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SEISMIC RETROFIT STUDY OF THE QUEENSBORO BRIDGE, N.Y.: ROCK MOTIONS AND MODE I.D. BY AMBIENT VIBRATION MEASUREMENTS.

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ABSTRACT

A comprehensive seismic hazard assessment of the Queensboro Bridge (QBB) in New York City has been carried out. The assessment is made for two levels of performance. The motions for events with a 500-yr recurrence period are linked to the bridge performance criteria for continued functionality (serviceability) of the bridge, while those for the events with a 2,500-yr recurrence period are used to check the structural safety of the bridge (no collapse). Given the local (NYC) and regional (Atlantic Coast) seismic history of the last three hundred years, three magnitudes M=5, 6, and 7 per recurrence period are considered. These magnitudes are associated with distances d=22, 54 and 131 km for the 500-yr, and d=10, 24 and 58 km for the 2,500-yr recurrence period. Modeled ground motions on rock show peak accelerations of 0.1 to 0.3g and durations between 5 and 30sec depending on M-d combination and recurrence period. Ground motions are provided in the response-spectral and time domain. The latter is used by the Geotechnical Engineer as input for nonlinear soil response computations for the approach spans founded on soils. The computed free-field relative displacements on rock between adjacent piers of the main spans are limited to ≤10 cm. Mode types, natural periods and associated damping values for various bridge spans are determined by cross-spectral analysis of ambient vibration data. Vibrations are measured using a novel technology that relies on programmable digital recorders that do not need cabling to a central recording site. They permit fast instrument deployment and measurements that rarely require lane closings.

