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Estimation of seismic earth pressure on basement walls underlain by bedrock using numerical analysis

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ABSTRACT

The dynamic increase in earth pressure is a critical factor in the seismic design of underground basement structures. Traditional analytical and empirical methods, which were developed for rigid retaining walls, are often used to estimate this pressure. However, these approaches frequently neglect two key parameters: the flexibility ratio (*F*), which describes the relative stiffness between the structure and the surrounding soil, and the aspect ratio (*L*/*H*) of the basement. This study presents a series of dynamic numerical simulations conducted for various basement configurations founded on bedrock and subjected to different soil conditions. The findings indicate that both *F* and *L*/*H* significantly influence the magnitude of seismic earth pressure. Stiffer basements with larger *L*/*H* ratios are shown to experience greater pressure increments, while more flexible systems with lower *L*/*H* values are subjected to smaller seismic demands. To improve estimation accuracy, an empirical regression model was developed that incorporates both *F* and *L*/*H*. Residual analysis confirms that the proposed model provides reliable and unbiased predictions across the range of scenarios considered in this study.

1. INTRODUCTION

Underground structures have traditionally been considered less susceptible to seismic damage compared to above-ground facilities. However, notable failures, such as damage to underground reservoirs during the San Fernando earthquake and the collapse of the Daikai Subway Station during the Kobe earthquake, have emphasized the need for thorough seismic performance evaluations of underground structures.

For tunnels and culverts, seismic behavior is commonly assessed using relationships between the flexibility ratio (*F*), which represents the relative stiffness of the structure compared to the surrounding soil, and the racking ratio (*R*), which quantifies the deformation of the structure relative to the free-field ground movement.

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Basements, however, differ from tunnels in that they are not covered by soil above the top slab, meaning the conventional *F*–*R* correlations may not be directly applicable.

Instead, the seismic behavior of basement walls is typically estimated using methods such as the Mononobe–Okabe (M–O) approach (Okabe, 1924; Mononobe and Matsuo, 1929), which was developed for yielding retaining walls under the assumption of dry, cohesionless soil. While later studies have introduced modifications to account for factors such as cohesion and wall flexibility, many of these approaches still fail to consider the aspect ratio of the basement (*L*/*H*) and the effects of soil-structure interaction, both of which are critical to accurately estimating seismic earth pressure.

Previous experimental and numerical investigations have confirmed that both *F* and *L*/*H* substantially affect the dynamic earth pressure acting on basement walls. In the case of flexible walls, seismic pressures tend to align with empirical estimates such as those by Seed and Whitman (1970), whereas stiff walls produce results more consistent with predictions from the M–O method or the elastic solution proposed by Wood (1973). Despite these findings, comprehensive design guidance that simultaneously considers structural flexibility and geometric effects remains underdeveloped for basement walls.

To address this limitation, the present study performs a series of dynamic analyses covering a range of basement geometries, soil conditions, and input ground motions. The effects of both *F* and *L/H* on seismic earth pressure are systematically investigated, and an empirical framework is proposed to enhance the reliability of pressure predictions for the seismic design of basement structures.

2. NUMERICAL ANALYSIS

2.1 Validation of numerical model

Dynamic simulations were performed using ABAQUS (SIMULIA, 2014) with a two-dimensional (2D) plane strain finite element model. The soil was represented by four-node plane strain elements (CPE4R), while the basement walls were modeled as linear elastic beam elements (B21). To approximate nonlinear soil behavior, equivalent-linear (EQL) properties were assigned, derived from one-dimensional (1D) ground response analyses (GRAs) conducted in DEEPSOIL v.7 (DEEPSOIL, 2024).

To replicate free-field motion, multi-point constraints were applied along the lateral boundaries. Soil-structure interaction was modeled using surface-to-node interfaces, applying Coulomb friction with a typical interface friction angle of 0.33, consistent with previous studies (Deng et al., 2016; Zhang et al., 2017). The soil profiles were based on Nevada sand, with depth-dependent density distributions. Shear moduli were estimated using Hardin’s correlation (Hardin, 1978).

EQL soil properties were obtained by scaling the maximum shear strains from the nonlinear GRA to effective shear strains and assigning the corresponding stiffness and damping parameters to each layer in the 2D model. Rayleigh damping coefficients were determined based on site frequency and higher-mode frequencies, while the non-Masing rule was adopted to better represent soil hysteresis (Darendeli, 2001; Kwok et al., 2007; Phillips and Hashash, 2009).

The model was validated by comparing calculated responses with centrifuge test results, demonstrating strong agreement in terms of peak ground acceleration (PGA) profiles and response spectra, both in the free-field and along the basement walls. Dynamic earth pressures were calculated by subtracting static pressures from the total computed pressures. The coefficient of dynamic increment of earth pressure (ΔK_{ae}) was then evaluated following established procedures from the literature. Overall, the EQL-based modeling approach proved effective in capturing the seismic response of basement structures underlain by bedrock.

