SITE RESPONSE ANALYSIS FOR THE SEISMIC RISK ASSESSMENT OF SCHOOLS IN BRITISH COLUMBIA, CANADA

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ABSTRACT

There is a major seismic mitigation program for reducing the risk to life safety in British Columbia schools. To support this initiative, a new and comprehensive risk evaluation procedure has been developed based on the results of nonlinear Incremental Dynamic Analysis of representative classes of low rise buildings. Initially all analyses were conducted for buildings on the reference soil class for the Canadian Building Code, Site Class C. These very general analyses for different building types and ground motion intensities make any further analyses unnecessary for any school on a Site Class C site in the greater Vancouver Metropolitan Area (VMA). To avoid having to conduct analyses for other site conditions during the risk evaluation process, the concept of the Equivalent Intensity Factor (EIF) was introduced to convert the results of IDA analyses of Class C sites for the Vancouver area to other areas with different intensities of motion and different site conditions. The EIF is a function of building type, intensity of shaking and site conditions. They were determined by nonlinear analyses for a carefully selected set of the functional variables. Median EIF values are calculated for the crustal, subcrustal and subduction earthquake suites of motions adopted for this project. The EIF approach has two distinct advantages: it avoids specific-site response analyses for risk evaluation and its associated costs and it speeds the risk assessment of schools located in soft soils. This paper focuses on the development of a range of EIF values schools on soft soil sites.

Introduction

A seismic risk assessment (SRA) program is being implemented for all the schools in British Columbia, Canada. Several schools are located in areas with soft soils and most of them may require specific site response analyses.

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Site response analysis is an alternative procedure to code-based site factors for the prediction of site effects. In engineering practice, these site effects refer to the propagation of outcrop ground motions through specific soil conditions to the surface. Outcrop or rock ground motions are usually available from a wide range of instrumented stations, which is not the case for motions recorded on specific sites.

Soft rock site ground motions have been selected as input motions for structural non-linear dynamic analyses of BC school building systems. These records are representative of the seismicity of most cities in BC located in soft rock sites (site class C per code classification). Currently, these ground motions have been linearly scaled to code demands of schools located in soft soils defined by the national building code, NBCC 2005 (NRCC 2005). However, a previous study (APEGBC 2006) has shown that scaling ground motions to code levels for soft soils produces very high demands when using those scaled motions for non-linear dynamic analysis.

Procedures for site response analysis differ by the mathematical non-linear modeling or representation of the underlying soil. Nonlinear dynamic analysis is the most sophisticated procedure for site response analysis. Equivalent linear representation of the nonlinear behaviour of soils is nevertheless the most commonly used tool in engineering practice. This simplified procedure gives approximate results for lower intensity levels of the outcrop motions, but it usually over-predicts the surface motions at higher intensity levels (Stewart et al. 2008).

The objective of this study is to conduct a preliminary analytical program to investigate the non-linear response of soft soil profiles taken from existing school locations, and how this response affects the behavior of the structural systems located at the site. Input ground motions are scaled to several intensity levels to capture different damage states of representative structural systems. The results of this study can be directly applied to the overall seismic risk assessment procedure as an alternative to specific-site response analysis. Running specific-site response analysis for each school can certainly delay and increase costs of the overall seismic risk reduction program. A statistical procedure that takes into account representative sites and structural systems of BC school buildings can certainly speed the assessment program and reduce the respective costs involved in a site-specific study.

Seismic risk assessment procedure for soft soils

SRA Procedure for hard soil

In this part we will discuss the modifications to the seismic risk assessment (SRA) tool for buildings located in soft soils. We may refer at this point to a companion paper presented by the authors for further details on the SRA procedure (Taylor et al. 2010).