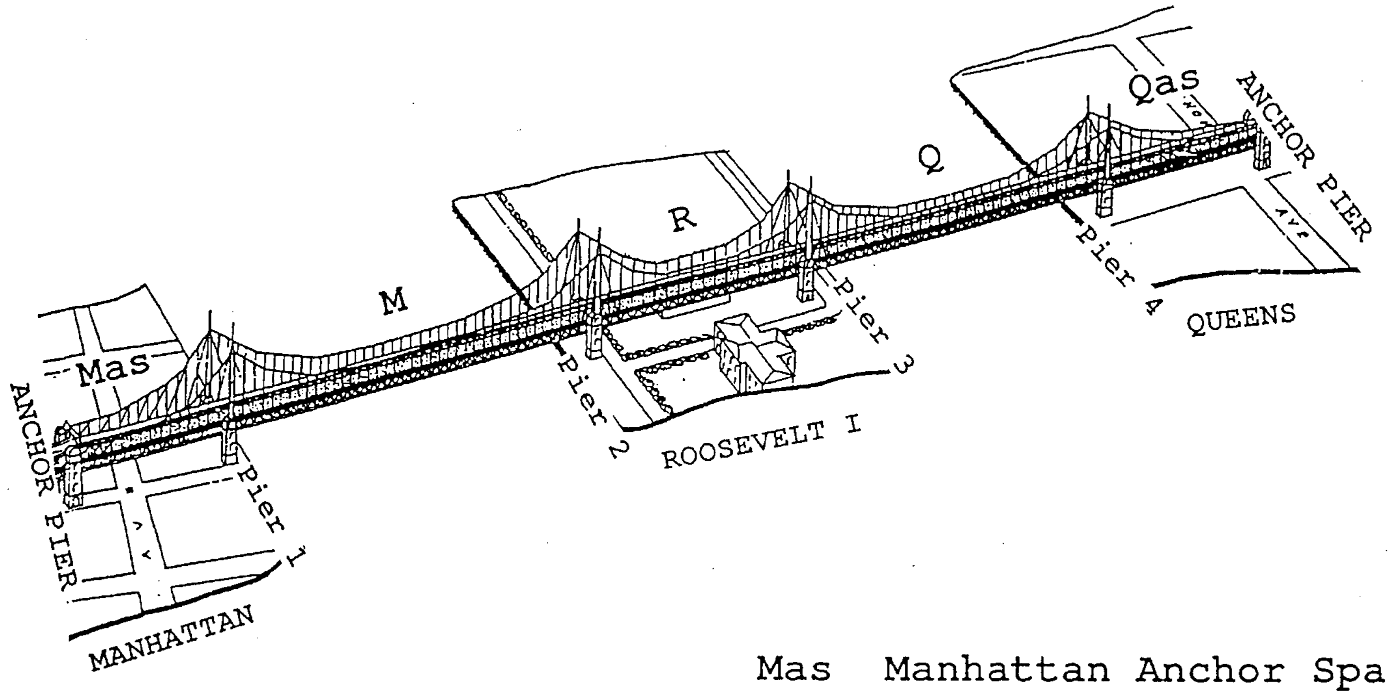
KEYWORDS

Long-span bridge; seismic retrofit; performance criteria; recurrence periods; rock motions; design spectra; free-field relative displacements; two-level design; ambient vibrations; system identification; modes;

INTRODUCTION

The Queensboro Bridge (QBB) in New York City was built in the first decade of this century. It connects Manhattan with Queens across two arms of the East River and intervening Roosevelt Island (Fig. 1). It is a critical bridge carrying, on average, more than 100,000 vehicles per day. It is a cantilevered steel bridge with five main spans and very long approaches. The piers of the main spans are constructed of stone masonry founded essentially directly on rock. Approaches are founded on piling through soil to rock. A comprehensive seismic hazard assessment of the QBB site has been carried out providing the results described below.

QUEENSBORO BRIDGE



Mas	Manhattan Anchor Span
M	Manhattan Main Span
R	Roosevelt Isl. Span
Q	Queens Main Span
Qas	Queens Anchor Span

Fig.1. Sketch of five cantilevered steel spans of the Queensboro Bridge (QBB). Roosevelt Island divides the East River into two arms. Approach spans in Manhattan (left) and Queens (right) are not shown.

SEISMIC HAZARD ASSESSMENT

Seismic Environment.

The QBB site lies in the a region of moderate seismicity, typical for Eastern North America (Fig. 2), and is located in the midst of the North American Plate, at the eastern edge of the North American continent where it abuts against the passive margin of the Atlantic shelf. The NY region has experienced in the last 300 years earthquakes with magnitudes up to $M \approx 5.2$. Elsewhere along the Atlantic Coast of North America, earthquakes with magnitudes $M \approx 6$ and 7 have occurred and cannot be ruled out to occur near New York City.

Seismotectonics and Seismicity Rates.

The "Manhattan Prong" seismic source zone forms a seismic provenance surrounding New York City. It includes portions of the Paleozoic (and older) Hudson Highlands, the Triassic Newark Basin, and the Mesozoic Atlantic passive margin which are delineated and crossed by several known ancient fault zones (Camerons Line, Ramapo Fault Zone, NW-striking Cretaceous faults etc.). Some of these faults appear to be reactivated by the current NE-SW directed compressive stress regime of the region. Strike-slip motion with some thrusting at depths between about 5 and 15 km dominates. The seismic zone comprises an area of about 6,500 km^2. The combined historic (≈300 years) and instrumentally recorded (≈25 years) seismicity rate as a function of magnitude is fitted to a Gutenberg-Richter relation of the normalized cumulative number of events

$$\log n\ (yr^{-1}\ km^{-2}) = a - bM = -2.305 - 0.775\ M \qquad (1)$$

for earthquakes with magnitudes $M=3^1/_4$ and larger. The range of magnitudes taken into account for design is M=5 to 7. Equ. (1) gives cumulative (≥M) seismic rates normalized per unit time (yr) and unit area (km^2).

Seismic Performance Criteria and Constant Recurrence Periods (CRP).

Seismic performance criteria for a two-level design procedure are considered. The two performance criteria are for service and collapse states and are linked to two distinct seismic hazard levels with their associated recurrence periods. The owner opted to link the performance criteria to a constant average recurrence period of 500 years for continued serviceability of the bridge, and to 2,500 years for structural safety (no collapse).

