Site-Specific Seismic Studies for Optimal Structural Design

Part II - Applications

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This article is Part II of an article published in STRUCTURE® magazine (February 2008) that presented the benefits of performing site-specific studies in determining design ground motions. This article presents the impact of site specific studies on actual projects in cities located in the New York City (NYC) tri-state area.

Local Site Conditions and Seismicity

Seismic design guidelines in the US are based primarily on research and practical experience of case histories in areas of high seismic activity. The New York City tri-state metropolitan area is located at the eastern edge of the North American lithosphere, a stable continental region thousands of miles away from the nearest plate boundary. Earthquakes experienced in the area are typically intraplate events of moderate magnitude and, therefore, little experience from events in this part of the US has been incorporated in current seismic codes.

Known significant earthquake events around NYC have occurred in the late 19th and early 20th centuries prior to seismic instrumentation, and have been studied primarily from archived news articles (Sykes, 2008). Compared to the Western US, only a few records of actual earthquakes are available in the NYC tri-state area. Earthquake records are essential to seismic analysis and design as they describe the movement of the ground for the duration of the earthquake event. Since there are no existing major earthquake records in NYC tri-state area, records of actual earthquakes from other areas are usually modified and used in design.

Although the seismic hazard in the region is moderate, the unique soil geology of the NYC tri-state area (Tamaro et al., 2000) can generate impressive soil amplification effects during earthquakes (Nikolaou, 2004). For example, the particularly hard, crystalline bedrock in the area has a shear wave velocity, V_s, of usually more than 2500 feet per second (fps), which is higher than typical V_s values of rock in other parts of the US. This characteristic, when combined with soft overburden soils can result in significant ground motions at the ground surface.

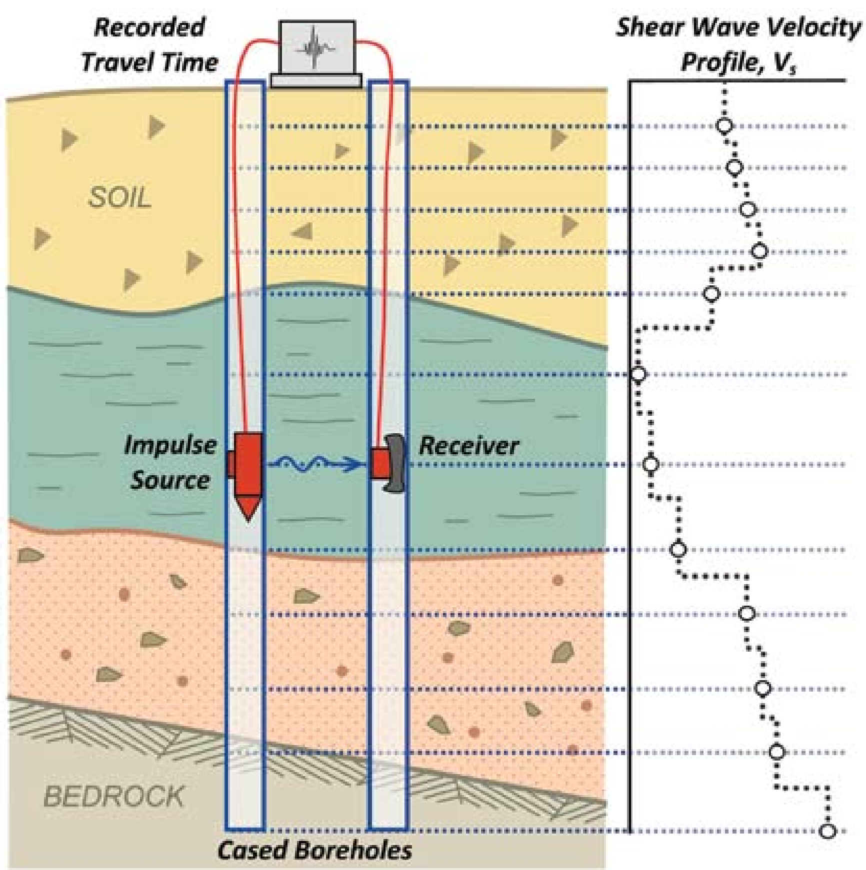

Figure 1: MRCE Crosshole Seismic test set-up.