2.2 Case matrix for numerical analysis

The geometries of the basement structures analyzed in this study are shown in Fig. 1, with associated properties summarized in Tables 1 and 2. To accommodate increasing earth pressures with depth, wall thicknesses were designed to vary accordingly. The numerical models included a range of basement layouts with different embedment depths and widths to investigate the influence of the aspect ratio (L/H) on seismic earth pressure behavior.

Both three- and five-story basements were considered, with each story assigned a height of 4 m. The total basement heights (H) ranged from 8 to 16 m, and widths (L) were varied between 8 and 160 m. Six L/H ratios were analyzed: 0.67, 0.8, 1.33, 2, 4, and 8. These configurations were selected to reflect common basement geometries found in subway stations, underground shopping centers, and parking facilities that are not directly connected to superstructures.

Table 1. Properties of basement structure

Structures	Axial rigidity (EA, kg·m/s^2)	Flexural rigidity (EI, kg·m^3/s^2)
Wall (B1)	2.01E+10	2.71E+09
Wall (B2)	2.22E+10	3.63E+09
Wall (B3)	2.48E+10	5.06E+09
Wall (B4)	2.78E+10	7.09E+09
Wall (B5)	2.78E+10	7.09E+09
Slab	6.90E+09	3.01E+08
Column	4.86E+09	5.83E+08
Base	3.49E+10	5.69E+09

Table 2. Case matrix

Case No.	Embedment depth, H (m)	Width, L (m)	Aspect ratio, L/H	Flexibility ratio, F
1	12	8	0.67	2.87
2	12	16	1.33	4.16
3	12	24	2	4.87
4	12	48	4	5.85
5	12	96	8	6.32
6	20	16	0.8	3.58
7	20	40	2	4.76
8	20	80	4	5.88
9	20	160	8	6.22

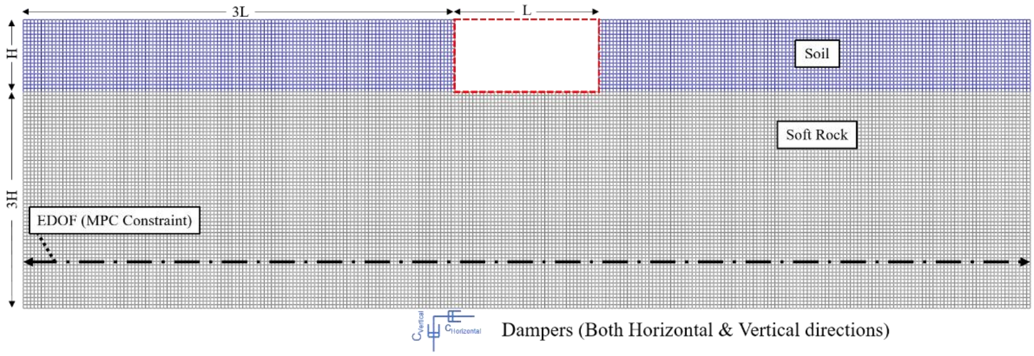

Fig. 1. Schematic of soil-basement structure.

2.3 Selected soil profiles

A total of six soil profiles were developed to represent different basement configurations with varying embedment depths. These are summarized in Table 3. The selected profiles span a wide range of shear wave velocities (V_S), with time-averaged V_S (denoted as $V_{S,soil}$) ranging from 150 to 300 m/s for profiles extending to 12 m and from 150 to 400 m/s for profiles reaching 20 m. The time-averaged V_S over a given depth H was calculated using the Eq. (1):

$$V_{S,soil} = \frac{H}{\sum_{i=1}^{n} \frac{\Delta z_{i,i}}{V_{S,i}}} \tag{1}$$

where Δz_i denotes the thickness and $V_{S,i}$ the V_S of the i-th soil layer. All models assumed that bedrock exists directly beneath the basement base to prevent rocking effects. This reflects typical shallow bedrock conditions found in inland regions of Korea. The shear wave velocity of the bedrock was set to 760 m/s. 1D GRAs were conducted for each profile to obtain equivalent-linear (EQL) soil properties. Input motions were applied assuming an elastic half-space.

Table 3. Soil profiles used in this study

Embedment depth (m)	Profile	$V_{S,soil}$ (m/s)	V_{S30} (m/s)
12	P1	150	290
	P2	200	360
	P3	300	470
20	P4	150	205
	P5	200	265
	P6	400	475

2.4 Input ground motions

Seven recorded ground motions from rock outcrops were selected from the NGA-West2 database provided by the Pacific Earthquake Engineering Research (PEER) Center. Since the EQL approach is inherently linear and may not capture nonlinear soil response under high-intensity shaking, input motions were carefully selected to maintain reliability. Based on findings by Stewart et al. (2008), EQL and nonlinear analyses are generally consistent for stiff soils when PGA remains below 0.4g, within the frequency range of 0.1 to 100 Hz. Therefore, only motions with PGA values less than 0.4g were considered in this study to ensure the suitability of the EQL method.

