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OVERLOOKED MECHANISMS BEHIND SEISMIC DAMAGE

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Photographs of aboveground and underground structural failures after earthquakes uncover simple but not widely recognized physics.

On 17 January 1995, a devastating earthquake struck the port city of Kobe in southern-central Japan and the densely populated surrounding area. The quake, officially named the Hyogo-ken Nanbu earthquake, had a moment magnitude of 6.9. The seismic rupture initiated at a shallow depth of 16 km and propagated to the northeast and southwest along the crust's local geological fault system (figure 1a). It released tectonic energy stored on and near the fault system and converted part of that energy into seismic waves.

What made the Kobe event unusual was that seismic rupture—the slipping in Earth's crust—propagated along a fault that ran directly through a developed area with a population of more than three million. The distance between the city center and the earthquake's epicenter was only about 20 km; often it's hundreds of kilometers or more because most cities are located farther from geologic faults. The Kobe area was therefore directly hit by strong seismic waves that hadn't yet attenuated through propagation. The quake totally or partially destroyed approx-

imately 640 000 buildings throughout the area.

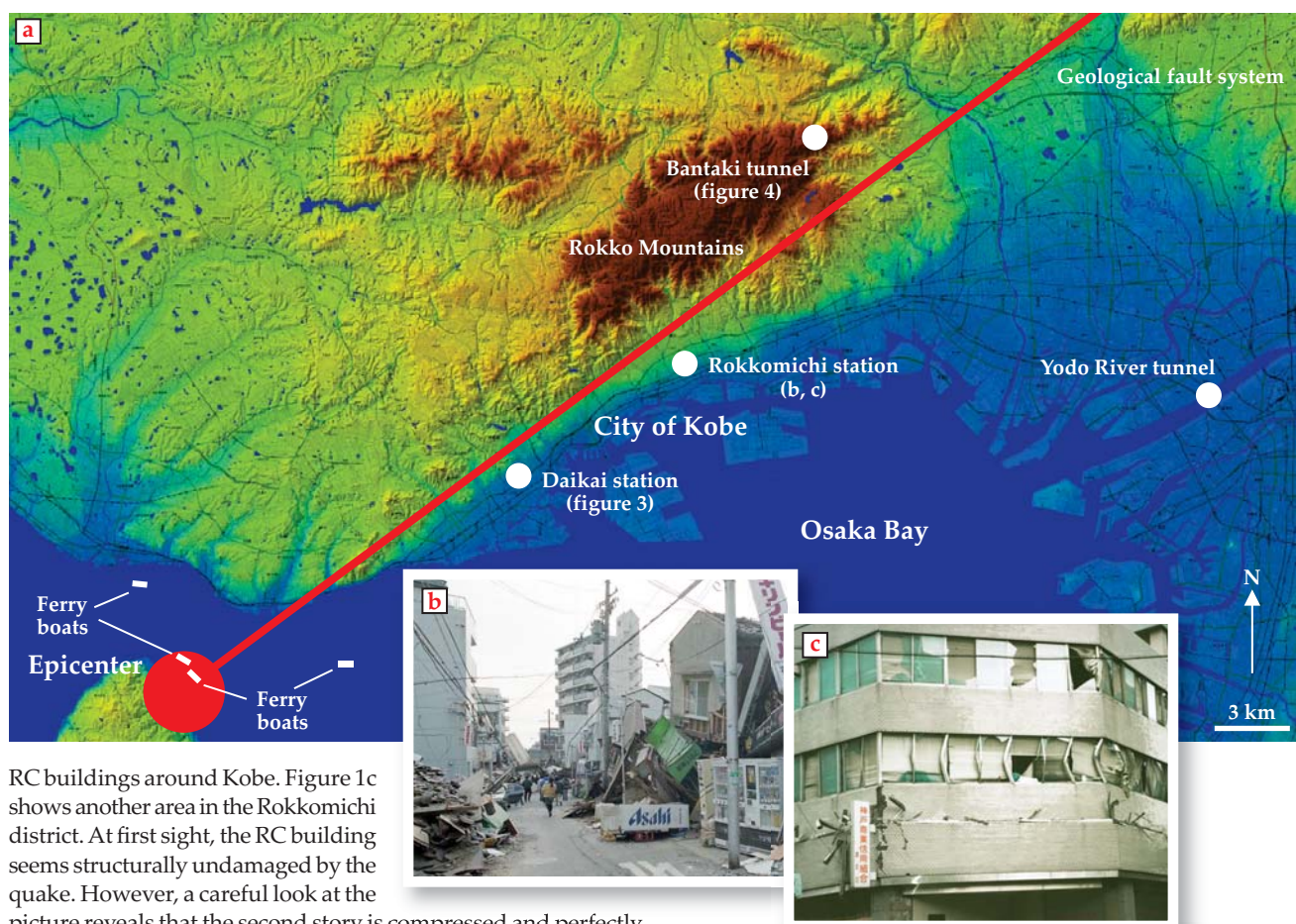
The photograph in figure 1b was taken near Kobe's Rokkomichi railway station and shows archetypal seismic disaster: Wooden houses were completely destroyed, whereas those made of reinforced concrete (RC) were left standing, seemingly unharmed. It agrees with an intuitive image of seismic disasters in which similar structures experience comparable amounts of damage.

