tion-levels (typically 0.1 to 0.2g peak accelerations on rock) that are probabilistically specified in the eastern U.S. by most nationally applicable code-provisions.

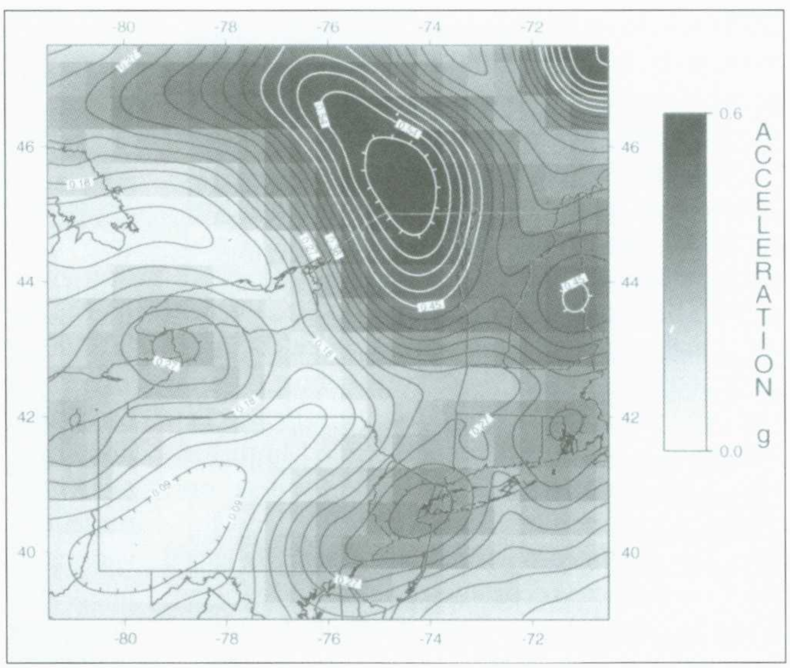
These insights and results have lead to actions, in cooperation with NCEER's Geotechnical Program, that resulted in workshops and code writing committee proposals, that sharpened the definitions of site classifications (see Earthquake Site Response and Seismic Code Provisions in this volume). The proposals also led to an increase in the amplitude range of site amplification factors beyond their original range of 1 to 2. For instance, the New York City and New York State drafts for Seismic Building Code Provisions increased their range of site factors from 0.67 on hard rock to 2.5 on soft soils, thus providing response spectral ratios of up to 3.75 between extreme site conditions (figure 4). Further research with input from NCEER's geotechnical research group, the Structural Engineers Association of California (SEAOC) and U.S. Geological Survey researchers has led to the entire redefinition of soil categories and soil amplification factors for short-period (0.3 seconds) and long-period (1.0 second) motions separately, and as a function of input accelerations. These results were directly incorporated into the imminent 1994 edition of the NEHRP Recommended Seismic Code Provisions.

Applying the Research Results

For this and other NCEER programs, one, although not the only, measure of performance is whether and how it has affected engineering practice and public life. To have an effect, all the research and input elements, starting from earthquake catalogs, seismic source definition, ground motion modeling, site response, to statistical treatment must be tied together with an understanding of the regulatory environment to address practical engineering needs. Only then can developed products be used and have impact. The following examples show how research resulting from NCEER's Seismic Hazard and Ground Motion programs have been used.

