

Factor building. An important parallel effort is the *Network for Earthquake Engineering Simulation* (NEES), an NSF facility supporting advanced research, experimentation and simulation of the ways buildings, bridges, utility systems and geomaterials perform during seismic events.

DOWNSTREAM ECONOMIC BENEFITS

In 2003, the USGS commissioned a study by the National Research Council (NRC) on the economic benefits of improved seismic monitoring. Specifically, the USGS asked the NRC to examine how improved monitoring could reduce future losses and to estimate the benefits that could be realized by the full deployment of ANSS. The committee found that seismic monitoring provides the key to understanding how the built environment responds to significant earthquakes, and specifically that detailed structural response data offer the potential for fine-tuning the design process so that seismic safety requirements are adequately—but not excessively—met. The NRC panel esti-

mated a total building-related annualized loss avoidance of \$142 million per year, nearly three times the projected annual costs of operating the full ANSS.

THE BOTTOM LINE

When ANSS is fully implemented, hundreds of structures will be extensively instrumented. Through this effort, the USGS and its cooperators are poised to greatly expand strong-motion recordings in high-risk urban areas, both on the ground and in buildings, bridges, and other structures. This will provide the earthquake engineering community with the data it needs to improve seismic design practices and thereby reduce future earthquake losses. ■

WEB LINKS TO MORE INFORMATION

www.anss.org • www.nees.org • www.nap.edu/openbook.php?isbn=0309096952 • earthquake.usgs.gov/research/monitoring/anss/docs/ANSS_Guideline_civil.pdf

Incoherent Vibrations Caused by an Earthquake Retrieving the Response of a Building

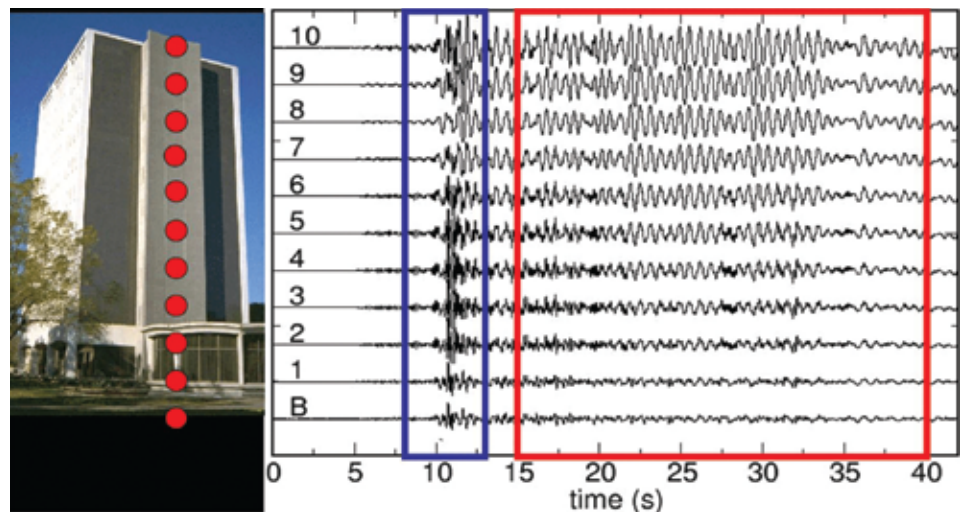
Roel Snieder • Colorado School of Mines

The motion of a building during an earthquake – one of the threats to its structural integrity – depends on not only the shaking by the earthquake, but also on the coupling of the building to the ground and the mechanical properties of the building. Measurements of the motion in the building provide information on the combination of these three ingredients, but structural engineers seek to retrieve the mechanical properties of the building from the recorded motion. A first step in this analysis is to extract the building response from recorded vibrations in the building, which I illustrate using the horizontal motion recorded by accelerometers in the Robert A. Millikan library of the California Institute of Technology.

EXTRACTING THE BUILDING RESPONSE

Recent tutorials give an overview of the rapidly growing field of seismic interferometry, a technique to extract the impulse response of a system from vibrations recorded in that system [Curtis *et al.*, 2006; Larose *et al.*, 2006]. For the Millikan Library, we can retrieve the building response by deconvolving the motion at each level with the motion recorded in the basement [Snieder and Safak, 2006].

