Appraising the Broo

New York City's Department of Transportation is in the process of evaluating and, if necessary, rehabilitating its many important bridges to meet seismic guidelines. In a comprehensive two-part evaluation of the foundations of the Brooklyn Bridge that used the latest modeling techniques, engineers determined that the bridge's foundations have the ability to withstand a 2,500-year event without any sliding or separation at their bases, obviating the need for retrofits that might alter the architectural form of the renowned crossing.

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oklyn Bridge

The Brooklyn Bridge is the oldest of the East River bridges in New York City. Since 1883 it has remained one of the world's most revered engineering achievements and one of the most recognizable and nationally celebrated landmarks. Its importance to the city and surrounding areas as an integral facet of infrastructure and to the country at large as a cultural symbol cannot be overstated.

Courtesy of Jason Bax, Parsons

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The Brooklyn Bridge is the oldest of the East River bridges in New York City. When completed, in 1883, it was the world's only steel suspension bridge and had a center span 40 percent longer than that of any other bridge. Since that time it has stood as one of the world's most revered engineering achievements and one of the world's most recognizable and nationally celebrated landmarks. Its importance to the city and surrounding areas as an integral facet of infrastructure and to the country at large as a cultural symbol cannot be overstated.

The idea of building a bridge linking the boroughs of Brooklyn and Manhattan was conceived in 1857 by the visionary engineer John A. Roebling. But it was not until 1869 that the plan for the bridge was approved, and unfortunately Roebling died that year from tetanus brought on by an accident that occurred while he was determining the alignment of the bridge in the East River (see "Landmarks in Civil Engineering: Brooklyn Bridge," *Civil Engineering,* November/December 2002, pages 108–09). The task of designing and building the bridge fell on the shoulders of his son, Washington A. Roebling, a civil engineering graduate of Rensselaer Polytechnic Institute.

Construction of the bridge commenced in 1870, and in 1872 Roebling and six others were struck with "caisson disease" (now known as decompression sickness or the bends) while sinking the Brooklyn Bridge's tower caissons beneath the mud line. Roebling became crippled and was confined to his home, directing the construction of the bridge with the help of his wife, Emily, from a window overlooking the East River. On May 24, 1883, the Brooklyn Bridge opened and celebrations ensued.

A comprehensive seismic evaluation of the Brooklyn Bridge was recently completed by New York City's Department of Transportation (DOT), the New York City office of Parsons Corporation, and Northeastern University to assess its vulnerabilities and potential retrofit requirements. The scope included the Manhattan and Brooklyn masonry and steel approach structures as well as the approach ramps. This project was part of a larger effort by the DOT to

Courtesy of the Brooklyn Museum

Called the Great East River Bridge and the Great Suspension Bridge at the time, the Brooklyn Bridge was opened in 1883 amid great fanfare.

rehabilitate its bridges and to meet the seismic guidelines that govern the safety of its bridges. In recognition of the historical importance and unique architecture of the bridge, the DOT decided that the seismic safety assessment of the bridge would be based on geotechnical and structural information pertaining to the site in combination with the most advanced analytical procedures to determine what, if anything, was required to retrofit the bridge. Such an approach, it was hoped, would avoid excessive conservatism, which posed the danger of unnecessary retrofits that might detract from the architecture of the bridge.

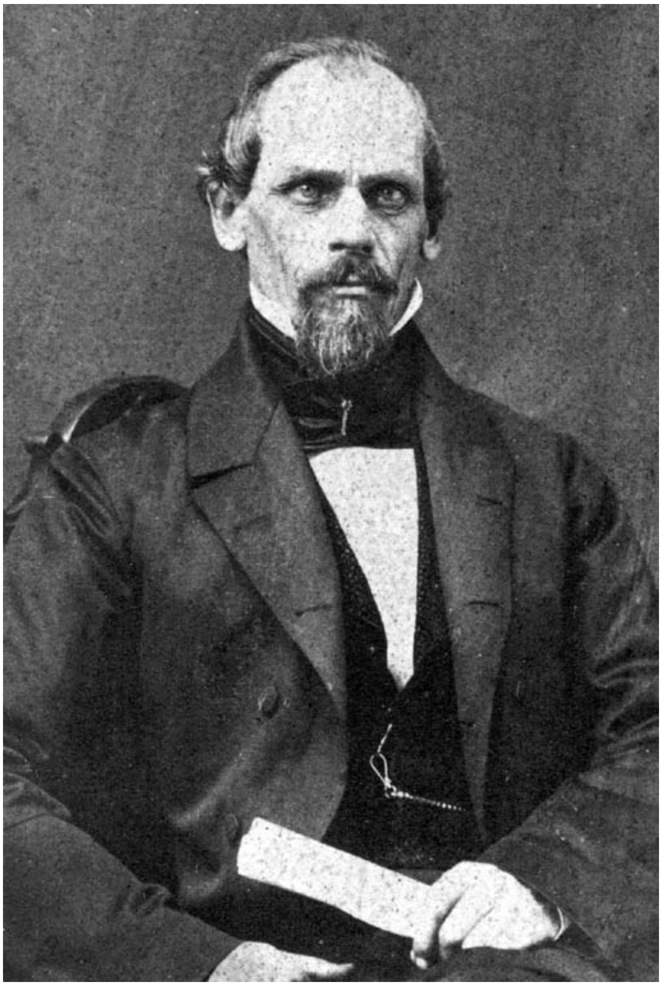
The focus here will be on the seismic evaluation of the foundations of the main bridge, including the main tower caissons and cable anchorages on the Manhattan and Brooklyn sides. The bridge has a center span of 1,595.5 ft (486 m) and side spans of 933 ft (284 m). Its two towers are founded on caissons, which include a timber grillage 22 ft (6.7 m) thick at the Manhattan tower caisson and a 15 ft (4.5 m) thick grillage at the Brooklyn tower caisson. The figure at the top of page 42 shows the shape and materials of the towers and their caissons. The cable anchorages are founded on a 4 ft (1.2 m) thick timber grillages constructed of 12 by 12 in. (305 by 305 mm) southern pine.