Three Magnitude-Distance Pairs for Each Constant Recurrence Period (CRP).

For each constant recurrence period (CRP) we determine distinct magnitude-distance (M-d) "event" combinations that are consistent with the above regional seismicity rates. M-d combinations are derived from the a- and b-values for a given recurrence period T. The distance d(km) is the median (50- percentile) distance for a magnitude M or larger with average recurrence period T (years) to occur as defined by:

$$\log d = (bM - a - \log T - \log 2\pi)/2 \qquad (2)$$

Three discrete event magnitudes are considered, M=5, 6 and 7. Based on the respective a- and b- values for the Manhattan Prong seismic source zone, the median distances for the 500-year events are computed to be 22, 54, and 131 km, for the thee magnitudes respectively; and for the 2500-year events they are 10, 24, and 58 km, respectively.

Ground Motion Time Series.

We compute three-component ground motion acceleration time series on hard rock associated with the M-d event combinations for the CRP=500 and 2500 years. We use the method of Horton (1994) which combines deterministic models of wave propagation in a flat-layered crust with models of random elastic 3-d wave scattering. The method yields three-component (Z=vertical, T=transverse, and R= radial component) ground motions with peak accelerations between about 0.1 and 0.3 g and durations of 5 to 30 seconds, depending on magnitude, distance and recurrence period of the events modeled (Fig. 3). Up to 5 realizations of the hard-

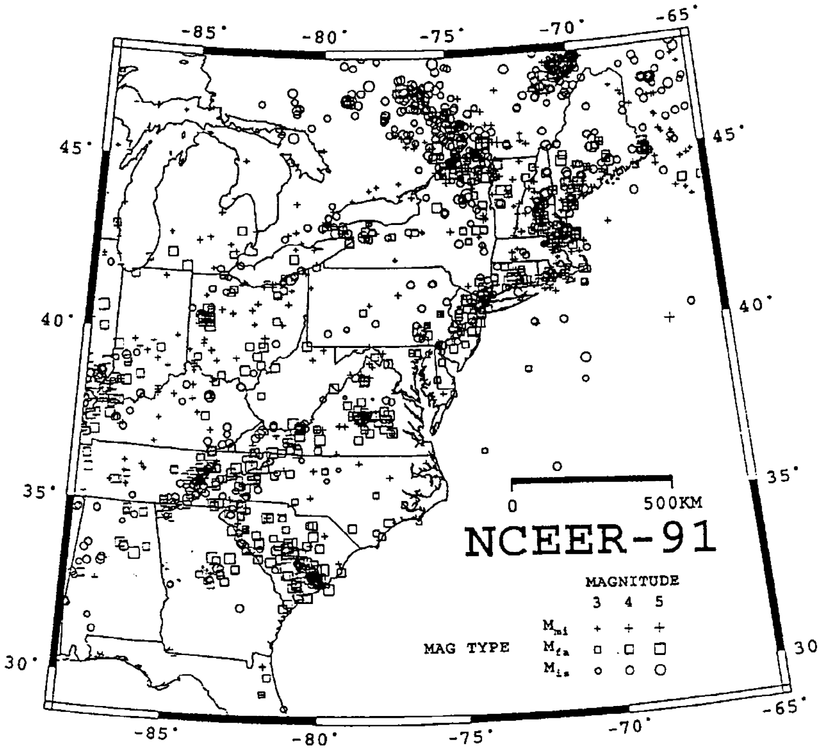


Fig. 2. Seismicity in the Eastern U.S. from NCEER-91 earthquake catalog by Seeber and Armbruster (1991). Three different magnitude symbols are plotted: Mmi based on maximum intensity, Mfa based on felt area, and Mis based on instrumental measurements. Study area is at 40.5 N and 74.0 W.

