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A comparative study on design of geosynthetic reinforced modular block wall in tiered arrangement

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ABSTRACT: This paper presents the results of a comparative study on the design approaches for geosynthetic reinforced modular block walls in a tiered configuration. Stability calculations were made on a number of field walls using the currently available design approaches and the discrepancies between the two approaches were identified. Finite element analyses were additionally conducted using a calibrated finite element model on design cases having various offset distances. The qualitative and quantitative discrepancies between the results from the limit equilibrium-based models and the finite element model were also presented. The results indicated among other things that the calculation models adopted in the current design approaches tend to yield significantly larger reinforcement loads in bottom layers of lower tier when compared to those computed by the finite element model. Practical implications of the findings obtained from this study are highlighted.

1 INTRODUCTION

There are many situations where geosynthetics reinforced modular block walls (MBWs) are constructed in a tiered configuration for a variety of reasons such as aesthetics, stability, and construction constraints, etc. Such a tiered configuration, however, tends to give designers and contractors unnecessarily high confidence in terms of wall performance, especially for walls with an intermediate to large offset distance (D), as defined in Fig. 1, i.e., D = 0.3 to 1.0 times lower tier height. A previous numerical investigation by Yoo and Kim (2002), however, revealed that for cases with such a range of offset distances, the interaction between the upper and the lower tiers is significant causing larger wall deformation and reinforcements loads than what might be anticipated, and that the equivalent surcharge approaches adopted in the current design approaches (Collins 1997, Elias and Christopher 1997) may yield unconservative results in some cases. In-depth studies are, therefore, required to improve the current design approaches for MBWs.

This study presents the results of a comparative study on the design approaches for geosynthetic reinforced modular block walls in a tiered configuration. A number of field design cases were analyzed using the currently available design procedures, i.e., NCMA (Collins 1997) and FHWA (Elias and Christopher 1997) design approaches to investigate the discrepancies in the internal and external stability calculation models between the two. A series of finite element (FE) analyses were additionally performed using one of the field walls by varying the offset distance. The results of the FE analyses were then used to evaluate the appropriateness of the calculation models, especially for reinforcement loads, being adopted in the current design approaches. This paper discusses the qualitative and quantitative discrepancies in stability calculation results between the NCMA and FHWA design approaches, appropriateness of the calculation models being adopted in the two design approaches for reinforcement loads, and finally, practical implications for design.

2 REIVEW OF DESIGN APPROACHES

2.1 *NCMA design approach*

The NCMA design approach basically replaces the upper tier with an equivalent surcharge of which the magnitude is determined according to the offset distance D (Fig. 1). External and internal stability calculations of the lower tier are performed assuming the lower tier being a single wall under the equivalent surcharge (q_{eq}). The upper wall is designed as if it were a single wall without taking into consideration of the possible interaction between the upper and the lower tiers. As for a single wall, the local stability

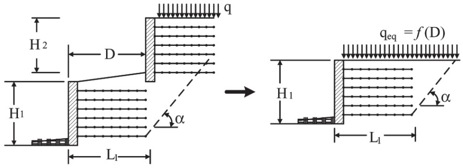

Figure 1. Equivalent surcharge model (NCMA).

calculations for the connection failure, local overturning, and internal sliding should be performed for both tiers. Details of the design procedure are available in Collin (1997).

2.2 *FHWA design approach*

The FHWA design guideline requires determining the reinforcement length L that satisfies external stability requirements based on the following criteria (Fig. 2).

- $D > H_1$ tan $(90 - \phi)$
  No interaction. Each tier is independently designed.
- $D \leq 1/20(H_1 + H_2)$
  Design for a single wall with a height of $H = H_1 + H_2$.
- $D > 1/20(H_1 + H_2)$

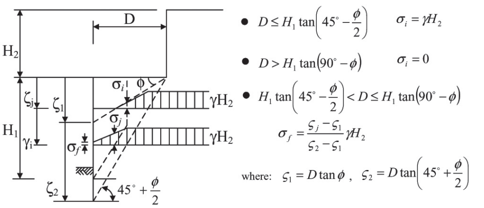

Figure 2. Calculation model for vertical stress increase due to upper tier (FHWA).

For lower tier: $L_1 \geq 0.6\, H_1$ For upper tier: $L_2 \geq 0.7\, H_2$ where H_1 = lower tier height, H_2 = upper wall height, L_1 and L_2 = reinforcement length of lower and upper tier, respectively, and ϕ = internal friction angle of backfill.

For internal stability calculations, additional vertical stresses at depths due to the upper tier are computed based on the criteria shown in Fig. 2. The location of the potential failure surface required for the pullout capacity calculation is selected based on the offset distance D (Elias and Christopher 1997). Note, however, that these criteria are geometrically derived and empirical in nature. As for the NCMA approach, no provision is made to take into account the possible interaction between the upper and the lower tiers when designing the upper tier. The connection failure should also be checked for both tiers as part of internal stability check based on the procedure for a single wall (Elias and Christopher 1997).