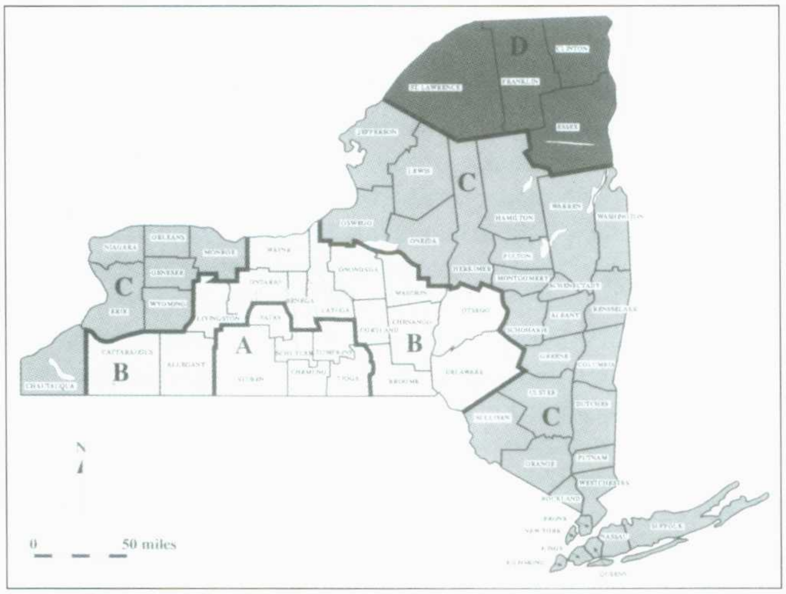
Probabilistic Seismic Hazard Maps for the Northeastern U.S.

The NCEER team produced a test set of probabilistic seismic hazard maps for the northeastern U.S. with the following goals in mind: to prove that usage of the NCEER-91 earthquake catalog depicts seismicity more accurately than other catalogs; that gridding of seismicity is an objective way to delineate seismic source zones; that the new attenuation relations can reproduce observed ground motions and thus represent east-



■ Figure 5

Peak accelerations (g) with 10% probability of exceedance in 250 years, in the northeastern US, using gridded seismicity (figure 2) and new attenuation relations (see text). Only contributions from magnitudes M≥4 were considered. Reference site condition is hard-rock S_0 = 0.67. Contour steps are 0.03 g apart.



■ **Figure 6**

Seismic zoning map for New York State seismic building code. The Z factor measures 0.09, 0.12, 0.15, and 0.18 in zones A, B, C, D, respectively. Z is referenced to S_1 =1.0 site conditions.

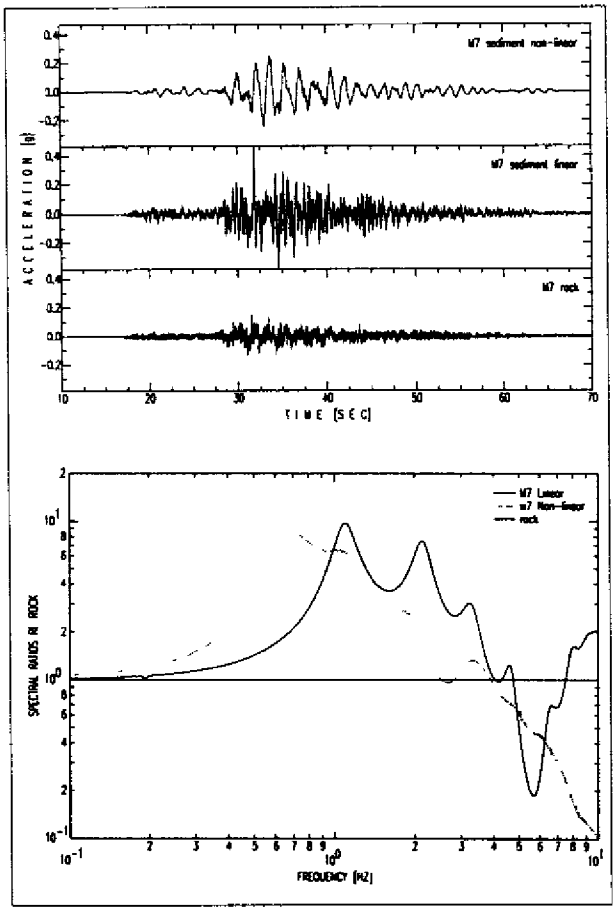
ern high-stress-drop earthquakes well. Earlier relations mixed eastern high and normal stress drop events indistinguishably. The results from this comprehensive mapping effort (Jacob et al., 1994) together with additional tests were presented to the U.S. Geological Survey-sponsored *Northeastern U.S. Regional Workshop for the National Seismic Hazard Mapping Program*, held at LDEO on August 2 - 3, 1994. Partly as a consequence of the presented mapping effort (e.g. figure 5), the U.S. Geological Survey plans to adopt many of the features spearheaded by the NCEER group: east of the Rockies, the NCEER-91 catalog will be the input standard; gridding of the seismicity will be adopted; multiple but separate runs for low and high-stress drop attenuation laws may be performed that then can be combined by a weighting scheme according to relative frequency of occurrence of the various stress levels.

