지하벽체의 최대부재력 산정을 위한 차트의 개발

김영찬† · 김주범*
부경대학교 건축공학과 · *펜실베니아주립대학교 토목공학과

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Development of Design Charts to Estimate Member Forces on Basement Wall

Youngchan Kim† · Jubum Kim*
Department of Architectural Engineering, Pukyong National University
*Department of Civil Engineering, Pennsylvania State University at Harrisburg

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Abstract : It is a common practice to design basement walls acting as a one-way slab or plate with idealized boundary conditions, resulting in potentially inefficient design. The walls are often supported by buttress columns and side walls in the vertical direction, thereby acting as a two-way slab. In this study, structural behavior of single-story, three-span basement wall subjected to lateral soil pressure was investigated. Three dimensional finite element analyses were conducted to determine the force distribution on the wall. Based on the numerical studies, a regression analysis was carried out to determine the design values of moments in vertical and horizontal directions as well as shear forces on the wall and design charts are developed. The proposed design method with accompanying design charts would enable practicing engineers to estimate member forces on the wall for preliminary design purpose without resorting to finite element analysis. Numerical examples demonstrated the applicability of the proposed method.

Key Words : structural design, basement wall, finite element analysis, reinforced concrete wall, soil pressure

1. Introduction

A commercial or residential building in an urban setting typically includes basement floors for an efficient land use. The exterior walls in the basement are supported laterally by floor slabs at the top and foundations or slabs-on-ground at the bottom. They are designed to resist lateral soil pressure. The backfill is typically compact granular fill that drains water well into the footing, thereby reducing additional lateral loads due to water pressure.

Solutions of plates or walls with specific aspect ratios and idealized boundary conditions subjected to various transverse loading can be obtained by analytical methods in the literature[1-3]. However, the analytical solution becomes difficult to get if the boundary conditions differ from the idealized conditions as is in the basement wall structure. Therefore an approximate approach, where the basement wall is assumed to act as one-way slab spanning vertically between the floors with simple or fixed-end boundary conditions, is often used in practice to proportion member sizes and reinforcement. While this results in a simple design procedure, the design may become too conservative as actual boundary conditions at top and bottom of the walls may differ significantly from the assumption. Furthermore, walls on sides provide additional constraints. As such, the basement wall may well be subjected to two-way action where the loading is distributed to horizontal as well as vertical direction. Bending moments in slabs resting on all four sides are less than those in one-way slabs resting on two sides, as two-way action reduces moment demands on the walls or slabs. The maximum bending moments per unit width in a square slab with different boundary conditions are com

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† To whom correspondence should be addressed.
yckim@pknu.ac.kr

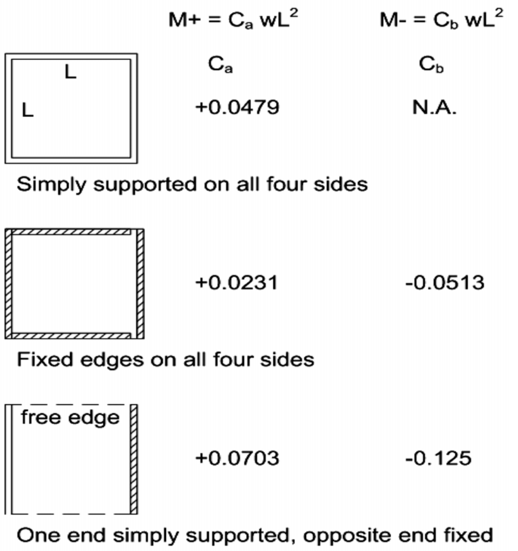


Fig. 1. Maximum bending moments in uniformly loaded square plates.

pared in Fig. 1.

