RECOMMENDATIONS FOR THE SEISMIC DESIGN OF DEEP BASEMENT WALLS

E. Amirzehni¹, W. D. L. Finn², R. H. DeVall³, C. E. Ventura⁴

ABSTRACT

The current state of practice for seismic design of basement walls in Vancouver, BC is based on the Mononobe-Okabe (M-O) method incorporating the Peak Ground Acceleration (PGA) mandated by the National Building Code of Canada (NBCC, 2010). Because there is limited evidence of any significant damage to basement walls during major earthquakes, the Structural Engineers Association of British Columbia (SEABC) became concerned that current basement wall design was too conservative. In order to address this concern, SEABC set up a task force to review the current seismic design procedure. As part of this effort, a series of nonlinear dynamic analyses using input motions matched to the Uniform Hazard Spectrum for Vancouver, BC was conducted to evaluate the performance of 4-storey basement walls designed for different levels of the code PGA. The study showed that a design acceleration of 50% to 60% of PGA would lead to safe cost-effective seismic design. To support a revised recommendation for design practice, SEABC requested a much broader database taking into account a wider range of soil properties and basement configurations. The seismic response of the walls is evaluated by subjecting them to suites of ground motions associated with shallow crustal, deep intra-slab subcrustal, interface earthquakes from the Cascadia subduction sources. This paper describes the development and results of the expanded study. The new analyses incorporate a much more representative soil constitutive model.

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Recommendations for the seismic design of deep basement walls

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\textbf{ABSTRACT}

The current state of practice for seismic design of basement walls in Vancouver is based on the Mononobe-Okabe (M-O) method incorporating the Peak Ground Acceleration (PGA) mandated by the 2010 National Building Code of Canada. Because there is limited evidence of any significant damage to basement walls during major earthquakes, the Structural Engineers Association of British Columbia (SEABC) became concerned that current basement wall design was too conservative. In order to address this concern, SEABC set up a task force to review the current seismic design procedure. As part of this effort, a series of nonlinear dynamic analyses using input motions matched to the Uniform Hazard Spectrum for Vancouver was conducted to evaluate the performance of 4-storey basement walls designed for different levels of the code PGA. The study showed that a design acceleration of 50\% to 60\% of PGA would lead to safe cost-effective seismic design. To support a revised recommendation for design practice, SEABC requested a much broader database taking into account a wider range of soil properties and basement configurations. The seismic response of the walls is evaluated by subjecting them to suites of ground motions associated with shallow crustal, deep intra-slab subcrustal, interface earthquakes from the Cascadia subduction sources. This paper describes the development and results of the expanded study. The new analyses incorporate a much more representative soil constitutive model.

\textbf{Introduction}

The current state of practice for seismic design of basement walls in British Columbia, Canada is based on the Mononobe-Okabe (M-O) method, incorporating the Peak Ground Acceleration (PGA) mandated by the 2010 National Building Code of Canada (NBCC) \cite{1}. This method

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provides the total lateral seismic forces against the wall but does not give the distributions of the lateral static and seismic wall pressures. In current practice, the static pressure is assumed to vary linearly with depth and the seismic pressure to be distributed in a triangular fashion with the maximum value at the top of the wall [2].

Al-Atik and Sitar, and Lew et al. [3, 4] reported on the performance of basement walls during past earthquake events inside and outside the United States and concluded that failure was rare, even though no particular seismic design method had been implemented. Their report stated that no damage to building basement walls was found after the San Fernando (1971), Whittier Narrows (1987), Loma Prieta (1989), and Northridge (1994) earthquakes in California. Because of this lack of damage to basement walls during major earthquakes, SEABC became concerned that the basement walls were being designed too conservatively using the full NBCC (2010) probabilistic PGA. To deal with this issue, SEABC set up a task force to review the current seismic design and make recommendations for safe, cost-effective seismic design. As part of this effort, the University of British Columbia was asked to carry out a study to determine an appropriate fraction of PGA to use with the M-O method for design of basement walls in Vancouver.

