Quantifying Seismic Hazard and Providing Realistic Ground Motions for Engineering Applications Primarily in the Eastern United States

by Klaus Jacob

Abstract

NCEER's research program on Seismic Hazard and Ground Motions is a comprehensive and systematic program to produce quantitative hazard estimates and ground motion predictions for engineering research and practical applications. In eight years, this program has successfully contributed to NCEER s goal of mitigating the risk from earthquakes in several innovative ways. One important contribution is the development of a fundamentally new way of collecting strong-motion data and redistributing these data to a diverse user community. A 33-station digital strong-motion network is operated, the data of which are retrieved remotely by computer and phone. It has greatly increased the number of strong-motion recordings in the eastern U.S. The NCEER and other, global strong-motion data are maintained in a relational digital data base called STRONGMO, from which users can query and retrieve data by computer or phone/modem from anywhere in the world. Another important contribution is a new eastern U S. earthquake catalog. NCEER-91. which has become an acknowledged standard for seismic hazard assessments in that region. A new method has been developed to predict ground motions based on a combination of geophysically constrained Earth models and stochastic models of wave propagation. NCEER's probabilistic seismic hazard mapping and site response studies have had a strong impact on acceptance and technical updating of national and local building codes. Realistic, hazard-consistent design ground motions that account for non-linear site response have been delivered for immediate engineering applications in seismic retrofit projects of large east-coast bridges. Ambient vibration measurement techniques that use modern, microprocessor-controlled seismic instrumentation have been developed and have revolutionized how the modes of large structures can be cost-effectively determined. The impact of this program is strongest in the U.S. east of the Rockies, but results have contributed to basic knowledge and data that effect engineering practice, code development and seismic mitigation measures nationally and internationally.

Collaboration

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Objectives and Approach

The NCEER program on Seismic Hazard and Ground Motions has the objective to provide accurate, data-based estimates of the seismic hazard and quantitative ground motions for different geologic regions and site conditions. The program aims at delivering ground motion data and other seismic hazard information to users in the engineering community for applications in research and practice. Results also serve other users inside and outside the National Earthquake Hazards Reduction Program (NEHRP). The geographical emphasis of the program is mostly, but not exclusively, on the United States east of the Rocky Mountains where seismicity is low or moderate; where few strong ground motion records have been available in the past; and where the practicing engineering community only recently has experienced a strongly increased demand for quantitative seismic data and information.

This research is part of NCEER's program in Seismic Hazard and Ground Motion. Task numbers are 86-1011, 86-1012, 86-1013, 86-1014, 87-1301, 87-1302, 87-1303, 88-1301, 88-1302, 88-1303, 89-1301, 89-1302, 89-1303, 89-1306, 90-1301, 90-1302, 90-1303, 90-1305, 91-1011, 91-1021, 91-1031, 91-1041, 91-1511, 92-1001, 92-1002, 92-1003, 92-1004, 93-1001, 93-1002, 93-1003, 93-1004, and 93-1701.

Introduction

The program on Seismic Hazard and Ground Motion provides ground motion input to NCEER's research projects, most directly to the Building and Highway Projects; it also responds to the needs from the building code and practicing engineering community nationwide. While fulfilling these important service functions, the program is committed to carrying out high-quality research It thereby increases the pool of available Ph.D - level professionals in engineering seismology. The program is divided into five tasks that reflect the elements for quantifying seismic hazard and for transferring research results into practice The tasks are:

■ *Seismicity/Earthquake Catalogs*: Ensure that complete, updated earthquake catalogs are available to accurately define seismicity in the time/space/magnitude domain.

■ *Ground Motion Instrumentation:* Apply modern seismic instrumentation and computer network options to acquire needed ground motion data and to distribute them to the users.

■ *Ground Motion and Site Response*: Quantify, parameterize, and simulate ground motions for practical use, in applications and research.

■ *Seismic Hazards*: Use existing methods, and develop new ones where needed, to allow probabilistic and deterministic hazard assessments that serve engineering needs in practice and research. This includes the production of probabilistic seismic hazard (ground motion) maps when needs justify such efforts; and providing hazard-consistent ground motion time series and design response spectra for immediate engineering applications in demonstration projects, shaking table experiments, and computer-modeling of seismic building and bridge response.

