es and preconceptions must be subjected to critical scrutiny. As long as there is no explicit concern with the logic of inference—how we know what we think we know about the past—there can be no consensus.

References

1. G. A. Clark, *Am. Anthropol.* **90**, 357 (1988).
2. D. W. Frayer *et al.*, *ibid.* **95**, 14 (1993); C. B. Stringer and G. Bräuer, *ibid.* **96**, 416 (1994).
3. Tables listing the tenets of the replacement and continuity paradigms can be found at www.sciencemag.org/feature/data/990029.shl.
4. C. M. Willermet, *Am. J. Phys. Anthropol.* **18**, 207 (1994); C. M. Willermet and G. A. Clark, *J. Hum. Evol.* **29**, 487 (1995).
5. G. A. Clark, in *The Middle Paleolithic: Adaptation, Behavior and Variability*, H. Dibble and P. Mellars, Eds. (University of Pennsylvania Museum, Philadelphia, PA, 1992), pp. 183–205; *Recherche* **25**, 316 (1994); in *Conceptual Issues in Modern Human Origins Research*, G. Clark and C. Willermet, Eds. (Gruyter, New York, 1997), pp. 60–76.
6. L. G. Straus, *Nature* **342**, 476 (1989); *Evol. Anthropol.* **2**, 195 (1994).
7. P. Mellars, in *The Human Revolution*, P. Mellars and C. Stringer, Eds. (Edinburgh Univ. Press, Edinburgh, 1989), pp. 338–365; *Curr. Anthropol.* **30**, 349 (1989).
8. H. Dibble, *Am. Antiq.* **52**, 109 (1987); *J. Anthropol. Res.* **47**, 239 (1991); *J. Archaeol. Method Theory* **2**, 299 (1995).
9. C. M. Barton, N. Coinman, D. Olszewski, *J. Field Archaeol.* **23**, 111 (1996); M. Neeley and C. Barton, *Antiquity* **68**, 275 (1994).
10. G. A. Clark, *Norw. Archaeol. Rev.* **30**, 25 (1997).
11. S. Kuhn, *Mousterian Lithic Technology* (Princeton Univ. Press, Princeton, NJ, 1995); M. Stiner, *Honor Among Thieves* (Princeton Univ. Press, Princeton, NJ, 1994).
12. Standard model: R. White, in *The Human Revolution*, P. Mellars and C. Stringer, Eds. (Edinburgh University Press, Edinburgh, 1989), pp. 385–394; P. Mellars, *Curr. Anthropol.* **30**, 349 (1989). Demographic compression model: A. Marshack, *Yearb. Phys. Anthropol.* **32**, 1 (1989); J. M. Lindly and G. A. Clark, *Curr. Anthropol.* **31**, 233 (1990); A. Duff, G. A. Clark, T. Chadderdon, *Cambridge Archaeol. J.* **2**, 211 (1992); C. M. Barton, G. A. Clark, A. Cohen, *World Archaeol.* **26**, 185 (1994).
13. R. Klein, *The Human Career* (Univ. of Chicago Press, Chicago, IL, 1989); K. Feder and M. Park, *Human Antiquity* (Mayfield, Mountain View, CA, 1993); C. Jolly and R. White, *Physical Anthropology and Archaeology* (Knopf, New York, 1995); D. Johanson and B. Edgar, *From Lucy to Language* (Simon and Schuster, New York, 1996); I. Tattersall, *Becoming Human* (Harcourt, Brace, New York, 1998).

PERSPECTIVES: EARTHQUAKE GROUND MOTION

How Does the Ground Shake?

Arthur D. Frankel

When a multistory building is subjected to ground shaking from an earthquake, elastic waves travel up the structure, with some of the energy reflected at each floor and the remainder reflected from the top of the building. As the shaking continues, the structure begins to vibrate at various frequencies. Earthquakes generate ground motions over a wide range of frequencies, from static offsets to tens of cycles per second [hertz (Hz)]. Most man-made structures have natural frequencies of vibration between about 0.1 and 20 Hz; a typical 10-story building has a natural frequency around 1 Hz. Each structure is most sensitive to ground motions with frequencies near its natural frequency. Damage to a building thus depends on its properties and on the character of the earthquake ground motions, such as peak acceleration and velocity, duration, frequency content, kinetic energy, and phasing and coherence.