Why Perform Site-Specific Seismic Studies?

As outlined in Part I, the decision to perform site-specific studies is driven by:

- *Cost Optimization*: To reduce design and construction costs, an Owner may request a site-specific study be performed, aimed at reducing dynamic loads and detailing requirements.
- *Site Classification*: If subsurface conditions are vulnerable to earthquake shaking (Site Class F as per code), the engineer is required to perform a site-specific study.
- *Analysis Methods*: The type, site conditions, or importance of a structure could require analysis with input parameters not covered in the code, such as:
  - Liquefaction hazard
  - Displacement determination (as for slope stability, underground structures, etc.)
  - Soil-Structure Interaction parameters (as for pile-supported structures)

We refer the reader to Part I of this series, and *Table 1* below for determination of Seismic Design Category (SDC) in Building Codes applicable in the NYC tri-state area.

Case Studies

We have selected four case studies that illustrate the first two benefits: Cost Optimization and Site Classification. Site-specific seismic studies can be performed by: 1) solely doing seismic field testing, 2) solely performing desk studies of the site

Table 1: Seismic Design Category based on short-period and 1-second response accelerations (S_{DS} & S_{D1}).

S_{DS}	SUG (OC) I (I/II)	II (III)	III (IV)
S_{DS} < 0.167g	A	A	A
0.167 ≤ S_{DS} < 0.33g	B	B	C
0.33 ≤ S_{DS} < 0.50g	C	C	D
S_{DS} > 0.50g	D	D	D

S_{D1}	SUG (OC) I (I/II)	II (III)	III (IV)
S_{D1} < 0.067g	A	A	A
0.067 ≤ S_{D1} < 0.133g	B	B	C
0.133 ≤ S_{D1} < 0.20g	C	C	D
S_{D1} > 0.20g	D	D	D

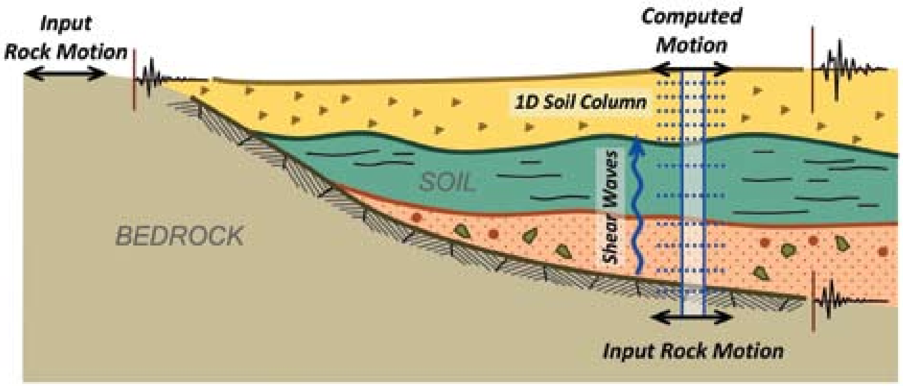

Figure 2: 1-D site response analysis.

Table 2: Summary of case studies: methods and results.

Case Study	Method		Results		
	Field Testing	*SHAKE Analysis*	*Site Class*	S_{DS}, S_{D1}	*SDC*
I	x		↓	↓	↓
II		x	—	↓	↓
III	x	x	↑	↓	↓
IV	x	x	—	—	—

response, or 3) a combination of both 1) and 2). The approach we used and the results we achieved in each case study are shown in *Table 2*. For these case histories, we chose the Cross-hole Seismic (CS) test for our field testing, and one-dimensional (1-D) SHAKE analysis for our desk studies of the site response.

