Site-Specific Seismic Studies for Optimal Structural Design

Part I - General

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This article presents the benefits of performing site-specific studies to determine design seismic ground motions. Part 1, presented herein, shows the general procedure required for the studies, and how the results can optimize structural design by not only providing site-appropriate reduced loads, but also by adjusting the Seismic Design Category classification, which affects design analyses and construction costs. Part 2, which will follow in an upcoming issue, will provide pertinent examples with emphasis on East Coast practices.

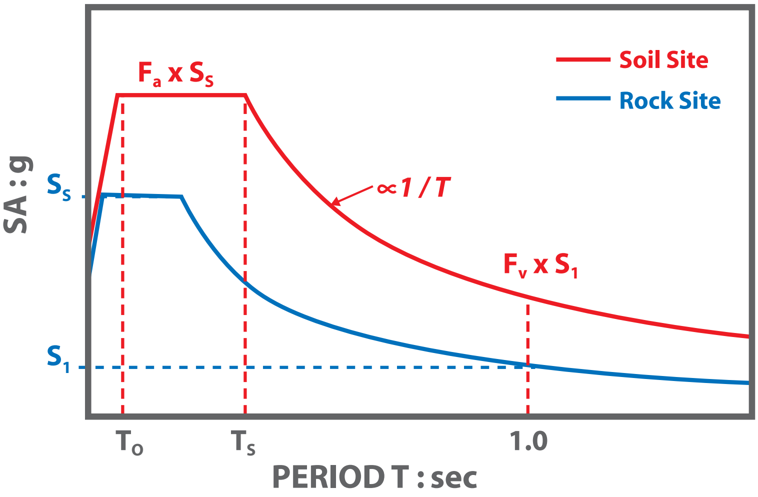

Figure 1: Code procedure to derive the Maximum Considered Earthquake (MCE) acceleration response spectrum (SA). The MCE spectrum is reduced by a factor of ⅔ for design.

Code

The International Building Code (IBC) is the basis of most state seismic codes. IBC is derived from previous recommendations by the National Earthquake Hazards Reduction Program (NEHRP), the Applied Technology Council (ATC), the Uniform Building Code (UBC) and others. The IBC seismic criteria are taken from ASCE 7.

The Code provides seismic ground motion parameters as spectral acceleration coefficients S_s and S_1 (for 0.2- and 1-second periods) assuming Site Class "B" (i.e., rock with a shear wave velocity, V_s, between 760 and 1500 m/sec). For the 2006 IBC, these acceleration values come from the 2002 United States Geological Survey (USGS) seismic hazard maps, which are available from **www.usgs.gov**.

The S_s and S_1 coefficients correspond to the Maximum Considered Earthquake (MCE), which is defined as "collapse prevention" motion. On the East Coast, the MCE is equivalent to an event with return period T_r of 2,500 years (or an event with 2% probability of being exceeded in 50 years), whereas on the West Coast, MCE corresponds to a 2,500-year event often truncated by the "deterministic limit" (Malhotra, 2007).

To account for soil conditions, these coefficients are increased or reduced by site coefficients, F_a and F_v, which are determined based upon the soil Site Classification (see *Figure 1* and next section). The design seismic coefficients are further reduced by ⅔ from these values and, in combination, produce the design response spectrum at a site.

$S_{DS} = \frac{2}{3} \times F_a \times S_s$ (Equation 1a)

$S_{D1} = \frac{2}{3} \times F_v \times S_1$ (Equation 1b)

The reduction of the MCE ground motions by the ⅔ factor was introduced because the provisions in the Code provide a minimum safety margin of 1.5 against collapse and therefore include an inherent conservatism (Green et al, 2007). The impact in design is generally greater on the East Coast. In areas of high seismicity on the West Coast, the ⅔ factored motions are comparable with the 500-year motions that were used in previous Building Codes. This is not the case in the East, where the ⅔ loads are significantly higher than the 500-year ones. *Figure 2* compares design spectra for Site Class D estimated using the 2003 IBC for Los Angeles and New York City.