The SRA procedure uses incremental dynamic analyses, IDA (Vamvatsikos and Cornell 2002), to estimate the incremental inter-storey deformation drifts for three different earthquake scenarios: crustal, subcrustal and subduction earthquakes. Input motions recorded in soft rock (site class C) were selected to represent each earthquake types. Conditional probabilities of drift exceedance are built at each intensity increment of these input motions. The conditional probabilities are convoluted with the annual frequency of intensity occurrence. The annual frequency of intensity occurrence is obtained from the hazard data calculated for each type of earthquake by means of Probabilistic Seismic Hazard Analyses, PSHA, in a soft rock site. The total annual frequency of drift exceedance is given by the contribution of all the individual frequencies calculated at each intensity level. The total annual frequency of drift exceedance is translated into probabilities by means of a Poisson process for a specific time frame defined in this SRA program.

Equivalent Intensity Factor

The equivalent intensity factor, *EIF*, is the ratio of the intensity in the actual or soft site to the intensity in the rock or reference site calculated at the same structural response. The calculation of this *EIF* is based on a combination of two analyses. The first analysis is a geotechnical analysis of a soil column that resembles the propagation of the input ground motions upwards from firm ground through the overlying soil to the surface. The second analysis is a structural analysis of the building to these surface ground motions. Nonlinear dynamic analyses have been adopted in both site/structure analyses by using simple models of the underlying soil and structures.

Figure 1 shows a scheme of the EIF calculation process. In this example, the reference and specific sites correspond to sites class C and class D, respectively. IDA curves (structural Damage Measure versus input motion Intensity) are first obtained from the combined site response and structural analyses. Figure 1 shows the incremental responses of a structural system under the *j*-th input motion for the two sites – note that for a given intensity level the IDA curve for Site D has a larger damage measure value, which is equivalent to amplification of the structural response.

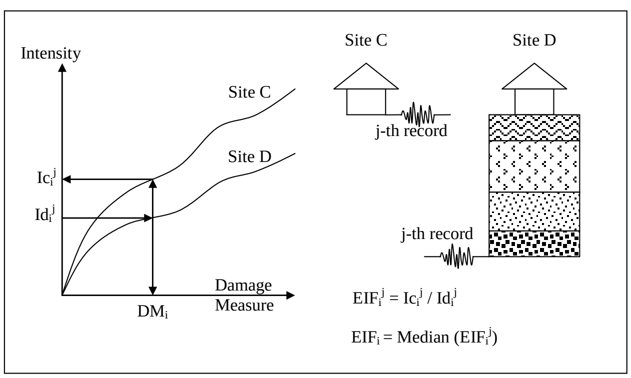

Figure 1. Calculation process of the Equivalent Intensity Factor, *EIF*, for a specific site (Site D), for a given *i*-th intensity of the *j*-th record

The EIF is calculated at the *i*-th intensity level of the Site D curve, Id_i^j. The associated structural damage measure is DM_i. From the Site C curve, we can read the intensity level, Ic_i^j, at the DM_i damage measure. The equivalent intensity factor for the *j*-th record and for the *i*-th intensity level is then given by the ratio of these two intensities. This process is repeated for all the records with the same *i*-th intensity level and the median value is calculated. The median value is considered here as the characteristic EIF for the specific site.

Modified SRA procedure

The Equivalent Intensity Factors normalize the rock-site-based IDA curves to account for other site conditions. This factor only moves the resulting IDA to a different 100% intensity level indicating de-amplification or amplification of the structural response as a consequence of the new site conditions. This process is repeated (i) at different intensity levels of the IDA curves, (ii) for different structures and (iii) for each type of earthquake.

Site Response Analysis

Site Description

This study is preliminary and corresponds to 3 schools located on sites D in the Greater Vancouver and 2 schools located on a sites D and D/E in the Greater Victoria. Figure 2 shows the actual sites where the bore-holes were conducted.