Field Testing

Available field testing methods were presented in an article by Kelly in the STRUCTURE (December 2006). The CS test is one of the most reliable methods available to measure in-situ Shear Wave Velocity (V_s). The V_s is the key geotechnical parameter that controls the response of the soil to the earthquake excitation that primarily consists of shear waves propagating from the bedrock up to the ground surface. The CS test set-up includes two boreholes spaced about 10 feet apart, with an impulse source in one borehole and a receiver in the other borehole (*Figure 1*). By fixing the source and receiver at the same depth in each borehole, the velocity of shear wave propagation at that depth can be measured as the ratio of the distance between the two boreholes and the time it takes for the wave to travel from the source to the receiver.

Desk Studies

In a SHAKE analysis, the soil is modeled as a 1-D column subjected to vertically propagating shear waves generated at the rock (*Figure 2*). The result is the ground motion at the ground surface or at selected depths, expressed as site-specific acceleration time histories and design spectra, including the S_{DS} and S_{D1} design parameters. The required inputs to a site-response analysis include soil properties such as V_s, unit weight, soil type, ground water conditions and acceleration time histories at the bedrock. The soil properties are modified over several iterations during the analysis to be compatible with the level of strain from the earthquake (Schnabel, 1972).

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Case Study I

Site Class C/D in Yonkers, NY

In Case Study I, we simply performed a field CS test to measure the soil's V_s at the top 100 feet, in an attempt to lower the Site Class that was derived using conventional boring data.

The project, located in the NYC metropolitan area, is a liquid-containing structure that is part of a critical water facility founded on engineered fill and underlain by glacial till. The design of the structure must comply with the NY State Building Code, which is based on the 2003 edition of International Building Code (IBC). Subsurface conditions consist mainly of 50 feet of medium compact to very compact fill with Standard Penetration Test (SPT) blow count (N)-values ranging from 25 to more than 50 blows per foot (bpf), overlying very compact glacial till with N-values > 50 bpf (*Figure 3*). Even though the arithmetic mean of the N-values for the top 100 feet is greater than 50 bpf, the calculated average $\overline{N}$ according to the code classifies the site as D (Stiff Soil Site) due to the presence of isolated pockets of medium compact soils (25 < N < 50 bpf). Design parameters for the Site Class D site are S_{DS} = 0.363 and S_{D1} = 0.113.

Using the measured in-situ V_s, the calculated average $\overline{V_s}$ at the top 100 feet was found to be more than 1,200 fps, thus reclassifying the site as Class C. This result supersedes the SPT

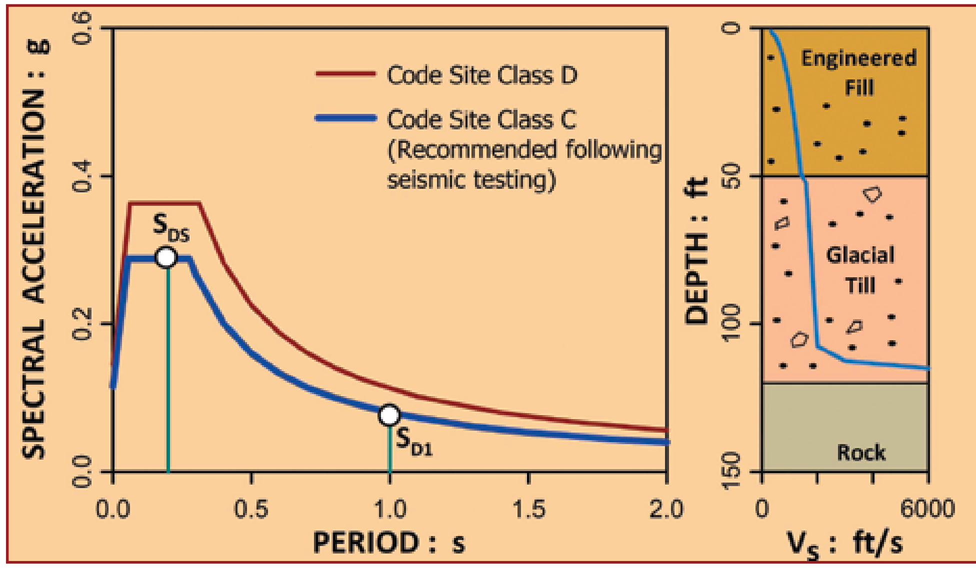

Figure 3: Case Study I soil profile and site specific results and recommendations.