That wasn't the case everywhere, though. Surprising structural damage was found in





A 1976 earthquake in Friuli, Italy, produced a periodic structural failure pattern in adjacent, mechanically similar buildings. (H. P. Rossmanith, Vienna University of Technology, Austria.)



RC buildings around Kobe. Figure 1c shows another area in the Rokkomichi district. At first sight, the RC building seems structurally undamaged by the quake. However, a careful look at the picture reveals that the second story is compressed and perfectly flattened. Surprisingly, the signboards remained unaffected, and the upper floors shifted vertically with almost no horizontal movement or deformation. Similar structural damage was observed in other RC buildings near the city center.

Seismic waves and structural vibrations

To understand how the Kobe earthquake caused such damage to supposedly earthquake-resistant RC buildings, we first consider the basic characteristics of typical seismic waves. In a linear elastic solid like Earth's crust, the force per unit area, or stress, in the material is linearly proportional to the local deformation per unit length, or strain.¹ Continuum mechanics accommodates two types of body waves, primary longitudinal (P) and secondary shear (S) waves. P waves propagate the fastest, and they cause the ground to move parallel to the direction of the wave's propagation (figure 2a). If they approach the surface from below, they produce vertical shaking with compressive and extensional forces. P waves can also travel through fluids. On the other hand, S waves exist only in solids. They cause motion normal to the wave's propagation direction, so if they come from below, they cause horizontal shaking with no volumetric change (figure 2b).

In addition to body waves, earthquakes also generate surface waves, typically Rayleigh (R) waves. R waves moving along a stress-free boundary like Earth's surface induce both horizontal and vertical shaking at the surface. They also attenuate more slowly than body waves as they propagate: The amplitude of an R wave decreases as $1/r^{1/2}$ with distance r from its origin,

FIGURE 1. (a) THE 1995 HYOGO-KEN NANBU EARTHQUAKE near Kobe, Japan, produced structural failures throughout the area and at the specific locations indicated. (Adapted from topographic map provided by Geospatial Information Authority of Japan and ref. 3.) **(b)** Mechanically similar structures normally suffer similar levels of damage during an earthquake. In this image taken near Rokkomichi railway station, wooden houses have collapsed while reinforced concrete buildings remain standing. (Courtesy of the City of Kobe.) **(c)** Despite being built from reinforced concrete, a nearby building had its second story vertically compressed so that it completely disappeared. High-frequency seismic waves can account for such localized damage. (Courtesy of Shunsuke Sakurai, Kobe University.)

whereas a body wave's amplitude dies off as $1/r^2$ along the surface and $1/r$ in the bulk.¹

A wave's attenuation is also affected by its frequency. Lower-frequency waves propagate farther and with less attenuation than higher-frequency ones. High-frequency P and S waves should therefore be more abundant in seismological recordings near an earthquake's focus. On the other hand, if a seismograph is installed far from the focus, lower-frequency R waves dominate the recorded shaking.