Needs and Requirements

Because the Code design parameters are generic, they are also generally conservative. The Code includes provisions for use of a site-specific seismic study to derive structural design parameters. The decision to perform this study can be driven by the following factors:

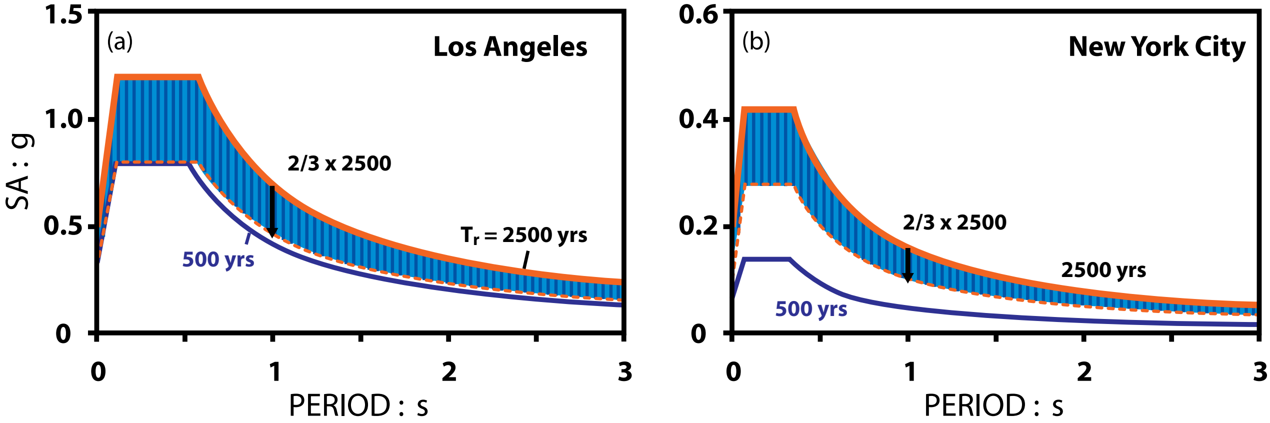

Figure 2: Effect of the "⅔" factor for Site Class D in 2003 IBC, for: (a) Los Angeles and (b) New York City (Nikolaou, 2003).

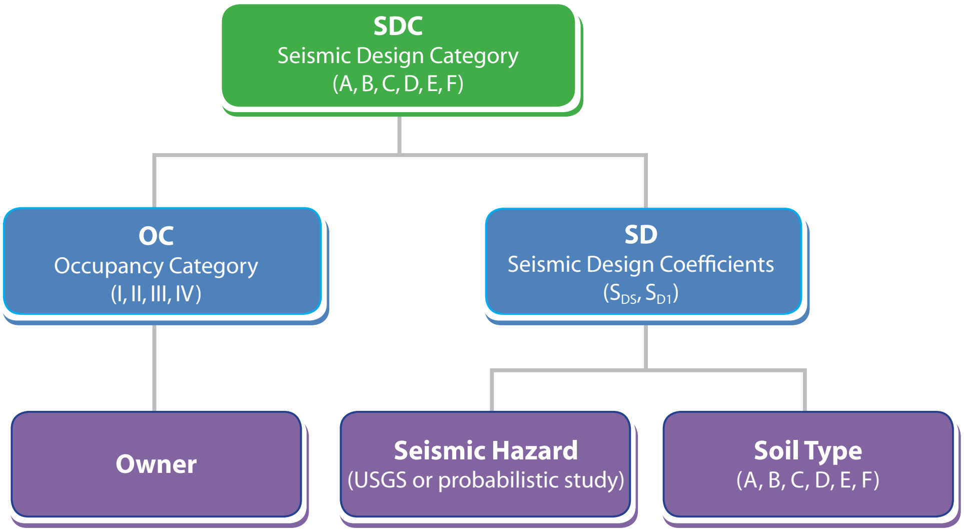

Table 1: Steps to derive the Seismic Design Category (SDC) as per 2006 IBC. In 2003 IBC, Seismic Use Group (SUG, ranging from I to III) is used instead of OC.

- Site Classification: If the subsurface conditions indicate Site Class F, the Code requires that a site-specific study be performed.
- Cost Optimization: If the Owner wants to reduce construction and analysis costs, a site-specific study can be performed to reduce dynamic loads and the Seismic Design Category (SDC). The study adds a few thousand dollars to the budget of the project, which is minimal compared to the potential construction cost savings.
- Analysis Methods: The importance or the site conditions of the structure may require input parameters for the seismic analysis not covered in the Code.

Site Classification

Sites are classified from A to F in the Code, with A being the hardest rock and F being the weakest soil. Sites classified as F require a site-specific study. Examples of Class F sites are those containing potentially liquefiable soils, thick clay layers, peat or highly organic or plastic clays, etc. A comprehensive review on deriving site classification was provided by Dominic Kelly in the December 2006 issue of STRUCTURE magazine. (Visit **www.STRUCTUREmag.org** for the archived article)

For site classes other than F, a site-specific study is permitted. However, design acceleration values obtained from the study cannot be less than 80% of the Code values for the particular site conditions.