3 COMPARISON OF DESIGN APPROACHES

For the purpose of making a direct comparison between the two design approaches stability calculations were made on four field walls implemented in Korea. Figure 3 shows geometries of the walls examined. As can be seen, the offset distance ranges 0.7~0.9 times the lower tier height (H_1) with the reinforcement lengths of (0.7~1.3) H_1. Table 1 summarizes the results of the external and the internal calculations. It should be noted that an internal friction angle of $\phi = 30°$ and a unit weight of γ = 18 kN/m^3 were used for the backfill soils as used in their original designs. This is justified since the purpose of the comparisons was not to examine the performance of the walls but to demonstrate the differences between the two design approaches.

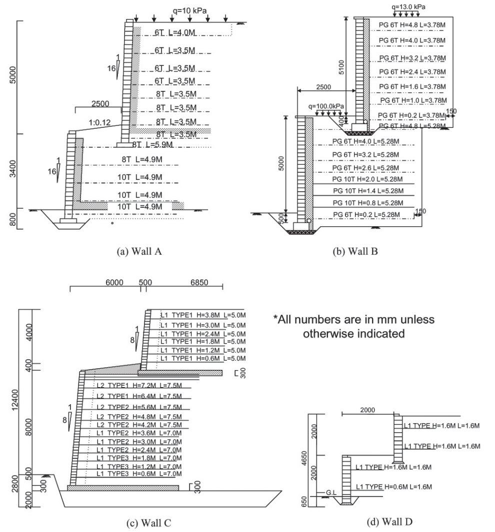

Figure 3. Field walls examined.

As seen in Table 1, the factors of safety against direct sliding based on the FHWA design approach appear to be approximately 40 to 70% smaller than those based on the NCMA design approach except for wall D. In fact, the walls A, B, and C do not satisfy the base sliding requirements specified by the FHWA design approach although they satisfy the NCMA requirement. A similar trend is observed for the overturning. The results of the internal stability calculations also show that the FHWA design approach gives larger maximum reinforcement loads than the NCMA design approach. In addition the FHWA design approach tends to yield larger embedment lengths beyond active failure surfaces than the NCMA design approach, which in turn results in larger pullout capacities. It should be noted that the maximum reinforcement load for the lower tier is presented

Table 1. Results of external and internal stability calculations for field cases.

Wall	External			
	FS_{bsl}		FS_{ot}	
	NCMA	FHWA	NCMA	FHWA
A	3.13	1.27	8.87	2.13
B	2.19	1.23	4.53	1.76
C	2.79	2.02	6.09	5.01
D	1.28	1.67	3.54	1.65
Wall	**Internal**			
	$T_{i,\max}$ (kN/m)		L_e (m)	
	NCMA	FHWA	NCMA	FHWA
A	19.7	30.5	3.4	4.1
B	19.8	36.9	1.5	2.5
C	16.0	37.5	2.4	3.9
D	9.9	19.7	0.3	0.3

Note (1) FS_{bsl} = factor of safety against base sliding; (2) FS_{ot} = factor of safety against overturning; (3) $T_{i,\max}$ = maximum reinforcement force within lower tier; (4) L_e = embedded length beyond active zone for top-most reinforcement in lower tier; (5) For Wall D, FHWA design guideline assumes no interaction

instead of the factor of safety against tensile overstress failure to allow for a direct comparison between the two approaches. Likewise, the embedment length beyond the active zone for the top most layer of lower tier is used for the pullout check.

The comparison of the results from the two design approaches clearly indicates that the FHWA design approach tends to give rather smaller factors of safety for both the external and the internal stability calculations than the NCMA design approach. Apart from the different design earth pressures adopted in these design approaches, the differences in the calculation models (i.e., the way in which the upper tier is treated) adopted in the two design approaches may also be responsible for the discrepancies. On account of the limited number of cases considered in this study, general conclusions cannot be drawn from these comparisons. Further investigation is warranted to fill the gap between the two design approaches.

4 FINITE ELEMENT ANALYSIS

A series of finite element analysis were carried in order to investigate the effect of offset distance on the reinforcement load distribution and to check the appropriateness of the calculation models being adopted in the design guidelines.

4.1 *Case considered*

Wall B in Fig. 3 was considered in the analysis. The wall was assumed to be situated on a non-yielding foundation condition and backfilled with a weathered granite residual soil having $\phi = 30°$, a typical soil being used in Korea. Three levels of offset distance, i.e., D = 0.25H, 0.5H, 1.0H, were considered in the analysis but with the same reinforcement distribution, i.e., $L_1 = L_2 = 0.7\text{H}$.