■ *Technology Transfer/Knowledge Utilization:* An important task is active participation in the seismic building code updating process on national and regional levels (e.g. NEHRP/BSSC, New York State and New York City). Other tasks are ensuring that the research results from NCEER's Seismic Hazard and Ground Motion program are directly used in the practicing community. This is accomplished partly by participation in engineering projects (e.g Tappan Zee and Queensboro Bridge seismic retrofit evaluation projects), and through workshops and seminars aimed at the continuing education of the practicing engineering community (e.g. through NCEER, American Society of Civil Engineers, Earthquake Engineering Research Institute, U.S. Geological Survey, Applied Technology Council, Environmental Protection Agency and others) Last but not least, interaction with the media is an effective effort under this program to educate the general public on earthquake issues.

Accomplishments

Background

Never before in U.S. history east of the Rocky Mountains has engineering seismology experienced such wide-spread acceptance in engineering practice than in the last few years When first efforts were beginning in the sixties, they were almost exclusively aimed at the seismic safety of nuclear power plants owned by electric utilities: but these efforts by-passed most other sectors of public life. With the exception of new bridges, Corps of Engineers dams, and Veteran's hospitals, most civil structures, hospitals, schools, high-rises and private residential and commercial buildings continued to be built without considering the earthquake threat. During the last five years, however, seismic building code provisions began to be introduced and implemented by local governments in many eastern states. Furthermore, some of the monumental highway bridges built earlier this century without considering seismic loads are now beginning to be assessed for seismic retrofit. Federal courthouses are being remodeled to resist earthquakes. Finally, new municipal solid waste landfills are now designed to resist earthquakes.

More than one factor contributed to this new awareness of seismic hazards. Various earth science and earthquake engineering research efforts have begun to be more popularly accepted, thanks largely to the National Earthquake Hazard Reduction Program (NEHRP) Decision makers have also responded to experiences from earthquakes elsewhere. They and the public in general have begun to learn lessons from the often dramatic TV and news reports following earthquakes in San Fernando, Whittier, Coalinga, Mexico City, Armenia, Loma Prieta, Landers, Northridge and other locations. From these reports, the public understands that for now, the eastern U.S. has been spared but, by extension, New Madrid, Charleston, Cape Ann and Grand Bank-type eastern destructive earthquakes will sooner or later revisit. Such earthquakes will then strike a technologically more complex and vulnerable society compared to when such earthquakes first struck many decades or centuries ago.

NCEER, by a combination of foresight, good timing and well-planned research, became an agent and catalyst for the progressing acceptance by the public that the earthquake threat is not just in California, but nationwide. By working together with many organizations, institutions and professions, NCEER clearly helped to bring about this change in public perceptions and policies, and is poised to follow through in the future. This paper highlights some of the developments and achievements in the area of seismic hazard assessment and ground motion research that NCEER launched as part of its multidisciplinary systematic approach. The results from the Center's research efforts have already had significant impact on engineering practice with consequence for the public's safety and future. New research insights have altered past practice and regulations.

Assessing Seismic Hazard: Past Practice

To assess seismic hazard, one must combine knowledge of a number of distinct variables and use it in a formal procedure. It is necessary to quantify seismicity, ground motion attenuation and the near-surface geological site conditions, and treat these inputs within an analytical framework that captures their variability and uncertainties for probabilistic estimates; and their median, mean or otherwise defined (e.g. 'maximum credible") values for deterministic evaluations In either case, the objective is to provide hazard-consistent ground motion parameters that an engineer, architect, planner or owner can use.

In the past, seismic hazard in the eastern U.S. was largely defined for engineering applications in two practical ways:

(1) For nuclear power plants, often costly, site-specific studies were commissioned by the utilities for licensing by the U.S. Nuclear Regulatory Commission.These assessments were carried out based on methodologies and data largely developed by the utilities (e.g. by Electric Power Research Institute (EPRI)), national labs (e.g. Lawrence Livermore National Laboratory (LLNL)) and geotechnical engineering consultants, and by research contributions from the U.S. Geological Survey and academia. With time, this methodology (aimed at low exceedance probabilities) became elaborate and costly and, hence, impractical for ordinary structures. Seismic hazard assessments were made for discrete sites ($\leq$ 100) where nuclear facilities were located, but the method was not applied nor meant to be applied to regional mapping of seismic hazards.