Various researchers have proposed a reduced seismic coefficient based on a fraction of the peak ground acceleration for the design of basement walls [2,4,5,6]. Recent centrifuge modeling studies by [3,4,6,7] on model cantilever walls and non-displacing cross-braced basement wall structures founded on dry medium-dense sand showed that estimating seismic lateral pressures utilizing the full peak ground acceleration overestimates the seismic earth pressure on the walls. However, none of these findings has yet influenced code based design.

In a preliminary study conducted by the authors [8], a 4-level basement wall structure with a total height of 11.7 m was designed following the current state of practice for different fractions of the NBCC (2010) PGA for Vancouver, BC (0.46 g), varying from 100% down to 50%. Dynamic nonlinear soil-structure interaction analyses were conducted on the different models of the 4-level basement wall structures using FLAC 2D to capture the essential features and response characteristics of the basement wall-backfill system under seismic loading. The foundation soils were modeled by a simple elastic-plastic Mohr-Coulomb constitutive model with a non-associated flow rule. From results of equivalent linear analyses of the soil system in the far field, effective degraded elastic moduli and equivalent damping ratios were selected for a better representation of the soil properties in the elastic region of the Mohr-Coulomb model. Each wall was subjected to the full seismic demand imposed by a suite of crustal ground motions spectrally matched to the Uniform Hazard Spectrum (UHS) for Vancouver. The results showed that flexibility, yielding, and deflection of the wall had significant effects on the distribution of the seismic lateral pressures on the wall. Because all the walls were subjected to ground motion representing the full shaking intensity of the UHS for Vancouver, the total lateral force on each wall was approximately the same. However, the lateral earth pressure distribution changed as the wall yielded. The results of the preliminary study suggested that the walls designed for 100% PGA were overly conservative. However, the behavior of the basement wall designed for 50% to 60% PGA resulted in a satisfactory performance when subjected to the full NBCC (2010) seismic hazard for Vancouver.

Because of the radical shift in design practice suggested by these preliminary findings, more extensive studies were commissioned by SEABC to more fully validate the major conclusions on
Seismic demand for design. This paper reports on series of additional analyses that have been carried out to evaluate the fraction of the code mandated PGA to be used in the M-O method for seismic design of the basement walls to ensure a safe cost-effective design. In the current study, the seismic performance of the basement walls founded on soil deposits with different shear wave velocity profiles was investigated. A more representative nonlinear constitutive soil model UBCHYST [9], was adopted instead of the elastic-plastic Mohr-Coulomb model for the expanded study. A variety of the 4-level and 6-level basement walls with different heights, thicknesses, and configurations were analyzed. Moreover, the seismic analyses were conducted for a much greater range of input motions than was used for the preliminary study. Ground motions representative of all three types of seismic sources that control the hazard in South-Western BC were selected for analysis: shallow crustal, intra-slab subcrustal, and interface earthquakes from the Cascadia subduction zone. All the motions were scaled/matched to the UHS for Vancouver to ensure that they were representative of the prescribed hazard intensity. In addition to spectral matching which was used in the preliminary study, five different methods of linear scaling were utilized. Linear scaling generally considered to capture the inherent motion-to-motion variability better than spectral matching. The seismic performance of the basement walls in the form of drift ratio was evaluated, and the level of variability of the response was quantified by a standard deviation.