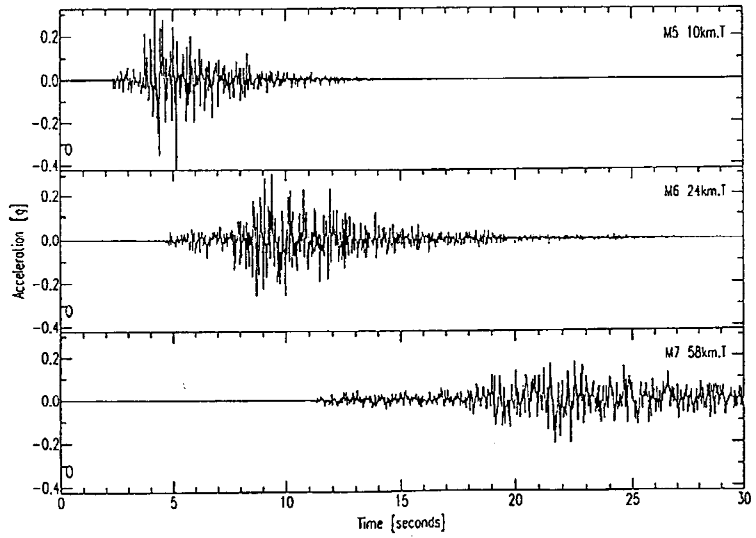


Fig.3. Simulated, transverse-component accelerograms for a QBB hard-rock site and a constant recurrence period CRP= 2,500 years. The three records are for equally probable magnitude-distance (M-d) combinations of M=5 at d=10km, M=6 at 24km, and M=7 at 48km.

rock ground motions are provided for each M-d event-combination to allow the assessment of the variability of nonlinear soil response by the Geotechnical Engineer as described in a companion paper (Dobry et al., this volume).

Damped Response Spectra and CRP Envelope Spectra.

Damped acceleration response spectra for the Z, T, and R components of the ground motions for the three M-d combinations for each of the two adopted recurrence periods are computed: 2.5 % damping is used for the 500-yr, and 5%-damping for the 2500-yr events to reflect increased structural damping with stronger excitation levels. The three spectra (one for each M-d combination) per each ground motion component and for each CRP are then enveloped (i.e. for each period the largest response spectral value among the three M-d combinations per CRP and component is chosen). Thereby two sets of envelope spectra are obtained, one for the suite of M-d events with CRP=500 years, the other for CRP=2,500 years, respectively. The CRP envelope spectra can be used for design of portions of the bridge structure founded directly on hard rock (i.e. the structures associated with the five main spans, see Fig. 1). The CRP envelope spectra have a similar function as uniform hazard spectra have in probabilistic seismic hazard assessments for seismic design.

Comparison to Code Spectra.

We compare the CRP envelope spectra to relevant bridge code spectra (AASHTO) and other code spectra currently used in the NY City area (Fig. 4). We find that the 500-year CRP envelope spectrum exceeds the code spectrum at short periods ($T \leq 0.2$sec), while at longer periods it falls generally below the code spectrum. The 2500-year CRP envelope spectrum stays generally above the 500-year code spectrum for the entire period range considered (T= 0 to 4 sec).

Displacements and Spatial Variations.