(2) The non-nuclear domain has relied on the seismic zoning maps developed by ATC-3-06 for seismic hazard assessments, and on the ground motion maps produced and periodically updated by the U.S. Geological Survey. The maps were adopted often with considerable delay either in original or modified form into the various building codes (e.g. UBC, BOCA - now National Building Code, Standard Building Code, and the model Seismic Provisions of NEHRP), or into seismic provisions and guidelines for highway bridges (AASHTO). Inputs into the seismic hazard maps were sometimes based on imprecise data, e.g. poorly scrutinized pre-instrumental intensity observations which in turn can control seismicity rates. In the 1980's, eastern ground motion attenuation relations were used for seismic hazard maps that were for the first time based on eastern North American *instrumentally* recorded seismic data, mostly from Canadian earthquakes. However, strong-motion recordings from larger magnitude earthquakes and at many distances are still missing.This lack of data can introduce large uncertainties in the ground motion attenuation relations. The soil categories used in building codes were poorly defined, being too coarse in depth and frequency resolution. The associated site amplification factors were based mostly on California experience which did not always capture the ground motion site amplifications that apply to many eastern U.S. site conditions (Jacob, 1991).There, soft soils can overlie very hard, high-impedance bedrock. Consequently, the ground motions between soft soils and hard-rock sites can vary considerably more than commonly observed for the generally less contrasting site conditions in California.Therefore, the mostly California experience-based site factors embedded in national codes were found to provide misleading guidance for many eastern sites. Also, the spectral shapes used in national seismic code provisions do not generally account well for the stronger high-frequency content of eastern seismic motions

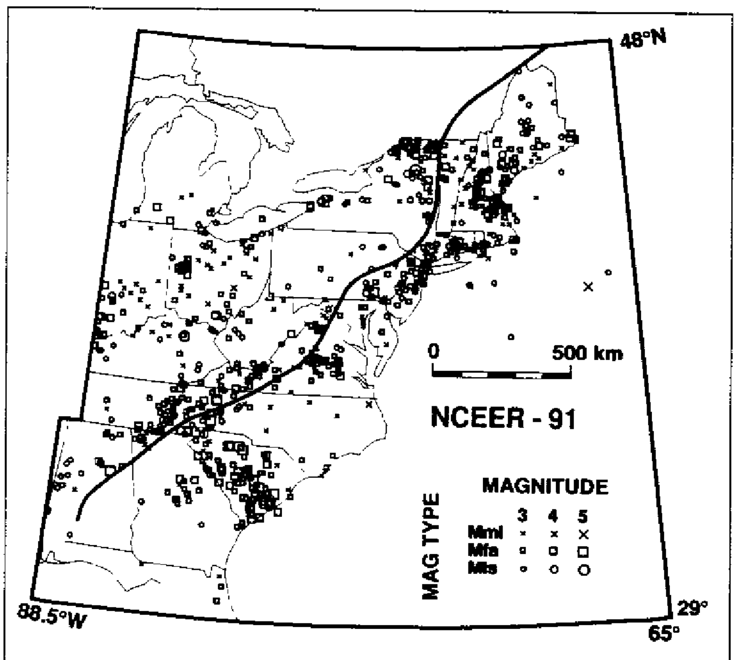
It was in this environment that NCEER commenced its seismic hazard and ground motion research program. Tasks were carefully planned and executed to help put seismic hazard assessment on a sound, modern, data-based footing, and to transfer new data, information, analysis methods and results to the practicing engineering community as quickly as possible. A few examples are given here to demonstrate NCEER's approach and successes.

Redefining Essential Seismic Hazard Elements

Seismicity: the NCEER-91 Earthquake Catalog

Until now, the U.S. Geological Survey has used for its seismic hazard assessment a catalog of U.S. Earthquakes, that in the eastern U.S. heavily relies on historic data using intensity observations. The portion of modern instrumentally constrained data is small.The Electric Power Research Institute (EPRI) made a major effort to consolidate a number of different earthquake catalogs into a single catalog for eastern U.S. earthquakes In translating the historic observations into magnitudes and epicentral locations, EPRI heavily relied on maximum intensities and did not revisit original sources for intensity reports.