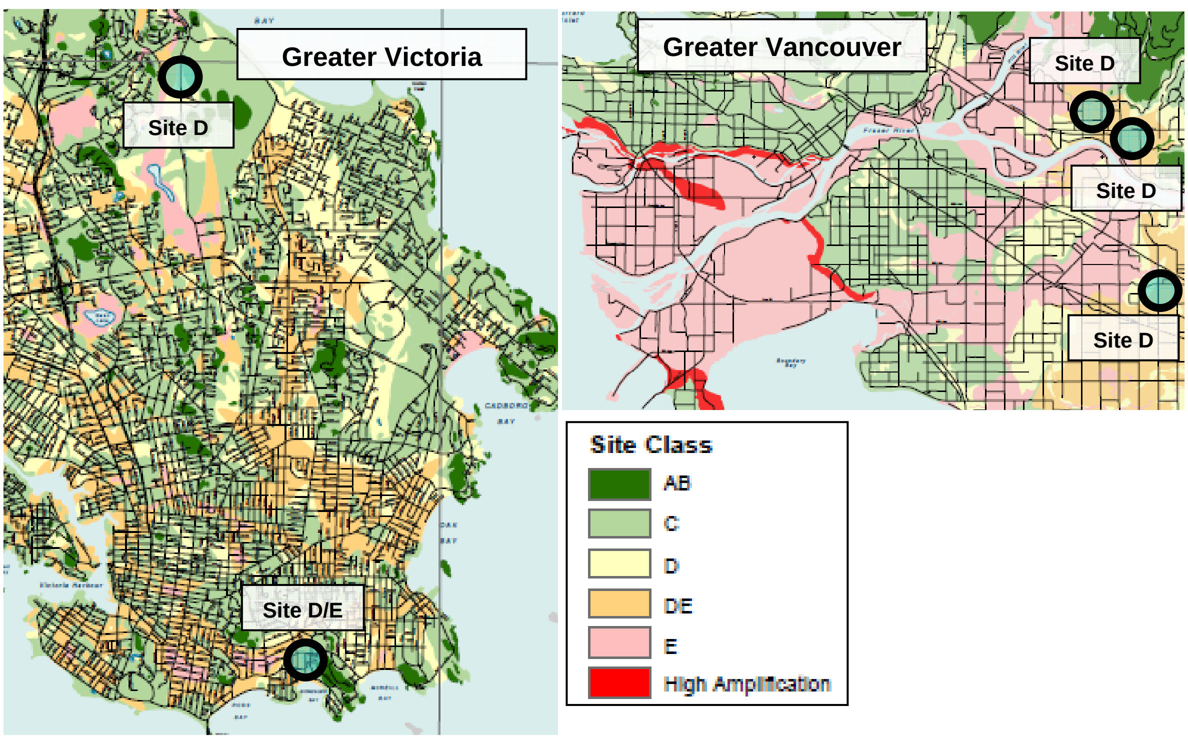

Figure 2. Location of sites in the Greater Vancouver and in the Greater Victoria for the combined geotechnical/structural analyses (adapted from APEGBC 2006)

Figure 3 shows the distribution of shear wave velocities of 11 soil columns representing the 5 selected sites. Four sites are represented by two soil columns and one site by three soil columns. The difference between soil columns in a site is due to different soil properties assigned in the mathematical models.

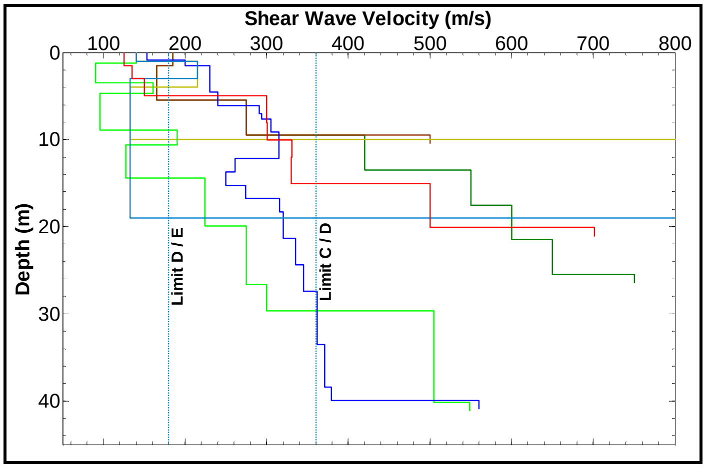

Figure 3. Distribution of shear wave velocities in 11 soil columns representing the selected 5 sites

Modeling and numerical processing

Three suites of 10 class-C site ground motions were selected to represent the seismicity in Vancouver of 2500yr return period crustal, subcrustal and subduction earthquakes. Information regarding to these suites is provided in a companion paper (Pina et al. 2010). The median spectral pseudo-velocities of the ten records are shown in Figure 4b for the three earthquakes.

