforced zone. An issue of wall settlement due to low foundation stiffness should be examined separately and is beyond the scope of this study.

5. Effect of Surface Loading

Horizontal Deformation and Reinforcement Tensile Load

Figure 9 illustrates the horizontal deformation profiles at the wall face as well as behind and within the reinforced soil zone for the range of b/H ratios considered. As is evident in this figure, the effect of surface loading is to increase the horizontal wall deformation. Of particular interest to note is that the variation of horizontal wall deformation with b/H is less pronounced than would be expected. This can be explained by examining the horizontal deformation profiles behind and within the reinforced soil zone in Figure 9. As seen in this figure, when b/H is less than L/H (i.e., when the surface loading is above the reinforced soil zone), the variation of horizontal deformation with b/H mainly occurs within the reinforced soil zone. In contrast, when b/H is greater than L/H, the horizontal deformation behind and within the reinforced soil zone significantly increases due to the increased lateral thrust acting back of the reinforced soil zone. Note that the internal horizontal deformation within the reinforced soil zone significantly increases when the surface loading is just behind the reinforced soil zone (i.e., b/H=0.63). These findings suggest that the effect of surface loading on the behavior of reinforced soil wall should not be over-looked even when the surface loading is present behind the reinforced soil zone.

The effect of surface loading on the incremental reinforcement tensile load ($\triangle T_{max}$) is illustrated in Figure 10. Also shown are the $\triangle T_{max}$ distributions computed based on the Boussinesq solution. Note

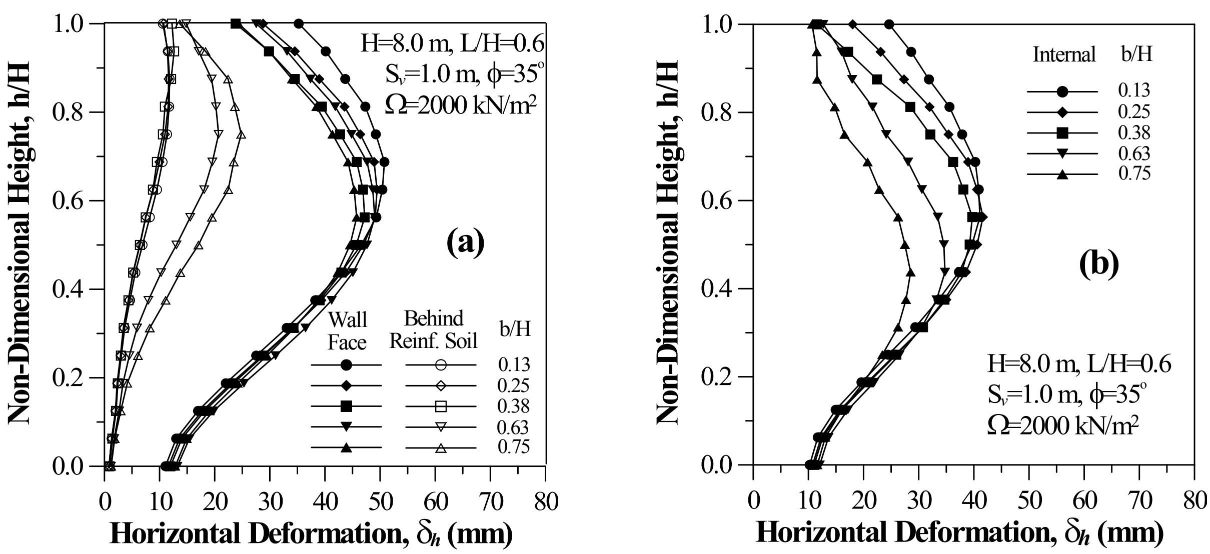


Fig. 9. Variation of Horizontal Deformation Profile with b/H for S_v=1.0 m: (a) At wall face and Behind Reinforced Soil Zone; (b) Within Reinforced Soil Zone