Seismologists have used the fundamental characteristics of waves described above to derive relationships between the shaking recorded by seismographs and the invisible waves that radiate from earthquake hypocenters. (See the article by Hiroo Kanamori and Emily E. Brodsky, *PHYSICS TODAY*, June 2001,

page 34.) A primary objective has traditionally been to shed light—or, more precisely, waves—on the inner structures of Earth through which seismic waves propagate. That study has focused on the far-reaching low-frequency waves that travel thousands of kilometers from hypocenters to seismological recording stations worldwide. For earthquakes, low frequency means less than 1 Hz. A 1 Hz *P* wave travels at about 6 km/s in granite, so its wavelength would be 6 km. That is sufficiently small to resolve the details of the geological structures, which are on the order of tens or hundreds of kilometers, by analyzing wave interactions such as refraction, reflection, and diffraction.

Engineers, on the other hand, are often concerned with earthquakes' effects on natural and artificial structures like slopes and buildings, whose relevant length scales range from a few to hundreds of meters—far smaller than Earth's interior structures. Low-frequency seismic waves are much longer than those structures, so their detailed features are usually not considered when designing buildings and testing their earthquake readiness. Instead, the vibrations recorded at nearby seismological stations are low-pass filtered, and target structures under test are subjected only to low-frequency horizontal vibrations. Both vertical shaking from *P* and *R* waves and dynamic interactions between incoming waves and the target are neglected.

The insights gained from that sort of conventional engineering have been invaluable. However, localized structural failures whose length scales are on the order of meters or tens of meters, like that in figure 1c, can't be straightforwardly explained by low-frequency horizontal vibrations alone. Consider a 1 Hz *S* wave that propagates at 1 km/s. Its wavelength is 1 km. If it strikes a 10-m-diameter underground tunnel from below, the phase difference between the tunnel's floor and ceiling is negligibly small. The tunnel should therefore move like a rigid body, and the wave shouldn't generate localized damage. According to that picture, a tunnel is perfectly earthquake resistant. Although that may be true if the epicenter is far from the structure and low-frequency seismic waves prevail, the situation isn't necessarily the same for structures near epicenters where high-frequency seismic waves can be dominant.

Unexpected, then forgotten

Underground structures are generally believed to be sufficiently strong against earthquakes. And usually they are. But in 1995, the Daikai railway station in downtown Kobe catastrophically failed. At the station, about 5 m below ground, vertical collapse of the reinforced concrete columns supporting the roof (figure 3a) resulted in the failure of the roof and the sinking of the street above (figure 3b).

The central section of the approximately 1750-m-long Bantaki road tunnel through the Rokko Mountains was also damaged. The concrete wall, which was reinforced with steel bars, frac-

