The Use of Equivalent Intensity Factors to Model Site Conditions for Performance Based Design of School Buildings in British Columbia, Canada

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SUMMARY
British Columbia Ministry of Education is conducting a $1.5 billion seismic mitigation program to make all public elementary and secondary school buildings safe. The University of British Columbia (UBC) developed performance-based technical guidelines and extensive list of retrofit options for the program based on an extensive applied research program. The retrofit methodology is based on an Incremental Non-linear Dynamic Analysis (INLDA). Common types of low-rise school buildings have been analyzed for the full range of ground shaking in all regions of the province to generate a huge database on crucial retrofit parameters such as drift ratios, factored resistances and percent probability of life safety. These results are made available to engineers assessing and retrofitting school buildings through the use of an electronic interface called the Seismic Performance Analyzer. All analyses were conducted for schools on the reference site for the Canadian Building Code, Site Class C with an average shear wave velocity between 360m/s and 760m/s. It took 9 million analyses to populate the data base for Site Class C. To repeat such analyses for the other 3 site classes in the code, Site Classes D, E. and F would be an intolerable burden. The Equivalent Intensity Factor (EIF) was developed to convert directly the retrofit data for the Class C sites to other site classes without repeating all the analyses. EIF is defined as the ratio of the seismic intensity on Site Class C to the intensity on Site Class D that gives the same drift ratio for the structure on Site Class D. The procedure for determining EIF will be presented for Site Class D. The EIFs were evaluated for 5 different Class D sites, generic school models covering a range in structural stiffnesses and 150 different ground motions. INLDA curves of spectral accelerations versus drift ratio were developed for each structural model on each site. When the INLDA curves for a given structure and site are compared at a given drift ratio, the ratio of the intensities is the EIF. The retrofit parameters such as factored resistance for a building on Site Class D for intensity I_D are determined from the Site Class C data base at the intensity level $I_C = I_D EIF$. This conversion has made it unnecessary to develop independent data bases for the Site Classes D, E and F.

Keywords: Assessment and Retrofit, Intensity Factor, Site Condition, Incremental Non-linear Dynamic Analysis

1. INTRODUCTION

In 2004, the British Columbia Ministry of Education initiated a $1.5 billion seismic mitigation program to make all public elementary and secondary school buildings safe. This seismic safety program is being implemented by the BC Ministry of Education (MOE) in collaboration with the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC). APEGBC has been contracted by MOE to develop a set of state-of-the-art performance-based technical guidelines for structural engineers to use in the seismic risk assessment and retrofit design of low-rise school buildings, 3 storeys or less. In undertaking this technical development program, APEGBC contracted the University of British Columbia (UBC) to draft the performance-based technical guidelines based on an extensive applied research program (APEGBC, 2006). Each draft of these technical guidelines has been peer-reviewed by a BC peer review committee of experienced local consulting engineers and by an external peer review committee comprised of prominent California consulting engineers and researchers. Research on innovative retrofit methods is still being conducted and technical guidelines are issued to keep current with research developments.

The three overall objectives of the guidelines are enhanced life safety, cost effective retrofits and user-friendly technical guidelines. The life safety philosophy of these guidelines is enhanced life safety through minimizing the probability of structural collapse by the use of rational performance-based engineering (PBEE) methods of earthquake damage estimation. The performance criterion of life safety is defined by acceptable drift ratios specified for each generic school building type. The process for evaluating critical drift ratios and establishing the probability of collapse is described below.

2. DESIGN GROUND MOTIONS

The seismic hazard to schools is deaggregated by considering the seismic hazard posed by subduction, deep (sub-crustal) and crustal earthquake sources affecting British Columbia separately. The sources are shown in Fig. 2.1. Seismic hazard data for each type of earthquake was generated using the commercially available computer program EZ-RISK (Risk Engineering, 2008). The analysis results have been verified where possible with reference to the data provided by the Geological Survey of Canada, GSC in Open Source File 4459 (Adams and Halchuk, 2003).