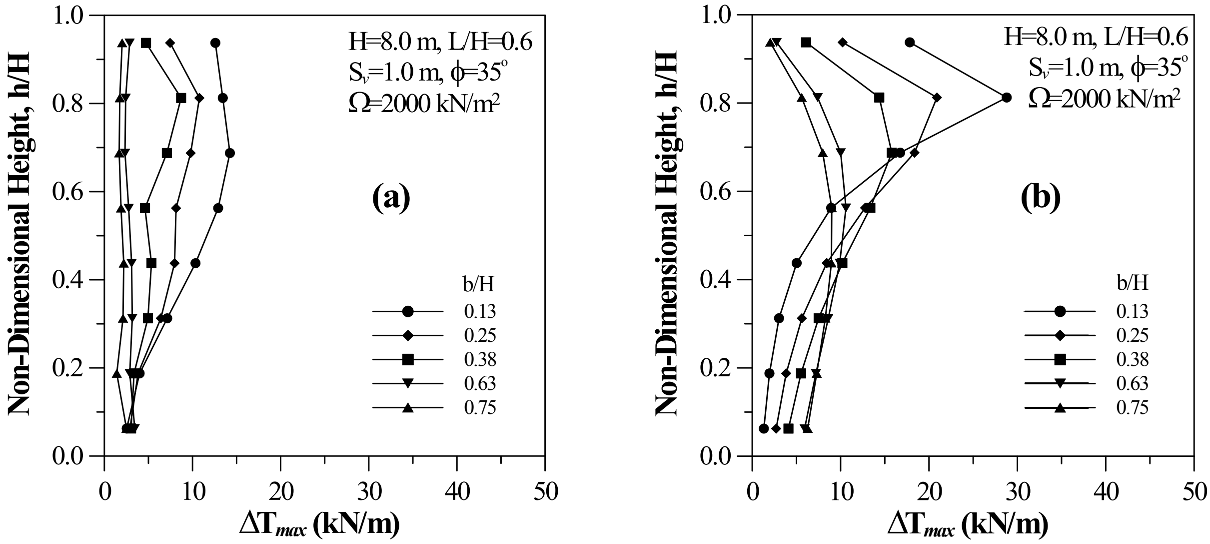


Fig. 10. Variation of Reinforcement Tensile Load Distribution with b/H: (a) Finite Element Analysis; (b) Boussinesq Solution

that the general trend of $\triangle T_{max}$ distribution resembles that of the internal horizontal deformation within the reinforced soil zone. As would be expected, $\triangle T_{max}$ decreases with an increase in distance of the surface loading from the wall face. This trend becomes more pronounced when the surface loading is located above the reinforced zone (i.e., b/H<L/H). Comparison between the predicted and the computed based on the Boussinesq solution reveals that the incremental reinforcement tensile load may be significantly over-estimated when adopting the Boussinesq solution. Further investigation is required to develop a generalized method for estimating the increase in reinforcement tensile load cause by surface loading.

Vertical and Horizontal Stress Distributions

The variation of vertical stress at the base of reinforced soil zone is shown in Figure 11. As is evident in this figure, an increase in b/H increases the maximum vertical stress $\sigma_{v,max}$. This trend is in contrast to what would be expected and may be attributed to an increased lateral thrust as the surface loading moves farther away from the wall face. When the surface loading is just outside the reinforced soil zone, the predicted $\sigma_{v,max}$ value slightly exceeds that computed based on the Meyerhof distribution. A further study is required to draw a general conclusion on the appropriateness of the Meyerhof distribution when using for walls subjected to a surface loading behind the wall crest.

Horizontal stress distributions are presented in Figure 11 for a range of b/H. As illustrated, the horizontal stress increases at the top and slightly decreases at the bottom as the surface loading moves away from the wall face (i.e., b/H increases), resulting in more uniform distribution. The increase at the top is more pronounced when the surface loading is outside the reinforced soil zone. This observation is as would be expected and supports the trend for the vertical stress distribution. With greater horizontal stress at the back of the reinforced soil zone with a uniform distribution, a greater lateral thrust is expected, thereby increasing the vertical stress at the base of the reinforced soil zone. The