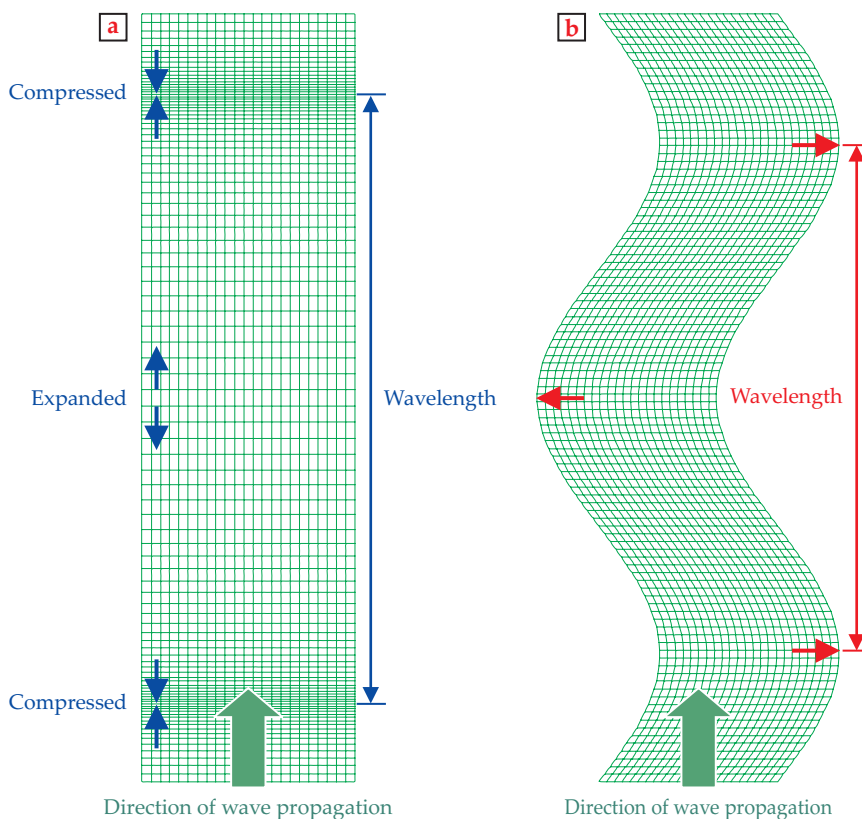


FIGURE 2. (a) A LONGITUDINAL (*P*) WAVE MOVING THROUGH A SOLID MEDIUM generates compressive and extensional motions that cause local volumetric changes in the medium. The wave moves at a constant speed through the medium. **(b) A shear (*S*) wave**, which travels at a constant speed smaller than that of a *P* wave, produces transverse or shearing motion that doesn't cause volumetric change.

tured from compressive force, and the road surface jumped up from the underlying concrete, known as the invert (see figure 4). Strangely, however, the ceiling, the invert, and the surrounding ground sustained no damage. The geological faults crossing the tunnel hadn't moved.

The unexpected failures at the Daiki station and the Bantaki tunnel were the first that could not be attributed to, say, instability near the portal of the tunnel; they may have been directly induced by seismic waves. Then, in 2004, a failure pattern similar to that in Bantaki was observed after the magnitude 6.6 Niigata-ken Chuetsu earthquake. The damage was observed in the near-epicenter Uonuma tunnel, which is part of the Shinkansen high-speed train system. Together, the observations support the idea that structural failures should be expected in underground structures sufficiently close to an earthquake's epicenter.

To understand the mechanism behind the Bantaki failure, consider a *P* wave causing vertical shaking and an *S* wave causing horizontal vibrations, both propagating up toward the tunnel (figure 4). If the *P* wave has a wavelength twice the height of the tunnel—20 m for the approximately 10-m-high Bantaki tunnel—the wave has opposite phases at the tunnel's floor and ceiling. In that case, the wave can leave the top and bottom of the tube intact while generating a large compressive stress in its midsection that destroys the concrete and bends the steel bars reinforcing the wall (figure 4). If the *P* wave's speed is



FIGURE 3. THE UNDERGROUND DAIKAI STATION in Kobe, Japan, collapsed during a 1995 earthquake. **(a)** The reinforced concrete columns supporting the roof gave way and **(b)** the street above the station sank in a 100 m × 20 m area; in some places, it fell as much as 2.5 m. The failure disproves the myth that underground structures are safe against earthquakes. (Photographs courtesy of Shunsuke Sakurai, Kobe University.)

2 km/s in the already-fractured surrounding rock, then the frequency of the incident wave would be 100 Hz, which is well into the high-frequency range.