New York State Seismic Zoning Map

The New York State Seismic Building Code Committee adopted for its drafted code a seismic zoning map, that not entirely but largely follows the recommendations by the NCEER group. The New York State seismic zoning map (figure 6) will be reproduced in the 1994 edition of the NEHRP/BSSC Seismic Provisions as one of several examples of regional seismic zoning maps.

Design Ground Motions for Monumental East Coast Bridges

Using the NCEER-91 catalog and the ground motion simulation procedure by Horton (1994) outlined above, three-component hazard-consistent design ground motions are computed using a deterministic, hazard-consistent method called the CRP method (for Constant Recurrence Period). Ground motions are computed for a suite of M=5, 6 and 7 earthquakes at different distances that are consistent with local seismicity and a constant recurrence period of 500 and 1,000 years for the Tappan Zee Bridge, New York; and 500 and 2,500 years for the Queensboro Bridge in New York City (see Seismic Hazard Assessment of the Queensboro Bridge in this volume). Since the pile foundations and buoyant caissons of the Tappan Zee Bridge are embedded in unusually soft soils (shear wave velocities as low as 100 ft/s), special care was taken to account for the nonlinear soil response using methods developed or refined by the NCEER team (Barstow et al., 1994; Horton et al., 1994; Jacob et al., 1994a and 1994b). Frequency-dependent site amplification on soft soils compared to hard crystalline bedrock underlying the several 100 feet thick soft sediments reached amplification factors of 5 to 10 at periods between 1 and 2 seconds (figure 7). It should be noted



■ **Figure 7**
Top: **Simulated 1,000-year hard-rock horizontal acceleration, and linear and nonlinear soil response for a M=7 earthquake at d = 92km at the site of one of the Tappan Zee Bridge foundations.**
Bottom: **Corresponding spectral ratios ($\leq$10) of linear and nonlinear soil response vs. rock.**

that this period range is close to important modes of the main spans of the bridge.

For these bridge projects, the NCEER team used the microprocessor-controlled portable seismic instrumentation that is normally used for aftershock observations, and recorded the ambient vibrations and related low-level bridge response. The vibration data were analyzed with a newly developed software package (Gavin et al., 1992) to determine modal periods and damping estimates The instrumental data acquisition scheme is novel, fast and very cost-effective since it does not require any wiring between sensors at different observation points. The results have been very useful to the bridge engineers to calibrate dynamic computer models, at least under low-excitation conditions, in the current, often quite deteriorated maintenance, or structurally modified states of these old and aged bridges. Both bridges have an average traffic volume larger than 100,000 vehicles per day.

These studies, aimed at developing seismic retrofit options for major east coast bridges, are among the first in the eastern United States that use up-to-date data and methodologies on major existing engineering structures outside the nuclear domain. These studies would probably not have taken place without NCEER at least helping to alert the local bridge owners and engineers to the need for careful consideration of seismic factors during major bridge rehabilitation and maintenance work. The awareness was created largely by NCEER investigators participating in local ASCE and similar professional seminars. These are but a few examples where NCEER research and related education and implementation efforts have been directly and very effectively transferred into engineering practice

Conclusions

NCEER's program on Seismic Hazard and Ground Motions has changed how strong-motion data are being collected and distributed: it spearheaded the retrieval of data over phone lines from remote digital stations; it developed the first relational strong-motion data base, STRONGMO, that can be queried and allows electronic transfer of data to users anywhere over Internet or phone/modem. It has introduced new concepts for modeling strong motions. It developed the CRP method for presenting suites of hazard-consistent ground motions and response spectra. It has refined measurements of site response and computing nonlinear site response of soft soils It helped update building codes, seismic zoning maps, soil classifications and site/soil factors. It delivered knowledge aimed at seismic rehabilitation of major east coast bridges. Moreover, NCEER, through this and other programs, has raised earthquake awareness in the eastern U.S. in the engineering profession and the public alike. Finally, this high-quality academic research produced results and trained Ph D.-level professional experts in engineering seismology.