NCEER investigators Seeber and Armbruster (1991) revisited original sources to improve the EPRI catalog (figure 1). They searched through thousands of pages of original newspaper reports in scores of libraries across the eastern United States. They found many new earthquakes and identified false entries in the existing catalogs as man-made events (explosions, mine collapses) Where possible, they used felt area to translate the historic observations into magnitudes and locations. Seeber and Armbruster developed an algorithm called MACRO that rigorously fits an optimal solution to the intensity data to determine the magnitude, epicenter and depth. MACRO also estimates the uncertainty for magnitude and location. Seeber and Armbruster found that with the redetermined events and magnitudes, the new NCEER-91 catalog produced more stable rates of seismicity over long periods of time, regardless of whether the different periods were dominated by intensity or instrumental data. Earlier catalogs had shown fluctuations that seemed to systematically depend on whether the entries were based on maximum intensity, felt area, or instrumental data.



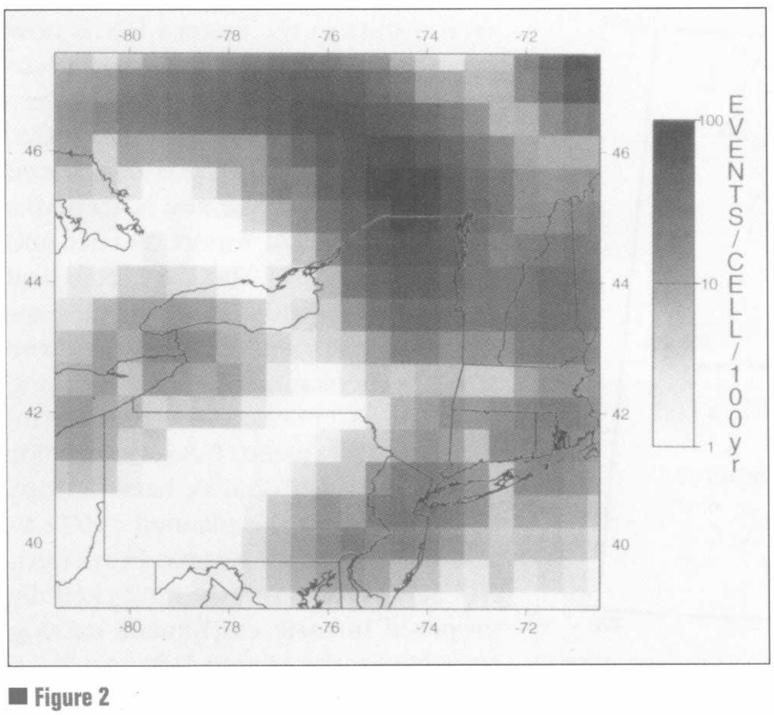
■ **Figure 1**
Seismicity of the NCEER-91 catalog for the eastern portion of the eastern U.S. that has been revised from the EPRI catalog. Three different magnitude symbols are plotted: Mmi based on maximum intensity, Mfa based on felt area, and Mis based on instrumental measurements.

The new NCEER-91 catalog for earthquakes in the eastern U.S. is now used for all of NCEER's deterministic hazard assessments and probabilistic hazard mapping efforts in the eastern U.S. (see below) The catalog is distributed by NCEER on diskette, and is accompanied by a detailed report (Seeber and Armbruster, 1991). The U.S. Geological Survey has recently made several tests for using this catalog. Based on these tests, the Geological Survey is planning to adopt NCEER-91 as the primary input source for eastern U.S. seismicity for its new set of probabilistic hazards maps to be issued for the planned 1997-edition of the NEHRP Seismic Provisions NCEER-91 is currently the most carefully prepared historic earthquake catalog available for the eastern U.S