The M_L 4.8 Yorba Linda earthquake of Sep 3, 2002, about 50 km southeast of Caltech, caused the Millikan Library



Accelerometers (red circles) are located in the basement and on each of the ten floors of the Millikan Library. The north-south component of acceleration in the west side of the building consists primarily of impulsive shear waves (arriving in the blue box), and surface waves (indicated by the red box).

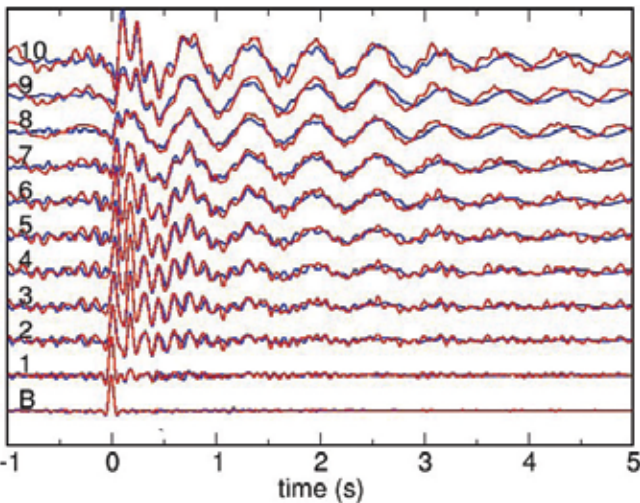
to sway and, as expected, the motion increases with height. After deconvolution with the basement records, we see a superposition of upgoing and downgoing traveling waves for early times ($t < 1$ s), and of a resonance of the building for later times ($t > 1$ s). That is, the building behaves similarly to a plucked guitar string; for early times the motion is best described by traveling waves, while for later times the motion is better characterized by a normal mode. Seismic interferometry has turned the incoherent motion of the building into the building response.

One might expect that the S-waves would give the traveling waves in the building response, and that the surface waves would give the resonance of the building. Instead, perhaps surprisingly, seismic interferometry applied to either the S-waves or to the surface waves each give both the traveling waves and the resonance. The building response is encoded in the spectral properties of the wave motion, and part of the building recorded motion is sufficient to extract the building response. This is reminiscent of holography in optics, where an image of an →

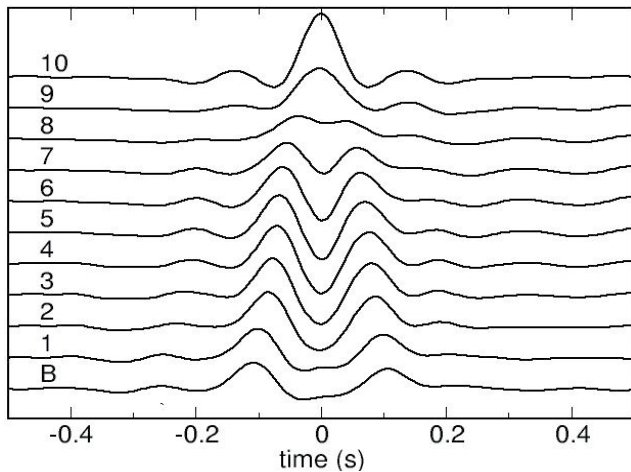
object is reconstructed by the interference of the waves emitted by a hologram and a reference light beam. The hologram is a piece of developed film. When one cuts a hologram in two, the holographic image is still intact, just as the building response can be retrieved from part of the recorded motion in the building.

WHAT IF THE BUILDING HAD A DIFFERENT GROUND COUPLING?