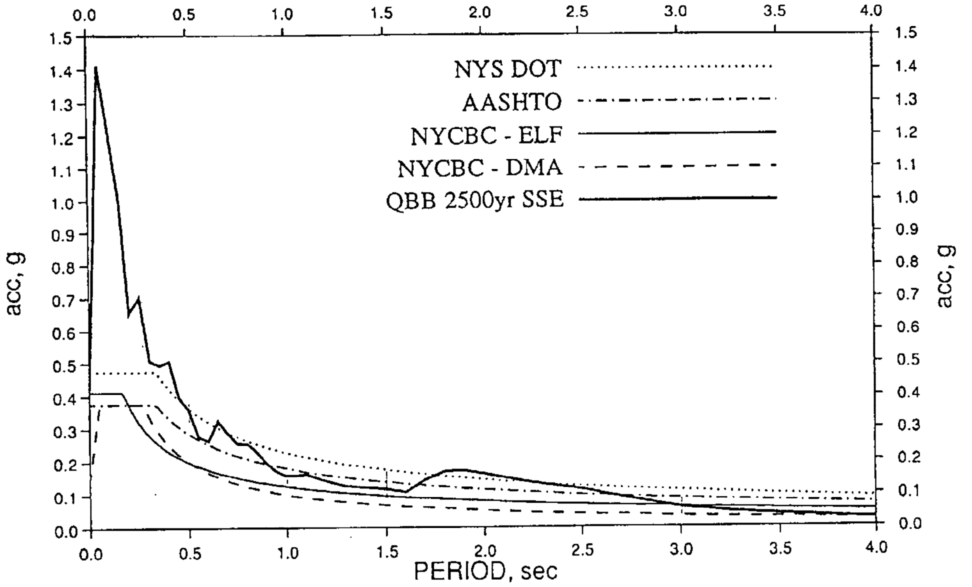
We also quantify the absolute displacements of the ground motions on hard rock, and provide an equation that specifies lag times of motions between multiple support points as a function of vertical angle of incidence, azimuth of wave approach, and distance between support points. The relative displacements on hard rock between main-span supports are typically on the order of a few centimeters for the events considered.

MODE IDENTIFICATION FROM AMBIENT VIBRATION MEASUREMENTS.

A novel measurement technique was used for the first time on a bridge in New York City, to identify the modes of dynamic structural response under ambient vibration conditions. The new technique can be performed without having to string wires between sensors and a central recording unit. Instead, pre-programmable digital seismic recorders are used that work on a virtually common time base. The new technique allowed to make the measurements on the five main-spans of the QBB in one day, and on the QBB's Manhattan and Queens approaches together during another day. The measurements and subsequent cross-spectral data analysis resolved the essential transverse, vertical and torsional modes involving large length scales. Longitudinal modes were identified, but they tended to be masked by more dominating other modes. *Transverse* modes of the Manhattan and Queens main spans had the longest periods, 2.65 and 2.09 seconds, respectively; followed by their *vertical* modes measuring 2.17 and 1.80 seconds. All other resolved modes for the main spans were measured to have shorter periods, between 0.5 and 1.3 seconds. Damping for the Manhattan and Queens main spans for the first four modes with periods at or above 1.80 seconds measured 5.2, 4.3, 3.5 and 3.2 %. Modes of the Queens approach had measured periods of less than 1.0 sec, and for the apparently stiffer Manhattan approach less than 0.4 sec. Damping values for modes of the measured Queens approach structure are 0.8 to 2.2% , and those for the Manhattan approach 1.1 to 2.1%.

All modal parameters measured are for low-level excitation from ambient vibrations during which the bridge and its subsystems are expected to respond linearly. During seismic excitation it is likely that nonlinear response occurs. Under such nonlinear conditions modal periods and related damping tend to increase, and boundary conditions at joints and connections are expected to change. Therefore, results from ambient