Seismic design and computational model of basement walls

In order to determine an appropriate fraction of the horizontal seismic coefficient to be used in the M-O method to ensure safe and cost-effective seismic design, four basement walls were designed by SEABC structural engineers for different values of the horizontal ground acceleration varying from 100% down to 50% of the NBCC (2010) PGA (=0.46g). Each wall was subjected to dynamic analyses using scaled recorded ground motions corresponding to the 2% in 50 years hazard level of NBCC (2010). Following the state of practice in British Columbia, two load combinations prescribed by the NBCC (2010) were used by structural engineers for seismic design of the basement walls: (1) \( 1.5 p_A(z) \), which \( p_A(z) \) is not less than 20 kPa compaction/surcharge pressure. (2) \( p_{AE}(z) = p_A(z) + \Delta p_{AE}(z) \), where \( p_{AE}(z) \) is the total active lateral pressure, \( p_A(z) \) is the static lateral active pressure and \( \Delta p_{AE}(z) \) is the dynamic increment of the lateral earth pressure acting on the wall. The value of PGA/g is used as the pseudo-static horizontal seismic coefficient \( k_h \) in the calculation of the dynamic increments, \( \Delta p_{AE}(z) \). Following the state of practice in Vancouver \( \Delta p_{AE}(z) \) is distributed as a triangular wall pressure distribution with the maximum at the surface [2]. Figure 1 shows the distribution of the pressures along the height of the 4-level basement wall with a total height of 11.7 m designed for two aforementioned load combinations. In this Figure, the red and black lines correspond to the static and dynamic components of the lateral earth pressures, respectively.

A series of two-dimensional nonlinear dynamic analyses were conducted to assess the seismic performance of the basement walls using the finite difference computer program FLAC 2D [10]. The wall model consisted of two-dimensional plane-strain quadrilateral elements to represent the soil medium and beam elements to represent structural components. The nonlinear total stress UBCHYST model was adopted as the soil constitutive model. To ensure a proper initial stress distribution on the structure, the actual construction sequence was modeled in stages to simulate the actual excavation process. As each stage was excavated, an excavation support was installed and removed when the wall was built. Under this condition, the soil pressures applied to the wall
were representative of the actual pressures. Interface elements represented by two elastic-perfectly plastic normal and shear springs between the soil and the structure were utilized to simulate the interaction between the concrete structure and surrounding soil and facilitated modeling opening (separation) and slippage. To prevent reflection of outward propagating waves back into the model, quiet (viscous) boundaries, comprising independent dashpots in the normal and shear directions, were placed at the base and lateral boundaries of the soil medium. The stress time history of the selected ground motions were applied at the quiet boundary. The lateral boundaries of the soil grid were coupled to the free-field boundaries at the sides of the model to simulate the free-field condition, which would exist in the absence of the structure. Details of the computational model can be found in Amirzehni [11]. The 2D computational model of the 4-level basement wall is presented in Figure 2. In consultation with geotechnical engineers of the SEABC Task Force, the soil properties listed in Table 1 were adopted for the two soil layers in Figure 2.

![Figure 1](image1.png)

**Figure 1**- (a) Elevation view of the 4-level basement wall and the calculated lateral earth pressure distributions from (b) the first load combination (c-f) the second load combination using the M-O method with 100%, 70%, 60% and 50% PGA, respectively, where PGA=0.46 g based on the NBCC (2010) for Vancouver.

![Figure 2](image2.png)

**Figure 2**- Elevation view of the 4-level braced basement wall model in FLAC 2D. Details of the Structural elements of the model including basement walls, interior walls, and braces can be found in Amirzehni [11].

**Table 1**- Soil layer material properties.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Density (kg/m³)</th>
<th>Poisson's ratio</th>
<th>Vₚ * (m/s)</th>
<th>Cohesion (kPa)</th>
<th>Friction Angle (deg.)</th>
<th>Dilation angle (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1950</td>
<td>0.28</td>
<td>200</td>
<td>0</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1950</td>
<td>0.28</td>
<td>400</td>
<td>20</td>
<td>40</td>
<td>0</td>
</tr>
</tbody>
</table>

* Normalized Shear wave velocity based on Robertson et al. [12].
Parametric studies on the effect of ground motion selection and scaling

The seismicity of South-Western British Columbia is due to shallow crustal earthquakes in the North America plate, deeper intra-slab subcrustal earthquakes in the subducting Juan de Fuca plate, and very large (M8+) subduction earthquakes at the interface of the Juan de Fuca and the North American plates. Therefore, three ground motion ensembles representative of the three source categories were selected as input motions for analyses. Differences amongst these ensembles can be observed in terms of spectral shapes and frequency content. Each ensemble affects the structure differently and therefore, the value of the engineering demand parameter (i.e. drift ratio) substantially varies amongst these types of earthquakes. Exploratory analyses showed that the Cascadia motions had no significant effect on the walls and are excluded from this study. Table 2 to 3 present the selected shallow crustal and deep intra-slab subcrustal earthquake motions.