The caissons were constructed of inverted watertight boxes, the timber sections bolted together to create the grillage. To protect the exterior of the caissons from sea worms and to minimize water infiltration, the caissons were wrapped with iron sheets. Compressed air was pumped into the excavation chambers to prevent river water from entering. As excavation progressed, massive limestone blocks were placed on the timber grillages to help sink the caissons into the soil beneath the river, and these blocks formed the foundations of the bridge towers. When the caissons reached the foundation level, the excavation chambers were filled with concrete. The construction of the Brooklyn tower caisson, being the first of its type, was plagued by numerous difficulties and challenges, including air blowouts, fire, and the toll taken by decompression sickness.

The Manhattan tower caisson is located entirely in the East River and is generally founded at an elevation of –78 ft (–24 m) on an approximately 7 ft (2 m) thick layer of very dense gravel, cobbles, and boulders overlying bedrock. The Brooklyn tower caisson is on land but a bulkhead retains 40 ft (12 m) of fill adjacent to the tower foundation. The base of the caisson is at an elevation of –45 ft (–13.7 m) in a layer of sand and gravel overlying a 30 ft (9 m) thick till layer above bedrock. The bedrock at the tower locations is slightly weathered.

Two advanced seismic analysis approaches were utilized to assess the vulnerabilities and retrofit needs of the main bridge, especially the tower caissons and cable anchorage foundations. In the first approach, referred to as the global analysis, the entire main bridge superstructure and the foundations were included in a single model using the finite-element analysis program ADINA, developed by ADINA R&D, Inc., of Watertown, Massachusetts (see the figure on the bottom of page 42). The cables of the bridge were modeled with nonlinear beam elements, the stays with linear straight elements (varying moduli accounting for their sag), and the suspended structure and towers as assemblies of linear beam elements. Nonlinear springs were incorporated at particular locations of the towers to account for the effects of cracking. The degree and locations of cracking were determined with separate detailed models of the towers consisting of solid elements using the computer program ABAQUS—produced by Dassault Systèmes, of Vélizy-Villacoublay, France, and licensed by its SIMULIA division, of Providence, Rhode Island—and the material properties were modeled using the ANACAP-U software, developed by Anatech Corporation, of San Diego.

As shown in the figure, a spine model created from beam elements representing the caisson and from rigid links representing distributed nonlinear springs and dashpots at the base and sidewalls of the caissons was used to simulate the interaction between soil and structure. Twenty-five springs at the base and 20 springs at each of two elevations along the sides of the caisson were applied. The springs included such features as gapping and slipping along the caisson-soil interface at the base and sidewalls. The figure at the top of page 43 shows a longitudinal cross section of the Brooklyn tower foundation depicting the locations of the springs and dashpots in the model.


Courtesy of Rensselaer Polytechnic Institute

The idea of building a bridge linking Brooklyn with Manhattan was conceived in 1857 by the visionary engineer John A. Roebling.

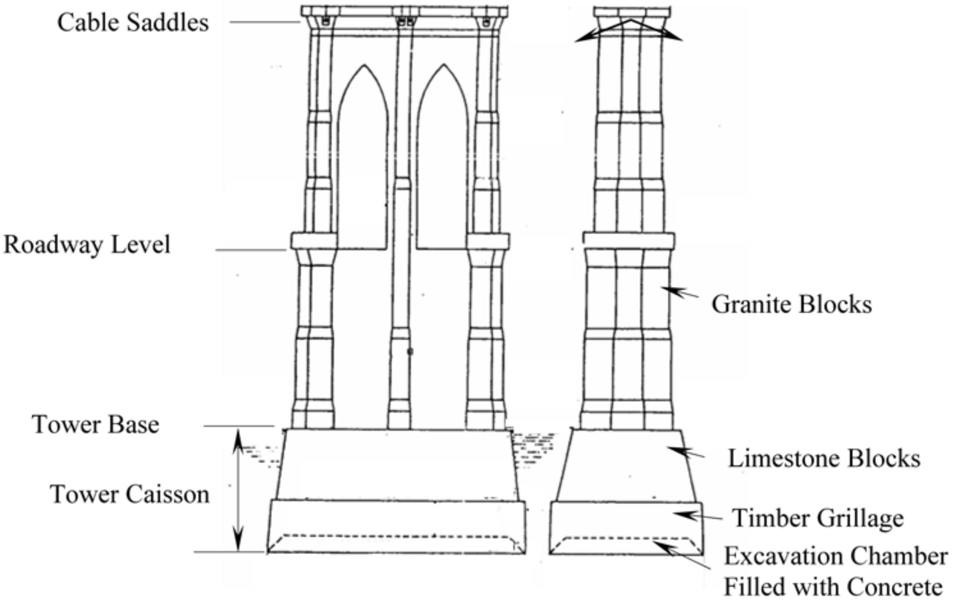
Extensive field geotechnical and geophysical testing programs were implemented to characterize the site conditions and obtain reliable estimates of the shear and compression wave velocities of the soils, bedrock, caisson timber grillages, and limestone blocks. This geotechnical work provided the foundation impedances—that is, the springs and dashpots—and the kinematic motions acting on the foundation impedances for use in the modeling.

In the second approach, referred to as the local analysis, each bridge tower, its caisson, and the surrounding soils were modeled using the computer program FLAC (Fast Lagrangian Analysis of Continua), developed by Itasca, an international consulting and software firm that has its U.S. headquarters in Minneapolis. In the analysis the tower, the caisson, and the soils were modeled as solid elements. The potential slipping and gapping along the interfaces between the soil and the caisson were modeled by using interface elements. The program uses the finite-difference numerical technique to solve the static and dynamic response of the continuum consisting of the bridge tower, its caisson, and the surrounding soils. The purpose of using two approaches for analyzing the interactions between the soil, the foundation, and the bridge was to confirm the accuracy of the kinematic motions and of the foundation and soil model used in the global analysis, to validate the analytical results from both analyses, and to ensure that the final conclusions regarding the need for retrofitting, especially with respect to the main bridge foundations, were realistic.