As shown in Fig. 2, buttress columns can be placed between side walls to increase the flexural rigidity of basement walls, enabling the wall to span in greater distance and/or reducing the thickness of basement wall. The structural behavior of such system is expected to differ significantly from a simple one-way slab action typically assumed in basement wall design, as discussed by Yoo et al.[4]. However, their study showed limitation in application due to simplification of boundary conditions of wall. Considering more realistic boundary conditions in 3-span wall, Kim and Kim[5,6] studied the distribution of member forces in basement walls, suggested a design procedure where column and wall interactions were accounted for in determining flexural demands in basement wall, and provided moment coefficients in a tabular form. However, the study analyzed two-dimensional wall structures, assuming simplified or idealized boundary conditions at four sides of wall. This may not represent realistic wall structure and the analytical results may not properly reflect the behavior of basement wall.

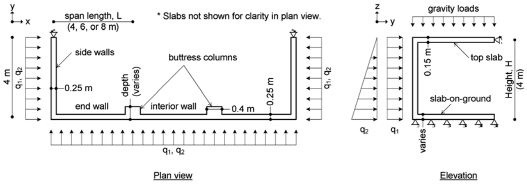


Fig. 2. Configuration of three-span wall with buttress columns.

In this study, rigorous three-dimensional finite element(FE) analyses were conducted to better understand the structural behavior of basement wall system by examining the contribution of each structural element. Based on the numerical studies, a simple yet robust design procedure was proposed to estimate design member forces on the wall. The design charts for moment and shear forces on the wall were generated using statistical approach based on the FE analysis results. Design examples were given to illustrate the applicability of proposed design method.

2. Basement Wall Modeling

A prototype basement wall analyzed in the study is shown schematically in Fig. 2. The wall consisted of three spans and was supported by a 4 m long side wall in the orthogonal direction at each end. The buttress columns were placed on the wall to provide additional stiffness and/or to reduce the wall thickness. The height and thickness of walls were 4 m and 0.25 m, respectively. The walls were rigidly connected to the 150 mm thick floor slab on the top and slab-on-ground at base.

Kim and Kim[5] showed that the relative stiffnesses of the buttress column to the basement wall had a significant influence on how the moment and shear forces are distributed to the wall system. Also, the ratio of span length to the wall height, or wall aspect ratio, affects the force distribution. Therefore, these two design parameters, the column-to-wall stiffness ratio (denoted here as CWS) and span-to-height ratio (SHR) of wall, were investigated in detail. The moment of inertia of the buttress column in out-of-plane direction was $bh^3/12$, where b and h were the column width and depth, respectively. Column depth varied so that the target values of CWS were 0.2, 0.8 and 1.4. Column width was 0.4 m for all cases. The wall stiffness was proportional to $Lt^3/12$, where L was wall span length that varied from 4 m to 8 m, while the wall thickness, t, was 0.25 m. A total of 9 numerical models with different wall configuration were

Table 1. Dimensions of basement wall structures

Wall		Buttress column		
Total length (m)	Span length (m)	Depth (cm)		
		CWS=0.2	CWS=0.8	CWS=1.4
12	4(1.0)*	32	50	60
18	6(1.5)	36	57	69
24	8(2.0)	40	63	76

*Number in parenthesis stands for SHR

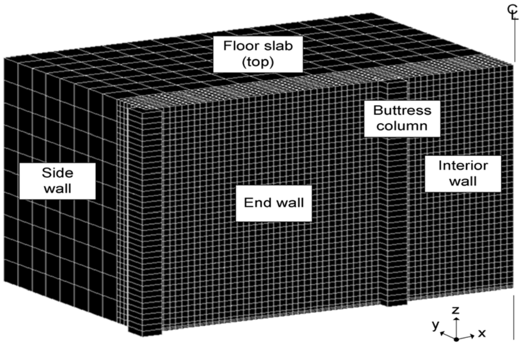


Fig. 3. 3D rendering of FE model.

analyzed as summarized in Table 1.

Three-dimensional numerical analysis was performed using MIDAS-GEN[7]. The schematic drawing of the FE model is shown in Fig. 3.