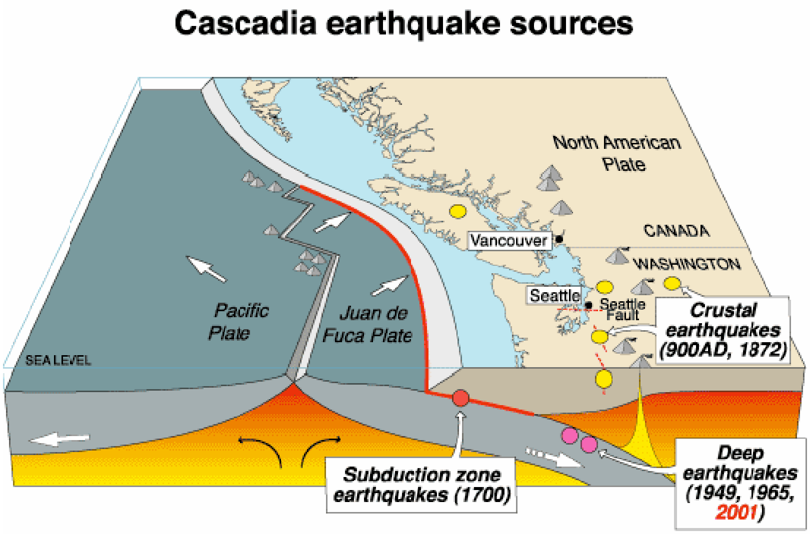

Figure 2.1. Subduction, deep (sub-crustal) and crustal earthquakes affecting British Columbia

Ground motion at any geographic location is modeled by three ground motion suites of ten ground motions per suite - one suite for each of crustal, sub-crustal and subduction earthquakes (Pina et al. 2010a). These records were selected on the basis of tectonic setting and appropriate magnitude, distance and site conditions. The crustal and sub-crustal suites of ground motion spectra have been scaled linearly in the period ranges of interest, T=0.5-1.0s and T=1-2s, for Vancouver's benchmark 100% level of shaking with a 2% exceedance rate in 50 years. The subduction suite of ground motion spectra have been scaled to Victoria's 100% level of shaking because of the larger cities, it is the one most affected by the subduction earthquake. Since structural velocity is considered as the best indicator of severe structural damage to a structure, as opposed to peak ground acceleration or displacement, the associated ground shaking intensity is defined by the average spectral pseudo velocity (PSV) spectrum for each geographic location. The selected ground motion suites are scaled linearly so that on average each suite matches the associated PSV design spectrum in the period range of interest.
The scaled design ground motions for the suite of crustal earthquakes are shown in Fig. 2.2. together with their average spectrum and the target PSV design spectrum. Note that the comparison between the average and the design spectrum in the period range of interest, T=1-2s, is quite good. There is an additional requirement that no spectrum should fall below 70% of the target spectrum.

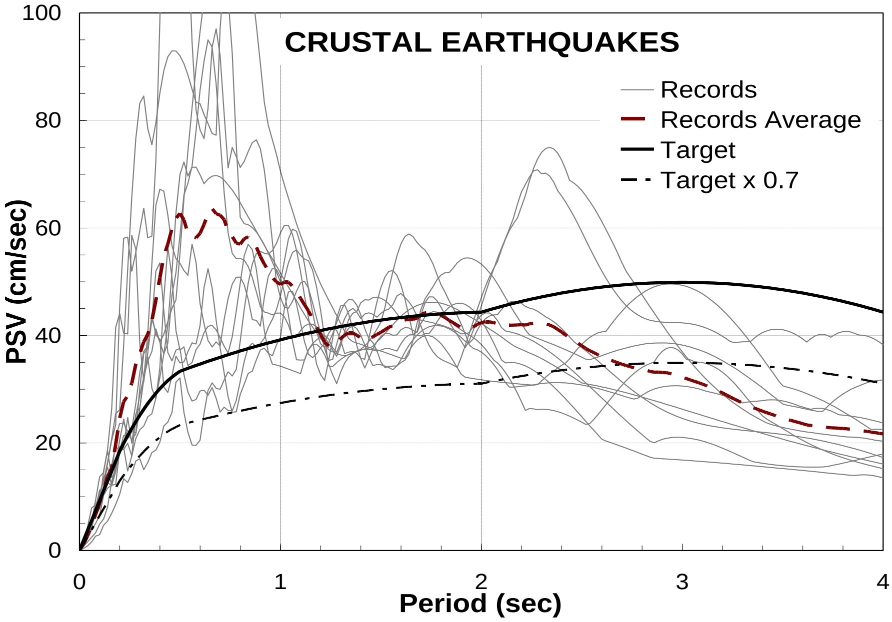

Figure 2.2. Design ground motions for crustal earthquakes scaled on average to the period range of interest of 1-2s (Pina et al. 2010a)