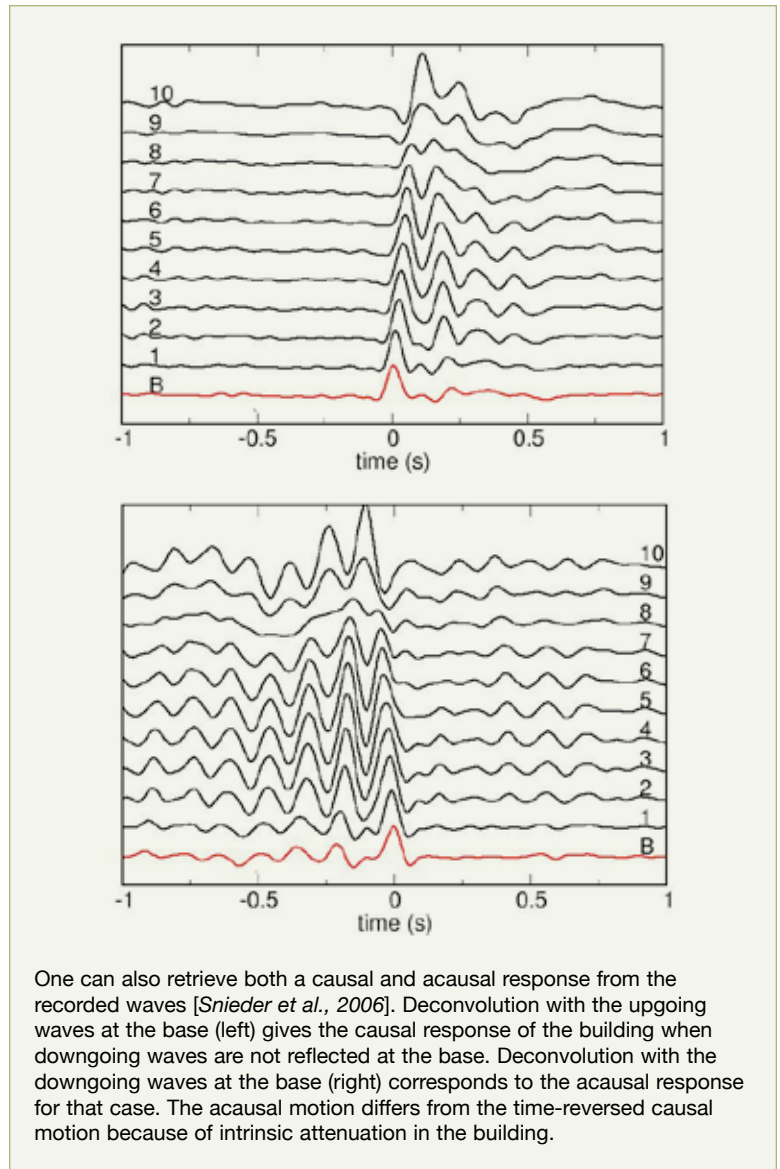
Rather than deconvolving the motion at every floor with the motion recorded in the basement, one can instead deconvolve the motion with the waves recorded at the top floor. Now the response consists of one upgoing wave for negative time, and one downgoing wave for positive time. Note that the downgoing wave is not reflected when it strikes the base of the building around 0.15 s! Of course the real building has a nonzero reflection coefficient at its base because of the large impedance contrast between the building and the subsurface. But in this wave state the downward propagating wave is not reflected upwards, meaning that this is the response that the building would have on a subsurface with an impedance equal to the impedance of the building.



Waveforms after deconvolution with the record from the basement. The blue waveforms are obtained by deconvolution of the S-waves in the blue box of the first figure, while the red waveforms are from the surface waves in the red box.



Waveforms after deconvolution with the record from the top floor.



One can also retrieve both a causal and acausal response from the recorded waves [Snieder *et al.*, 2006]. Deconvolution with the upgoing waves at the base (left) gives the causal response of the building when downgoing waves are not reflected at the base. Deconvolution with the downgoing waves at the base (right) corresponds to the acausal response for that case. The acausal motion differs from the time-reversed causal motion because of intrinsic attenuation in the building.

These examples show that in seismic interferometry one can indeed retrieve the response of the system for a variety of different boundary conditions. We can separate the response of the building from the coupling of the building to the subsurface by processing of the recorded data, and it is not necessary to use a numerical model of the building. The principle of changing the boundary conditions in seismic interferometry also finds application in seismic exploration where, in a collaborative project with Shell Research, we use the pressure and displacement recorded at an ocean-bottom network to remove the waves reflected from the water surface (multiples) from seismic data. ■

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