2,500-YEAR EARTHQUAKE



500-YEAR EARTHQUAKE

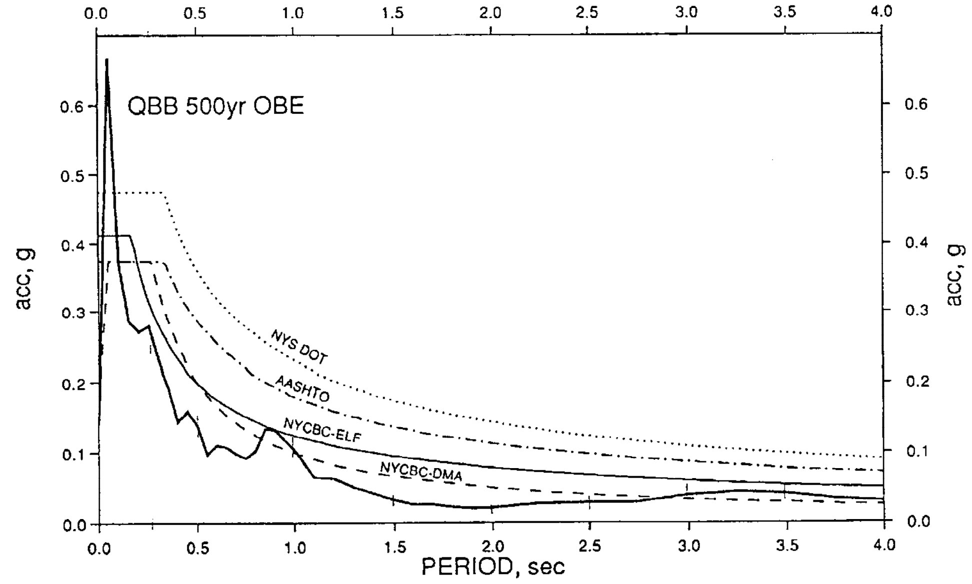


Fig.4. CRP envelope spectrum (bold line) for 500-year events (bottom) and 2,500-year events (top) compared to code design spectra for a rock site in NYC according to AASHTO and NYSDOT standards for ordinary bridges, and for two versions of the NYC building code (Jacob, 1990), i.e. the equivalent lateral force (ELF), and the dynamic modal analysis (DMA) procedure.

vibration measurements are used only to calibrate computer models in the *linear* response range of the bridge (see companion paper by Arzoumanidis et al., this volume). This linear model then becomes a starting model from which other, nonlinear dynamic models of the bridge can be derived that feature degraded member stiffnesses, modified boundary conditions at joints, bearings, supports and/or abutments, and increased damping values that are appropriate for higher, seismic excitation levels.

DISCUSSION AND CONCLUSIONS

A new (CRP) method of quantitative seismic hazard assessment was applied for a seismic retrofit study of the Queensboro Bridge in New York City. The used method is a hybrid between a probabilistic and a deterministic approach. The method yields a suite of highly realistic three-component ground motions for events (M-d combinations) associated with a given recurrence period T (or its inverse, the annual probability of occurrence). The CRP method does not provide ground motions with a given probability of exceedance that includes the uncertainties typically associated with ground motion attenuation laws. Instead the ground motions are deterministically modeled for the seismicity-related, hazard-consistent magnitude-distance (M-d) combinations of events for each given constant recurrence period (CRP). The ground motions are geophysically modeled for preselected source and crustal parameters. Modeling of motions provides an advantage in regions where only small earthquakes were recorded by weak-motion seismic networks, but strong-motion records from larger events are not available. The modeling method, while essentially deterministic, allows to compute a family of stochastically varying realizations of ground motion time series for each M-d combination by generating different random seeds in the portion of the computer program that simulates the 3-d scattering in an otherwise laterally homogeneous, flat-layered crust with given wave velocity, density and damping (1/Q) structure. These random realizations can be used to explore the variability for instance of nonlinear soil or structural responses to a "given event". For a given constant recurrence period (CRP) the response spectra for different M-d combinations are enveloped. The so obtained CRP envelope spectra are then used in a similar way as uniform hazard spectra (UHS) are typically used in probabilistic seismic hazard assessments as design spectra. CRP envelope response spectra and UHS yield very comparable spectral shapes and design levels. Using CRP envelope spectra it is directly apparent which magnitude-distance combination controls a certain period range of the design spectrum. The decomposition of a UHS into its constituent M-d events (known as de-aggregation) is generally more complex.

Since in this tectonic environment the direction of approach of seismic waves relative to the orientation of the bridge is not known because the location of faults with respect to the bridge is generally not known, the relative free-field displacements between supports of the bridge spans are estimated using the wave propagation effects and allowing random azimuths of wave approach.

A new and innovative method to measure the modes of the various portions of the QBB under ambient vibrations has been successfully used. Some two dozen modes (including transverse, vertical, torsional and longitudinal modes), their natural periods and estimates of their critical damping values have been obtained form these measurements. They are used for system identification for low excitation levels. These results are useful for calibrating dynamic computer models of bridge response only in the linear elastic range. Extrapolations to dynamic bridge properties under seismic excitation levels must be performed by other means.

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