The full range of possible ground shaking by the selected ground motions is divided into a series of ground shaking increments. All levels of shaking are expressed as a percentage of a benchmark level of shaking. The "100%" intensity level is taken as the benchmark level, and it corresponds to a level of shaking with a 2% probability of exceedance in 50 years. Each ground shaking increment has a range of 10%. For example, the ground shaking increment immediately below the benchmark level of shaking has a level of shaking that ranges from 90% to 100%. For any geographic location, the full range of ground shaking varies from the 30% to 250% level of benchmark shaking for each selected input motion in order to cover a wide range of intensities in potential input motions in exploring the response of school structures.

Site Class C (firm ground – very dense sand or soft rock) is the reference site classification used in the national building code for Canada, NBCC 2010, and was adopted as the reference site for the retrofit program.

All soils softer than the firm ground, amplify/de-amplify the level of shaking at the underside of the building foundations relative to the response at Site Class C. The effects of these soils corresponding to Site Class D are introduced in the analysis through the use of an Equivalent Intensity Factor (EIF) which is described later (Pina et al. 2010b). The equivalent intensity factor, EIF, is the ratio of the intensity at the reference site to the intensity at the actual site to achieve the same structural drift response level.

3. INCREMENTAL DYNAMIC ANALYSIS (IDA)

The retrofit methodology is based on an incremental probabilistic non-linear dynamic analysis (IPNLDA) or incremental dynamic analysis (IDA) as it is more commonly called (Vamvatsikos and Cornell, 2001). Common types of low-rise school buildings have been analyzed for the full range of ground shaking in all regions of the province to generate a large database of 9 million analysis results. These results are made available to engineers assessing and retrofitting school buildings through the use of an electronic interface with the web based database, called the Seismic Performance Analyzer.

4. SEISMIC PERFORMANCE ANALYZER

The Analyzer shown in Fig. 4.1. is the principal analytical tool of the retrofit methodology. It gives the engineer access to a highly advanced, peer-reviewed analytical database without requiring the engineer to be experienced in the use of nonlinear dynamic analysis techniques.