Seismic Source Zones: Gridding Replaces Subjective Outlining

In previous efforts by the U.S. Geological Survey, EPRI, LLNL or private consulting firms, seismic source zones in the regions east of the Rockies were drawn subjectively based on a combination of apparent seismicity patterns, inferred geologic-tectonic provinces, and geophysical patterns (gravity, magnetics). Truncated Gutenberg-Richter frequency-magnitude relations of the form log n = a - bM were defined for each seismic source zone, and a maximum magnitude Mmax was assigned. In some efforts, the number of events with certain intensities was used instead of magnitudes. After reviewing the literature showing numerous diverging choices for seismic source zone geometries, the NCEER team decided to take a radically new approach that appears less subjective (Jacob et al. 1994). The seismicity of the NCEER catalog for the entire northeastern U.S. and adjacent Canada is used to determine a common b-value (≈0.91) for the frequency-magnitude relation. The seismicity is gridded into 1/2-degree latitude/ longitude cells (figure 2). Keeping the b-value fixed (at 0.91), seismicity rates for all cells are computed. To do this, the observed catalog seismicity is smoothed and weighted with a cosine window that extends to a selectable distance, before being binned and normalized to each cell. In the northeastern U.S., 140km was found to be a convenient smoothing distance that captures the essential spatial patterns of seismicity.

The U.S. Geological Survey has recently tested this method and, based on positive results, plans to use it for its 1997-edition of the NEHRP maps. It will use the gridding method with minor modifications as one input option giving it a high weight, together with other input options that will (1) allow for a uniform background seismicity rate, but variable Mmax; and (2) reflect large historic earthquakes and pre-historic geologic/ paleoseismic information. These latter two options will be applied with lower weights. This new method of gridding the historic and instrumental seismicity is especially suitable in the eastern U.S. where, unlike in California or Nevada, seismogenic fault zones are poorly defined; and where the causes for seismicity and its spatial variations are poorly understood. Some details, such as whether a constant b-value and a single smoothing distance are justified; how to assign Mmax to each grid cell, and how to choose the size of grid cells, may need further attention. But even as it stands now, the method of gridded seismic zoning (Jacob et al., 1994) seems to be an accepted method of seismic hazard mapping procedures. Gridding reduces the subjectivity that has often plagued previous approaches to defining seismic source zones.



■ **Figure 2**

Seismicity rates in the northeastern U.S., gridded in 1/2-degree cells, expressed as number of events with magnitudes M≥2 per cell per century. The NCEER-91 catalog is the primary data source, with seismicity weighted by a cosine window to a distance of 140km from each grid node.

New Ground Motion Data, STRONGMO Data Base, and Attenuation Relations

Recognizing the sparse and outdated analog recording strong-motion instrumentation in the eastern U S., NCEER began from the outset of its program to install a limited number of modern digital strong-motion instruments from which digital data are retrieved remotely by computer/phone modem from the operational center at Lamont-Doherty Earth Observatory (LDEO), in Palisades, New York. This network of strong-motion instruments now comprises a total of 33 sites, most of them in the New Madrid Seismic Zone in the Mississippi Embayment, jointly operated/funded by LDEO/NCEER/USGS with additional support by a few utilities.The technical layout of this network and data management system described below has since been adopted, for instance, by the U.S. Bureau of Reclamation for its upgrading of strong-motion operations at dam sites in the western U S. Because of higher dynamic range and lower trigger threshold of the modern instruments, NCEER was able to greatly increase the number of strong-motion recordings available for the entire central and eastern U.S.

A modern data management system was established. Newly collected NCEER strong-motion data are stored in the relational data base STRONGMO that can be accessed via Internet or via phone/modem (Friberg and Susch, 1990). Information in the relational database can be searched by queries for scores of descriptive and numerical header parameters.The queries can be as complex and detailed as chosen by the user. The ground motion time series so selected by the queries can then be instantly retrieved (by FTP) over Internet or phone/modem. Hundreds of engineering firms and researchers from most continents and from many countries have freely accessed the STRONGMO data base, which contains many national and international data sets besides the data collected by the NCEER strong-motion network.To our knowledge, it is the only globally accessible strong-motion database.

Only days after NCEER's initial strong-motion network was installed, the Saguenay earthquake ($Mw \approx 5.9$; $Mblg \approx 6.5$) occurred in Quebec, Canada, and was widely recorded from Maine to New York City on NCEER stations. These and several recordings from lesser earthquakes, together with several analog-to-digital converted Canadian strong-motion records, were analyzed to obtain ground motion attenuation relations for eastern North American hard-rock sites. By multiple regression of peak acceleration and velocity vs. magnitude and distance, the following attenuation relations were obtained.