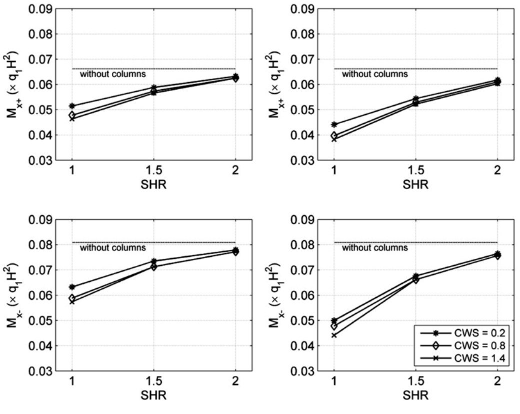
In the model, the walls and slabs were represented by 4-node quadrilateral plate/shell elements. A typical element size on the wall was 100 mm by 100 mm. The finer mesh size of 25 mm by 100 mm was used near the interface between walls and slabs. The buttress columns were represented by prismatic, isotropic beam element consisting of 6 DOFs at each node. The elements for slab-on-ground were restrained against translation but free against rotation, as they rest on soil or foundation. The ends of side wall and floor slab were also restrained against translation as shown in Fig. 2.

Given the symmetric nature of geometry and loading, only half the structure is modeled to reduce computational time. A total number of nodes for 8 m span wall model, for example, were 8019. All the elements were assumed to remain linear elastic. Young's modulus of uncracked concrete model was 24 GPa and Poisson's ratio was 0.167. The three-span basement wall was subjected to two types of lateral pressure: uniformly distributed load, q1, of 8.34 kN/m^2 representing surcharge on top of soil and linearly distributed load, q_2, of 60.0 kN/m^2 representing soil pressure. Side walls were also subjected to the same loading.

3. Numerical Results

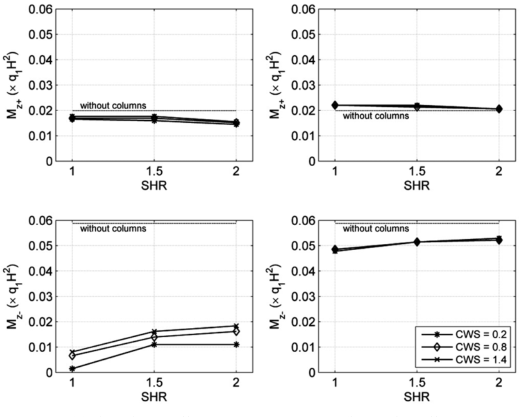
To determine the effects of the design parameters on the force distribution, moments and shear forces on the walls from each model were examined and compared. The following forces were of particular interest: moments about vertical axis, M_{x+}, M_{x-}, moments about horizontal axis, M_{z+}, M_{z-}, and shear force, V.

As buttress columns stiffened the basement wall, their size and spacing changed member force distri



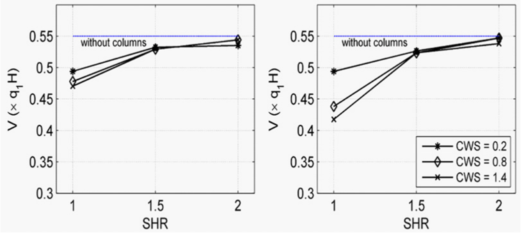
(a) interior wall (b) end wall

Fig. 4. Normalized moment M_x, under q_1.



(a) interior wall (b) end wall

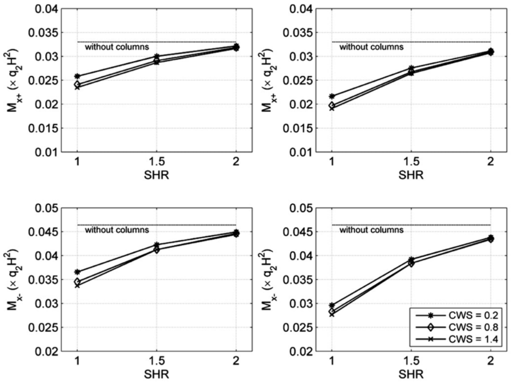
Fig. 5. Normalized moment M_z, under q_1.