3. RESULTS OF DYNAMIC EARTH PRESSURE

3.1 Comparison with centrifuge test results

To verify the accuracy of the numerical model, computed seismic earth pressures were compared with results from centrifuge experiments. The simulation cases were categorized based on structural stiffness, with F < 1 representing stiff basements and F > 1 representing flexible basements. Prior studies by Al Atik and Sitar (2010) examined both stiff and flexible U-shaped basement walls, while Hushmand et al. (2016) conducted tests on box-type structures with F values ranging from 0.5 to 2, classifying them into stiff, baseline, and flexible groups. In this study, a similar classification was adopted. Additional tests by Wagner and Sitar (2016) and Candia et al. (2016) focused on stiff basements with intermediate struts. Most centrifuge models used in previous studies, including those by Al Atik and Sitar (2010), Mikola et al. (2016), Candia et al. (2016), and Hushmand et al. (2016), had L/H ratios near 1.7. In contrast, Wagner and Sitar (2016) tested a basement with L/H = 0.44. For numerical comparison, simulation results were presented for cases with L/H = 0.8 and 2.

Figures 2 and 3 display the dynamic increment coefficient (ΔK_{ae}) plotted against surface PGA for selected stiff and flexible basements, respectively. The results show that flexible basements consistently exhibit lower ΔK_{ae} values than stiff ones, emphasizing the importance of flexibility in seismic design. Although some scatter exists, the centrifuge measurements generally align with the numerical simulations. In particular, recordings from Hushmand et al. (2016) slightly exceeded predictions, while results from Wagner and Sitar (2016) were near the lower bound. Al Atik and Sitar's (2010) data for flexible structures also showed good agreement with the computed results. Despite wider variability due to the range of F values modeled, the numerical trends correspond well with experimental findings.

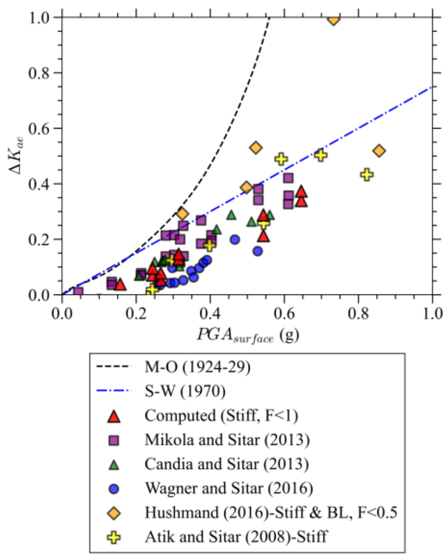

Fig. 2. Comparison of ΔK_{ae} with centrifuge results (stiff cases).

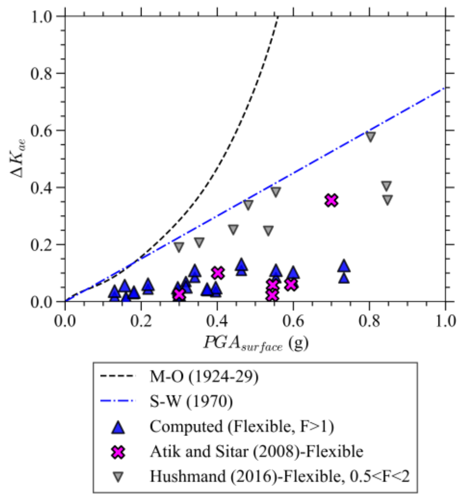

Fig. 3. Comparison of ΔK_{ae} with centrifuge results (Flexible cases).

4. CONCLUSIONS

This study investigated the seismic earth pressure acting on basement walls through a series of dynamic numerical analyses. Unlike traditional approaches that rely on rigid wall assumptions, the current framework explicitly considered the effects of soil-structure stiffness and basement aspect ratio, while excluding the influence of superstructures.

The results confirmed that both F and L/H are critical in determining seismic racking behavior and dynamic pressures. For basements with L/H less than 1, the computed racking ratios were consistent with existing empirical correlations. However, for higher L/H values, notable deviations were observed, indicating the need for updated predictive models that incorporate both F and L/H.

It was also demonstrated that flexible basement structures experience significantly lower dynamic earth pressures than stiff ones. Furthermore, increasing L/H generally leads to larger pressure increments due to reduced constraint and greater deformation capacity. These findings contribute to more reliable design guidance for buried basement structures in seismic regions.

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