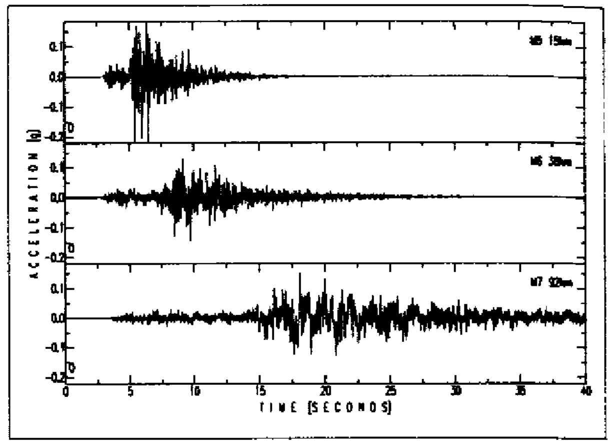
$$\log A\,(g) = -1.43 \pm 0.25 + 0.31M - 0.62 \log d\,(km) - 0.0026\, d\,(km)$$
$$\log V\,(cm/s) = -1.18 \pm 0.25 + 0.58M - 0.79 \log d\,(km) - 0.0015\, d\,(km)$$

These regressions are dominated by the data from the Saguenay earthquake, which had unusual source depth ($\approx$28km) and probably high asperity-stress-drop ($\approx$500 bars). It is therefore not surprising that these relations yield two to four times higher accelerations and velocities than inferred by most other published attenuation relations for the eastern U S. They usually rely on larger data sets that include lower-stress-drop events and, sometimes, synthetic data generated by the band-limited white-noise random-vibration method. The above relations are characteristic for high-stress drop conditions, and therefore should only be used when such conditions are being modeled. To account for stress-drop variations reflected by the different attenuation models, the U.S. Geological Survey is currently considering making multiple probabilistic hazard evaluations using these and other attenuation relations, and then combining the results by weighting them according to the perceived frequency of occurrence of high- vs. lower-stress-drop earthquakes. The issue of the proportion of high- vs. low-stress-drop earthquakes is probably the single most important unresolved issue for seismic hazard assessment in the eastern U.S.

New Method for Realistic Ground Motion Simulation

To supplement the still sparse eastern U.S. strong-motion data base, and to extend it to magnitude ($M \geq 6$), distance, and long-period ($T \geq 2$ sec) ranges not yet covered by the observations, NCEER's ground motion program embarked on developing a new method that realistically models synthetic ground motions constrained by geophysically known crustal parameters and source properties of a region. The method developed by Horton (1994) is based on the following approach·

A full-wave number integration scheme is applied which uses the geophysically derived crustal models for velocity and attenuation properties of the region (i.e. P- and S-wave velocities, viscoelastic damping 1/Q, and density as a function of depth) to compute synthetic three-component (vertical, transverse and longitudinal) ground motion acceleration records. Source properties must be prescribed. For the New York metropolitan area for instance, sources with average stress drop of 100 bars were used with an average depth of 7km, and a mixture of strike-slip and thrusting on generic faults. The computed synthetic records are then modified by convolving them with an energy-preserving scattering function based on a rigorous theoretical model of forward-scattering. It accounts for the random perturbations in a realistic Earth that deviate from a model of flat layers with laterally homogeneous elastic properties This scattering model is empirically constrained for a given region by measuring the envelope duration of the observed ground motion records as a function of distance, after subtracting out the magnitude-dependent source duration. Examples of hazard-consistent simulated strong-motion records used for a major bridge retrofitting project near New York City are shown in figure 3. The new method for simulating ground motions is among the most advanced currently available anywhere, short of only those that directly model three-dimensional basin response.



■ **Figure 3**
Suite of simulated hard-rock accelerations (transverse component) for earthquakes with magnitude M=5, 6 and 7 at distances 15, 38 and 92 km, respectively, for a constant recurrence period (CRP) of 1,000 years for a site near New York City, based on the method by Horton (1994).