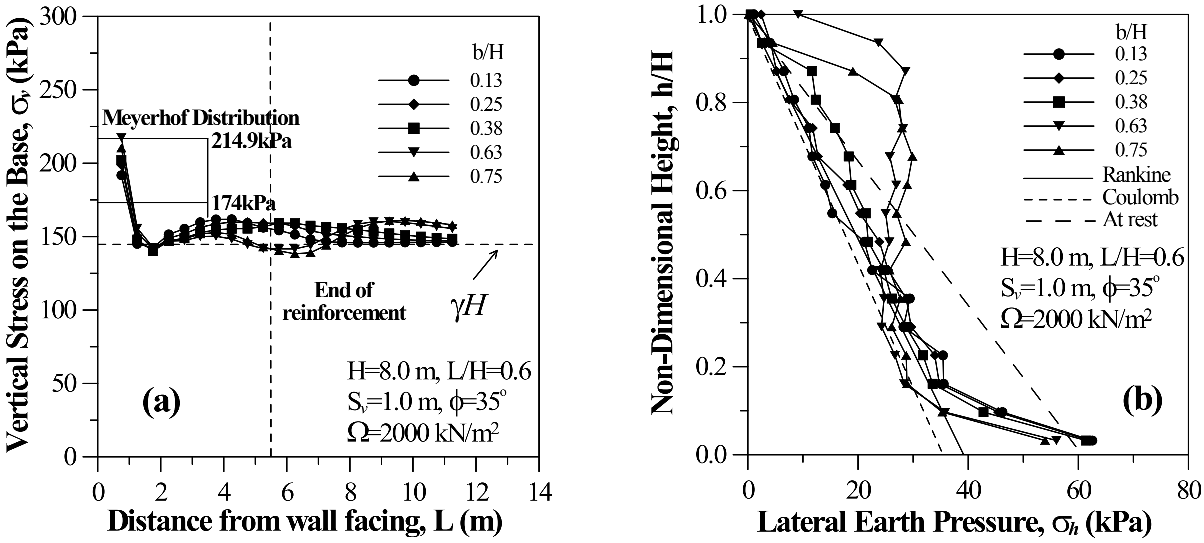


Fig. 11. Variation of Stress Distribution with b/H: (a) Vertical Stress at Base of Wall; (b) Horizontal Stress at Back of Reinforced Soil Zone

practical implication from these general observations is that the external stability of reinforced wall should be carefully examined when a surface loading is present just outside the reinforced soil zone.

6. Conclusions

The results of finite element analysis on the effects of foundation stiffness and the surface loading on the behavior of soil-reinforced segmental retaining walls have been presented. Among the results examined include horizontal deformation, reinforcement tensile load, horizontal and vertical stresses at the back and the base of the reinforced zone. Based on the results of analysis, the following conclusions can be drawn.

1. Horizontal deformation behind the reinforcement soil zone significantly increases with decreasing the foundation stiffness, thereby increasing the horizontal deformation at the wall face. Counter measures should be provided to reduce the horizontal deformation behind the reinforced soil zone for such cases. The effect of foundation stiffness on horizontal wall deformation becomes negligible when the foundation stiffness is ten times (or greater) than the backfill stiffness.
2. The effect of foundation stiffness on tensile load in reinforcement layers is not as significant and diminishes as the reinforcement density increases. Vertical and horizontal stress distributions at the base and the back of the reinforced soil zone are not significantly affected by the presence of poor foundation conditions. The wall deformation and settlement criteria are likely to govern the design of walls on poor soil rather than the external or internal stability.
3. The current design approaches based on the theory of elasticity used to estimate increase in lateral stress caused by surface loads tend to over-estimate the magnitude of reinforcement tensile load. The degree of conservatism increases as the location of surface loading moves away from the wall face.
4. Vertical and horizontal stresses at the base and the back of the reinforced soil zone increase with

an increase in the distance between the surface loading and the wall, largely due to the increased lateral thrust behind the reinforced soil zone. Both internal and external stability should be checked with great care for walls subjected to surface loading.

5. The findings from this study should be validated against field measurements or large-scale model test results before implementing in the design of soil reinforced segmental retaining walls.

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