The figure at the bottom of page 43 shows the typical locations of the springs and dashpots for the Brooklyn cable anchorage. Similar springs and dashpots were used for the Manhattan cable anchorage.

Springs and dashpots were placed at nine locations within the base and four locations along the sides of each anchorage, representing the interaction between the soil and the caisson at the cable anchorages. Their values were determined using the computer program SASSI (System for Analysis of Soil-Structure Interaction), developed by a group of graduate students under the direction of the late John Lysmer, Ph.D., a professor of geotechnical engineering at the University of California at Berkeley. The frequency-dependent stiffness coefficients were compared with values computed on the basis of simple stiffness equations applicable to shallow foundations. Typically, within the frequency range of relevance to the anchorages (above 2 Hz), the simple equations overestimate the stiffness coefficients for the two cable anchorages. Such overestimation would have led to underestimates of the motions of the Brooklyn cable anchorage and, conversely, overestimates of the

Details of the Bridge Towers and Their Caissons

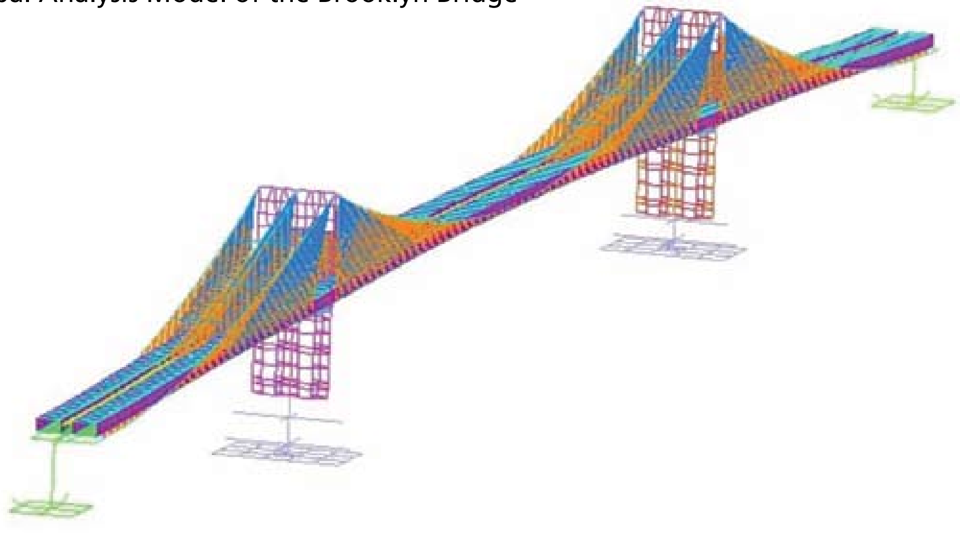


motions of the Manhattan cable anchorage. From the comparisons between the results from the advanced stiffness calculations and those from the simplified approach, it was evident that realistic estimates of seismic responses, especially for such a significant structure as the Brooklyn Bridge, warranted the application of advanced analytical procedures.

Several rock motion time histories were selected from the set of records that the DOT released in 2004 for the analysis of its bridges. The appropriate records were selected and modified to represent the spatial variability of the motions and the rock condition at each of the bridge foundation locations. The global analysis evaluated motions corresponding to an event with a 2,500-year return period, which would generate a peak acceleration of 0.2*g* at the surface of a hard rock outcrop.

To account for the effect of the spatial variability of the motions along the longitudinal axis of the bridge, the global analysis was performed using multisupport excitation. Here the displacement time histories were specified at all foundation springs and dashpots, those points representing the interaction between the foundations of the bridge and the soils. These displacement records for the cable caissons were obtained from the acceleration records calculated from the SASSI program after making the appropriate baseline corrections. The figure at the bottom right of the opposite page shows a typical displacement record that was specified in the global analysis at the base and sides of the Brooklyn cable anchorage. Similar records were computed for the Manhattan cable anchorage. The analyses of the interaction between the soil and caissons showed that the motion along the side of the caissons is almost identical to that at the bases, thus indicating that, owing to the large size of their bases, the caissons are not likely to rock.

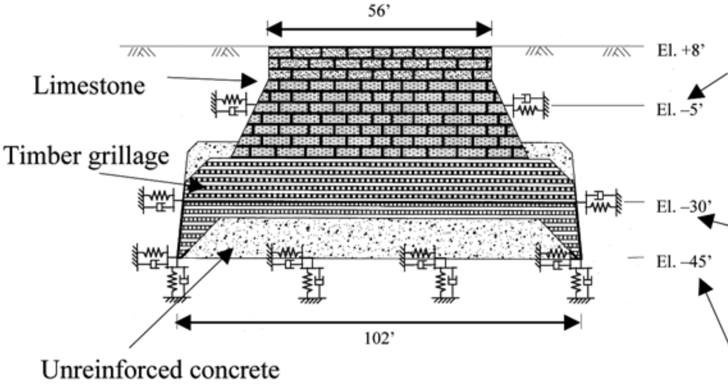
Global Analysis Model of the Brooklyn Bridge



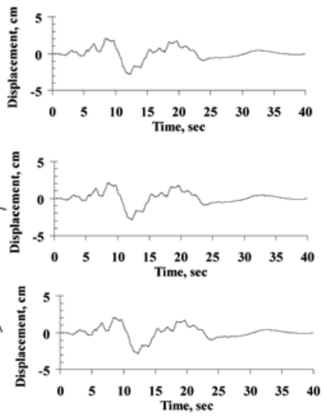
For the global model, the kinematic motions applied at the locations of the caisson springs were computed using FLAC. The figure at the top of page 44 shows the FLAC model of the Brooklyn tower foundation. Using variable support excitation in the global analysis of the bridge requires the application of ground motions in the form of displacement time histories at each foundation spring and dashpot. Typical displacement time histories along the base and sides of the Brooklyn tower caisson are shown in the figure at right. Similar ground motions were developed for the Manhattan tower caisson.