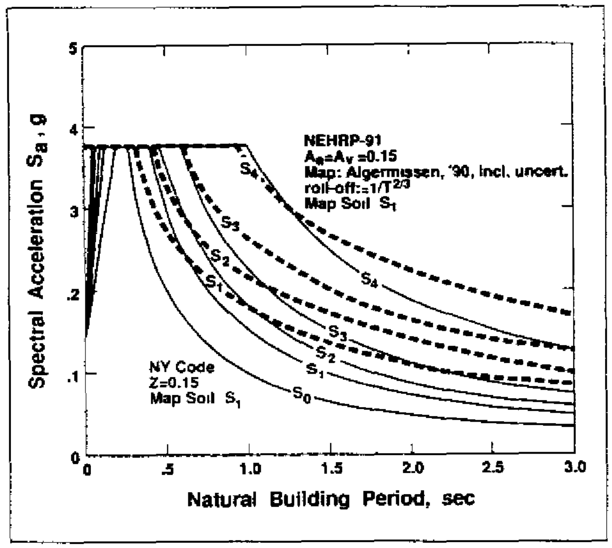
Site Response Estimation Techniques and Applications

Systematic Evaluation of Different Response Estimation Methods. NCEER's ground motion program focused on novel site response estimation techniques that are especially effective in seismic environments like the eastern U.S. where ground motion recordings from earthquakes are very sparse. Therefore, techniques that use geotechnical boring data or ambient seismic noise measurements to estimate the expected soil response at a given site must be used. Since soil amplification has proven over and over again to be one of the most important factors that control earthquake losses, the task to accurately quantify site response is not only a scientific challenge but also of great societal importance.

The NCEER research focused on how to obtain an accurate estimate of site response when (i) ground motions from earthquakes are recorded, and (ii) when no such records are available, and response must be inferred from geotechnical data or ambient noise measurements. Results from this research are presented by Field (1994) and a sequence of related papers.

For case (i) four site response estimating techniques were systematically evaluated (Field and Jacob: 1994) using mostly data from the site of the collapsed Nimitz freeway in Oakland, California, and aftershocks of the Loma Prieta earthquake. The results indicate that site response estimates based on spectral ratios made from a single pair of (three-component) soil vs. rock recordings are highly uncertain, even for linear soil response under low-strain excitation. The apparent cause for this uncertainty is signal-generated noise that is not entirely random but is partially correlated with the incoming seismic signal for a given source-site combination. To obtain stable spectral estimates, spectral ratios need to be averaged over at least one or two dozen recordings or more. Under these conditions, spectral ratios provide a less biased estimate than cross-spectral methods, and therefore the latter should not be used

A particularly promising method, which works for both earthquakes (case i) and ambient ground noise recordings (case ii) is "Nakamura's" method. It has the additional advantage that it does not require a rock reference site to give good site response estimates The method utilizes the spectral ratios of the *horizontal to vertical components* of three-component recordings at the site of interest. It yields surprisingly accurate and stable results for both the amplitude and period of the fundamental site response mode, but deteriorates towards higher modes. Since the fundamental site mode is generally the most important one for many engineering applications, Nakamura's method is recommended both for sites with event recordings on soil where no nearby rock reference site is available, and for sites, like in the eastern U.S., that generally lack prior earthquake recordings; in these instances it can be applied very cost-effectively to three-component ambient seismic noise measurements. Although Nakamura's method has not yet been tested under nonlinear soil response conditions, it is expected to perform reasonably well in these cases



■ Figure 4

New York building code design spectra (for dynamic modal analysis, five site conditions S_0 to S_4), vs. design spectra for NEHRP 91-edition (four site conditions S_1 to S_4). Note large amplitude ratio (3.75) between extreme New York City sites (S_4 to S_0) vs. small ratio (2.0) between NEHRP sites (S_4 to S_1), and shift of New York spectra to shorter periods especially for the S_0 hard-rock site.

Applications of Site Response Research Results: Bridge Demonstration Projects and Code Provisions The NCEER ground motion team deployed its portable instruments for ground motion site response studies using aftershocks of the Loma Prieta, Landers, and Northridge earthquakes in California, and in Leninakan several months after the tragic Armenian earthquake that caused more than 25,000 fatalities. Extensive linear and non-linear computations of site response at and near New York City (e.g. Tappan Zee Bridge project) have been made and compared to observations and results from ambient-noise measurements. In almost all instances, the site amplification factors that building or bridge codes assign to the types of soil profiles at the studied soil sites have been found to be generally insufficient. Often they do not account for observed or predicted soil-amplifications. This is especially true for sites with moderate seismicity and lower-level excita-