Simple but rigorous elastodynamic analyses confirm that if 100 Hz *P* waves interacted with the tunnel, the compressive vertical stress acting on the concrete lining could become more than three times as large as that in the incident wave, and the vertical acceleration would be doubled at the tunnel's floor.² That stress and acceleration can explain why the tunnel's concrete lining failed in compression and why the road surface detached in response to the earthquake. On the other hand, high-frequency *S* waves and conventional low-frequency waves produce much smaller vertical compressive stress on the wall and acceleration at the bottom. Hence, it seems unlikely that they generated the failures in Bantaki. High-frequency *P* waves are also a likely culprit for the flattened second floor in figure 1c and the collapsed Daikai station in figure 3.^{3,4}

The question of detection

Although the unusual structural failure patterns observed after the 1995 Kobe earthquake suggest the existence of higher-frequency vertically oscillating seismic waves, the seismographs widely installed at that time had sensitivities that fell drastically for frequencies above 20 Hz. Additionally, shaking over 10 Hz was filtered out in seismic analyses because of contamination by scattering off inhomogeneities. Strong high-frequency vibrations were therefore scarcely detected at Kobe (figure 5a) despite multiple accounts from people who experienced strong vertical shocks near the earthquake's epicenter.

Vertical shocks were even felt on ferries (identified in figure 1a) and fishing boats that were at sea during the seismic event.^{3,5} Vertical disturbances at sea, known as seaquakes, are felt only near earthquake epicenters. Thousands have been reported, but few are listed in reports like Lloyd's List, which tracks maritime incidents. Thus the study of the vertical shocks near epicenters is difficult.³

The failure of the concrete lining in Bantaki was nearly forgotten, and the potential importance of higher-frequency seismic waves largely ignored, until a pair of earthquakes occurred in Kumamoto in 2016. A magnitude 6.2 quake struck the city on the island of Kyushu at 9:26pm on 14 April and was followed

by an even-stronger magnitude 7.0 main shock at 1:25am on 16 April. The events were enlightening because they produced clear and significant evidence of dominant higher-frequency vertical shaking near their epicenters.

As usual, horizontal vibrations prevailed below 1 Hz. But seismograms of the main shock that were recorded with upgraded seismographs in Uki some 20 km away displayed a peak in vertical shaking just below 10 Hz (figure 5b), which indicates that vertical rather than horizontal shaking dominated in the high-frequency range. Although the exact geological situation in Uki differs from that in Kobe, the clear detection of dominant high-frequency waves near the epicenter of a seismic event of similar magnitude and focal depth gives credence to anecdotal accounts from Kobe more than 20 years after the quake.

Evidence is still lacking for the 100 Hz waves estimated from the Bantaki failure. Even upgraded seismographs are not sensitive to seismic waves of 100 Hz, and signals become contaminated by scattering above 10–20 Hz. The signals are not impossible to record: Sensors that detect vibrations from blasting can capture frequencies up to 1 kHz. But to capture an earthquake's signal without undue noise, specialized sensors appropriate for the frequency range and duration still need to be developed. Even though such high frequencies generated by earthquakes have not yet been recorded, it's conceivable they exist.^{4,6}

Dynamically deformed town

Small-scale earthquake-induced failures point to a need for seismographs that are more sensitive to high frequencies. However, even horizontal vibrations well within the range being recorded can cause unusual damage on the scale of a single structure. A building or tunnel can be deformed by seismic waves, but so can an entire town.