The foundation spring and dashpot coefficients for the tower caissons were initially computed as a function of frequency and of the estimated loads on the caissons using FLAC and a hysteretic soil model that approximated the nonlinear soil behavior. The total caisson foundation soil stiffness and damping coefficients were computed by applying sinusoidal forces and moments at the center of gravity of the caissons. These coefficients were then distributed to the 25 springs along the base and the 20 springs at each of two elevations along the sidewalls of the caissons. The distribution ensured that the cumulative stiffness and damping of the individual springs along the sidewalls and base of a caisson matched the total stiffness and damping coefficients. These foundation impedances were used in a preliminary seismic global analysis of the bridge to estimate the inertial loads on the caissons of the towers and to conduct a preliminary assessment of the retrofit requirements of the tower caissons.

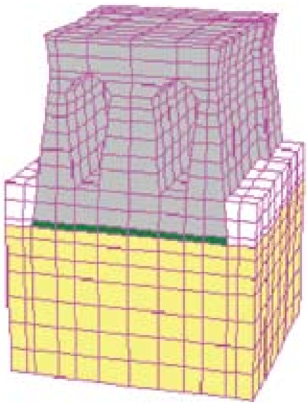
Transverse Elevation of the Brooklyn Tower Foundation Showing the Locations of the Springs and Dashpots



Kinematic Displacement Records



SASSI Model

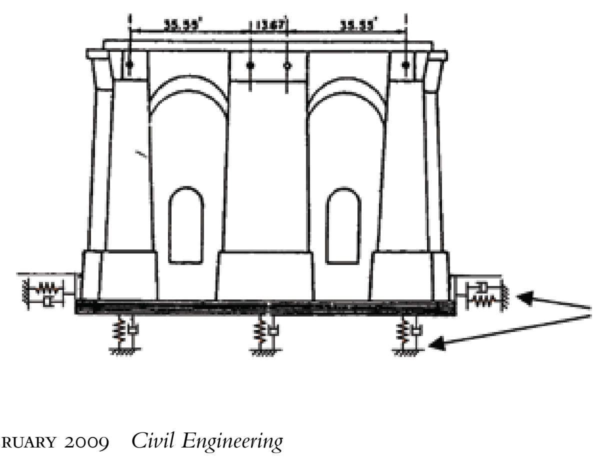


To account for the effect of potential sliding and tilting of the tower caissons on the seismic response of the caissons, the FLAC model (shown at the top of the next page) was modified by including slip and gap elements along the interfaces between the soil and caisson. The analysis involved first applying gravity to compute the initial stresses within the interface elements and then applying forces and moments on the caissons, one direction at a time (as in pushover analyses). The displacements and rotations of the caisson were then computed.

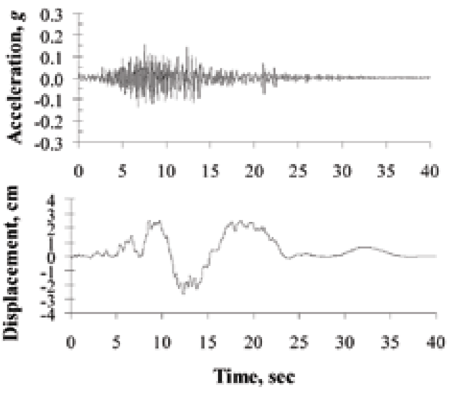
Also included in the model were static and equivalent dynamic cable forces and deck loads on the tower, which were computed by the initial global analysis of the bridge. The properties of the interface elements included the friction angle of the cohesionless soils, the undrained shear strength of the clay, and the normal and shear stiffnesses of the interface elements, which were based on the shear modulus of the soil and the dimensions of the soil elements adjacent to the interface elements.

The moduli of the timber grillage and the limestone of the tower

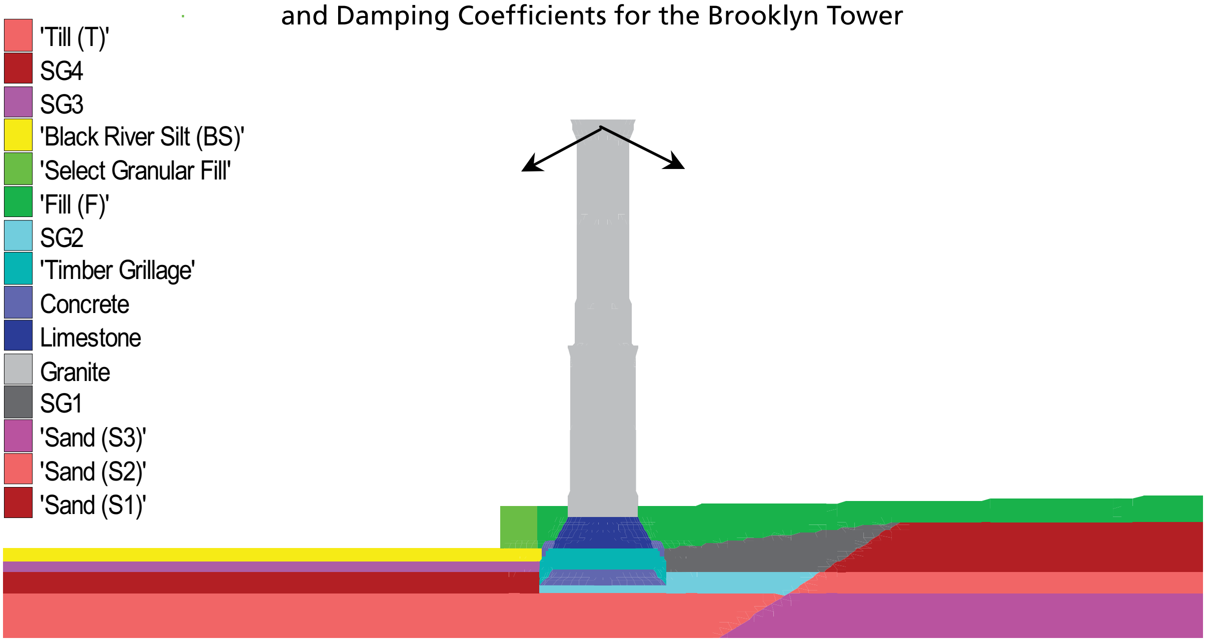
Transverse Elevation of the Brooklyn Cable Anchorage Showing the Locations of the Springs and Dashpots