Seismic Design Category (SDC)

The Code requires that every new structure and portion thereof be assigned a Seismic Design Category (SDC), and designed and constructed to resist effects of earthquake motions. SDC is based upon the Occupancy Category and the severity of the design earthquake ground motion as expressed by S_{DS} and S_{D1}.

SDC defines the required level of structural analysis and construction detailing (Section 1613.5.6 in 2006 IBC). SDC determines permissible structural systems, limitations on height and irregularity, requirements for design of components for seismic resistance, and types of lateral force analyses that should be performed. The structural engineer must follow the steps in *Table 1* (IBC) to derive the SDC and perform seismic analyses. SDC ranges from A to F, with F being the most stringent. The Occupancy Category is typically defined by the Owner and ranges from I to IV, depending upon the consequences of a potential failure and the need for operational accessibility following a seismic event.

Application of the Code methodology in several areas of the East Coast has resulted in the requirement that severe SDC classification of C or D be used when there are soft soils, such as those associated with Site Class E. For example, *Table 2* (IBC) shows design acceleration coefficients for several cities and the resulting SDC. In many cases, a reduction of the design acceleration coefficients by less than 20% would result in a reduction of the SDC by one class. Such a reduction may be possible if a site-specific seismic study is performed.

Analysis Methods

There are cases that require input not covered by general Code guidelines. For important projects such as tanks, power plants, or critical bridges, the structural engineer may perform time domain analyses that require acceleration time histories instead of the spectral acceleration input. When soil-structure interaction is accounted for, typically a profile of ground accelerations and displacements vs. depth is required. The same holds for evaluation of slope stability risk and calculation of dynamic earth pressures. In cases of liquefiable soils, analyses would be performed to study the effects of this phenomenon on a proposed structure. In all these examples, a site-specific study would be necessary to provide the required input.

Location	**IBC-06 / USGS-02**		**SOIL CLASS E**				**SDC**	
	S_S	**S_1**	**F_a**	**F_v**	**S_{DS}**	**S_{D1}**	**OC = I to III**	**OC = IV**
Boston, MA	0.279	0.068	2.41	3.5	0.448	0.159	C	D
Buffalo, NY	0.287	0.059	2.38	3.5	0.456	0.138	C	D
East Rutherford, NJ	0.365	0.071	2.13	3.5	0.519	0.166	D	C
Hartford, CT	0.239	0.064	2.50	3.5	0.398	0.149	C	D
New York City	0.363	0.07	2.14	3.5	0.517	0.163	D	D
Philadelphia, PA	0.275	0.06	2.42	3.5	0.443	0.140	C	D
Providence, RI	0.234	0.061	2.50	3.5	0.390	0.142	C	D
Washington, DC	0.153	0.05	2.50	3.5	0.255	0.117	B	C

Table 2: Seismic Design Category and ground motion parameters for East Coast soft sites using 2006 IBC with 2002 USGS hazard mapping.

Description of Study

Establishing site responses is an interdisciplinary activity that involves engineering geologists, seismologists, geotechnical engineers and structural engineers. The basic steps are:

(i) defining the geological and seismological backgrounds of the site;
(ii) performing a subsurface exploration program and developing dynamic soil properties;
(iii) identifying seismic hazard parameters to meet the design criteria;
(iv) performing soil amplification studies; and
(v) defining seismic design parameters.

Geologic and Seismologic Backgrounds

Thorough seismologic background research can provide information on regional geology and seismicity, and also assist in planning the most effective subsurface investigation. The background may reveal active faults, other geologic hazards such as slopes, and frequency of past seismic events. In areas within the stable continental interior region of North America where seismicity is low to moderate, like most of the East Coast, few data are available, even from historical sources. In these areas, there is no characterization of active tectonic zones, defined by the Code as faults with average historic slip rates of 1 millimeter per year or more, or areas with geologic evidence of seismic activity within Holocene times (i.e. the past 11,000 years). Understanding the state of practice-established methodologies that address seismicity is most valuable in this case.

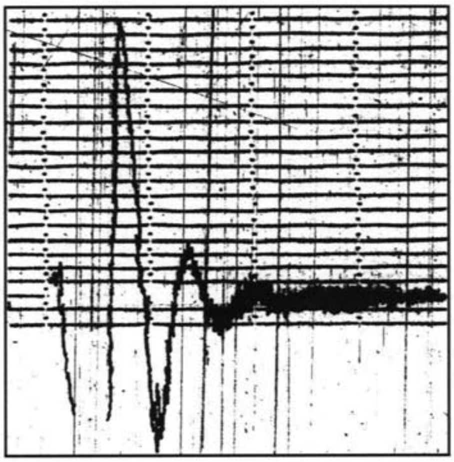

Figure 3: 20-second seismogram of the 1884 New York earthquake (Dominion Observatory, Can.). From NY Tribune - scale not available.