A commercial finite element code ABAQUS (Hibbitt, Karlsson, and Sorensen 2002) was used for analysis. The wall facing, the backfill soil, and the foundation were discretized using 8-node plane strain elements (CPE8R) with reduced integration, while the reinforcement was modeled using 3-node truss elements (T3D2). A refined mesh (Fig. 4), consisting of over 5800 nodes and elements, respectively, was adopted to fully account for the construction procedure and to minimize the effect of mesh dependency on the results of finite element analyses. The lateral and bottom boundaries were placed at locations with sufficient distances. The interface behavior between the wall facing and the backfill soil was modeled using a layer of interface elements (Desai et al. 1984) with appropriate mechanical properties. No interface was introduced between the soil and the reinforcements assuming no slip between the backfill and the reinforcements.

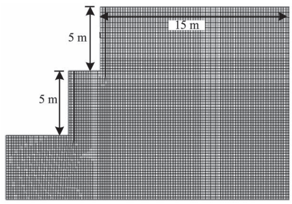

Figure 4. Finite-element mesh.

In the analysis, the backfill and the foundation soil were assumed to follow the modified version of hyperbolic stress-strain and bulk modulus model proposed by Duncan et al. (1980) while the wall facing block and the reinforcement were assumed to behave in a linear elastic manner. In addition, for the interface elements between the wall facing block and the backfill soil, a relatively low shear modulus but with a high bulk modulus was assigned to permit relative movement between the two media. The constitutive laws for the soil and the interface were implemented to ABAQUS with the help of built-in "User Subroutine" capability.

For the backfill soil, the Mohr-Coulomb soil strength parameters of $c' = 0$ kPa and $\phi' = 30°$ were assumed in conjunction with the hyperbolic model parameters including stiffness modulus number for primary loading $K = 350$, stiffness modulus number for unloading-reloading $K_{ur=350}$, bulk modulus number $K_b = 175$, stiffness modulus exponent $n = 0.5$, bulk modulus exponent $m = 0.2$, and failure ratio $R_f = 0.8$. Considering the free draining characteristic of the typical decomposed granite soils in Korea, a fully drained condition was assumed. It should be noted that the hyperbolic parameters for the backfill are the "best-estimate" parameters based on local experience. On account of the discrete nature of the modular block facing, the Young's modulus of the facing block was reduced to 1/10 of that of concrete, giving a wall flexural stiffness of $(EI)_w$ = 20 MN-m^2/m. The detailed construction sequence was carefully simulated by adding layers of soil and reinforcement at designated steps. The finite element modeling approach adopted in this study was calibrated against available instrumentation data for a full-scale tiered modular block wall. Details of the model verification are available in Yoo (2003).

4.2 *Results and discussion*

Figure 5 presents the computed reinforcement loads from the FEA and those calculated using the calculation models adopted by the NCMA and FHWA design approaches. Of salient features are three folds. First, the discrepancies between the two design approaches tend to increase with decreasing the offset distance (i.e., the interaction between the two tiers increases) In fact, FHWA design approach yields 50% larger reinforcement loads than those from the NCMA design approach for D = 0.25H. Secondly, the two design approaches tend to give significantly larger reinforcement loads in the bottom 1/2 reinforcement layers installed in the lower tier when compared to those from the FEA. Thirdly, there appears to exist some evidence of interaction when D = 1.0 H according to the results of the FEA, especially in the upper portion of the lower tier, as the reinforcement loads tend to be uniform. Note that for D = 1.0 H no interaction is assumed in the calculation models in the design approaches. Another feature that can be noticed, although not significant, is that the computed reinforcement loads in the upper tier by FEM are greater than those for a single wall. This is an indication of possible interaction between the upper and the lower tiers. No interaction between the two tiers however is assumed for the upper wall in the current design approaches.

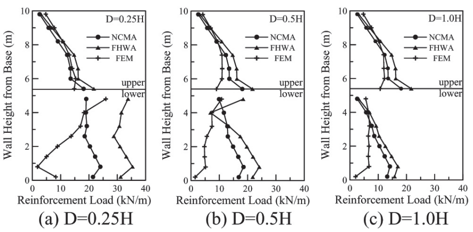

Figure 5. Comparison of reinforcement loads between design calculation models and FEA.

The comparison presented above clearly indicates that there exits discrepancies between the assumed behavior in the design models and that observed in the results of the finite element analysis. Although general conclusions cannot be drawn regarding the appropriateness of the current design guidelines due to the limited data available, other evidences together with the results of the finite element analysis clearly suggest the need for further study.

5 CONCLUSION

This paper presented the results of a comparative study on the design approaches for geosynthetic reinforced modular block walls in a tiered configuration. The results of FE analyses using a calibrated FE model were also used to evaluate the appropriateness of the current design approaches. The results indicated among other things that the FHWA design approach tends to give larger reinforcement loads in all levels of offset distances than the NCMA design approach. It was also revealed that the calculation models adopted in the NCMA and FHWA design approaches tend to overestimate reinforcement loads in the bottom 1/2 reinforcement layers in the lower tier when compared to the results of FE analyses. Systematic studies on this subject are warranted to improve the current design approaches.

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