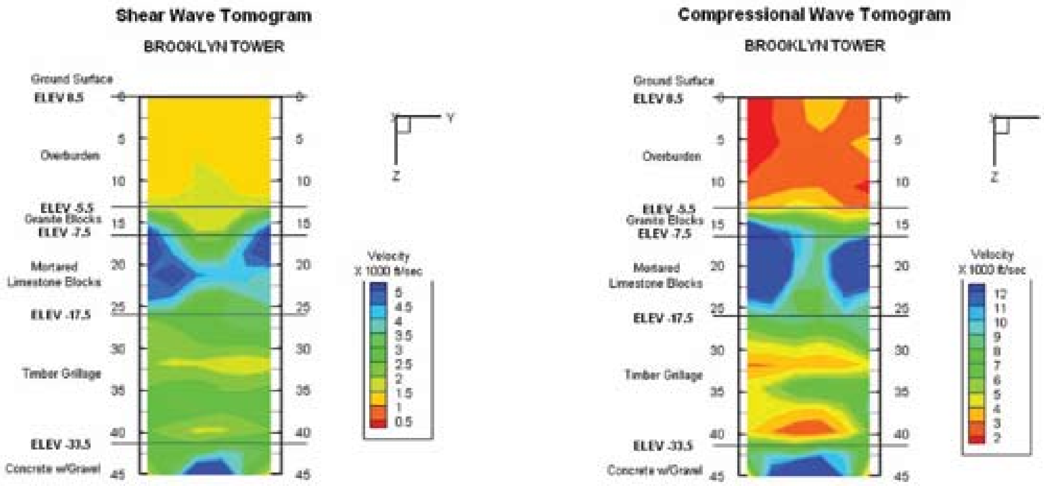
Kinematic Displacement Records



FLAC Model Used to Compute Kinematic Motions, Foundation Stiffness, and Damping Coefficients for the Brooklyn Tower



Shear and Compression Wave Tomography Results of the Timber Grillage and Limestone and Granite Blocks of the Brooklyn Tower Foundations



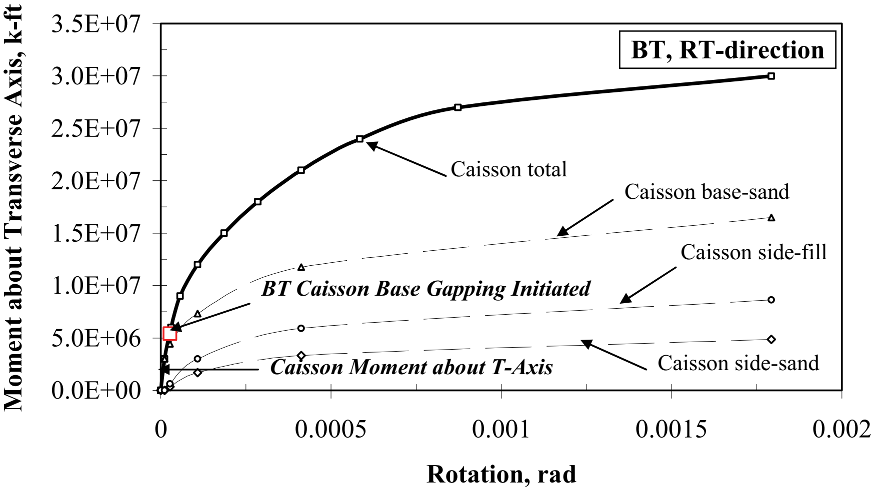
foundation were measured in the field using the geophysical shear and compression wave tomography plots. The bottom figure on page 44 shows the results obtained using two boreholes drilled through the Brooklyn tower caisson. On average, the shear and compression wave velocities of the timber grillage were respectively 2,700 ft/s (82,296 cm/s) and 5,700 ft/s (173,736 cm/s). The corresponding values for the limestone and granite blocks were respectively 8,700 ft/s (173,736 cm/s) and 13,600 ft/s (414,528 cm/s).

The figure at the top of page 46 shows the transverse moment versus rotation curve for the Brooklyn tower caisson, along with the relative contribution to this response from the sidewalls and base of the caisson. The results show that gapping will be initiated along the base of the caisson only if the acting transverse moment on the caisson exceeds 5.5 × 10^6 kip-ft

Fireworks illuminated the Brooklyn Bridge last year in celebrations marking the vital structure's 125th anniversary.