Enhanced online at www.sciencemag.org/cgi/content/full/283/5410/2032

One of the major goals of modern seismology is the prediction of the time series (or "time histories") of the ground motions at specific locations when a large earthquake occurs on a particular fault. These artificial time histories are then used to model the response and improve the resistance of structures such as buildings, bridges, or power plants to damage from ground shaking. Many time histories have been recorded at sites near earthquakes in the western United States and elsewhere, although these are mostly for earthquakes with magnitudes (**M**) ≤ 7. In producing artificial time histories for engineering applications, the most attention has been paid to simulating horizontal shear-wave motion (where ground motion is perpendicular to the direction of wave propagation), because it is most damaging to structures. On page 2045, O'Connell (*1*) considers an inherent property of Earth's crust that is often overlooked when ground motions are simulated: its randomness.

Predicting earthquake ground motions requires a detailed description of the source, that is, the slip between opposite sides of the fault during the earthquake rupture process, and of the path along which the seismic waves propagate from the fault to the site of interest. Variations of material properties and stress in the crust occur over a wide range of spatial scales, from the small-scale variety of minerals in a rock to the large-scale complexity of a geologic map, affecting both source and path of the seismic waves.

Earthquakes nucleate when the slip between sides of a fault accelerates in a small patch. The interaction of the resulting propagating rupture with the stress and strength variations on the fault generates seismic waves over a broad frequency range. A fractal distribution of stress release on a fault, with stress release independent of scale, can explain the white spectrum of ground accelerations commonly observed above about 1 Hz for large earthquakes (*2*).

Once generated, seismic waves are refracted and reflected by approximately horizontal boundaries in the crust. At shallow depth, seismic velocities under a site can often be approximated by horizontal layers of soil over bedrock. Multiple reflections within soil layers can cause resonances of ground motions. Superimposed on this structure variation with depth are lateral variations in rock type and composition, fractures, and fluid pressure. Variations in seismic velocity and density on a scale of tens to hundreds of meters scatter seismic waves with frequencies above about 0.5 Hz, producing much of the tail of energy observed after the arrival of shear waves traveling directly from the source. Such scattering can lower the coherence of the shear-wave motion over the dimensions of the foundation of a building, which can affect building response.

At frequencies below about 1 Hz, relatively simple deterministic models (*3*) can reproduce the strong pulse of coherent ground motion observed at locations in the direction of rupture propagation. At high frequencies above about 5 Hz, the small-scale variation of stress on the fault and scatterers in the crust affects the generation and propagation of seismic waves substantially, and stochastic approaches (*4*) are used to match the duration or envelope (or both) of the ground motion and its spectrum, rather than attempting a "wiggle for wiggle" match to observed seismograms.

In the important frequency range of 0.5 to 5 Hz, where many buildings have their natural frequencies, the deterministic and stochastic approaches need to be combined to achieve a reasonable match to observed seismograms and to produce synthetic time histories suitable for use in engineering design (*5*). It is this problematic frequency range that O'Connell addresses in his research article.