(a) interior wall (b) end wall

Fig. 6. Normalized shear force V, under q_1.

bution. To evaluate stiffening effects by columns, a reference wall structure was also analyzed in which the wall spanned 12 m with no buttress columns. Member forces for q_1 are presented as functions of CWS and SHR in Figs 4-7 where member forces are normalized for easy interpretation of results. The magnitudes of M_{x+}, M_{x-}, and V, which are crucial in determining wall thickness and flexural reinforcement, became close to those on the wall without buttress columns as SHR approached 2.0, showing transition from two-way action to one-way action. The normalized moment about x-axis, M_x, in Fig. 4 increased with increasing SHR. The changes in Mz with respect to SHR shown in Fig. 5 were not as significant, indicating that the aspect ratio or SHR would affect the placement of vertical reinforcement more than horizontal reinforcement on the wall. Figs. 4-6 also show that the column stiffness or CWS reduced design forces and that its effect was more pronounced as SHR approached 1.0. Similar trends were observed for q_2 as seen in Fig. 7.



(a) interior wall (b) end wall

Fig. 7. Normalized moment M_x, under q_2.

Table 2. Ratios of maximum member forces on end walls to interior wall

SHR	CWS	Mx+	Mx-	Mz+	Mz-	V
1.0	0.2	0.84	0.81	1.26	13.82	0.94
	0.8	0.82	0.82	1.22	5.47	0.93
	1.4	0.82	0.81	1.21	4.75	0.93
1.5	0.2	0.92	0.93	1.33	5.33	0.99
	0.8	0.92	0.93	1.26	3.39	0.99
	1.4	0.92	0.93	1.23	2.93	0.99
2.0	0.2	0.97	0.98	1.38	4.33	1.00
	0.8	0.97	0.98	1.33	3.11	1.00
	1.4	0.97	0.98	1.30	2.67	1.00

Force distribution on interior and end walls was different. The interior wall had buttress columns at both ends whereas the end walls had buttress column at one end and side wall at the other. The relative magnitudes of member forces are examined in Table 2. The member forces for M_x and V were greater on the interior wall. As SHR approached 2.0, the ratios approached 1.0, indicating that the design forces for both walls in vertical direction should be close to each other. When SHR was less than 1.5, the ratio for M_x was no greater than 0.92 and therefore the vertical reinforcement at end wall may be reduced. The ratio for M_z was greater than 1.0. In particular, the ratio for maximum negative moment about z-axis, M_{z-}, was high, indicating that care should be taken in determining the horizontal reinforcement at end wall.

4. Design Chart to Estimate Member Forces on Basement Wall

Based on the numerical results from the finite element analysis discussed above, design charts were generated with which basement wall design forces can be obtained without resorting to rigorous FE analysis. The maximum moments, M, and shear force, V, in a basement wall of a particular geometric configuration can be expressed using coefficients α and β, or non-dimensional coefficients for uniformly (q_1) and linearly distributed (q_2) loading, respectively:

$$M=\alpha q_1 L_x^2+\beta q_2 L_x^2,\quad V=\alpha q_1 L_x+\beta q_2 L_x \qquad (1)$$

where L_x = min(L, H). The coefficients α and β for particular CWS and SHR values were computed

Table 3. Design coefficients for interior walls

SHR	CWS	M_{x+}		M_{x-}	
		α	β	α	β
1.0	0.2	0.0515	0.0258	0.0632	0.0360
	0.8	0.0478	0.0241	0.0588	0.0345
	1.4	0.0463	0.0235	0.0573	0.0337
1.5	0.2	0.0588	0.0300	0.0735	0.0422
	0.8	0.0574	0.0291	0.0713	0.0412
	1.4	0.0566	0.0287	0.0713	0.0412
2.0	0.2	0.0632	0.0322	0.0779	0.0449
	0.8	0.0625	0.0319	0.0772	0.0446
	1.4	0.0625	0.0317	0.0772	0.0444

using interior wall member forces obtained from FE analysis. Table 3 lists, for example, the coefficients for positive and negative moments about x-axis. Member forces in a wall of different geometric configuration can be then estimated by linear interpolation. For example, M_{x+} for a wall with L = 6 m, H = 4 m (SHR = 1.5), CWS = 1.0, q_1 = 10 kN/m^2, and q_2 = 20 kN/m^2, is:

$$\begin{aligned} M_{x+} &= \alpha q_1 L_x^2 + \beta q_2 L_x^2 \\ &= 0.0571 \times 10 \times 4^2 + 0.0290 \times 20 \times 4^2 \\ &= 18.4 kNm/m \end{aligned}$$