Courtesy of Jason Bax, Parsons

Nonlinear Moment-Rotation Relationship about the Transverse Axis for the Brooklyn Tower Caisson



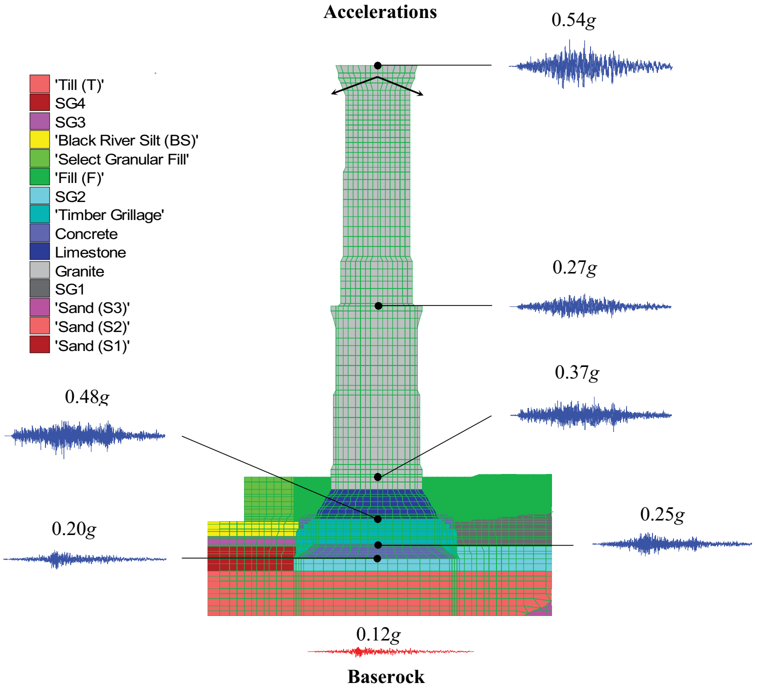
(7.5 × 10^6 kN-m), which is significantly greater than the 3.5 × 10^6 kip-ft (4.746 × 10^6 kN-m) computed in the initial global analysis using the frequency-dependent foundation impedances. Hence no portion of the Brooklyn tower caisson is expected to separate from the underlying soils during the 2,500-year event, a conclusion that was later confirmed by the local analysis of the tower and its foundation. Similar calculations using horizontal force–displacement curves for the Brooklyn and Manhattan tower caissons led to the same conclusions, namely, that the caissons are safe against sliding and separation.

A total of three translational force–displacement and three moment-rotation curves were generated for each tower caisson using the FLAC models and interface slip and gap elements. These total stiffness curves were then distributed to the base and sidewall springs, and the global analysis was repeated to obtain the final results.

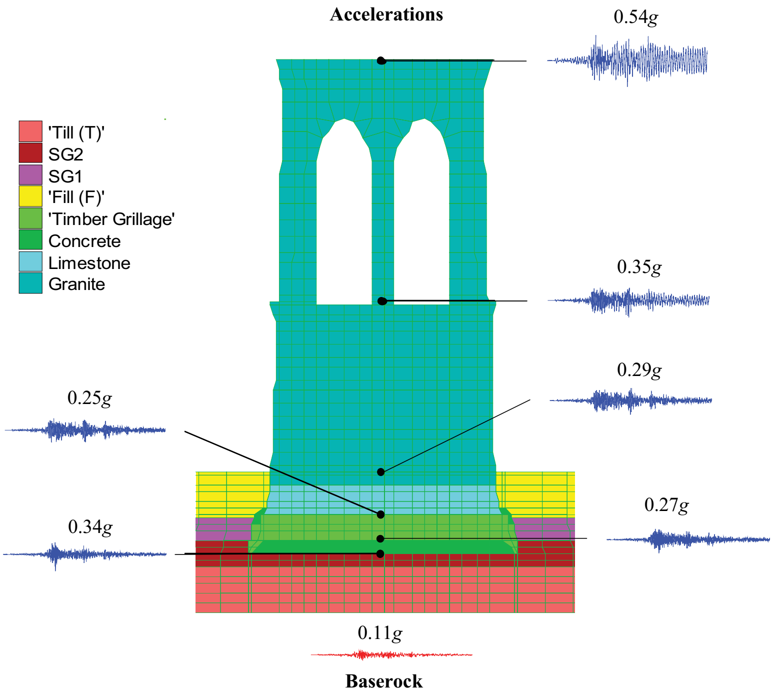
The towers and caissons of the Brooklyn Bridge are massive and rigid, and its superstructure is flexible. Furthermore, the design rock motions are rich in high frequencies but have little energy in the low-frequency range. It is therefore quite reasonable to expect that the dynamic inertial loads from the deck and the cables contribute very little to the seismic response of each tower and caisson. This expectation was clearly observed in the global analysis of the bridge, which also confirmed that the towers respond nearly linearly for the 2,500-year return period event. Hence it was of interest to perform a local seismic analysis of each of the two towers with their caissons and surrounding soils using the FLAC program. Such an analysis avoided the various assumptions made in calculating the kinematic motions and the foundation stiffness and damping coefficients. It also more accurately modeled the soil's nonlinear behavior and computed in detail the stress field within the caissons as well as the soil bearing stresses along the caisson sidewalls and bases.

The Brooklyn tower caisson model shown at the top of page 44 was used in the local analysis to investigate the vulnerability of the caisson. It included static and equivalent dynamic cable forces as well as hydrostatic effects. For the soils, a hysteretic model was used in which the soil moduli and damping ratios were adjusted at every step of time integration based on parameters that approximated appropriate normalized moduli versus shear strain curves. The model of the soil, caisson, and tower was first subjected to gravitational loads and then to the same 2,500-year base rock horizontal and vertical motions that were used in calculating the kinematic caisson motions. The

Longitudinal and Transverse Responses of the Brooklyn Tower and Its Foundation (Longitudinal Model) under the 2,500-Year Seismic Event



Longitudinal and Transverse Responses of the Brooklyn Tower and Its Foundation (Transverse Model) under the 2,500-Year Seismic Event.