Nearly half a century ago, an astonishingly periodic structural failure pattern was seen in Italy after the magnitude 6.5 Friuli earthquake (see opening figure). The quake produced an alternating pattern of collapsed and undamaged buildings near the epicenter. In a traditional seismic model, if mechanically and geologically similar buildings are densely packed and subjected to the same seismic waves, they all experience the

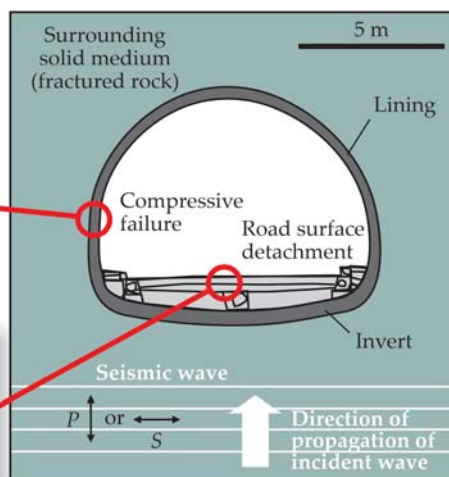


FIGURE 4. THE BANTAKI TUNNEL experienced unfamiliar structural damage during the Hyogo-ken Nanbu earthquake. A high-frequency *P* wave impinging on the tunnel could have caused vertical shaking that dynamically compressed the tunnel and caused the failure observed in Bantaki—namely, the fracture of the concrete wall and the detachment of the road from the tunnel's underlying concrete. An *S* wave with horizontal vibration could not have produced the necessary compressive force in the tunnel's wall. (Photographs courtesy of Shunsuke Sakurai, Kobe University.)

same level of shaking and damage. Buildings at different locations become effectively identical: If a vibration is sufficiently strong to induce collapse of a single building, then all the buildings will collapse. However, that assumes unrealistic waves of infinitely large wavelength, akin to the rigid shaking of a table in a laboratory experiment (upper panel of figure 6).

Buildings subjected to identical vibration can be endowed with different mechanical characteristics to model the nonuniform levels of damage observed in real earthquakes. But that doesn't explain the regularly alternating damage to similar structures in the opening image. The surprising failure pattern arises naturally, however, if waves with wavelengths on the order of a few buildings are accounted for. Even if only conventional *S* waves with horizontal shaking are assumed, the inclusion of higher-frequency waves and the dynamic interaction between waves and the buildings results in individual buildings in a densely built town experiencing totally dissimilar vibrations.

