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PERFORMANCE-BASED RETROFIT GUIDELINES FOR LOW-RISE SCHOOL BUILDINGS IN BRITISH COLUMBIA, CANADA

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ABSTRACT :

In 2004, the Province of British Columbia, on the West Coast of Canada, announced an ambitious 10-15 year, $1.5 billion seismic retrofit program for the province's 750 at-risk schools. The purpose of this earthquake preparedness initiative is to accelerate the upgrading of school public safety in the moderate and high seismicity regions of the province. Given the magnitude of the mitigation program, the Ministry of Education and Western Economic Diversification Canada made a commitment to support the development of state-of-the-art performance-based seismic engineering technology for achieving optimum safety within a cost-effective mitigation framework, which could not be achieved based on best current practice.

This paper describes one component of this technical development program, the formulation of performance-based structural assessment and retrofit design guidelines. This paper also describes some current areas of study such as the selection of a more representative suite of ground motions for the province and the nonlinear response analysis of soft sites

The guidelines include seventeen different types lateral deformation resisting systems found in low-rise construction. They provide minimum lateral strength requirements to achieve different levels of drift. The guidelines have procedures to allow engineers to combine different structural systems, and to account for existing materials that are typically discounted in current practice.

Non-linear dynamic analysis was used to predict the response of the prototype models, which represent the generic response of a given type of low-rise construction. Ground motions records were scaled to match the seismic demands specified in the 2005 National Building Code of Canada.

KEYWORDS: Performance-based seismic assessment, retrofit, low-rise buildings, ground motions, site response analysis

1 INTRODUCTION

The primary focus of the Ministry of Education's seismic mitigation program in British Columbia (BC) is the structural upgrading of at-risk public school buildings located in areas of moderate or high seismicity in BC.

One crucial component to the retrofit design process is a multi-year development of policy and technical standards that are to guide the mitigation program. The development of these standards commenced in 2004. The objective of these standards is the development of rational, performance-based cost-effective retrofit strategies that reflect community-based life safety standards.

Given the need to commence retrofit construction prior to the completion of the multi-year standards development, an interim set of Bridging Guidelines (BG) was developed in 2005 and 2006. This paper provides an overview of the development of the Second Edition Bridging Guidelines [1] for the seismic upgrading of low-rise school buildings in British Columbia, as well as improvements planned for the following editions. The reader may find further information related to this project and applications of the guidelines in references [2] to [5].

Performance-based seismic design engineering for low-rise buildings is uncommon in British Columbia and the rest of Canada, despite low-rise buildings accounted for the majority of the at-risk building stock. The recently released 2005 edition of the National Building Code of Canada [6] states overall performance objectives but is not intended for the upgrade of existing buildings, and typically results in overly-conservative and costly seismic retrofits.

The Bridging Guidelines provide performance-based seismic design engineering solutions in a simple and rational format. The technical requirements of the guidelines are based on non-linear time history analysis that estimates inelastic earthquake damage from a system-dependent governing drift limit as a function of seismicity, soil type and lateral structural system.

2 THE BRIDGING GUIDELINES

The development of these seismic retrofit guidelines was undertaken by collaboration between government (Ministry of Education), industry (APEG-BC and local consulting firms) and academia (The University of British Columbia).

The first project was the Performance-based Seismic Risk Assessment Tool UBC-100 [7], completed in 2004. UBC-100 was successfully used to priority rank 125 high risk schools, which aided the Ministry of Education in deciding where the initial funds would be spent.

The 1st Edition of the Bridging Guidelines [8] was completed in 2005, and was used by local practitioners until October, 2006, when the 2nd Edition Bridging Guidelines [1] were released.

2.1 Background and Development of Guidelines

2.1.1 Project Participants

UBC team (UBC): The UBC-100 and Bridging Guidelines were fully developed by practitioners and researchers from the Department of Civil Engineering at the University of British Columbia. The project team members are highly experienced Geotechnical and Earthquake Engineers who have extensive experience in developing tools for the seismic risk assessment of civil engineering infrastructures.

Peer Review Process (PRC): APEG-BC assembled a “Seismic Risk Task Force” committee to pier review the development of UBC-100. This same group, comprised of leading, local, highly experienced engineers, continued to serve in a peer review capacity for the BG, and the eventual Technical Guidelines. The peer reviewers not only provided critique at regular meetings, but also tested the BG on school feasibility and retrofit design projects.