Geotechnical engineers provided the soil properties for the site and assisted in the generation of free surface ground motions from site response analyses. For this study the nonlinear program DESRA (Lee and Finn, 1978) was used to generate these motions. Detailed information of each site was provided by the BC geotechnical consultant responsible for each site (APEGBC 2006).

Results

Surface acceleration time histories are the ultimate results of site response analyses. However, some other results, such as the distribution of motion parameters across the profile, can provide a better understanding of the nonlinear behaviour of the soil columns investigated. Figure 4 shows the distribution of peak accelerations along the depth of the underlaying soils. Figure 5 provides the median pseudo-velocity spectra of the reference-site and specific-site motions.

The amplification of peak accelerations is evident for subcrustal and subduction earthquake motions, but not the for crustal earthquake motions. In terms of spectral velocities, the amplification is larger in crustal motions than in the other two earthquake cases for intermediate period ranges, say 0.5s to 2.0s. Although these are only median results and dispersion certainly increased after running site response analyses, we can clearly observe different patterns of results for each type of earthquake. These important observations confirm the basic idea of estimating structural response for each type of earthquake individually and of assessing the total risk at a very late stage in the procedure.

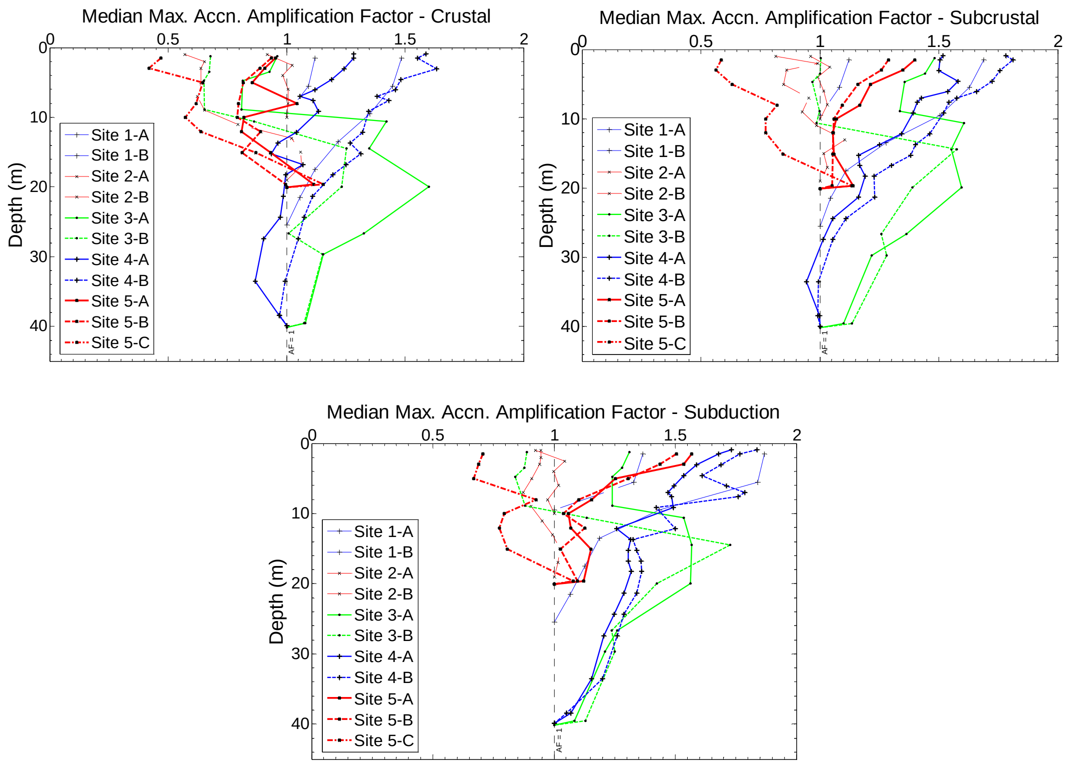

Figure 4. Distribution of the amplification of median maximum accelerations of 11 soil columns of the selected 5 sites for the 100% intensity of crustal, subcrustal and subduction earthquake motions

The same procedure described above was repeated for other four levels of intensities: 50%, 75%, 150% and 200%. Five new suites of surface motions were thus obtained for each soil column and then applied to the structures.