After the coefficients α and β for the wall configurations analyzed in this study were computed, statistical analysis was carried out to calibrate them for different geometric configurations. The coefficients α and β are variables of two independent parameters, CWS and SHR. A set of nine data of varying CWS and SHR values were used to construct the surface function of design member force, using a commercial program called TableCurve-3D[8]. The program combines a surface fitter to find the ideal equation to describe three dimensional empirical data. Among the possible curve-fitting equation the one with the best fit was chosen. For example, the calibrated equation of a for M_{x+} was as follows:

$$\alpha = \frac{-0.06789 + 0.2701 \times SHR - 0.04484 \times \ln(CWS)}{4.278 - 0.6916 \times \ln(CWS) - 0.2444 \times [\ln(CWS)]^2}$$

which was a linear function of SHR for a given CWS. The coefficient of determination, R^2, was 0.9998. The equation can also be presented in a two-dimensional form as shown in Fig. 8, from which the coefficient α can be determined for any given SHR and CWS. Design charts for other member forces, M_{x-}, M_{z+}, M_{z-} and V, are listed in Appendix. Span-to-depth ratio (SHR) used in the charts were in a range of 1.0 to 2.0.

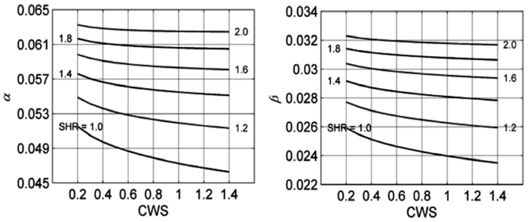


Fig. 8. Coefficients α and β for M_{x+}.

5. Design Examples

Two design examples are given to illustrate the robustness of design charts. The coefficients to determine the design shear force and moments in basement wall structure were obtained from the charts. The design values were then compared to those from the FE analysis results as well as from the analytical solution in which the wall was assumed to be a one-way slab with one end (top) being simply supported and the other end (bottom) fixed.

Example 1: A three-span basement wall had the following geometric and loading configurations: L = 5.4 m, H = 4 m, wall thickness = 0.28 m, slab thickness = 0.16 m, column size = 0.4 m × 0.7 m, q_1 = 8.33 kN/m^2, and q_2 = 60.02 kN/m^2. The corresponding design parameters were: SHR = 1.35 and CWS = 1.16. All the resulting member forces on interior wall are summarized in Table 4. The coefficients, a and b, for maximum shear force on the wall, for example, were obtained from Fig. A4 and plugged into Eq. (1): V = 0.5175 × 8.33 × 4 + 0.354 × 60.02 × 4 = 102.2 kN/m. As seen in Table 4, the member forces using the design charts were close to

Table 4. Design member forces for example 1

Forces	Coefficients ($\times 10^{-4}$)		Design chart (a)	1-way action (b)	FE analysis (c)	Comparison (%)	
	α	β				a/c	b/c
M_{x+}	545	275	33.7	37.7	35.7	-5.7	5.6
M_{x-}	685	397.5	47.3	80.6	45.8	-3.3	76.0
M_{z+}	172	91.5	11.1	-	10.9	1.6	-
M_{z-}	136	80	9.5	-	7.0	35.6	-
V	5175	3540	102.2	116.9	102.1	0.1	14.5

those of FE analysis results. The difference was within 6% except the negative moment about z-axis, Mz-. On the other hand, the member forces obtained by simple, one-way action assumption overestimated the demands, in particular the maximum negative moment about x-axis by 76%.

Example 2: All the design parameters but the loading conditions were the same as in Example 1. Uniform pressure load, q_1, of 18.63 kN/m^2 was applied with no linearly distributed load (q_2 = 0). The results are summarized in Table 5. Again, similar trends were observed: the member forces determined from the design charts were closer to FE analysis results than those from one-way action assumption. The solution of one-way slab overestimated member forces, albeit being conservative.