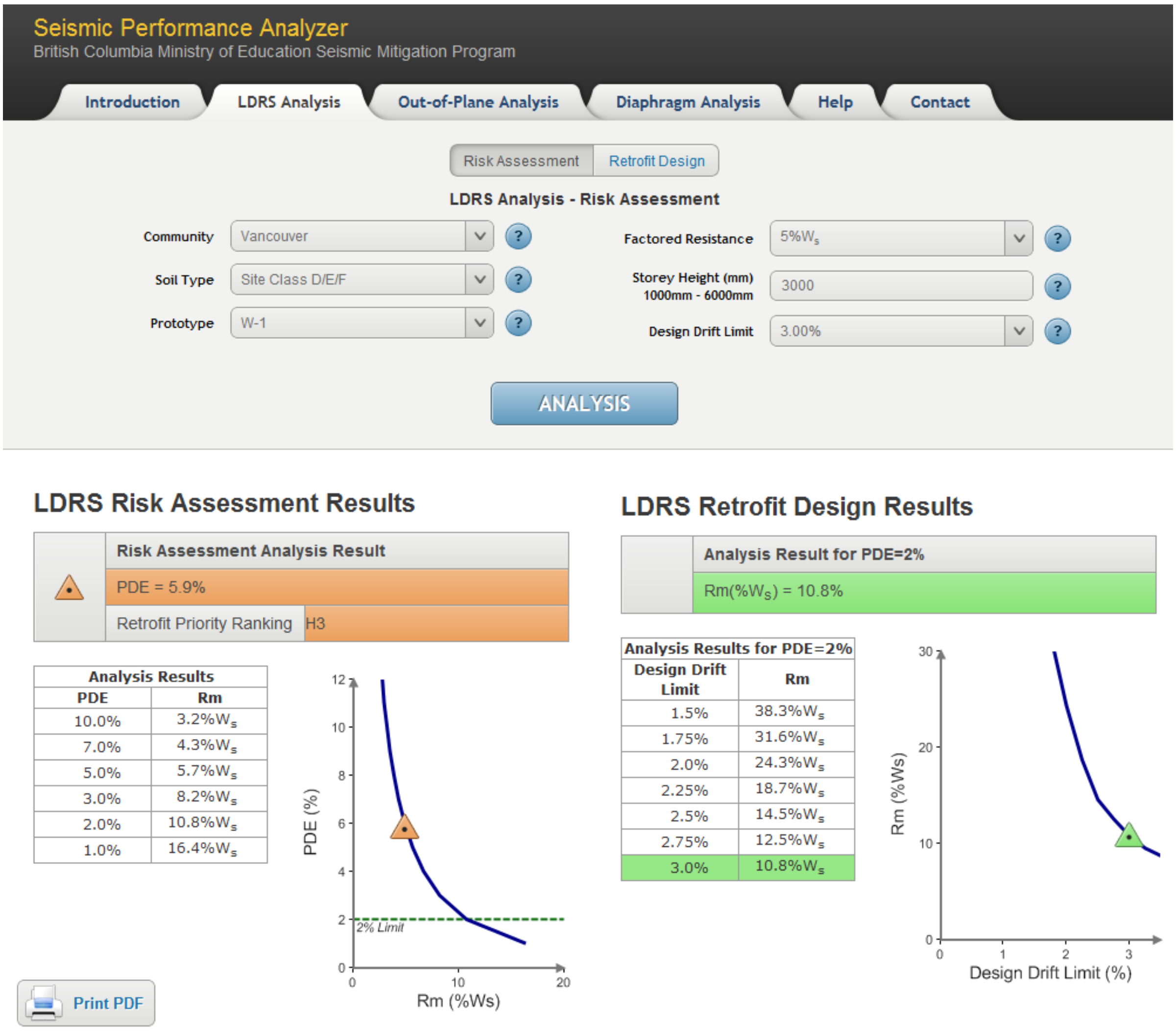

Figure 4.1. The Seismic Performance Analyzer

The Analyzer permits the engineer to quickly analyze the three principal building elements that have analytically complex behavior. These are LDRSs, walls rocking out-of-plane and diaphragms. For each of these three building elements, the Analyzer performs a risk assessment or a retrofit design (either basic or detailed). After making the basic parametric selections (input data), the engineer clicks on the Analysis button and the analysis results are instantly displayed. For acceptable performance the PDE must be less than 2%.

5. EQUIVALENT INTENSITY FACTOR (EIF)

It took 9 million analyses to provide a complete data base for schools on the reference Site Class C. To avoid a similar massive computational burden for other site classes, an investigation was conducted to determine if the resistance requirements for example Site Class D could be established by manipulation of the Site Class C data base. This investigation led to the concept of the Equivalent Intensity Factor.

Fig.5.1 shows how the EIF is calculated. In this example, the reference and specific sites correspond to Site Class C and Site Class D, respectively. Incremental Dynamic Analysis (IDA) curves (structural damage measure (drift ratio) versus input motion Intensity) are first obtained from the combined site response and structural analyses. Fig. 5.1. shows the incremental responses of a structural system under the j-th input motion for the two sites. Given the intensity on Site Class D, the relevant retrofit data for Site Class D can be obtained from the Site Class C data base by using intensity equal to the intensity on Site Class D multiplied by the EIF. This procedure will work if the EIF for Site Class D is fairly stable

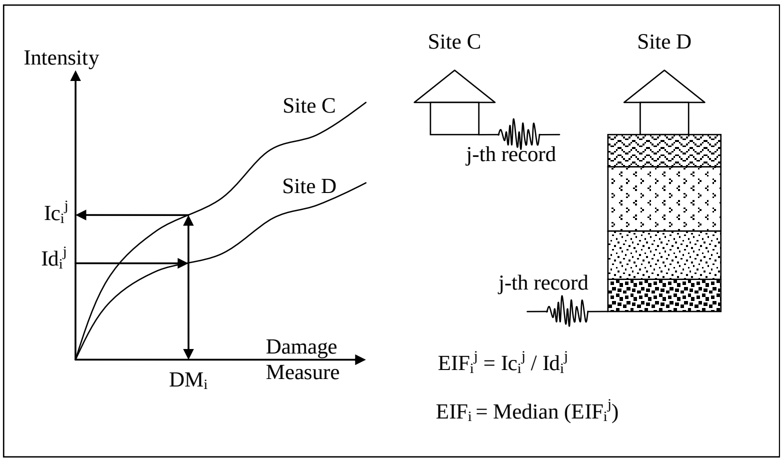

Figure 5.1. Calculation process of the Equivalent Intensity Factor, EIF, for a specific site (Site D), for a given i-th intensity of the j-th record (Pina et al, 2010b)