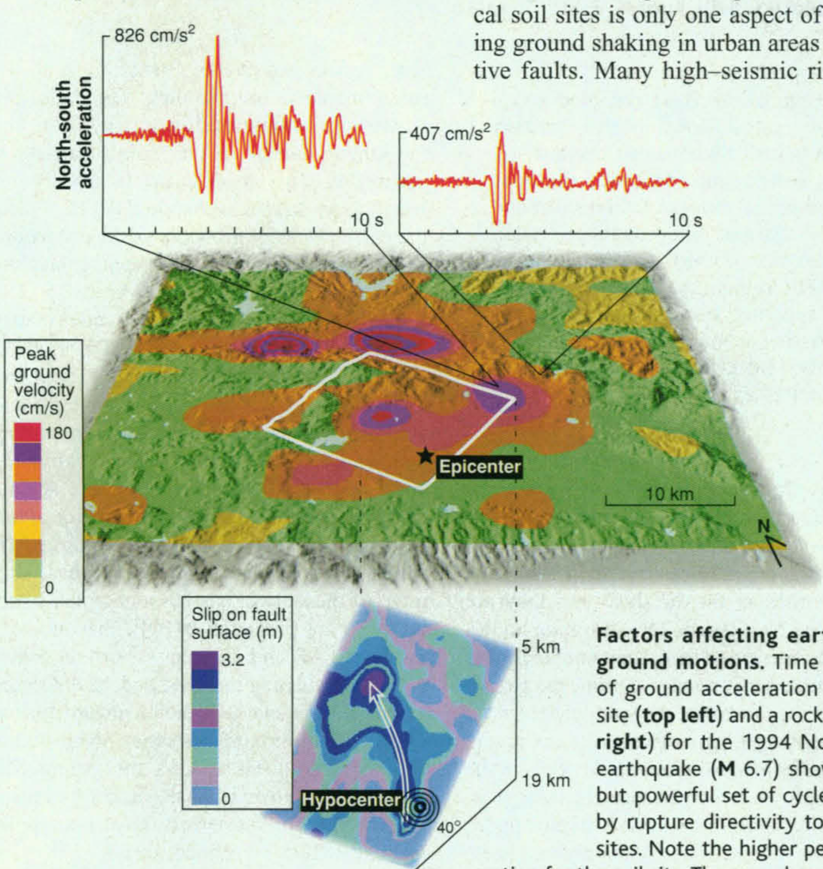
It is of particular importance to building codes and engineering design to establish what happens to seismic waves as they propagate through the unconsolidated material at shallow depths beneath a site. Soil sites amplify ground motions more than rock sites, at least at frequencies of about 2 Hz and lower, because of the lower rigidity of soils. However, laboratory experiments have demonstrated that soil behavior becomes nonlinear at the high strains achieved near large earthquakes. Such nonlinear behavior would reduce the amplitude of seismic waves at frequencies above about 2 Hz and lower resonant frequencies caused by the soil. Modern building codes such as the Uniform Building Code in the United States include nonlinear soil behavior in their amplification factors.

The author is with the U.S. Geological Survey, DFC, Denver, CO 80225, USA. E-mail: afrankel@usgs.gov

The question of nonlinear behavior during earthquakes remains controversial, particularly for the stiff soils that are common in most urban areas. Recent studies have claimed evidence for a nonlinear response of stiff soils during the **M** 6.7 Northridge earthquake of 1994 (see the figure), where the amplification between soil and rock sites was less for the mainshock shaking than for the weaker aftershock motions (*6*). O'Connell contends that this difference could be a direct result of seismic-wave scattering (*1*). If scattering is more intense under soil sites than rock sites, it could cause more incoherence of seismic energy at soil sites in the frequency range of 1 to 5 Hz. The seismic waves from the mainshock sample a wider zone of the crust than those from an aftershock, and thus scattering effects under the sites could cause different amplification factors for mainshock and aftershock motions. O'Connell simulates wave propagation through a three-dimensional random medium to show that scattering in a linear medium can, at least in some cases, mimic one of the observations cited as evidence for soil nonlinearity.

To resolve this question, we require a more thorough investigation of scattering effects. We must determine the statistical properties of velocity and density variations under typical rock and soil sites using borehole information and recordings from closely spaced seismometers. It is important to discriminate between nonlinear soil response and scattering. Nonlinear response would cause a maximum limit to ground accelerations, whereas scattering would produce occasional accelerations much larger than average.

Understanding the amplification of local soil sites is only one aspect of predicting ground shaking in urban areas near active faults. Many high–seismic risk areas are situated on deep sedimentary basins with relatively unconsolidated deposits of soil and sedimentary rock that can be several kilometers thick. The three-dimensional geometry of these sedimentary basins focuses seismic waves at certain locations, resulting in narrow zones with destructive ground motions, as illustrated by the 1995 **M** 6.9 Kobe earthquake (*7*). Seismic waves can be trapped in these basins as surface waves, causing low-frequency shaking over a long time period, which causes particular damage to tall buildings. Three-dimensional simulations of low-frequency ground motions (usually less than 1.0 Hz) in these basins have been performed (*8*), but our limited knowledge of the deep basin configuration precludes more accurate prediction of strong shaking in high–seismic risk areas such as Los Angeles, San Jose, and Seattle.