Even with the successes listed herein, much remains to be accomplished. To date, the long completed drafts for the New York State and New York City seismic code provisions have not been voted into law. The U.S. Geological Survey' spectral seismic ground motion hazard maps have not been voted for inclusion into the 1994 edition of the NEHRP seismic provisions. In revised form, to which NCEER is poised to contribute, they will be resubmitted for inclusion into the 1997 edition. The STRONGMO data base needs to be expanded into an expert system to include not just observed ground motions, but predicted ground motions for different exposure times, site conditions and geographical areas. It is envisioned that in the future, the U.S. Geological Survey, California Division of Mines and Geology, the U.S Bureau of Reclamation, NCEER, National Oceanic and Atmospheric Administration, Southern California Earthquake Center, utilities and most other strong-motion data producers and distributors in and around the world would broadcast their data on Internet using a common, STRONGMO-like software tool

Personnel and Institutions

NCEER's Seismic Hazard and Ground Motion program is largely located at the Lamont Doherty Earth Observatory of Columbia University.

The participating investigators and researchers are listed as the collaborators for this paper. To the program s credit, many investigators/researchers that once served with this NCEER program have moved on to a variety of institutions where they practice their skills, as can be seen from their current affiliations.

Interaction with NCEER's Building Project was directed by Peter Gergely, Cornell University; with the Geotechnical Program by Ricardo Dobry, Rennselaer Polytechnic Institute, with the Bridge Demonstration Projects by Ian Buckle and Ian Friedland, NCEER, University at Buffalo, with the Lifeline and Bridge projects regarding Spatial Variation of Ground Motions by Masanobu Shinozuka and George Deodatis, Princeton University; and on Code Issues with Ricardo Dobry, Peter Gergely, Geoffrey Martin, University of Southern California, and others.

Major cooperation on the ground motion program occurred with the U.S. Geological Survey (joint LDEO- NCEER-USGS strong-motion network in the New Madrid Seismic Zone); and to a lesser degree (software exchange, technical assistance) with the U.S. Bureau of Reclamation, Denver; a joint strong-motion network is operated north of New York City with the New York Power Authority (NYPA) Demonstration projects were performed with F.R.Harris Inc. and Hardesty & Hanover Consulting Engineers (both in New York City) for the Tappan Zee Bridge (owner. New York Thruway Authority); and through NCEER with Steinman Consulting Engineers, New York City, on the Queensboro Bridge, New York City. And with the firm of Rosenwasser Associates (J Grossmann), New York City, for the ambient vibration response of New York City high-rise buildings Code-related work was performed for NEHRP with the Building Seismic Safety Council (BSSC), and with the New York City and New York State Seismic Code Committees, with Guy Nordenson of the Engineering Firm Ove Arup, with Dr. Mohammed Ettouney of Weidlinger Associates, with Dr. Jim Gould and Peter Edinger of Mueser Rutledge Inc., all of New York City Continuing education and knowledge transfer was achieved through seminars organized by NCEER, ASCE (especially its New York City Metropolitan Chapter), EERI, ATC-35 (Chris Rojahn) U.S. EPA and New York DEC and many others. The NEHRP National Earthquake Hazard Mapping Program of the U S. Geological Survey office in Denver (group leader formerly Dr. Ted Algermissen, now Dr. Arthur Frankel) chose the NCEER seismic-hazard/ ground motion facility at LDEO as a host for its Northeastern U.S. Regional Workshop, to which NCEER/LDEO contributed heavily in personnel, facilities and technical knowledge.

Acknowledgments

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