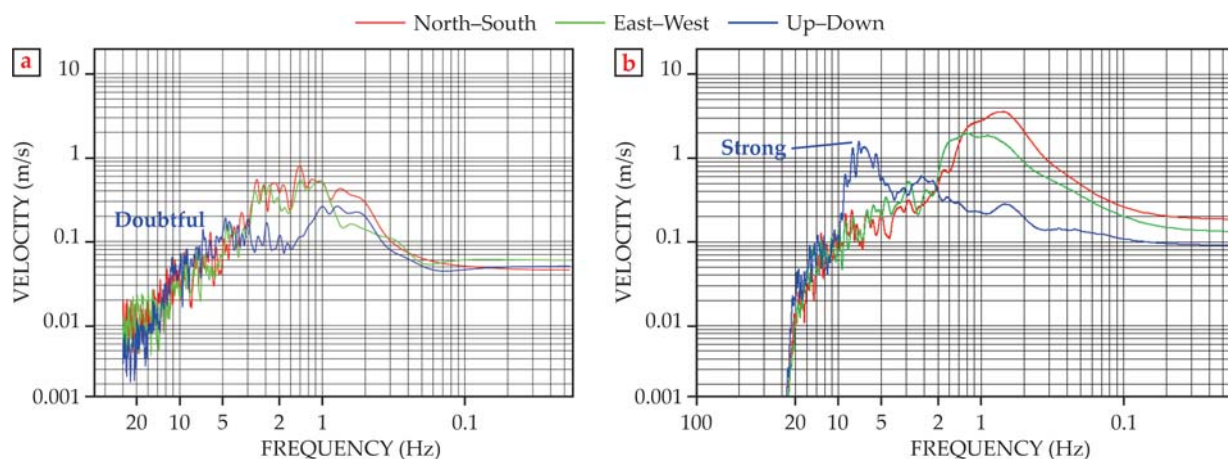


FIGURE 5. THE FOURIER SPECTRA OF SEISMOGRAMS show the vibrations recorded for (a) the 1995 Hyogo-ken Nanbu earthquake and (b) the 2016 Kumamoto earthquake. Contrary to verbal anecdotes of vertical shocks during the earliest stage of seismic shaking in the 1995 event, a seismogram recorded in Kobe, just 16 km from the epicenter, suggests that the up and down vibrations from *P* waves were weak and that horizontal shaking was dominant. However, it's not clear that seismographs at the time would have been able to detect high-frequency vibrations. Upgraded seismographs deployed during the 2016 quake captured the arrival of stronger *P* waves. Dominant high-frequency vertical motion was recorded in Uki, 14 km from the epicenter. (Based on online data provided by the Japan Meteorological Agency, <https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin>. Site is in Japanese.)

In a town's fundamental vibrational mode, illustrated in the center panel of figure 6, the buildings at the center of the town vibrate the most whereas those at the edges experience no translational motion. In a higher mode, depicted in the lower panel, every other building may vibrate strongly while the others remain at rest. That disparity in the mechanical behavior of each building is called the town or city effect.⁷ In Friuli, where the speed of an S wave through the soft soil is about 225 m/s, generating damage by that mechanism would require a wave with a frequency of about 4 Hz and a wavelength of about 60 m. Those parameters are consistent with the dominant frequencies recorded at the nearby Tolmezzo-Ambiesta dam during the Friuli 1976–77 earthquake sequence. The magnitude 6.2 Dinar earthquake in Turkey in October 1995 produced a similar periodic failure pattern.

The idea that urban areas might interact differently with seismic waves was theoretically developed in France. It appeared after the 1985 Michoacán earthquake that generated severe damage in Mexico City.⁸ Classical computational methods could not explain seismic records, and researchers wondered whether some of the seismic energy transmitted to the buildings could still affect neighboring buildings through interactions between vibrating structures and waves in the ground.

It's hard to imagine the ground under one's feet dynamically deforming on such short length scales. But during the 1995 Kobe event, a surveyor working in a straight, flat section of a railway tunnel 40 m below the Yodo River in Osaka, more than 40 km from the epicenter (figure 1a), reported just that. He saw the tunnel horizontally winding with apparent amplitude of about 1 m and wavelength of 40–50 m, which supports the idea of town-scale dynamic ground deformation.⁵

Higher or lower?

The now-dated photographs of Kobe and Bantaki point to the possibility that high-frequency seismic waves have had previously unrecognized effects on structures near earthquake epicenters. The images show damage that cannot be explained systematically using conventional low-frequency approaches. In their foundational textbook *Quantitative Seismology: Theory and Methods* (1980), Keiiti Aki and Paul Richards summarized classical, low pass-filtered seismology,⁹ which is now intensively employed in seismic research. However, in a 2005 historical overview of the field, Aki noted that even with the improved quality and quantity of seismological data and associated computational processing capabilities, it's hard to incorporate waves above 1 Hz into traditional low-frequency seismology models.⁶

Some earthquake scientists have long acknowledged the significance of including higher frequencies in their studies. A stochastic approach to seismology developed in the 1980s incorporates Earth's smaller-scale seismic inhomogeneities and accepts the presence of so-called coda waves, which decay slowly relative to other seismological signals. The scattering of high-frequency coda waves is used to study geological inhomogeneities.¹⁰

Research in engineering seismology is advancing in the opposite direction—to even lower frequencies. In 2011 long-wavelength vibrations from a magnitude 9.1 earthquake off the Pacific coast of Tohoku in northeastern Japan delivered long-lasting and large-amplitude shaking to the higher stories of