Even non-engineering references can shed some light where there is limited knowledge of seismic history. For example, the author recently came across a *New York Tribune* article from 1884 reporting on a seismic event in New York City. The article mentioned that chimneys fell and cracks appeared in houses all across southern New York, Connecticut, eastern Pennsylvania and northern New Jersey. It further reported that beach houses subsided and tilted, which was evidence of liquefaction of surficial sands. The article even provided a seismogram of the earthquake as recorded from the Dominion Observatory in Canada (*Figure 3*). Although the record had no apparent scale, it is valuable because it shows that the event had a short duration of less than 20 seconds and only a couple of significant cycles, indicating a low-magnitude event. Seismologists estimated the magnitude to be 5.1 in the local scale, based on correlations with the intensity felt and damage observed.

Subsurface Investigation

Dynamic soil properties, expressed primarily through the shear wave velocity V_s profile, are required as input for the site-specific analysis. The Code requires testing of the subsurface conditions to a minimum depth of 30 meters

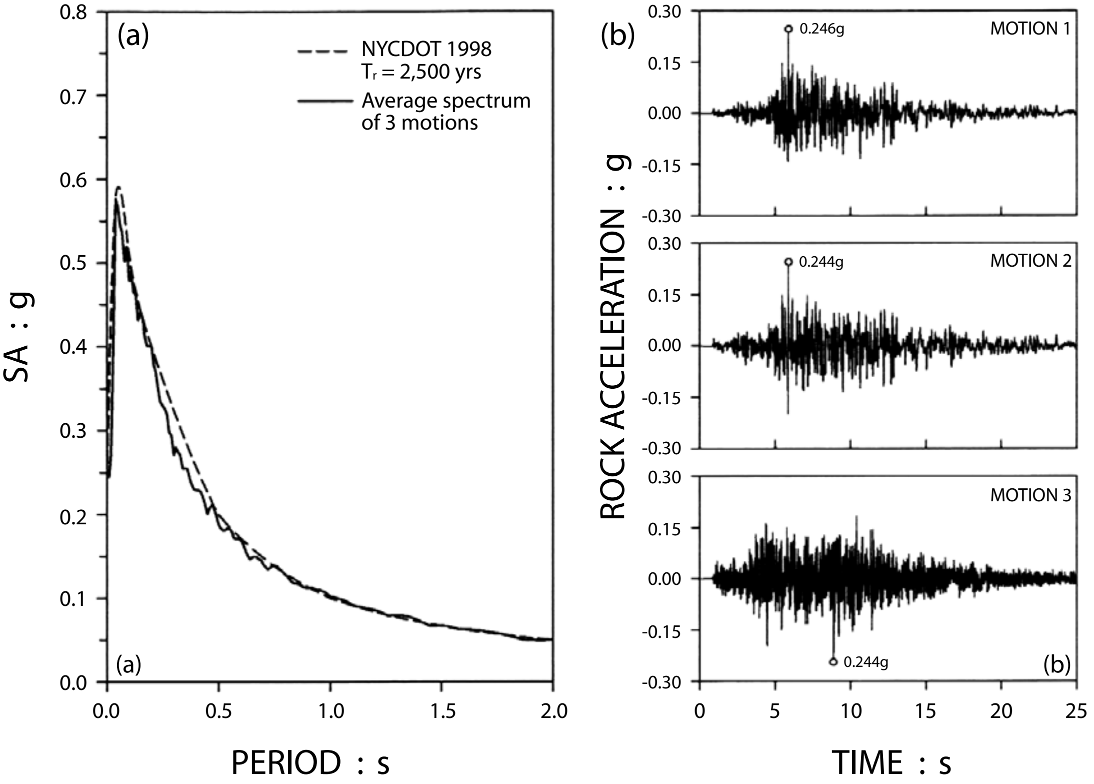

Figure 4: (a) Probabilistic response spectrum in New York City for Rock Class "A" and return period of 2,500 years. (b) Acceleration time histories that match the probabilistic spectrum based on actual records (NYCDOT, 1998).

(100 feet) and classifies a site using the average shear wave transmittal within the top 100 feet. An article by Kelly (2006) describes tests and methods that can be used to classify a site. Often borings are performed that only provide data for Standard Penetration Test (SPT) resistance, expressed in N-values. Correlating these N-values to V_s involves significant uncertainties and is not the preferred method among earthquake engineers for classifying a site.