External Peer Review Process (EPR): Prominent engineers from California were involved in reviewing the analysis procedures and other technical details. Their insight on non-linear dynamic analysis and developing guidelines provided valuable feedback which greatly improved the Bridging Guidelines, Figures, Tables and Equations

Local Practitioners: The Bridging Guidelines were developed to be used by local engineers. Seminars on the 1st and 2nd Edition Guidelines were given to disseminate the use of the guidelines to local engineers. In addition, a series of workshops and office visits has provided a less formal setting for practitioners to ask questions and give feedback on the BG. Both editions of the guidelines developed a Q&A document (after the workshops and office visits) which was circulated to all companies which attended the seminars.

2.1.2 *Scope of the Guidelines*

The three overall objectives of the BG are: 1) enhanced life safety structural performance, 2) cost-effective retrofits; and 3) user-friendly technical guidelines. The enhanced life safety philosophy of these guidelines is accomplished through minimizing the probability of structural collapse. Cost-effective strategies are achieved by providing a displacement-based rational method to account for the resistance of all new and existing structural materials. User-friendly technical guidelines have been developed and presented in the form of pre-determined minimum lateral resistance requirements. This format permits the practitioner to capitalize on the benefits of advanced performance-based engineering techniques without subjecting them to undertake complex analyses.

2.1.3 *Limitations*

The Bridging Guidelines are restricted in application to: (1) Low-rise existing buildings (1-3 stories) (2) buildings with a well-defined load path (3) buildings with diaphragms with adequate strength and wall connections (4) buildings with plan eccentricity not greater than 20% in one direction and 10% in the orthogonal direction (5) steel or wood frame buildings with no diaphragm torsional redistribution of inertia forces; and (6) building sites where soil liquefaction is not a significant hazard.

2.1.4 *Performance Objectives*

The principal performance objective of the BG is life safety. Damage mitigation and immediate occupancy are performance objectives not specifically addressed in the current guidelines. In the guidelines, the risk to life safety is managed by limiting the allowable drift of a given lateral deformation resisting system (LDRS) to be less than or equal to a corresponding instability drift limit (ISDL). The ISDL represents the maximum allowable drift of a given LDRS to maintain a low probability of structural collapse, which would lead to a catastrophic number of casualties. The risk to life safety from the failure of heavy partition walls is also included in the guidelines.

The performance objectives adopted in the Bridging Guidelines are similar to those given in the FEMA 356 [9] and FEMA 424 [10] publications. The ISDL values are a significant component of these performance objectives, and guidance on their values was taken from a combination of FEMA 356 and various experimental programs.

The Bridging Guidelines uses the results of the mean plus one standard deviation from a suite of ten ground motions for the retrofit design level. These results represent an overall demand greater than the design ground motion (2% in 50 years). The assessment of schools is based on 80% of the retrofit requirements.

2.1.5 *Seismic Zones and Soil Type*

In the Bridging Guidelines, the province of British Columbia has been divided into six seismic zones based on the spectral response acceleration values for a period of 1 second, as prescribed in the 2005 National Building Code of Canada [6]. Figure 1(a) shows the seismic zones for the south-west corner of British Columbia.

Soil hazard maps were developed for the two most populous regions of the province; the Lower Mainland on southwestern BC and Greater Victoria on southern Vancouver Island. These two soil hazard maps demarcate the geographic boundaries of the five major soil types, Site Class A (hard rock) to Site Class E (soft soil), which are based on the NEHRP soil classes for susceptibility to ground motion amplification. Figure 1(b) shows the soil hazard map for the Greater Regional District of Vancouver.

2.1.6 *Prototypes*

The range of common low-rise school buildings are modeled by a number of building prototypes that are differentiated by construction material and the main Lateral Deformation Resisting System (LDRS). The LDRS is comprised of vertical building elements that have similar seismic performance characteristics and that generate resistance to inter-storey horizontal shear deformations in the building. A total of 17 LDRSs are currently included considered in the Bridging Guidelines as listed in Table 2.1. Note that the ductility descriptions are the same as those used in the Table 4.1.8.9 of the 2005 NBCC.

2.1.7 Analysis Program for Resistance Tables

Non-linear analyses were used to determine the inelastic deformation performance of the LDRSs in the Bridging Guidelines. The following three independent non-linear analysis tools were used to compile the analysis results database:

- CANNY [11], a commercial 3-D dynamic analysis software package;
- Quakesoft [12], in-house customized software that models each lateral resisting system in each storey by a non-linear lateral deformation resisting element; and,
- FEMA 440 [13], the refined displacement modification method for use with non-linear static analysis.