Factors affecting earthquake ground motions. Time histories of ground acceleration at a soil site (**top left**) and a rock site (**top right**) for the 1994 Northridge earthquake (**M** 6.7) show a brief but powerful set of cycles caused by rupture directivity toward the sites. Note the higher peak acceleration for the soil site. The map shows the distribution of peak velocity for this earthquake derived from strong motion recordings (*10*). High peak velocities north of the epicenter were caused by the rupture propagating upward and northward along the fault plane. The plot below the map shows the slip on the fault, the initial rupture point (hypocenter), and the direction of rupture propagation (white arrow) (*10*). Map and fault plane diagram from (*11*).

Prediction of ground shaking will always involve deterministic and random elements. The exact slip distribution and rupture directivity of future events on a specific fault are unpredictable; time histories need to be generated for a wide variety of rupture models. Focusing points in sedimentary basins are likely to vary with the location of the earthquake. However, with detailed knowledge of the basin structure, seismologists can simulate different earthquake scenarios to develop maps of mean values of ground motion parameters and their uncertainties. Probabilistic seismic hazard maps (*9*) that incorporate basin focusing effects and rupture directivity can be developed by combining simulation results with the recurrence rates of large earthquakes on specific faults derived from geological investigations.

Improved prediction of shaking and mitigation of damage in high–seismic risk areas will require urban arrays of seismometers spaced about 1 km apart and geophysical surveys to determine the detailed basin structure under these areas. Specialized arrays with even closer spacing and borehole seismometers are needed to resolve the scattering versus nonlinearity problem. By recording small earthquakes, urban arrays can be used to verify our simulations of ground motions before large events occur. When the large shocks inevitably happen, these arrays of urban seismometers will be essential in documenting the relation between ground motions and building performance.

References and Notes

1. D. R. H. O'Connell, *Science* **283**, 2045 (1999).
2. A. Frankel, *J. Geophys. Res.* **96**, 6291 (1991); D. J. Andrews, *ibid.* **86**, 10821 (1981); T. C. Hanks, *ibid.* **84**, 2235 (1979); C. H. Scholz, *Bull. Seismol. Soc. Am.* **88**, 1325 (1998).
3. D. J. Wald, D. V. Helmberger, T. H. Heaton, *Bull. Seismol. Soc. Am.* **81**, 1540 (1991); P. G. Somerville, M. K. Sen, B. P. Cohee, *ibid.*, p. 1.
4. T. C. Hanks and R. K. McGuire, *ibid.* **71**, 2071 (1981); W. J. Silva *et al.*, in *Proceedings of the 4th U.S. National Conference on Earthquake Engineering* (Earthquake Engineering Research Institute, Oakland, CA, 1990), vol 1, pp. 487–494.
5. K. Kamae, K. Irikura, A. Pitarka, *Bull. Seismol. Soc. Am.* **88**, 357 (1998).
6. E. H. Field *et al.*, *J. Geophys. Res.* **103**, 26869 (1998).
7. H. Kawase, *Seismol. Res. Lett.* **67**, 25 (1996).
8. A. Frankel, *Bull. Seismol. Soc. Am.* **83**, 1020 (1993); R. W. Graves, *ibid.*, p. 1042; K. B. Olsen, R. J. Archuleta, J. R. Matarese, *Science* **270**, 1628 (1995).
9. USGS national seismic hazard maps, available at http://geohazards.cr.usgs.gov/eq/.
10. D. J. Wald, T. H. Heaton, K. W. Hudnut, *Bull. Seismol. Soc. Am.* **86**, S49 (1996).
11. U. S. Geological Survey, *Open-File Report 96-263* (1996) (available at http://geohazards.cr.usgs.gov/northridge).