N-value-based classification, as the CS test is a far more accurate and direct measurement of the dynamic characteristics of the soil. We note that site classification using measured V_s is the most accurate and unambiguous way to classify a site since code-based site amplification factors (F_a, F_v) were based on the average $\overline{V_s}$ in the top 30 feet (Borcherdt, 1994).

The impact of lowering the site class was two-fold: First, the design accelerations from the code were lowered by 20 to 30 % (S_{DS} = 0.288, S_{D1} = 0.08 for the reduced Site Class C as opposed to S_{DS} = 0.363, S_{D1} = 0.113 for Site Class D). Second, the Seismic Design Category (SDC) was reduced to the less stringent "B" from "C". The reduction of design accelerations lowered the seismic design loads and, in combination with the reduction in SDC, costs associated with structural design and detailing requirements were reduced. Due to the positive results after the CS test, we did not consider performing further analysis.

Case Study II

Site Class E in Brooklyn, NY

The second case study involved only a desk analysis based on boring data. Due to budgetary contraints, no CS testing was performed. The project is a proposed waste water treatment plant founded in the typical deep glacial outwash sands of Brooklyn, NY where rock is as deep as 500 feet below ground. The design must comply with the NY City Building Code. Subsurface conditions at the top 100 feet consist of 15 feet of loose fill, overlying loose grading to compact alluvial and glacial outwash sands (*Figure 4*). SPT N-values range from 5 to 20 bpf. The average N is 12 bpf, placing the project in the soft Site Class E with the highest design accelerations from code-based generic site classes of S_{DS} = 0.518 and S_{D1} = 0.166. Combined with the importance of the plant (or Seismic Use Group), the structure would have to be designed as SDC "D", which is the most stringent SDC in NYC.

The Owner, concerned with the cost implications of SDC "D" structural detailing requirements, asked us to perform a site specific study without going back to the site to perform seismic testing, due to budgetary constraints.

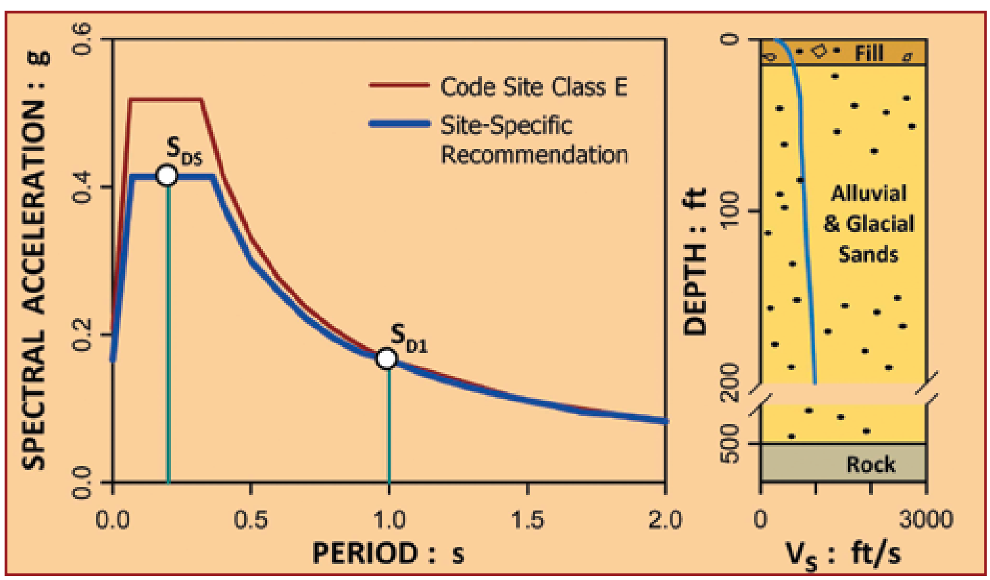

Figure 4: Case Study II soil profile and site specific results and recommendations.