Quakesoft was used to generate the response of all 17 prototype buildings in the 5 seismic zones on 3 site classes (C, D and E). CANNY and FEMA-440 were used to perform a validation of the results from the Quakesoft. Quakesoft was also used to generate the diaphragm resistance tables, while CANNY was used for validation.

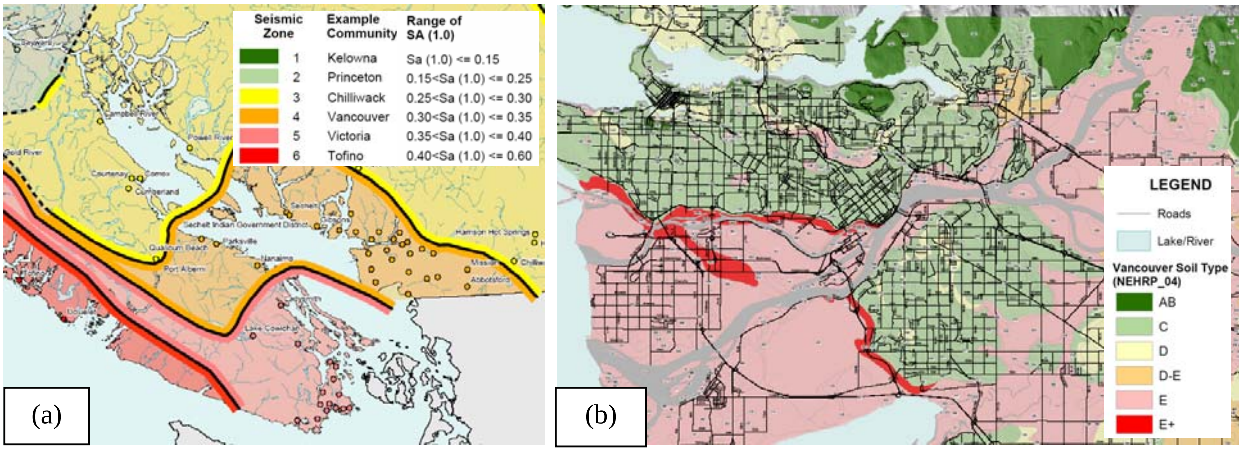


Figure 1 (a) Seismic Hazard Map for South Western British Columbia and (b) Soil Type Map for the Greater Vancouver Regional District

Both Quakesoft and CANNY used a suite of 10 ground motions. The ground motions were all crustal in nature and came from the 1994 Northridge and the 1989 Loma Prieta earthquakes. The records were scaled to the corresponding design spectra of the 2005 NBCC for each combination of seismic zone and site class. Mean plus one standard deviation values of the suites were then used in the resistance tables. Details of the ground motions can be found in Commentary C of the 2nd Edition Bridging Guidelines [1].

Since the FEMA-440 Displacement Modification Method does not require time histories, merely an acceleration spectrum. As such, the 2005 NBCC spectra were used directly.

All prototypes, or LDRSs, were modeled as a 2-D two-storey building, with lateral shear spring models at each level. Masses were lumped at the first floor and roof. The prototypes differ in the backbone curve (monotonic load-displacement relationship) and hysteretic model (cyclic loading rules). Figures for the backbone curves and the hysteretic models can be found in the Bridging Guidelines Commentary C [1].

The outcome of the extensive analysis was a set of resistance tables that list the minimum required strength values, for retrofit, to maintain a given drift limit. Each resistance table was for a specific prototype and seismic zone. A strength value is given to limit the drift to 1.0%, 1.5%, 2.0%, 3.0% and 4.0% on a given site class. The table also provides a plot of the required resistance vs. maximum drift. All values on the resistance tables have been divided by the code based Ro (given on Tables 1 and 2), such that they are compatible with the material design codes. An example resistance table for blocked plywood shearwalls is given in Figure 3.

Table 2.1 Listing of lateral deformation resisting systems (LDRS)