Crosshole Seismic (CS) tests or other in-situ measurements of the V_s values, such as Seismo-Cone Penetrometer Tests (SCPT), are ideal methods that certainly add to the cost of the investigation but:

- provide accurate dynamic soil properties;
- may directly reduce the Site Class providing ground motion that can be further reduced by the site-specific study;
- provide information for alternative analysis methods for liquefaction;
- provide the necessary elastic soil parameters for development of soil-structure interaction springs.

Seismic Hazard and Code Criteria

A seismic hazard study provides an alternative to the readily available USGS hazard maps to derive the S_S and S_1 coefficients for rock conditions for the geographic location examined and hazard level or return period T_r for which the structure has to be designed. The hazard assessment can be based on a deterministic scenario where, for example, an active fault ruptures for a given length and at some distance from the site. Alternatively, and especially when a potential fault rupture is not evident in the vicinity, a probabilistic seismic hazard study can be performed, or a readily available probabilistic hazard study may be applied.

A seismic hazard study may also be necessary in cases where USGS mapping is not available, such as when the return period exceeds 2,500 years, which may be required for critical structures. Once probabilistic parameters are estimated and compared to restrictions imposed by the Code with respect to any deterministic hazards, the rock acceleration spectrum is derived (*Figure 4*).

Input Time Histories

After defining the rock spectrum from the seismic hazard analysis or available hazard maps, the engineer must select or develop time histories that produce a response spectrum that matches the hazard rock spectrum. These time histories will be propagated through the soil layers to derive the ground motion at the foundation level.

The probabilistic seismic hazard analysis is based upon the aggregate of results from all possible seismic occurrences and ground motions that might create seismic loadings at a particular site. This overall analysis leads to the identification of the most likely magnitude, M, and the epicentral source-to-site distance, R, which when combined contribute most to the hazard. The M-R values are necessary for selecting the appropriate time histories and for establishing other parameters, such as duration and number of effective cycles of ground motion.

Based on deaggregation results (McGuire, 2004) from the seismic hazard study, the engineer can identify the M-R pairs that provide the major contribution to a given seismic parameter - usually the PGA - Peak Ground Acceleration and SA for particular structural periods. The identified M-R pairs are then used to select a set of actual earthquake records for the analysis. Attention should be given also to selecting time histories that are compatible with the rock type and the frequency content of the target spectrum. Most often, the selected records need to be scaled using time- or frequency-domain techniques to match the hazard rock (or "target") spectrum. Examples of time histories developed for New York City using frequency-domain techniques that are based upon actual records matching a 2,500-year seismic hazard study for bridge design are included in *Figure 4*.

Soil Amplification Analysis

A soil amplification study propagates the rock input motions through the soil profile to derive ground motions at the surface or the foundation level. The most typically used method is the one-dimensional, equivalent-linear wave propagation that is employed in programs like Shake (Schnabel et al, 1972). The soil is modeled as a single column with varying properties vs. depth that iteratively become compatible with the strains calculated in the soil for the level of excitation.

This method is applicable to most building structures, but may be limited in sites where topographic effects are significant, such as in valleys below bridges, and in cases of strong earthquakes that impose significant nonlinearities in the soil. Ignoring these effects is not always on the safe side for design, and thus would require the use of more sophisticated computer codes. A parametric study can be performed to account for variability in subsurface conditions and key soil characteristics, such as how plastic a clay layer is. However, the outlined soil amplification analyses do not account for the presence of the foundation in the soil; they are simply free-field studies. The impact that the foundation has on the ground motion is called kinematic effect and is beyond the scope of this article.

Design Recommendations & Constraints

Following completion of the site specific study, the engineer makes a recommendation in the form of a design response spectrum. Some constraints are imposed by the Code on the recommendations. The Code requires that the design spectrum cannot be lower than 20% from the Code-specified response spectrum for the Site Class assigned to the project. However, the Site Class may be reduced if the appropriate in-situ tests are performed. The Code also requires that the short-period design acceleration S_{DS} cannot be reduced by more than 10% from the peak observed in the analyses throughout the entire spectrum.

Conclusions

Site-specific studies can result in a significant reduction in construction costs, and can optimize the structural design by reducing the lateral loads and/or by reducing the seismic design category. The cost of such studies is substantially smaller than the potential benefits that can result from them. Part 2 of this article will follow in an upcoming issue, with examples from actual projects and considerations for the application of site-specific studies in the unique conditions of the East Coast.▪

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