Structural Nonlinear Dynamic Analysis

The resulting surface acceleration time histories are applied to a set of structures using nonlinear dynamic analysis (NDA). The NDA are repeated for the three suites of the 11 sites for the five levels of shaking: 50%, 75%, 100%, 150% and 200%. EIFs are calculated for each case using the procedure summarized in Figure 1. NDA was conducted using computer program CANNY (Li 2008). An in-house software program was developed for data post-processing.

Structures

NDA is performed for a regular 2-story building model (Figure 6a). The earthquake demand is resisted by lateral deformation resistance systems (LDRS) located in each floor. Mass of second floor has been assigned as 80% of the mass of the first floor, “m1”. A mass-lumped system with nonlinear shear springs models the system (Figure 6b).

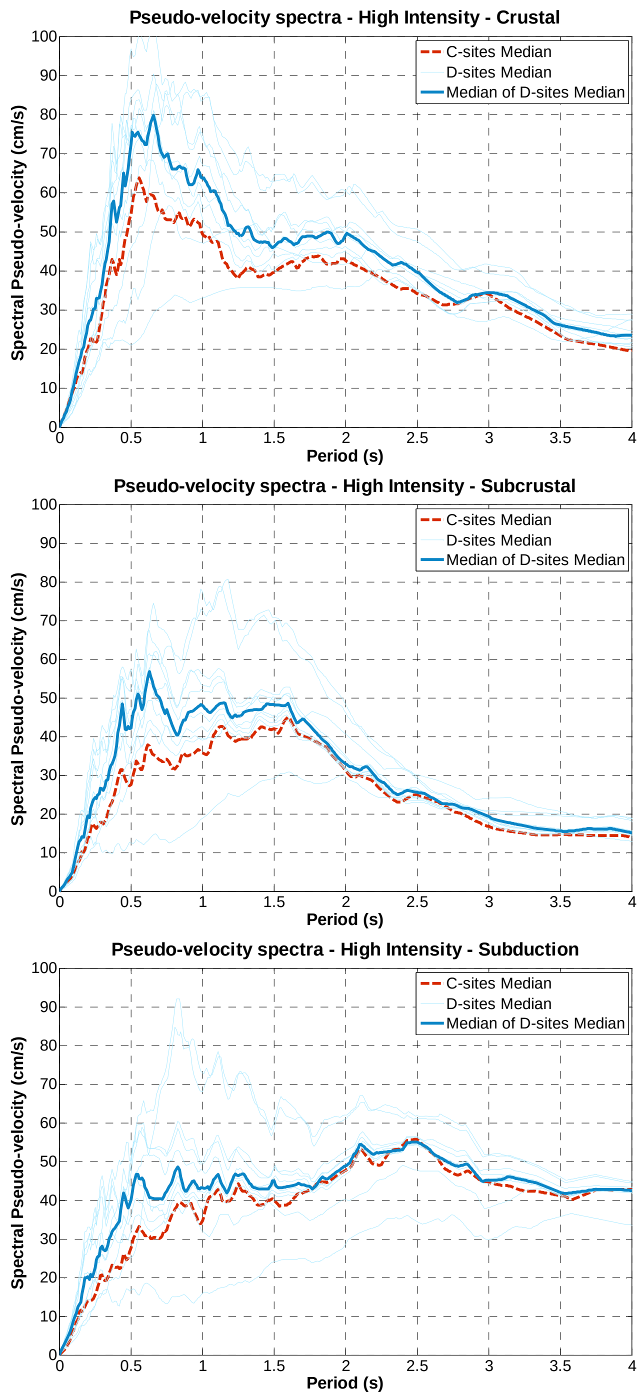

Figure 5. Distribution of the median pseudo-velocity spectra of 11 soil columns of the selected 5 sites for the 100% intensity of crustal, subcrustal and subduction earthquake motions