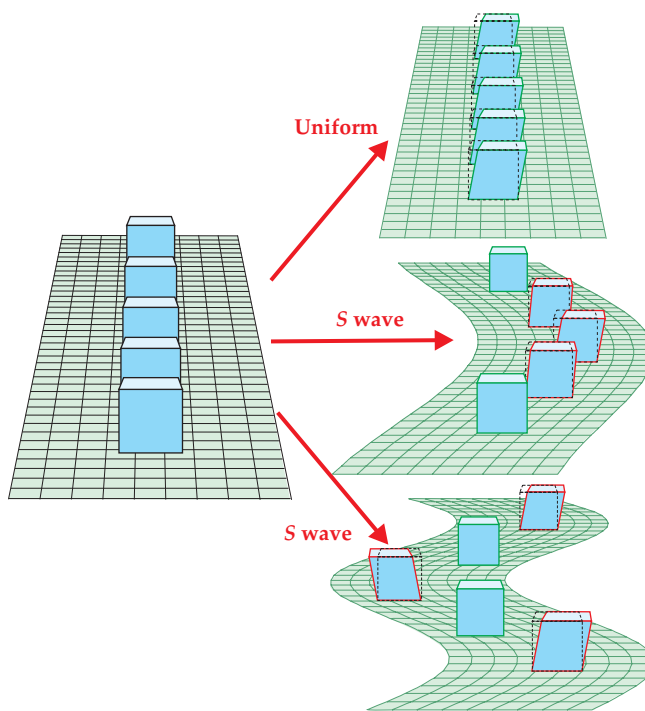


FIGURE 6. THE TOWN EFFECT challenges the conventional idea that earthquakes generate rigid-body shaking of unbending ground. Uniform shaking (top right) should cause the same level of vibration and damage to mechanically identical buildings; it can't generate the alternating failure pattern in the opening image. However, S waves propagating through a densely built town can deform the ground and deliver dissimilar vibrations and damage to identical buildings (center and lower right). The frequency of the vibration determines the damage pattern. (Adapted by Donna Padian from the author's original.)

skyscrapers in Osaka, about 700 km from the epicenter. Accounting for increasingly lower frequencies would certainly be useful in such cases. But although low-frequency analyses can teach us many meaningful things, they cannot tell us everything. The importance of higher-frequency seismic waves should also be recognized in engineering research. Waves both above and below the normal frequency range are needed to better understand the mechanisms behind the wide variety of earthquake damage.

REFERENCES

1. K. F. Graf, *Wave Motion in Elastic Solids*, Clarendon Press (1975).
2. K. Uenishi, *ASME J. Appl. Mech.* **79**, 031014 (2012).
3. K. Uenishi, *Annu. Rev. Earth Planet. Sci.* **46**, 387 (2018).
4. S. Sakurai, K. Uenishi, *J. Jpn. Soc. Civil Eng.* **90**(6), 48 (2005; in Japanese).
5. Y. Kawata, *Kagaku* **66**, 70 (1996; in Japanese).
6. K. Aki, *J. Seism. Soc. Jpn. 2nd Ser.* **57**, 317 (2005).
7. K. Uenishi, *Rock Mech. Rock Eng.* **43**, 811 (2010); M. Ghergu, I. R. Ionescu, *Int. J. Eng. Sci.* **47**, 342 (2009).
8. A. Wirgin, P.-Y. Bard, *Bull. Seismol. Soc. Am.* **86**, 914 (1996); P. Guéguen, P.-Y. Bard, F. J. Chávez-García, *Bull. Seismol. Soc. Am.* **92**, 794 (2002); C. Boutin, P. Roussillon, *Bull. Seismol. Soc. Am.* **94**, 251 (2004).
9. K. Aki, P. G. Richards, *Quantitative Seismology: Theory and Methods*, W. H. Freeman & Co (1980).
10. H. Sato, M. C. Fehler, *Seismic Wave Propagation and Scattering in the Heterogeneous Earth*, Springer-Verlag (1998).