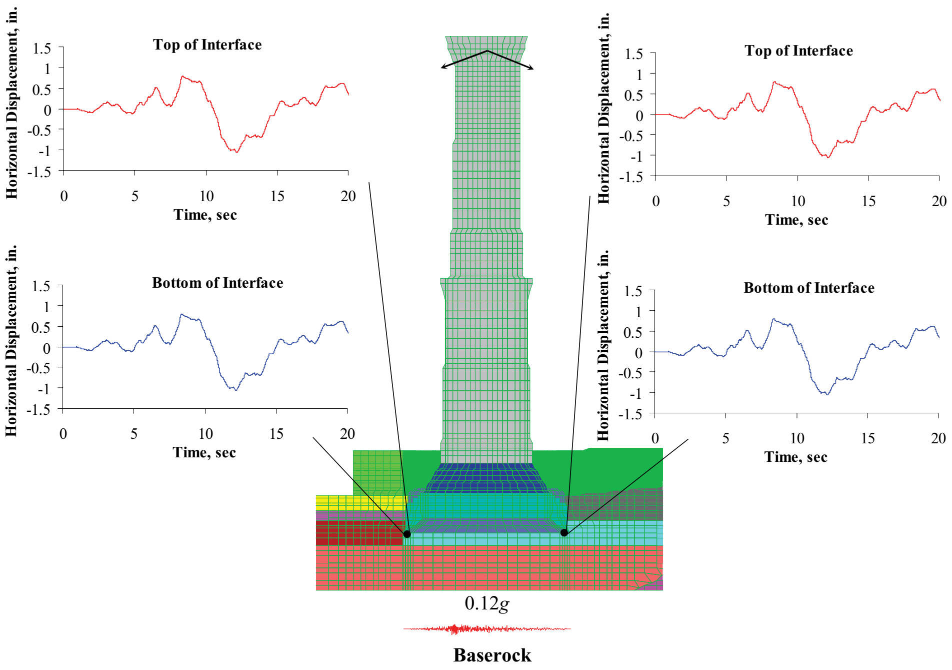
time histories of acceleration, displacement, shear stress, and vertical normal stress were computed at various nodes of interest, including the top and bottom of the interface elements placed along the bases of the caissons.

The figures at the bottom of the opposite page and the top of this page present summary plots of the accelerations at various nodes within the longitudinal and transverse models of the Brooklyn tower and its foundation. These results show that the base rock motion amplifies as it propagates through the structure. The acceleration response spectra of the computed motions show motion amplification at two particular periods, 0.2 second and 0.6 second. Simple calculations of the horizontal and rocking periods of the tower and its caisson confirmed that the first period corresponded to the longitudinal period of the tower, whereas the second is most likely associated with the rocking period about the transverse axis of the bridge. These modal periods were also within the period ranges that were observed through ambient vibration measurements of the bridge.

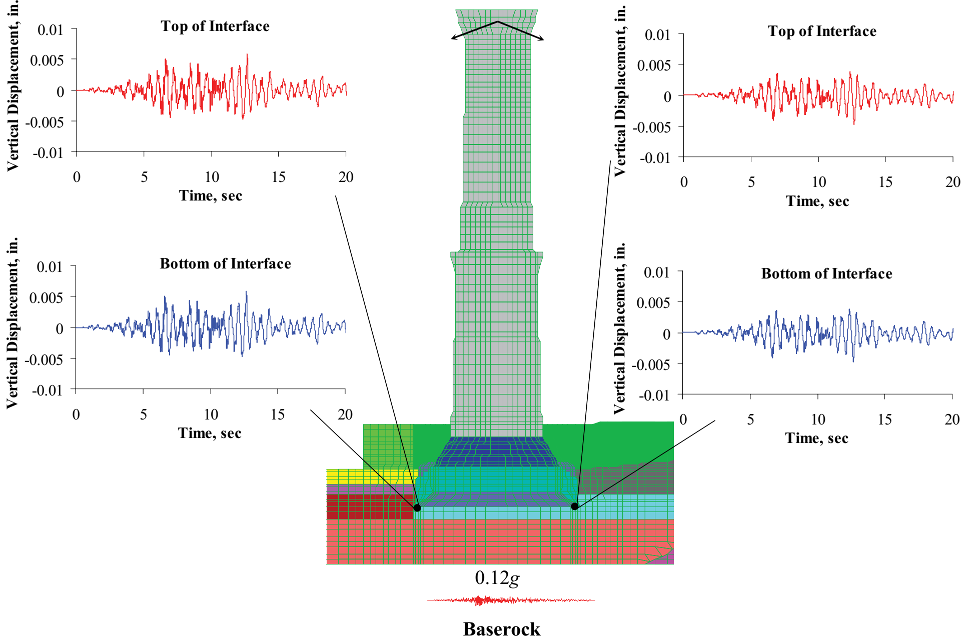
The figure below and the one at the top of page 48 show the horizontal and vertical displacement histories at respectively the top and bottom of the interface elements at the base of the caisson under the longitudinal earthquake excitation of the 2,500-year seismic event. The top and bottom displacements are identical, indicating that the interface elements do not exhibit slipping or gapping along the base of the tower. The figure at the bottom of page 48 shows a summary of the initial static and dynamic shear stresses along selected cross sections within the Brooklyn tower and its caisson. The maximum shear stress in the concrete of the caisson is about 45 psi (310 kPa), and in the timber grillage it is about 50 psi (345 kPa). These values are significantly smaller than the shear capacities that were measured in the laboratory for the concrete and timber specimens.

The figure at the top of page 49 shows the shear and effective vertical stresses along the base of the caisson induced by gravity and the combined horizontal and vertical excitations. Under this load combination, the maximum effective normal stress is roughly 125 psi (862 kPa), and the minimum effective

Horizontal Displacements at the Top and Bottom of the Interface Elements along the Base of the Brooklyn Tower Caisson under the 2,500-Year Event



Vertical Displacements at the Top and Bottom of the Interface Elements along the Base of the Brooklyn Tower Caisson under the 2,500-Year Event



normal stress is roughly 0 psi. These bearing stresses are very small relative to their ultimate capacity, which is more than 100 ksf (4,788 kPa).