Table 2- List of the selected crustal ground motions.

<table>
<thead>
<tr>
<th>No</th>
<th>Event Name</th>
<th>Year</th>
<th>Station</th>
<th>M</th>
<th>Vs30 (m/s)</th>
<th>Comp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>Friuli, Italy</td>
<td>1976</td>
<td>Tolmezzo</td>
<td>6.5</td>
<td>424.8</td>
<td>FN, FP</td>
</tr>
<tr>
<td>3, 4</td>
<td>Tabas, Iran</td>
<td>1978</td>
<td>Dayhook</td>
<td>7.35</td>
<td>659.6</td>
<td>FN, FP</td>
</tr>
<tr>
<td>5, 6</td>
<td>New Zealand</td>
<td>1987</td>
<td>Matahina Dam</td>
<td>6.6</td>
<td>424.8</td>
<td>FN, FP</td>
</tr>
<tr>
<td>7, 8</td>
<td>Loma Prieta, USA</td>
<td>1989</td>
<td>Coyote Lake Dam</td>
<td>6.93</td>
<td>597.1</td>
<td>FN, FP</td>
</tr>
<tr>
<td>9, 10</td>
<td>Hector Mine, USA</td>
<td>1999</td>
<td>Hector</td>
<td>7.13</td>
<td>684.9</td>
<td>FN, FP</td>
</tr>
</tbody>
</table>

Table 3- List of the selected subcrustal ground motions.

<table>
<thead>
<tr>
<th>No</th>
<th>Event Name</th>
<th>Year</th>
<th>Station</th>
<th>M</th>
<th>Vs30 (m/s)</th>
<th>Comp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>Miyagi Oki, Japan</td>
<td>2005</td>
<td>MYG016</td>
<td>7.2</td>
<td>580.0</td>
<td>EW, NS</td>
</tr>
<tr>
<td>3, 4</td>
<td></td>
<td></td>
<td>MY6014</td>
<td></td>
<td>706.2</td>
<td>EW, NS</td>
</tr>
<tr>
<td>5, 6</td>
<td></td>
<td></td>
<td>FKS010</td>
<td></td>
<td>585.9</td>
<td>EW, NS</td>
</tr>
<tr>
<td>7, 8</td>
<td></td>
<td></td>
<td>MYG013</td>
<td></td>
<td>535.5</td>
<td>EW, NS</td>
</tr>
<tr>
<td>9, 10</td>
<td></td>
<td></td>
<td>IWT011</td>
<td></td>
<td>565.3</td>
<td>EW, NS</td>
</tr>
<tr>
<td>11,12</td>
<td>Nisqually, WA</td>
<td>2001</td>
<td>Olympia Residence</td>
<td>6.8</td>
<td>-</td>
<td>EW, NS</td>
</tr>
<tr>
<td>13, 14</td>
<td></td>
<td></td>
<td>VILE</td>
<td>7.3</td>
<td>-</td>
<td>EW, NS</td>
</tr>
</tbody>
</table>