We used appropriate published empirical correlations for estimating V_s from SPT N-values, and performed a 1-D site-response analysis. To cover the uncertainties in the estimated V_s, we performed sensitivity analyses varying the estimated V_s values.

The analysis indicated that the site specific response spectrum is lower compared to the code's Site Class E spectrum (*Figure 4*). The code restricts the reduction of the design accelerations to 20% from the Class E values. Considering this restriction, we recommended design parameters S_{DS} = 0.41 and S_{D1} = 0.17, the minimum values permitted. Accordingly, the SDC was reduced to the less stringent "C" from "D". This case study proved to be successful in optimizing the structural design even in the absence of seismic field testing.

Case Study III

Site Class C/D in Brooklyn, NY

Following the two successful case studies, the third case study is a project where field testing properly addressed the site's characteristics, the lack of which could have led to an unconservative design. The project is a mixed-use development founded in similar glacial outwash geology and uses the same seismic design criteria as in Case Study II. The top 10 to 20 feet of soil consist of sands, gravels and boulders that are typical of this area (*Figure 5*). Site classification using the N-values would classify the site as "C" or very dense soil site with average N of more than 50 bpf. After reviewing all the geotechnical data at the site, we realized that the N-values were artificially high due to the presence of gravels and boulders. Considering the size and importance of the development, we performed in-situ field testing to properly characterize the site and performed site-response analyses.

The V_s measurements from the CS test indicated that the site has a softer site characterization of Site Class of D rather than the stiffer initial Site Class of C using the SPT data. This confirmed our concerns of a misleading site characterization using SPT data due to the gravelly soil conditions. The split spoon samplers used in SPT have less than 2-inch diameter openings and, thus, are suitable for sandy soils without gravel particles. Once the sampler hits a gravel or boulder, the large particles may block the penetration of the sampler materials around the sampler and the recorded N-value is artificially increased. Although the code does not explicitly address cases for gravelly soil conditions, we believe that using in-situ V_s measurements is the most appropriate means of classifying such sites.

Using the V_s measurements, we performed a site specific SHAKE analysis that resulted in lower spectral accelerations than the code's Class D values (*Figure 5*). Considering the 20% allowable reduction from the Class D values, our recommendation was S_{DS} = 0.32 and S_{D1} = 0.091. These parameters also reduced the SDC from "C" that would be applied for a Site Class D site, to "B" using the site specific analysis. In this case study, even though the Site Class was bumped up from "C" to "D" using the in-situ V_s measurements, results of the site specific SHAKE analysis reduced the spectral accelerations, ultimately reducing the SDC from C to B. This case history highlights the value of proper site characterization and potential pitfalls of blindly applying code procedures that may lead to unconservative designs.

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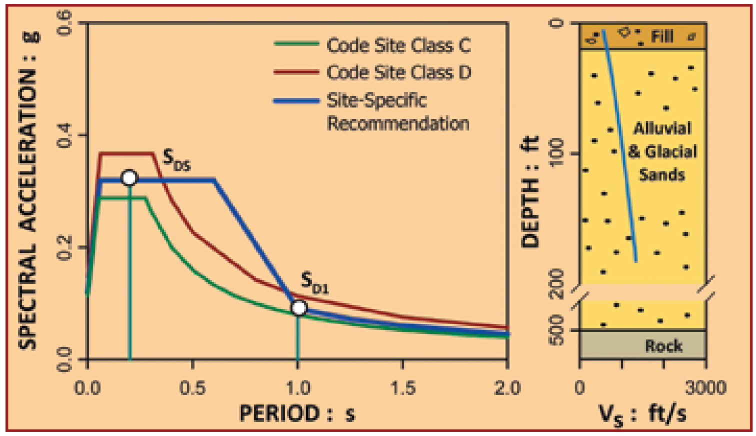

Figure 5: Case Study III soil profile and site specific results and recommendations.