Equivalent Intensity Factors were calculated for a number of generic school buildings on 11 different sites matching the Site Class D designation as described in NBCC 2010. EIFs for factored resistances necessary to limit drift ratios to specific values for four LDRSs will be presented here. The first LDRS is a Blocked OSB/Plywood Shearwall. The backbone curve for analysis is shown in Fig. 5.2 and the EIF from IDA analyses are shown in Fig. 5.3. EIF = 1.0 corresponds to the factored resistances for different specified drift ratios for structures on Site Class C sites. All other data points are for Site Class D sites. The results show that a constant EIF = 1.2 gives results very close to the mean of the computed responses for Site Class D sites.

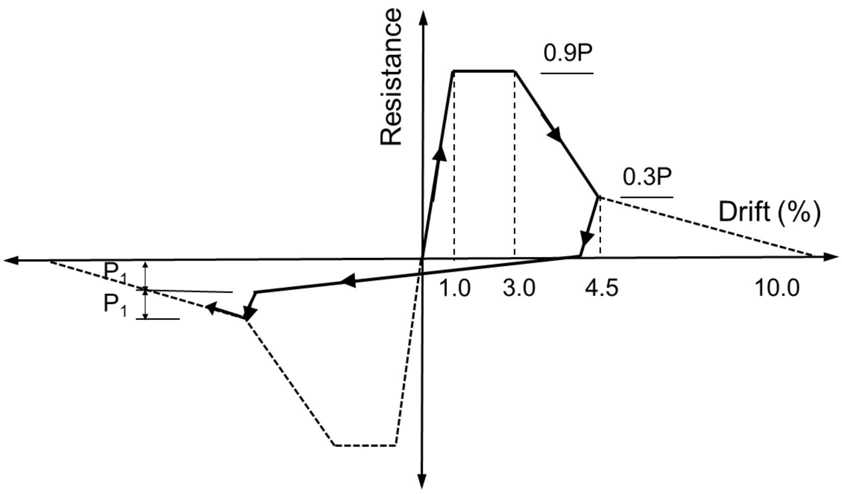

Figure 5.2. Backbone Curve for Prototype W-1: Blocked OSB/Plywood Shearwall

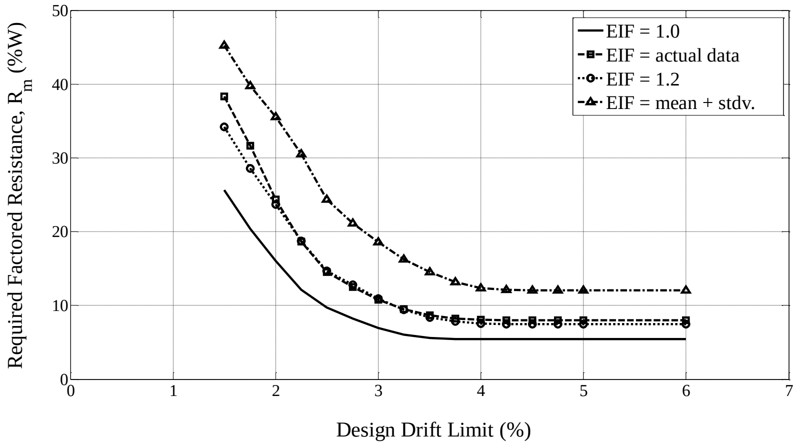

Figure 5.3. EIF for factored resistances for W-1: Blocked OSB/Plywood Shearwall with 3m height in Vancouver

EIF for 3 other prototypes are shown in Figs. 5.4, 5.5, and 5.6. The results suggest that an EIF =1.2 give a useful estimate of factored resistances for the high intensity region of the Vancouver Metropolitan area.