Dynamic nonlinear analysis requires input in the form of design time series with response spectra that were consistent with the target design spectrum. Design time series were developed by modifying initial time series using two main approaches: spectral matching and linear scaling. In the preliminary study [8] all selected crustal motions were spectrally matched to the target spectrum. The advantage of using spectrum compatible time series was to reduce the number of time series required for determining the stable mean response. However, spectral matching reduces the potential variability of the response and therefore if the variability of the response is a matter of interest, linear scaling would be the preferred method. Five methods of linear scaling were investigated in this study: (1) PGA scaling, (2) Sa (T1) scaling, where T1 is the fundamental period of the system, (3) ASCE scaling [13], (4) SIa scaling [14], and (5) Mean Squared Error (MSE) scaling. In all cases, the accelerogram time history of a candidate motion was multiplied by a scalar
A series of nonlinear dynamic analyses were performed on 4-level basement wall designed for different fractions of the code PGA, subjected to shallow crustal ground motions, spectrally matched and linearly scaled to the NBCC (2010) uniform hazard spectrum of Vancouver. Figure 3 shows a comparison of the resultant maximum drift ratio along the height of the basement walls designed for different fractions of the code PGA, subjected to 14 scaled/matched crustal ground motions. In order to establish a basis for comparison, it was legitimate to assume that the resultant drift ratio of the system subjected to the spectrally matched ground motions was an unbiased estimate of the mean response and was defined as a “reference” value. It can be concluded from this figure that the scatter in response were reduced significantly as one moves from: (1) linear scaling the records to match the target spectrum at PGA or the natural period of the system Sa (T1); to (2) linear scaling the records to match the target spectrum over the period range using different methods such as ASCE, MSE and Sla scaling; to (3) spectrally matching the records. Within the limitation of the sample size used in this study, discrepancy implies that the use of either linear-scaled records over a period range (Sla, MSE and ASCE methods) or spectrum-compatible records (Spectral matching) introduces a certain degree of bias in the computed structural response. Results of the analyses show that using Sla and MSE linear scaling methods lead to a mean drift ratio similar to the reference expected mean value of the response, calculated by using spectrally-matched motions, whereas ASCE scaling technique generates larger drift ratios.

A literature search was conducted to find a suitable performance criterion for basement walls. The recommendations of the ASCE Task Committee on Design of Blast-Resistant Buildings in Petrochemical Facilities [16] was adopted as the performance standard. This standard is described as “Localized component damage. The building can be used. However, repairs were required to restore the integrity of structural envelope. The total cost of repairs is moderate”. The response limits associated with this response states for “reinforced concrete wall panels (with no shear reinforcement)” was 1 degree hinge rotation at support (hence 1.7% drift ratio). Separate calculations were also conducted using the standard procedure for calculating curvature demand in reinforced concrete by SEABC Structural Engineers. The results suggest that even a slightly greater drift ratio can be adopted as the performance criterion safely. The ASCE criterion was developed for blast loading on petrochemical facilities and therefore is likely to be conservative. Based on the adopted performance criteria, it can be concluded that the basement wall founded on dense soil and subjected to scaled/matched crustal motions can be safely designed using the M-O method with 50% to 60% PGA.

Among five linear scaling methods investigated above, the MSE method, which is commonly used in practice, was selected as the basis for scaling subcrustal ground motions to the UHS of Vancouver. The results of the studies conducted using the subcrustal ground motions are illustrated in Figure 4. The results show that the performance of the 4-level basement wall designed for 50% and 60% of the code PGA fell within an acceptable range (< 1.7%).

The Cascadia subduction motions scaled/matched to the deterministic hazard values had no significant effect on the basement walls and resulted in very low drift ratios (< 0.2%) even on the
weakest wall designed for 50% PGA. This was due to the lower short-period deterministic NBCC (2010) hazard values compare to the probabilistic uniform hazard spectrum. Details of the analysis can be found in Amirzehni [11].

Figure 3- The resultant maximum drift ratios and the corresponding mean and mean ± one standard deviation along the height of the 11.7 m 4-level basement wall designed for different fractions of the code PGA subjected to 14 crustal ground motions scaled/matched to the NBCC (2010) target spectrum using various methods.
Figure 4- The resultant maximum drift ratios and the corresponding mean and mean ± one standard deviation along the height of the wall designed for 50% and 60% of PGA subjected to 14 linearly scaled and spectrally matched subcrustal ground motions.