To see the sensitivity of the EIF to the type of structure, we have purposely selected three different nonlinear behaviours of the springs, "k" (Figure 6c). The first case, W-1, corresponds to a very flexible unblocked plywood shear-wall, which hysteretic loops have strength degradation (D to E), stiffness deterioration (F to G) at many loading cycles and it is heavily pinched during the reloading (C to D to E). The second case, C-1, is a rigid reinforced concrete shear-wall with strength/stiffness-deteriorated loops. The third case, R-1, is a rigid rocking masonry wall with negligible hysteretic dissipative energy.

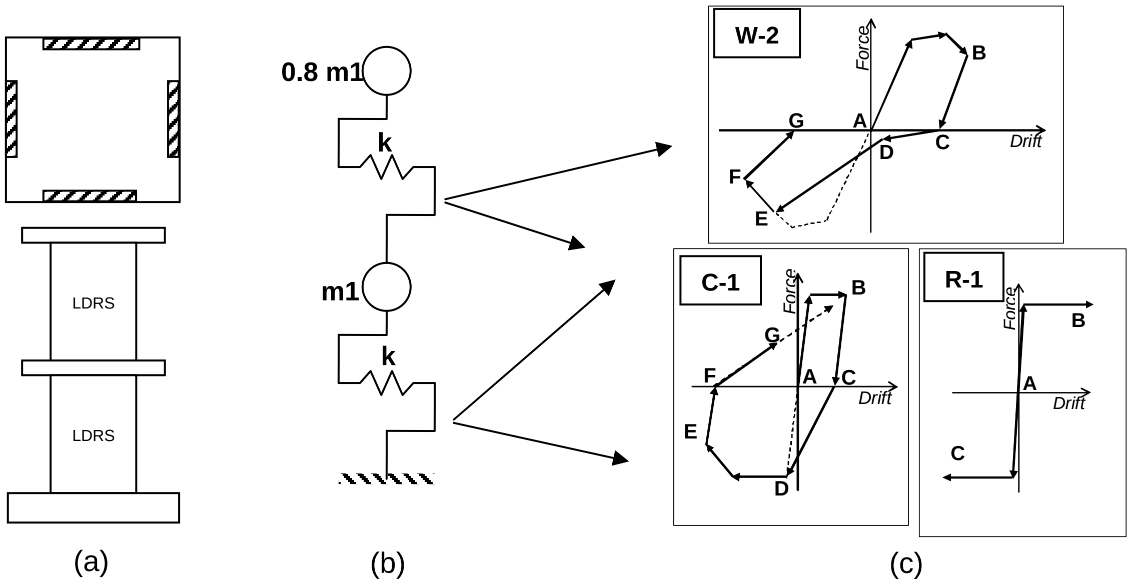

Figure 6. (a) Representation of a 2-storey building and (b) modeling for NDA including the (c) hysteretic rules of the lateral shear springs adopted

Results

EIF values were calculated for each type of earthquake separately and for the three structural systems, W-2, C-1, and R-1 at limit inter-storey drift deformations of 4%, 2% and 4%, respectively. Figure 7 shows the median EIF of each site (Median of Sites) and the median EIF for all the sites (Median of Medians) distributed for the 5 levels of shaking.

Median EIF values are very similar for the three structural systems within the same earthquake suite. Larger variations are seen on subcrustal motions at lower levels of shaking. In general terms, the maximum median EIF is 1.7 and is observed at the low intensity of 50% for subcrustal earthquake motions. We can observe that EIF values are between 1.0 and 1.2 for most other cases.

Remarks

Results of an integrated geotechnical/structural analysis have been described in this paper, with particular application to school building systems located in soft soils in British Columbia. Selected soft rock site records were propagated through several soil columns to the surface using a nonlinear dynamic site response analysis. Surface motions were input to structural system models using a nonlinear dynamic analysis. The exercise was repeated for different levels of input motion intensities to estimate different damage scenarios in the structure. Median equivalent intensity factors were calculated to account for the amplification of the structural response due to site effects.