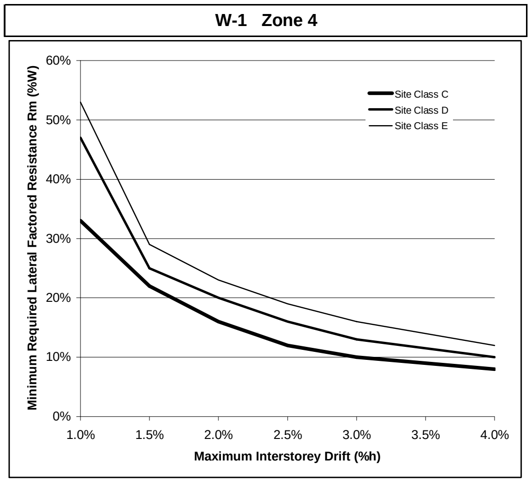
Material Group	**Prototype No.**	**Prototype Description and Failure Mode**	**ISDL**	**R_o**
Wood	W-1	Blocked OSB/plywood shearwall	4.0%	1.7
	W-2	Unblocked OSB/plywood shearwall	4.0%	1.7
Steel	S-1	Concentric braced frame (tension only)	4.0%	1.3
	S-2	Concentric braced frame (tension/compression)	1.0-2.5%	1.3
	S-3	Eccentric braced frame	4.0%	1.5
	S-4	Moment frame (moderately ductile)	4.0%	1.5
Concrete Masonry	M-1	In-plane unreinforced shearwall bed-joint sliding	1.5%	1.5
	M-2	In-plane reinforced masonry	1.5%	1.5
Reinforced Concrete	C-1	Shearwall (moderately ductile)	2.0%	1.4
	C-2	Shearwall (conventional construction)	1.5%	1.3
	C-3	Moment frame (ductile)	4.0%	1.7
	C-4	Moment frame (moderately ductile)	4.0%	1.4
	C-5	Moment frame (conventional construction)	4.0%	1.3
Clay Brick Masonry	B-1	In-plane shearwall bed-joint sliding	1.0%	1.5
Rocking	R-1	Low Aspect Ratio Rocking Element	4.0%	1.0
	R-2	Medium Aspect Ratio Rocking Element	4.0%	1.0
	R-3	Higher Aspect Ratio Rocking Element	4.0%	1.0

2.1.8 Validation of Resistance Tables

Each LDRS and diaphragm prototype was validated with an independent set of analyses. This validation was done to first check if there was an error in the modeling and secondly to compare the results to the 2005 NBCC. For most prototypes, this was equal to 60% of the seismic static force levels.

The validation process did find inconsistencies in the analysis results. This led to changes and re-analysis. A sample of one of the final validation charts is shown in Figure 4.

A third, more limited, set of analysis was done by the EPR. This analysis used the computer program RAM-Perform and in general produced less conservative values than the Quakesoft analysis.



Site Class	*1.0%*	*1.5%*	*2.0%*	*2.5%*	*3.0%*	*4.0%*
C	33%	22%	16%	12%	10%	8%
D	47%	25%	20%	16%	13%	10%
E	53%	29%	23%	19%	16%	12%

Figure 3-1(c)

Minimum Required Lateral Factored Resistance R_m (%W)
Wood Prototype W-1 Blocked OSB/Plywood
Seismic Zone 4 (Vancouver)

Figure 3 Resistance Table for Blocked Plywood Shearwalls in Vancouver

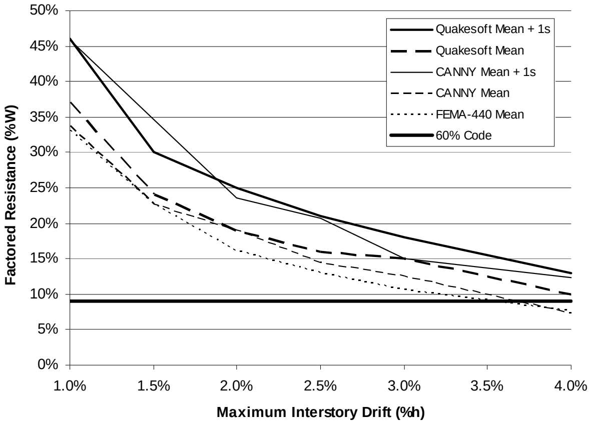


Figure 4 Validation Results for Steel Braced Frames (Tension Only)

3 THE TECHNICAL GUIDELINES

The 1st Edition of the Bridging Guidelines was completed in June 2005, and the 2nd Edition completed in the March of 2007. The Technical Guidelines (final version) are slated to be finished in 2010. There are several issues that need to be addressed in the final version. The research team is currently working on the selection of ground motions and the nonlinear response analysis of soft soils.

3.1 Selection of Ground Motions

The main objective of this preliminary study is the validation of the suite of ground motion used in the Second Edition of the Bridging Guidelines [1]. The validation process consists on comparing the nonlinear structural responses of structural prototypes under several earthquake scenarios. Ground motions were selected from shallow and deep earthquake records, mainly those recorded from Japanese and California's earthquake records (Table 3.1).