**Parametric studies on the effect of wall geometry**

Two additional basement configurations were designed by SEABC structural engineers for various fractions of the NBCC (2010) PGA: (1) 4-level basement wall with 5.0 m top storey and a total height of 13.1 m, and (2) 6-level basement wall with a total height of 17.1 m. Each wall was designed following the state of practice in Vancouver, using the two load combinations outlined earlier. The walls were subjected to 14 spectrally matched crustal ground motions. Details of the analyses can be found in Amirzehni et al. [11, 17]. Figure 5 confirms that both 4-level and 6-level basement walls designed for 50% PGA, founded on relatively dense sandy materials meet 1.7% performance criteria when subjected to the NBCC (2010) hazard level in Vancouver.

Figure 5- Average of the maximum envelopes of drift ratios and ± one standard deviation along the height of the 4-level and 6 level basement walls designed for 50% PGA and subjected to 14 ground motions spectrally-matched to the UHS of Vancouver.
Parametric studies on the effect of site conditions

In the preliminary analyses, the NBCC (2010) site class D soil profile was proposed by a group of geotechnical engineers as representative of the site condition relevant for high-rise construction in downtown Vancouver. In order to investigate the effect of the local site conditions on the dynamic response of the 4-level basement wall, ten soil profiles were selected that variation of the shear wave velocities of the first and the second soil layers differentiating the cases. Figure 6 summarizes the maximum resultant drift ratios along the height of the walls founded on ten site class D soil profiles. Horizontal axes represent the normalized shear wave velocities of the first and second soil layers, while the vertical axis presents the resultant maximum drift ratios along the height of the 4-level basement wall. In each case the wall was subjected to the selected 14 spectrally matched crustal ground motions. The results show that the presence of a soft soil layer underneath the basement wall structure and the relative stiffness between different soil layers characterized by the impedance contrast, affect the rate of ground motion amplification and consequently the resultant seismic deformation. In fact, the maximum drift ratio increases proportionally to the increase of the impedance contrast between two soil layers. The importance of the relative stiffness between soil layers on characterizing the nonlinear site response were assessed in terms of amplitude and frequency content and presented in Amirzehni [11]. This study showed that except for the case that the wall is embedded in a soft soil layer (V_s1=150 m/s), the wall designed for 60% PGA using the M-O method, performs adequately under the full seismic demand driven by the NBCC (2010).

![Graph showing Maximum Resultant Drift Ratios](image)

**Figure 6** - Average + one standard deviation of the maximum resultant drift ratios of the 4-level basement wall designed for 50% and 60% PGA and founded on ten site class D soil profiles. Each wall is subjected to 14 spectrally-matched crustal ground motions.

Conclusions

A major study on the seismic performance of basement walls during earthquakes was conducted at the University of British Columbia at the request of the SEABC to review the current seismic design and provide recommendations for safe, and cost-effective design. Because of the radical shift in a basement wall design practice suggested by the preliminary findings [8], more extensive studies were commissioned by SEABC to more fully validate the major conclusions on seismic demand for design. A much broader database taking into account a wider range of soil properties, and basement configurations were considered. The seismic response of the walls was evaluated by subjecting them to suites of ground motions associated with shallow crustal, deep subcrustal, interface earthquakes from the Cascadia subduction sources. The seismic performance of the
basement wall designed for different fractions of the NBCC (2010) PGA and subjected to current seismic hazard for Vancouver, which has an exceedance rate of 2% in 50 years, is evaluated.

Results from more than 600 nonlinear dynamic analyses confirm that within a significant range of variations, the basement wall founded on dry cohesionless medium dense soil, can be safely designed using the M-O method as presently used in Vancouver but with an acceleration of 60% PGA. The outliers are inappropriate scaling methods or very soft upper layers (Vs<200 m/s). It is worth to mention that the conclusion stands if the walls be designed according to the state of practice in Vancouver as outlined briefly in this paper, and more detailed in Amirzehni [11]. This conclusion in general is consistent with the observations of researches at the UC-Berkeley [3,6,7] and Lew et al. [4,5] based on a number of detailed centrifuge test studies.

Acknowledgments

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