These examples demonstrated that design member forces can be quickly estimated with the proposed design charts with reasonable accuracy, thereby providing design engineers a tool for preliminary design of basement wall structure

Table 5. Design member forces for example 2

Forces	Coefficients (×10^{-4})		Design chart (a)	1-way action (b)	FE analysis (c)	Comparison (%)	
	α	β				a/c	b/c
M_{x+}	545	275	16.2	21.0	18.2	-10.7	15.4
M_{x-}	685	397.5	20.4	37.2	20.9	-2.3	78.0
M_{z+}	172	91.5	5.1	-	5.5	-6.8	-
M_{z-}	136	80	4.1	-	3.0	35.1	-
V	5175	3540	38.6	46.6	39.6	-2.6	17.7

6. Conclusions

Structural behavior of basement wall was investigated. Three dimensional finite element analysis of wall structure with realistic wall boundaries, consisting of walls, floor slabs, side walls, and buttress columns, was carried out. The analysis showed the effects of column-to-wall stiffness (CWS) ratios and span-to height (SHR) ratios on force distribution on the basement wall:

(1) Buttress columns reduced the moment demands in the vertical direction of the wall more than it did in the horizontal direction and its effect was particularly noticeable when SHR was less than 1.5.

(2) The effect of SHR on the design forces was more pronounced than that of CWS.

Best-fit design curves to determine member forces on the basement wall subjected to either uniformly or linearly distributed soil pressure were developed based on the numerical studies and regression analysis. Two design examples demonstrated the feasibility of the proposed method. The estimated member forces were within 10% of those obtained from FE analysis, whereas analytical solutions used in practice may overestimate the demands as much as 76%. Shear force, which may control the wall thickness, was predicted within 3% of error. The model was developed using practical design configurations of the basement wall structure where CWS ranged between 0.2 and 1.4 and SHR from 1 to 2. As such, care should be taken to extend it beyond the limits of this study. The proposed design charts should serve as a useful design tool for practicing engineers to proportion basement walls in preliminary design.

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Appendix

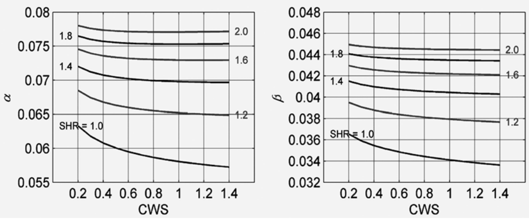

Fig. A1. Coefficients α and β for M_{x-}.

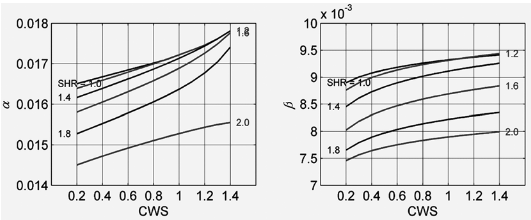

Fig. A2. Coefficients α and β for M_{z+}.

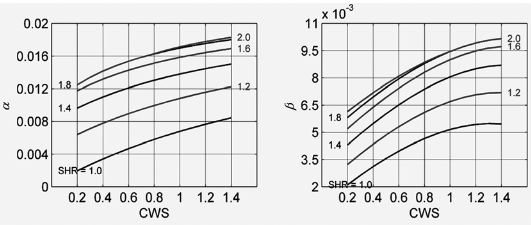

Fig. A3. Coefficients α and β for M_{z-}.

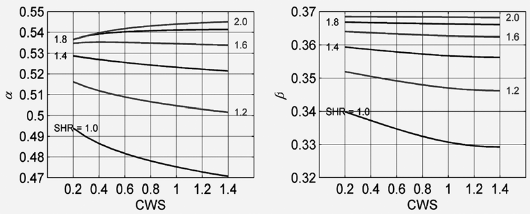

Fig. A4. Coefficients α and β for V.