Equivalent intensity factors are introduced in the original seismic risk assessment procedure to estimate the risk of BC schools located in soft soils. The use of the EIF may reduce the costs involved on specific-site response analyses and it speeds the risk assessment of many schools located in soft soils.

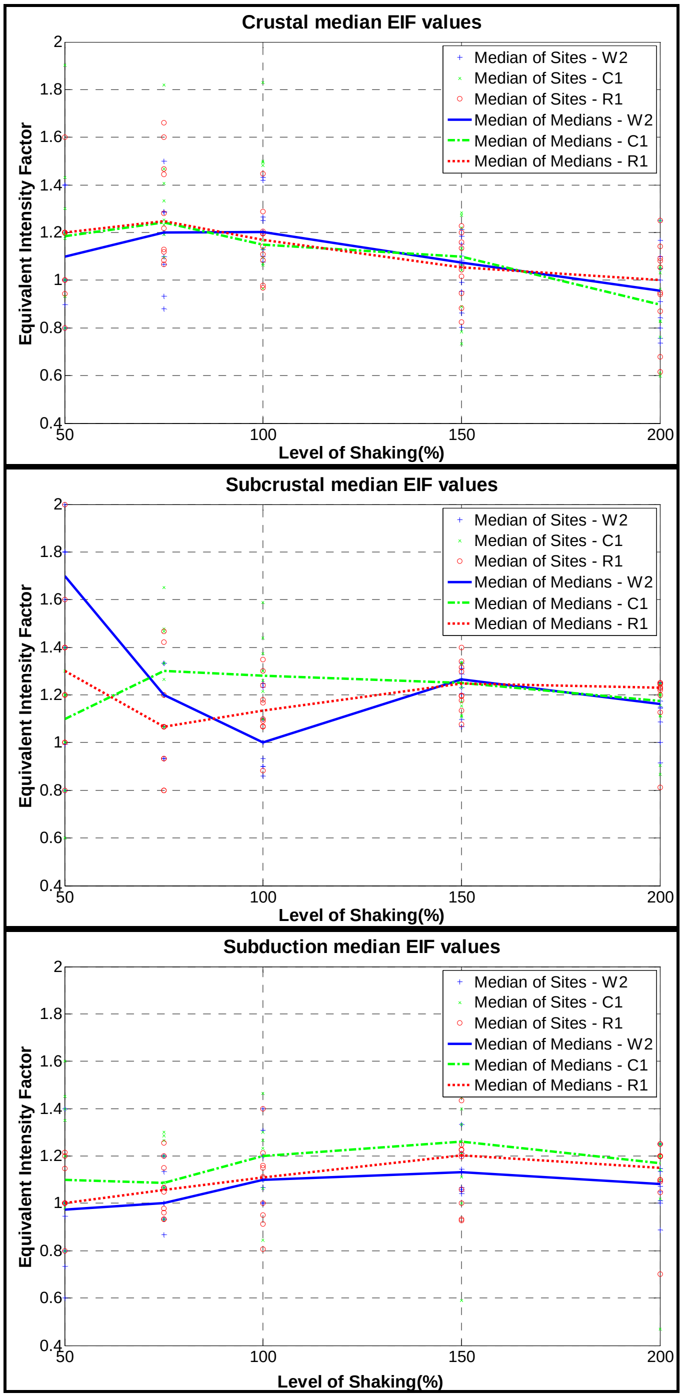

Figure 7. Distribution of median EIF values for the three structural systems, for each site and for each type of earthquake

This study is based on limited numbers of bore-holes and is only preliminary. Future studies will concentrate on investigating more sites for the integrated soil/structure analysis proposed in this study. The results of an SRA procedure that includes the calculated EIF values can give a fair estimate of schools located in similar sites studied here. Also, the methodology can be adopted for seismic risk calculations using specific-site response analysis.

Acknowledgements

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