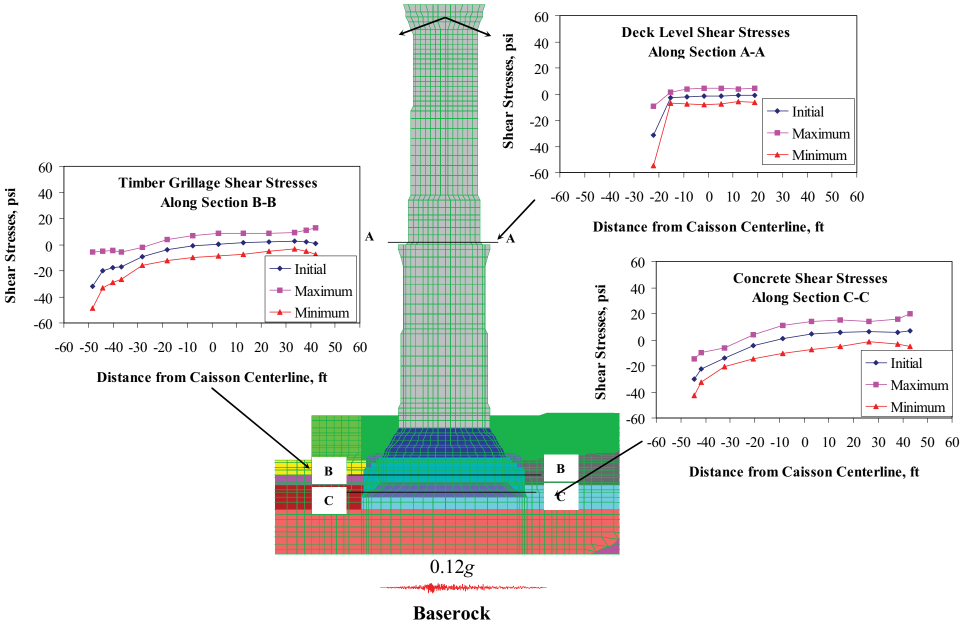
Similar investigations of the Brooklyn tower and its caisson were carried out considering seismic excitation in the transverse direction. The conclusions were identical to those obtained in the longitudinal analyses.

As described above, the global analysis of the Brooklyn Bridge incorporated the entire bridge, including the towers, cables, suspended structure, and foundations. Thus it provided the means by which to consider the cable effects and the masonry tower's potential for cracking. However, the simplified models of the caissons made it possible to calculate stresses at only a few selected locations where the springs were placed. In the figure at the bottom of the opposite page, a comparison is made of the effective vertical normal stress along the base of the Brooklyn tower caisson obtained from the global and local analyses. The agreement between the global and local analyses is quite good in view of the vast differences in the two analytical approaches.

Further comparisons of the results obtained from the local and global analyses for both the Brooklyn and Manhattan towers and their foundations led to the conclusions that the local and global analyses yielded similar results and that the main tower foundations are adequate to safely resist the 2,500-year event without experiencing sliding or separation at any portion of their bases and without bearing capacity failure. Hence, the foundations of the main span of the Brooklyn Bridge do not require retrofitting.

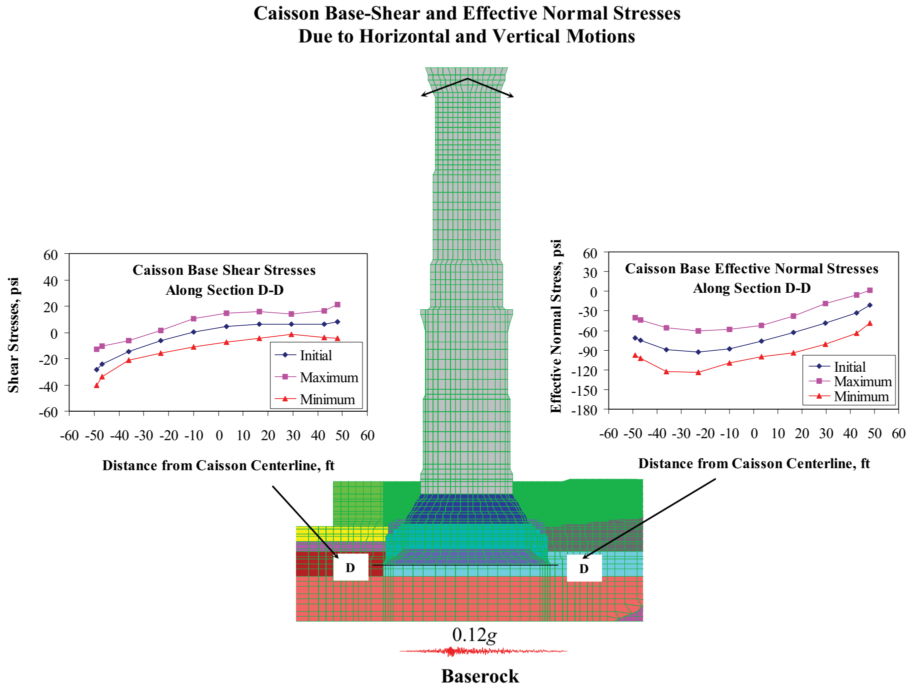
In conclusion, the seismic assessment of the bridge was completed using the most advanced engineering investigation methods available to ensure that the evaluation of the

Longitudinal Shear Stresses Computed Using the Model of the Brooklyn Tower and Its Foundation under the 2,500-Year Event



vulnerabilities and potential retrofit requirements was based on a rational framework and avoided the kinds of problems described by Ralph B. Peck, Dist.M.ASCE, in his article "Pitfalls of Overconservatism in Geotechnical Engineering" (*Civil Engineering*, February 1977), including the implementation of unnecessary retrofit schemes that might have detracted from the beauty of this beloved bridge. ■

Brooklyn Tower Caisson Base Shear and Effective Normal Stresses Induced by the Combined Longitudinal and Vertical Motions of the 2,500-Year Event



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Comparison of Effective Vertical Normal Stresses along the Base of the Brooklyn Tower Caisson Obtained from the Local and Global Analyses