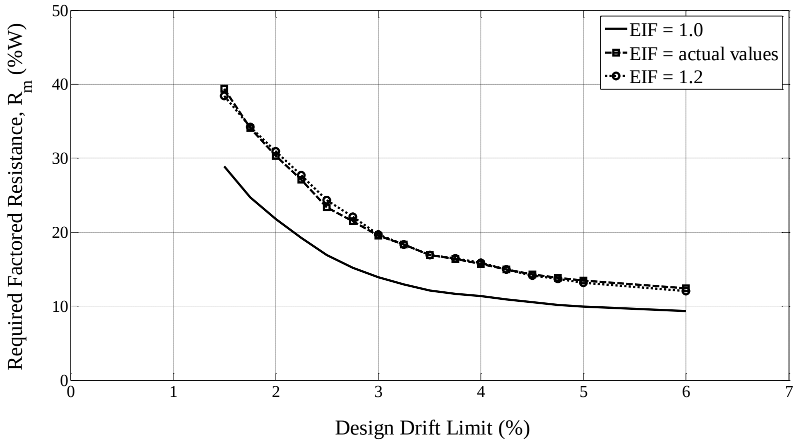

Figure 5.4. EIF for factored resistances for S-1: concentric steel braced frame – tension only with 3m height in Vancouver

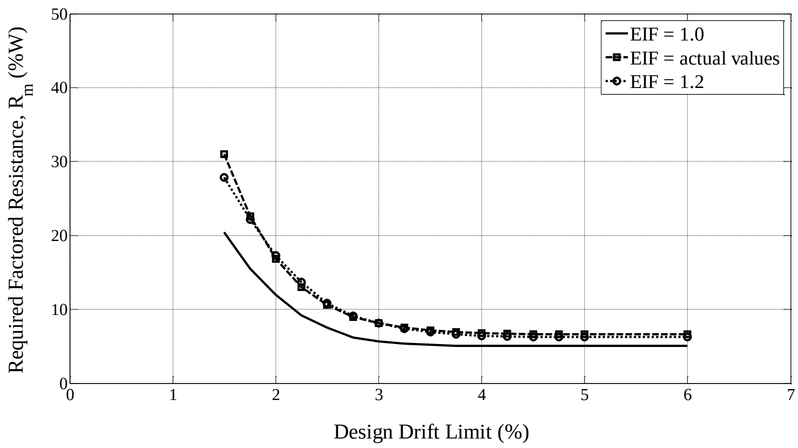

Figure 5.5. EIF for factored resistances for C-1: concrete ductile moment frame with 3m height in Vancouver

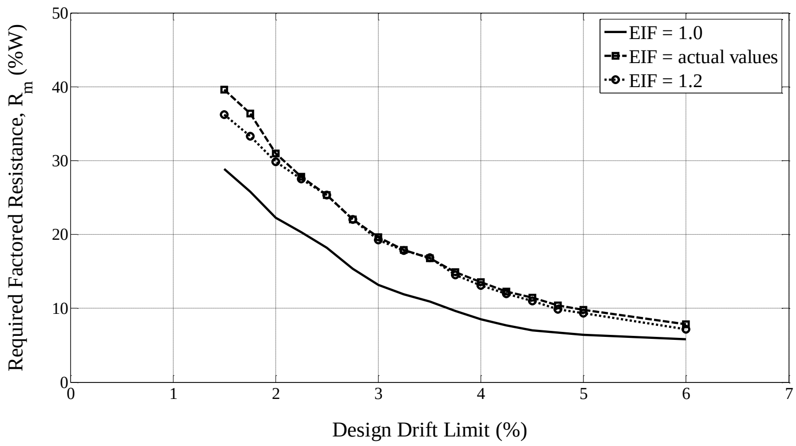

Figure 5.6. EIF for factored resistances for R-1: rocking with low aspect ratio (AR): AR ≤ 1.5 for cantilevers and 2 for pier with 3m height in Vancouver

Preliminary studies suggest that for areas dominated by subduction motions such as Victoria, an EIF = 1.4 may be more appropriate. More studies are being conducted to clarify this issue.

CONCLUSION

Seismic retrofits of British Columbia Schools are developed using a database of 9 million analytical results from dynamic nonlinear analyses of all generic school types and a wide range in intensity of shaking. All analyses were conducted for school on the reference Site Class C soils as defined in NBCC 2010. An Equivalent Intensity Factor, EIF, has been developed to a convert Site Classs C data to other siter class conditions. It has been shown above that an EIF = 1.2 gives factored resistances for design that closely replicate the results of nonlinear analysis for Site Class D sites and 4 very different structural prototypes. Studies are continuing to further validate EIF. Some preliminary recent studies suggest that when subduction motions are dominant that EIF= 1.4 may be more appropriate.

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