Table 3.1 Earthquake scenarios defined for Vancouver, BC

Scenario ID	Earthquake Scenario - Definition
Sc1	BG suite of records
Sc2	Crustal Earthquakes from California
Sc3	Crustal Earthquake from Japan
Sc4	Crustal Earthquakes (Mixed)
Sc5	Subcrustal Earthquakes from the Pacific North-West Coast
Sc6	Subcrustal Earthquakes from Japan
Sc7	Subcrustal Earthquakes (Mixed)
Sc8	Crustal and Subcrustal Earthquakes (mixed)
Sc9	Subduction Earthquakes recorded at 120 km or further

The selection was focused on ground motions recorded in earthquakes that represent a similar hazard for the school located in the city of Vancouver and in a site-class C. Each record was visually inspected and processed (baseline corrected and filtered). The time histories were scaled by using the same procedure as in the BG. Those records that possessed minimum modifications (lower scaling factors) were considered as potential candidates for the final selection. The modified records were then grouped in several earthquake scenarios depending on the type of earthquake and their location.

This preliminary study showed that the values of resistance defined in the BG are always conservative when they are compared to the results obtained from every earthquake scenario defined in Table 3.1. The definition of the suite of ground motions represents another source of conservatism in the high values defined in the resistance tables of the BG. In the interest of reducing these values, a different suite that includes both as many records as possible (say 20) and different types of earthquakes (crustal and subcrustal) may be considered and used for future research and guidelines.

This study also showed that there are no substantial differences between the results obtained from Japanese and Californian crustal earthquake scenarios. However, the selection of motions recorded from subcrustal earthquakes from Japan do not benefit from the scaling procedure and criteria established in this work and in the BG. Further studies on different scaling procedures as well as selection of records from deep Japanese earthquakes must be considered in the near future.

3.2 Soft Soils Study

During the development of the 2nd edition of the Bridging Guidelines, the need for site response analysis of Site Class D sites also arose from a unanimous PRC recommendation. Given the potentially high seismic demand at Site Class D sites, the PRC was of the opinion that the Ministry's commitment to promoting cost-effective retrofit solutions would be best served by assessing the surface response of at least 10 Site Class D sites using site response analysis. The data collected from this analysis could then be used to refine the minimum resistance tables in the second edition of the guidelines.

The study reported in the BG is in response to the PRC recommendation. The results presented are preliminary and correspond to schools located on sites C, D and E, rather than just D. Including analyses for different site classes provide valuable insight into the significant effect that the site class can have on the expected performance of the various structural systems considered within the scope of the Bridging Guidelines. It is anticipated that some Site Class D sites may exhibit substantial amplification of the surface ground motion.

The results of this study showed that NEHRP [14] site classification criteria for Site Class D sites seem to be a reliable indicator of high amplification sites for wood frame buildings. However, the NEHRP criteria do not appear to be a reliable indicator of the severity of site amplification for other site class/form of construction combinations. Thus, there is a clear need of further studies of the influence of site class on the expected response of a school building.

3.3 Future work

It is expected that the final document be completed by 2010. Some of the main tasks are listed as follows:

Experimental Testing and Prototypes: Additional experimental testing will be done to generate more accurate backbone/hysteretic curves for existing materials, such as concrete masonry (including infill walls). Testing will also be done on innovative retrofit techniques, to ensure they perform as predicted, and to incorporate them as LDRS prototypes in the Toolbox method. Some examples of this are FRP reinforced shearwalls and sheet metal on steel studs.

Comprehensive Validation of Toolbox Method: Three dimensional models of buildings with multiple LDRSs in each direction will be analyzed to ensure that the Toolbox method works for even the most extreme cases. In addition, inelastic diaphragms and inelastic LDRSs will be analyzed together to observe the interaction between the energy dissipating elements.

Adaptation to Eastern Canada: While the resistance tables are specific to British Columbia, the methodology behind them is universally applicable. The next logical step in the development of the Technical Guidelines is to develop resistance tables for Eastern Canada.

4 CLOSING REMARKS

Advanced performance-based seismic engineering solutions are now being introduced into engineering practice in British Columbia. The first application for this evolving seismic engineering technology is the $1.5 billion seismic mitigation program for the province's school buildings. The Bridging Guidelines described in this paper have been developed as a first step in accelerating the use of advanced engineering solutions for life safe and cost-effective earthquake preparedness in British Columbia. The next proposed step in this program is the development of a comprehensive Retrofit Strategies and Guidelines Manual that will refine and expand the scope of the Bridging Guidelines for the upgrading of provincial low-rise school buildings.

ACKNOWLEDGMENTS

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