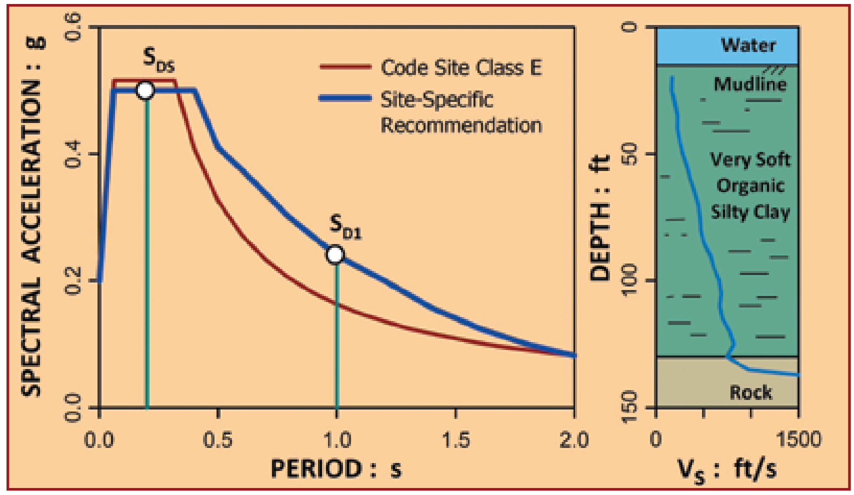

Figure 6: Case Study IV soil profile and site specific results and recommendations.

Case Study IV

Site Class F in Jersey City, NJ

The last case study addresses a Class F site, where the code specifically requires a site-specific investigation. The project includes two ten-story office buildings along the bank of the Hudson River in Jersey City, NJ. The local governing code is the 2006 IBC. The very soft subsurface consists of 65 to 200 feet of soft organic silty clay overlying serpentinite bedrock (*Figure 6*). The organic stratum has an average Plasticity Index (PI) of 37, moisture content (ω) of 66%, and undrained shear strength (s_u) of less than 1,000 psf (50 kPa). The site is classified as F, requiring a site-specific study.

The structural engineer used Site Class E design parameters to perform preliminary evaluations while the site specific study was underway. This is an approach usually followed in practice when a Class F site is identified. At this location, the Site Class E parameters would result in a Seismic Design Category (SDC) "D", the most stringent in the State of NJ.

The site-specific study included:

- Crosshole Seismic (CS) Test to a depth of 150 feet
- Laboratory tests to determine PI and ω
- One-dimensional (1-D) site-response analysis using SHAKE

The CS test (*Figure 1, page 12*) showed that the V_s for the organic silty clay stratum ranged from 240 to 800 fps, averaging 340 fps. Using these values, we generated a 1-D characteristic soil column model that we subjected to an earthquake motion at the rock base, consistent with the code. The site-response analysis resulted in even higher spectral values than the code's most severe Site Class E response at the structural period range between 0.9 and 1.2 seconds (*Figure 6*). Unfortunately, this period range coincides with the anticipated fundamental period of the building of about 1 second, which could create resonance effects. We recommended S_{DS} = 0.50 and S_{D1} = 0.24 (*Figure 6*). The S_{D1} value is higher that the Site Class E value of 0.17, and therefore the SDC remained at "D" (*Table 1, page 12*).

This case study highlights the importance of performing site-specific studies for areas categorized as Site Class F. Although engineers perceive that using Class E values for evaluation of Class F sites is a conservative approach, this is not the case here. The site conditions were so extreme that even using the most conservative code-based seismic parameters would not have been able to capture the actual site-response. Although no cost-savings could be offered, an optimal design spectrum was instead derived for this extreme site condition.

Conclusions and Recommendations

We have presented four case histories illustrating how site-specific seismic studies can optimize the structural design. Site-specific seismic studies ranging from simple field testing to full-blown studies can benefit the structural design of a project through potential reductions in Site Classification, Design Accelerations, and, as a result in many cases, Seismic Design Category. The benefits are reflected in cost savings due to lower base shear and less stringent structural detailing. The cost of these studies is minimal as compared to the potential design and construction cost reductions.▪

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